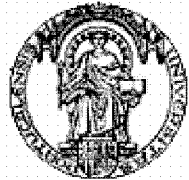


Faculty of Engineering of Porto University  
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STUDY OF THE RHEOLOGY OF DEFORMABLE  
POROUS MEDIA:  
APPLICATION TO PAPER PRODUCTION

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To my parents and brother

To Rafael and Hilário





## *Que escada de Jacob?*

a meu pai

10 de Dezembro de 2003

Na noite em que a lua foi pisada pela primeira vez,  
ainda a preto e branco a sua imagem,  
escafandros brancos, o reflexo do sol nas lentes baças,  
a escada que descia, o pó sem gravidade que a bota levantou,  
tão branco e mágico,  
nessa magia de duas da manhã, hora local, daqui,  
estavas comigo.

Comemos sopa às quatro da manhã,  
e eu vejo ainda aquela sala, a mesa lá ao fundo,  
o sofá grande, e eu de onze a sentir-me grande,  
porque assim me fazias e falavas.  
A lua a ser pisada: humana condição  
pela primeira vez.

No dia em que as ciências em exame mais longo se faziam,  
eu sem saber o grau das equações, que incógnitas havia  
a resolver, era verão e o sol do lado esquerdo,  
à esquerda da imagem tripartida à minha frente,  
teimando-me a ignorância,  
nessa angústia menor de três da tarde,  
sabia-te sentado atrás de mim, na carteira de trás,  
à espera, atravessado de nervos e ternura.

Passei. E vejo ainda o teu sorriso,  
o pó sem gravidade no olhar, e eu, quinze anos a sentir-me grande,  
porque assim me parecia.  
Uma galáxia à solta pelo corpo e o calor do sol  
tão transparente.

No dia em que o meu corpo se atravessou de nova dor,  
quase rasgado a meio, a luz do sol entrando  
pela janela antiga, os tectos altos, brancos,  
batas como escafandros,  
nesse dia tão longo em que o sol caminhou até ao fim,  
para do fim nascer, estiveste sempre lá.

Vejo-te ainda encostado à ombreira dessa porta alta,  
a voz dos escafandros tentando sossegar-te,

---

e tu, a soluçar baixinho, dividido entre amor  
e alegria.

Na noite em que a lua te deixou,  
em que deixaste de sentir a sua luz, o mais trémulo toque, tudo  
o que assim nos faz: frágil, imensa, humana condição,  
na noite dos fantasmas e escafandros cinzentos,  
eu não estava contigo.

A que sabia a sopa que comemos?  
Que escada de Jacob?

( Ana Luísa Amaral, in *UPorto*, Nº 11, Março de 2004)

# Abstract

Impulse drying technology is envisaged as a promising dewatering technique that combines the effect of mechanical pressure and intense heat, applied to paper in the press section of a paper machine, over a very short period of time. The combined action of such extreme operating conditions is expected to increase the dewatering rate, density and smoothness of paper along with a few other properties that are crucial in order to improve paper quality and performance according to its end use. Despite its potential benefits, the implementation of an impulse drying unit in the press section of a paper machine is regarded with caution. In fact, its industrial acceptance has been delayed by some difficulties in controlling the physical properties of the paper web under such intense conditions. Delamination has been pointed out as the main obstacle to the commercialization of impulse drying technology.

Understanding the mechanisms of heat and mass transfer along with the rheological behavior of paper within the impulse unit has been a matter of exhaustive study over the last three decades. Insight into the consolidation mechanism of paper using this high-intensity process is fundamental and may be gained by modeling and simulation of the transport phenomena involved in such process.

Transport phenomena inside paper are a complex subject because the cellulose fiber network does not remain inert during the drying/pressing process. For instance, water and water vapor interact with fibers; absorption of water in fibers leads to swelling that changes the porous structure of the fibrous network; water also influences the thermal conductivity and other physical properties of paper; and permeability, seen as an important factor controlling the development of internal vapor, is another relevant property that greatly depends on the structure of the porous material under study. One central issue in any investigation of the dewatering process by impulse drying is also the stress-strain behavior of the material.

The focus of this work is, therefore, on developing a mathematical description of the stress-strain behavior of the material taking into account the heat and mass transfer phenomena that may occur under specific operating conditions. The first part of this investigation was dedicated to setting up a laboratory platen press in order to simulate an impulse drying event allowing to acquire temperature, pressure and displacement experimental data. These results are fundamental to

the validation of the theoretical models developed in the present study.

The mathematical model presented here describes the simultaneous heat and mass transfer during the consolidation of paper and its supporting material, *i.e.* the felt. The role of multiphase flow in fibrous materials during high-intensity drying is of special interest, as liquid flow and steam formation are fundamental issues that need to be considered in the study of almost every paper grade. In addition, both paper and felt are considered to behave as viscoelastoplastic materials when submitted to a loading/deloading program. The stress-strain behavior is modeled according to the theory of cellular solids often used to describe the deformation and collapse of porous materials with an internal structure similar to that of honeycombs and foams.

The 3D unsteady-state global model was solved using a finite differences scheme for the spatial discretization of variables, and the resulting set of ODE's was solved using an integrator for *stiff* equations based on the Gear method. The model was used to predict the evolution of strain, elastic and viscous moduli, density, temperature, moisture ratio, pore saturation and gas pressure with time and at any given position in both paper and felt. It was concluded that the model can predict in an acceptable way the evolution of the key variables of the process and properties of the materials under study. However, given the complexity of the model, and the process itself, the numerical resolution of the resulting set of equations would most benefit from more advanced numerical and computational means.

# Sumário

A tecnologia de secagem por impulso térmico é encarada como uma técnica promissora na remoção de água, que combina o efeito da pressão mecânica e do calor intenso aplicados durante um curto período de tempo ao papel na secção de prensagem de uma máquina de papel. A acção combinada de condições de operação tão extremas pressupõe o aumento da taxa de remoção de água, da densidade e da lisura do papel, bem como de outras propriedades cruciais à melhoria da qualidade e do desempenho do papel de acordo com o fim ao qual se destina. Apesar dos seus potenciais benefícios, a implementação de uma unidade de secagem por impulso térmico na secção de prensagem de uma máquina de papel é encarada com precaução. De facto, a sua aceitação a nível industrial tem sido retardada devido a dificuldades no controlo das propriedades físicas da folha de papel quando sujeita a tais condições extremas. A delaminação do papel tem sido referida como o principal obstáculo à comercialização da tecnologia de secagem por impulso térmico.

Compreender os mecanismos de transferência de massa e calor, assim como o comportamento reológico do papel no interior de uma unidade de impulso térmico, tem sido o alvo de um estudo exaustivo nas três últimas décadas. O conhecimento do mecanismo de consolidação da folha de papel por este processo intensivo é fundamental, e pode ser obtido pela modelização e simulação dos fenómenos de transporte envolvidos no processo.

Os fenómenos de transporte no interior da folha de papel são um assunto complexo uma vez que a rede de fibras de celulose não permanece inerte durante o processo de prensagem/secagem. Como exemplo, a água e o vapor de água interagem com as fibras; a absorção de água pelas fibras provoca o seu inchamento, alterando a estrutura porosa da rede fibrosa; a água também influencia a condutividade térmica e outras propriedades físicas do papel; e a permeabilidade, vista como um importante factor no controlo da formação de vapor no interior da folha, é também uma propriedade que depende fortemente da estrutura do material poroso em estudo. Uma questão central em qualquer investigação do processo de remoção de água por impulso térmico é, também, o comportamento do material à compressão.

O ponto central deste trabalho é, por isso, o desenvolvimento da descrição matemática da resposta em deformação do material à compressão, tendo em

conta os fenômenos de transferência de massa e calor que podem ocorrer sob determinadas condições de operação. A primeira parte deste trabalho de investigação foi dedicada à preparação de uma prensa laboratorial de pratos planos, com o intuito de simular a prensagem por impulso térmico, permitindo assim a recolha de dados experimentais de temperatura, pressão e deformação. Estes resultados são fundamentais para a validação dos modelos teóricos desenvolvidos no presente trabalho.

O modelo matemático aqui apresentado descreve a transferência simultânea de calor e massa no decorrer da consolidação da folha de papel e do material de suporte, *i.e.* o feltro. O papel do escoamento multifásico em materiais fibrosos durante a secagem a elevada temperatura e pressão reveste-se de especial importância, uma vez que o escoamento da fase líquida e a formação de vapor são questões fundamentais que deverão ser consideradas no estudo de quase todos os tipos de papel. Adicionalmente, assumiu-se que tanto o papel como o feltro se comportam como materiais viscoelastoplásticos quando submetidos a um programa de compressão/descompressão. A modelização da resposta em deformação do material à compressão é baseada na teoria dos sólidos celulares, várias vezes usada na descrição da deformação e colapso de materiais porosos com uma estrutura interna semelhante à de espumas e materiais com estrutura tipo “ninho de abelha”.

O modelo global 3D em estado não estacionário foi resolvido usando o método das diferenças finitas para a discretização espacial das variáveis, e o sistema de EDO's resultante foi resolvido usando um integrador para equações *stiff* baseado no método de Gear. O modelo foi usado para prever a evolução da deformação, módulo de elasticidade e parâmetro viscoso, densidade, temperatura, teor de humidade, saturação e pressão da fase gasosa com o tempo e em determinada posição do papel e do feltro. Concluiu-se que o modelo consegue prever, de forma aceitável, a evolução das principais variáveis do processo e das propriedades dos materiais em estudo. Contudo, dada a complexidade do modelo, e do próprio processo, o uso de métodos numéricos e computacionais mais avançados beneficiariam significativamente a resolução numérica do sistema de equações resultante.

# Sommaire

La technologie de séchage par impulsion thermique est envisagée comme une technique prometteuse dans l'élimination d'eau, qui combine l'effet de la pression mécanique et de la chaleur intense appliquées pendant une courte période de temps au papier dans la section de pressage d'une machine à papier. L'action conjointe des conditions d'opération si extrêmes résulte dans l'augmentation du taux d'élimination d'eau, de la densité et de la lisure du papier, ainsi que d'autres propriétés cruciales à l'amélioration de la qualité et de la performance du papier selon les usages auxquels il est destiné. Malgré ses potentiels bénéfiques, la mise en oeuvre d'une unité de séchage par impulsion thermique dans la section de pressage d'une machine à papier est envisagée avec précaution. En effet, son acceptation à niveau industriel a été retardée dû à des difficultés dans le contrôle des propriétés physiques de la feuille soumises à telles conditions extrêmes. La délamination du papier a été rapportée comme le principal obstacle à la commercialisation de la technologie de séchage par impulsion thermique. Comprendre les mécanismes de transfert de masse et de chaleur, ainsi que le comportement rhéologique du papier à l'intérieur d'une unité d'impulsion thermique, a été l'objet d'une étude exhaustive dans les trois dernières décennies. La connaissance du mécanisme de consolidation de la feuille à papier par ce processus intensif est fondamentale, et peut être obtenue par la modélisation et la simulation des phénomènes de transport impliqués dans le processus.

Les phénomènes de transport à l'intérieur de la feuille constituent un sujet complexe car le réseau de fibres de cellulose ne reste pas inerte pendant le processus de pressage/séchage. Par exemple, l'eau liquide et sa vapeur interagissent avec les fibres; l'absorption d'eau par les fibres provoque son gonflement, modifiant la structure poreuse du réseau fibreux; l'eau aussi influence la conductivité thermique et d'autres propriétés physiques du papier; et la perméabilité, vue comme un important facteur dans le contrôle de la formation de la vapeur à l'intérieur de la feuille, est aussi une propriété qui dépend fortement de la structure du matériau poreux sous étude. Une question centrale dans quelque recherche du processus d'élimination d'eau par impulsion thermique est, aussi, le comportement du matériau à la compression.

Le point central de ce travail est donc, le développement de la description mathématique du comportement du matériau à la compression, en tenant compte

les phénomènes de transfert de masse et de chaleur qui peuvent se produire sous certaines conditions d'opération. La première partie de ce travail de recherche a été consacrée à la préparation d'une presse pleine de laboratoire, avec l'intention de simuler le pressage par impulsion thermique, en permettant d'obtenir des données expérimentales de température, contrainte et déformation. Ces résultats sont fondamentaux pour la validation des modèles théoriques développés dans le présent travail.

Le modèle mathématique ici présenté décrit le transfert simultané de masse et de chaleur pendant la consolidation de la feuille et du matériau de support, c.à.d. le feutre. Le rôle de l'écoulement multiphasique dans des matériaux fibreux pendant le séchage à des hautes températures et pressions est d'intérêt spécial, car l'écoulement de la phase liquide et la formation de la vapeur posent des questions fondamentales qui devront être considérées dans l'étude de la majorité des papiers. D'autre part, on a supposé que soit le papier soit le feutre se comportent comme des matériaux viscoelastoplastiques lorsqu'ils sont soumis à un programme de compression/décompression. La modélisation de la déformation du matériau en compression s'est basée sur la théorie des solides cellulaires, souvent utilisée dans la description de la déformation et du collapse des matériaux poreux ayant une structure interne similaire à des mousses et matériaux ayant une structure du type "nid d'abeille".

Le modèle global 3D en régime transitoire a été résolu en utilisant la méthode des différences finies pour la discretisation spatiale des variables, et l'ensemble d'EDO's résultant a été résolu en utilisant un intégrateur pour des équations *stiff* basé sur la méthode de Gear. Le modèle a été utilisé pour prévoir l'évolution de la déformation, module d'élasticité et paramètre visqueux, densité, température, teneur en eau, saturation et pression de la phase gazeuse en fonction du temps et de la position dans le papier et le feutre. On a conclu que le modèle prévoit, de façon acceptable, le comportement des principales variables du processus et des propriétés des matériaux sous étude. Néanmoins, du fait de la complexité du modèle, et du processus lui-même, l'utilisation des méthodes numériques et informatiques plus avancées bénéficieraient significativement la résolution numérique du système d'équations résultant.



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# Nomenclature

## Acronyms

|       |                                                           |
|-------|-----------------------------------------------------------|
| CD    | Cross machine direction                                   |
| CEPI  | Confederation of European Pulp and Paper Industry         |
| CHP   | Combined Heat and Power (“Co-generation”)                 |
| CSF   | Canadian standard freeness                                |
| EEA   | European Economic Area                                    |
| EFPG  | Ecole Francaise de Papeterie et des Industries Graphiques |
| ENP   | Extended Nip Presses                                      |
| EU    | European Union                                            |
| FIR   | Finite Impulse Response Filter                            |
| FPPRI | Finish Pulp and Paper Research Institute                  |
| GDP   | Gross Domestic Product                                    |
| HAPID | High Ambient Pressure Impulse Dryer                       |
| IIR   | Infinite Impulse Response Filter                          |
| IPC   | Institute of Paper Chemistry                              |
| IPCC  | Intergovernmental Panel on Climate Change                 |
| IPCP  | Integrated Prevention and Control of Pollution            |
| IPST  | Institute of Paper Science and Technology                 |
| KTH   | Royal Institute of Technology                             |
| LNP   | Long Nip Presses                                          |
| LVDT  | Linear Variable Displacement Transducer                   |
| LWC   | Light weight coated                                       |
| MD    | Machine direction                                         |
| MDF   | Medium density fibreboard                                 |
| MIPPS | Moving Interface Problems in Porous Systems               |
| MTS   | Material Test system                                      |
| ODEs  | Ordinary differential equations                           |
| PDEs  | Partial derivative equations                              |

|       |                                                          |
|-------|----------------------------------------------------------|
| SBK   | Softwood bleached kraft pulp                             |
| STFI  | Swedish Pulp and Paper Research Institute                |
| TMA   | Thermomechanical Analysis                                |
| TMP   | Thermomechanical pulp                                    |
| UMO   | University of Maine at Orono                             |
| UNCED | United Nations Conference on Environment and Development |
| 3D    | Three-dimensional                                        |
| 2D    | Bidimensional                                            |



|                 |                                                                              |              |
|-----------------|------------------------------------------------------------------------------|--------------|
| $A$             | contact surface area                                                         | $[m^2]$      |
| $a$             | parameter of the Silvy's model                                               | $[-]$        |
| $a^*, b^*$      | coefficients of proportionality                                              | $[-]$        |
| $A_1, A_2$      | parameters                                                                   | $[-]$        |
| $a_1, a_2, a_3$ | parameters of the sorption isotherm                                          | $[-]$        |
| $A_e$           | felt surface area exposed to the applied stress<br>in the Métravib apparatus | $[m^2]$      |
| $A_i$           | cross sectional area occupied by i ( $i = f, s, g, l$ )                      | $[m^2]$      |
| AKD             | alkyl ketene dimmer                                                          |              |
| $a_M, b_M$      | parameters of the permeability model (Mulder)                                | $[m^2], [-]$ |
| $A_T$           | total surface area of the web                                                | $[m^2]$      |
| $a_v$           | parameter of the permeability model (Vomhoff)                                | $[m^2]$      |
| $a_{xy}$        | parameter of the in-plane permeability model<br>(Reverdy-Bruas)              | $[m^2]$      |
| $A_z$           | surface area of the cell (RVE) open to fluid                                 | $[m^2]$      |
| $a_z$           | parameter of the transversal permeability model<br>(Reverdy-Bruas)           | $[m^2]$      |
| $b$             | parameter of the Silvy's model                                               | $[-]$        |
| $B_m$           | felt stiffness                                                               | $[N.m^{-1}]$ |
| $B_{m_i}$       | stiffness of each felt sample in a series<br>arrangement                     | $[N.m^{-1}]$ |
| $b_v$           | parameter of the permeability model (Vomhoff)                                | $[-]$        |
| $b_{xy}$        | parameter of the in-plane permeability model<br>(Reverdy-Bruas)              | $[-]$        |
| $b_z$           | parameter of the transversal permeability<br>model (Reverdy-Bruas)           | $[-]$        |
| $c$             | parameter of the Silvy's model                                               | $[-]$        |
| $C_1$           | constant of proportionality                                                  | $[-]$        |
| $C_2$           | linear elastic constant                                                      | $[-]$        |
| $C_3$           | constant (equal to $\varepsilon_y$ for $C_2 = 1$ )                           | $[-]$        |
| CC              | calcium carbonate                                                            |              |

|                                 |                                                                 |                       |
|---------------------------------|-----------------------------------------------------------------|-----------------------|
| $CCM$                           | creep compliance modulus                                        |                       |
| $cf$                            | compressibility factor (also denoted as $b_8$ )                 | [-]                   |
| $[C_{fiber}]$                   | fiber concentration                                             | $[g.cm^{-3}]$         |
| $C_p$                           | specific heat capacity of paper                                 | $[kJ.kg^{-1}.K^{-1}]$ |
| $C_p$                           | dimensionless specific heat capacity of paper                   | [-]                   |
| $C_{pi}$                        | specific heat capacity of i (i = air, b, dry, g, l, v)          | $[kJ.kg^{-1}.K^{-1}]$ |
| $C_{pi}$                        | dimensionless specific heat capacity of i                       | [-]                   |
| $CR$                            | compression ratio                                               | [-]                   |
| CS                              | cationic starch                                                 |                       |
| $Cst', Cst''$                   | constants                                                       | $[m^2], [-]$          |
| $Cst_1 \dots Cst_7$             | parameters of the sorption isotherm                             |                       |
| $c_{xy}$                        | parameter of the in-plane permeability model (Reverdy-Bruas)    | $[m^2]$               |
| $c_z$                           | parameter of the transversal permeability model (Reverdy-Bruas) | $[m^2]$               |
| $D_{AB}$                        | diffusivity of air-water mixture                                | $[m^2.s^{-1}]$        |
| $D_c$                           | critical hydraulic diameter                                     | $[m]$                 |
| $D_i^{eff}$                     | effective diffusivity of water vapor                            | $[m^2.s^{-1}]$        |
| $D_i^{eff}$                     | dimensionless effective diffusivity of water vapor              | [-]                   |
| $D_{felt}$                      | felt diameter                                                   | $[m]$                 |
| $D_h$                           | hydraulic diameter                                              | $[m]$                 |
| $D_h^o$                         | dimensionless hydraulic diameter                                | [-]                   |
| $\langle D_{h_{Silvy}} \rangle$ | mean hydraulic diameter                                         | $[m]$                 |
| $ds$                            | dry solids                                                      |                       |
| $d_{xy}$                        | parameter of the transversal permeability model (Reverdy-Bruas) | [-]                   |
| $d_z$                           | parameter of the transversal permeability model (Reverdy-Bruas) | [-]                   |
| $E$                             | elasticity or Young's modulus                                   | $[Pa]$                |
| $e$                             | parameter of the Silvy's model                                  | [-]                   |
| $(E^F)^*$                       | felt rigidity modulus                                           | $[Pa]$                |
| $E_A$                           | elastic parameter of the rheological model suggested by Lopez   | $[Pa]$                |
| $E_B$                           | elastic parameter of the rheological model suggested by Lopez   | $[Pa]$                |
| $E_{ffit}$                      | parameter of the fitting to determine $E_f$                     | $[MPa]$               |
| $E_i$                           | elasticity modulus of i (i = l, g, f, m, a, fluid, s, cw)       | $[Pa]$                |
| $E_{ij}$                        | elastic parameter of each ij column                             | $[Pa]$                |
| $E_{ij}$                        | dimensionless elastic parameter of each ij column               | [-]                   |
| $E_{ijk}$                       | elastic parameter of each RVE                                   | $[Pa]$                |
| $E_{ijk}$                       | dimensionless elastic parameter of each RVE                     | [-]                   |

|                                                           |                                                                           |                          |
|-----------------------------------------------------------|---------------------------------------------------------------------------|--------------------------|
| $E_K$                                                     | elastic parameter of a Voigt-Kelvin unit                                  | [Pa]                     |
| $E_T$                                                     | total elastic parameter of the paper web                                  | [Pa]                     |
| $\mathbf{E}_T$                                            | dimensionless elastic parameter of the paper web                          | [-]                      |
| $f$                                                       | dynamic load function                                                     |                          |
| $f^*$                                                     | hydraulic diameter density function                                       |                          |
| $F_f$                                                     | shape factor used for the calculus of G'                                  | [-]                      |
| $F_{o.s.}$                                                | normalized overstress                                                     | [-]                      |
| $\mathbf{Fo}_{m_x}, \mathbf{Fo}_{m_y}, \mathbf{Fo}_{m_z}$ | mass transfer Fourier number                                              | [-]                      |
| $\mathbf{Fo}_x, \mathbf{Fo}_y, \mathbf{Fo}_z$             | Fourier number                                                            | [-]                      |
| $f p_0 \dots f p_{13}$                                    | stress fitting parameters                                                 |                          |
| $f_s$                                                     | ratio of the maximum to the minimum dimension of the fiber cross section  | [-]                      |
| $F_{solid}$                                               | force carried by the solid phase                                          | [N]                      |
| $FSP$                                                     | fiber saturation point                                                    | [%]                      |
| $G^*$                                                     | complex modulus                                                           | [Pa]                     |
| $G', G''$                                                 | storage and loss moduli                                                   | [Pa], [Pa]               |
| $\Delta G, \Delta G_1, \Delta G_2$                        | activation energies                                                       | [kJ.mol <sup>-1</sup> ]  |
| $Gr$                                                      | grammage                                                                  | [g.m <sup>-2</sup> ]     |
| $\mathbf{H}_0$                                            | dimensionless elastic parameter                                           | [-]                      |
| $\Delta H_{vap}$                                          | latent heat of vaporization of water                                      | [J.kg <sup>-1</sup> ]    |
| $\langle i \rangle$                                       | direction of fluid penetration                                            |                          |
| ISEU                                                      | impulse specific energy use                                               | [kJ/kg H <sub>2</sub> O] |
| $J$                                                       | creep compliance                                                          | [Pa <sup>-1</sup> ]      |
| $K$                                                       | absolute permeability of the medium                                       | [m <sup>2</sup> ]        |
| $k_0$                                                     | shape factor                                                              | [-]                      |
| $K_0, K'_0$                                               | parameters of the exponential and power law fittings of felt permeability | [m <sup>2</sup> ]        |
| $K_f$                                                     | fiber wall permeability                                                   | [m <sup>2</sup> ]        |
| $K_{gx}, K_{gy}, K_{gz}$                                  | permeabilities of the gas phase in each i direction                       | [m <sup>2</sup> ]        |
| $\mathbf{K}_{gx}, \mathbf{K}_{gy}, \mathbf{K}_{gz}$       | dimensionless permeabilities of the gas phase in each main direction      | [-]                      |
| $K_i$                                                     | permeability of the fluid i in the porous medium (i = l, g)               | [m <sup>2</sup> ]        |
| $k_k$                                                     | Kozeny factor                                                             | [-]                      |
| $K_{lx}, K_{ly}, K_{lz}$                                  | permeabilities of the liquid phase in each main direction                 | [m <sup>2</sup> ]        |
| $\mathbf{K}_{lx}, \mathbf{K}_{ly}, \mathbf{K}_{lz}$       | dimensionless permeabilities of the liquid phase in each main direction   | [-]                      |
| $k_{ri}$                                                  | relative permeability of the phase i (i = l, g)                           | [-]                      |

|                                                        |                                                             |                                        |
|--------------------------------------------------------|-------------------------------------------------------------|----------------------------------------|
| $K_x, K_y, K_z$                                        | absolute permeability of the medium in each main direction  | [m <sup>2</sup> ]                      |
| $K_{xy}$                                               | in-plane permeability                                       | [m <sup>2</sup> ]                      |
| $L$                                                    | total thickness                                             | [m]                                    |
| $L_{eff}$                                              | effective path of fluid flow                                | [m]                                    |
| $L_i$                                                  | incompressible thickness or thickness at zero porosity      | [m]                                    |
| $L_{ij}$                                               | total thickness of an ij column                             | [m]                                    |
| $L_{min}$                                              | felt thickness at maximum applied stress                    | [m]                                    |
| $L_p$                                                  | length of fluid penetration                                 | [m]                                    |
| $L_{pipe}$                                             | length of the pipe                                          | [m]                                    |
| $L_x$                                                  | half length of the web                                      | [m]                                    |
| $L_y$                                                  | half width of the web                                       | [m]                                    |
| $L_z$                                                  | thickness of the web                                        | [m]                                    |
| $\mathbf{L}_z$                                         | dimensionless thickness of the web                          | [-]                                    |
| $\dot{M}$                                              | amount of vaporized water per unit time and volume          | [kg H <sub>2</sub> O/m <sup>3</sup> s] |
| $\dot{M}_b$                                            | amount of adsorbed water vaporized per unit time and volume | [kg H <sub>2</sub> O/m <sup>3</sup> s] |
| $m_i$                                                  | mass of i (i = a, b, cw, dry, s)                            | [kg]                                   |
| $\dot{M}_l$                                            | amount of liquid water vaporized per unit time and volume   | [kg H <sub>2</sub> O/m <sup>3</sup> s] |
| $MM_i$                                                 | molar mass of i (i = air, g, v)                             | [kg.mol <sup>-1</sup> ]                |
| MR                                                     | moisture ratio                                              | [kg H <sub>2</sub> O/kg ds]            |
| $\Delta MR$                                            | difference in moisture ratio                                | [kg H <sub>2</sub> O/kg ds]            |
| $m_{s,nylon}, m_{dry}^F$                               | dry mass of the felt sample                                 | [kg]                                   |
| $\dot{m}_{tot}$                                        | total water removal rate                                    | [kg H <sub>2</sub> O/s]                |
| $\dot{M}_v$                                            | amount of vaporized water per unit time and volume          | [kg H <sub>2</sub> O/m <sup>3</sup> s] |
| $N$                                                    | felt compressibility coefficient                            | [Pa <sup>-1</sup> ]                    |
| $N^*$                                                  | factor characterizing the permeability of the felt          | [-]                                    |
| $N_i$                                                  | number of RVEs in the machine direction                     |                                        |
| $N_{ijk}$                                              | total number of cells or RVEs                               |                                        |
| $N_j$                                                  | number of RVEs in the cross-machine direction               |                                        |
| $N_k$                                                  | number of RVEs in the thickness direction                   |                                        |
| $\mathbf{N}p_{gx}, \mathbf{N}p_{gy}, \mathbf{N}p_{gz}$ | Relative permeability parameter for the gas phase           | [-]                                    |

|                                         |                                                                      |                                         |
|-----------------------------------------|----------------------------------------------------------------------|-----------------------------------------|
| $N_{p_{l_x}}, N_{p_{l_y}}, N_{p_{l_z}}$ | Relative permeability parameter for the liquid phase                 | [-]                                     |
| o.d.                                    | oven dried                                                           |                                         |
| PAE                                     | polyamide-epichlorohydrin                                            |                                         |
| $P_{air}$                               | partial pressure of air in the ideal gas phase                       | [Pa]                                    |
| $P_{atm}$                               | atmospheric pressure                                                 | [Pa]                                    |
| $P_c$                                   | capillary pressure                                                   | [Pa]                                    |
| $P_c$                                   | dimensionless capillary pressure                                     | [-]                                     |
| PCC                                     | Precipitated calcium carbonate                                       |                                         |
| $Pe_{g_z}$                              | Peclet number for the gas phase                                      | [-]                                     |
| $Pe_{l_z}$                              | Peclet number for the liquid phase                                   | [-]                                     |
| $Pe_{mg_x}, Pe_{mg_y}, Pe_{mg_z}$       | mass transfer Peclet number                                          | [-]                                     |
| $\Delta P_{Felt}$                       | pressure drop across the felt sample                                 | [Pa]                                    |
| $P_{fh}$                                | structural pressure due to water transport within the fiber material | [Pa]                                    |
| $P_{flow}$                              | pressure required to transport water                                 | [Pa]                                    |
| $P_i$                                   | pressure of i (i = g, h, l, sat, st, v)                              | [Pa]                                    |
| $P_i$                                   | dimensionless pressure of i (i = g, l, sat, v)                       | [-]                                     |
| $P_{mec}$                               | pressure carried by the mechanical stiffness of the mat              | [Pa]                                    |
| $P_{sat_i}$                             | vapour pressure of the constituent i at temperature T                | [Pa]                                    |
| $P_{st}^o$                              | parameter (Kataja et al)                                             | [Pa]                                    |
| $P_t$                                   | total compressing pressure                                           | [Pa]                                    |
| $P_t^*$                                 | normalized structural pressure (according to El-Hosseiny)            | [-]                                     |
| $P_t'$                                  | pressure imposed to the felt to induce a stage of zero porosity      | [Pa]                                    |
| $\Delta P_{Total, Felt}$                | total pressure drop in a permeability test with a felt sample        | [Pa]                                    |
| $\Delta P_{Total, Blanc}$               | total pressure drop in a blanc permeability test                     | [Pa]                                    |
| $Q$                                     | volumetric flow rate                                                 | [m <sup>3</sup> .s <sup>-1</sup> ]      |
| $Q_l$                                   | differential heat of sorption for the wood-water system              | [J.kg <sup>-1</sup> ]                   |
| $R$                                     | universal gas constant                                               | [J.mol <sup>-1</sup> .K <sup>-1</sup> ] |
| $r$                                     | radius of the pipe                                                   | [m]                                     |
| $RBA$                                   | Relative bonded area                                                 |                                         |
| $R_{Felt}, R_{Blanc}$                   | slope of linear regressions                                          | [kPa.m <sup>-3</sup> .s]                |



|                              |                                                                                |                                    |
|------------------------------|--------------------------------------------------------------------------------|------------------------------------|
| $r_h$                        | mean hydraulic radius                                                          | [m]                                |
| $RVE$                        | Representative volume element                                                  |                                    |
| $\mathbf{R}_x, \mathbf{R}_y$ | dimensional ratio                                                              | [-]                                |
| $S'_f$                       | volume specific surface of the nylon fibers                                    | [cm <sup>-1</sup> ]                |
| $S'_m$                       | mass specific surface of the felt                                              | [m <sup>2</sup> .g <sup>-1</sup> ] |
| $S'_{m,nylon}$               | mass specific surface of the nylon fibers                                      | [m <sup>2</sup> .g <sup>-1</sup> ] |
| $S'_o$                       | volume specific surface of the constituent particles of the porous medium      | [m <sup>-1</sup> ]                 |
| $S'_v$                       | volume specific surface of the porous medium                                   | [m <sup>-1</sup> ]                 |
| $S_g$                        | gas saturation                                                                 | [-]                                |
| $S_{go}$                     | residual gas saturation                                                        | [-]                                |
| $S_l$                        | water saturation                                                               | [-]                                |
| $S_{l,eff}$                  | effective water saturation                                                     | [-]                                |
| $S_{lo}$                     | irreducible water saturation                                                   | [-]                                |
| $SR$                         | Schopper-Riegler degree                                                        | [°SR]                              |
| $SRM$                        | stress relaxation modulus                                                      |                                    |
| $T$                          | temperature                                                                    | [K]                                |
| $\mathbf{T}$                 | dimensionless temperature                                                      | [-]                                |
| $t$                          | time                                                                           | [s]                                |
| $\Delta t$                   | dwel time                                                                      | [s]                                |
| $T_0$                        | initial temperature                                                            | [K]                                |
| $T_a$                        | platen/paper interface temperature                                             | [K]                                |
| $T_{amb}$                    | ambient atmospheric temperature                                                | [K]                                |
| $T_b$                        | paper/felt interface temperature                                               | [K]                                |
| $T_{fit}$                    | parameter of the fitting to determine $E_f$                                    | [°C]                               |
| $T_g$                        | softening temperature                                                          | [°C]                               |
| $T_H$                        | temperature of the heated source                                               | [°C]                               |
| $T_{ini}$                    | initial temperature of the body                                                | [°C]                               |
| $T_l$                        | temperature of the liquid phase                                                | [°C]                               |
| $T_m$                        | melting temperature                                                            | [°C]                               |
| $T_o$                        | reference temperature                                                          | [°C]                               |
| $T_p$                        | temperature of the heated plate                                                | [K]                                |
| $T_{sat}$                    | saturation temperature                                                         | [°C]                               |
| TSEU                         | total specific energy use                                                      | [kJ/kg H <sub>2</sub> O]           |
| $T_v$                        | temperature of the vapor phase                                                 | [°C]                               |
| $V$                          | volume                                                                         | [m <sup>3</sup> ]                  |
| $\mathbf{V}_0$               | viscoelastic parameter                                                         | [-]                                |
| $Var_i$                      | generic variable                                                               |                                    |
| $V_i$                        | volume of i (i = f, m, p, s, g, l, voids, a, cw)                               | [m <sup>3</sup> ]                  |
| $v_{gx}, v_{gy}, v_{gz}$     | superficial or apparent velocity of the gas phase in the three main directions | [m.s <sup>-1</sup> ]               |

|                                     |                                                    |                                        |
|-------------------------------------|----------------------------------------------------|----------------------------------------|
| $\mathbf{v}_{gx}, \mathbf{v}_{gy},$ | dimensionless superficial velocity of the          |                                        |
| $\mathbf{v}_{gz}$                   | gas phase in the three main directions             | [-]                                    |
| $v_{gz0}$                           | reference superficial gas velocity in the          |                                        |
|                                     | z-direction                                        | [m.s <sup>-1</sup> ]                   |
| $v_{lx}, v_{ly},$                   | superficial or apparent velocity of the            |                                        |
| $v_{lz}$                            | liquid phase in the three main directions          | [m.s <sup>-1</sup> ]                   |
| $\mathbf{v}_{lx}, \mathbf{v}_{ly},$ | dimensionless superficial velocity of the          |                                        |
| $\mathbf{v}_{lz}$                   | liquid phase in the three main directions          | [-]                                    |
| $WR_{tot}$                          | total water removal rate per unit area             | [kg H <sub>2</sub> O/m <sup>2</sup> s] |
| WRV                                 | water retention value                              | [%]                                    |
| WUR                                 | water uptake rate per unit area                    | [kg H <sub>2</sub> O/m <sup>2</sup> s] |
| $x, i$                              | coordinate axis (machine direction)                |                                        |
| $\mathbf{X}$                        | normalized $x$ -coordinate                         | [-]                                    |
| $\mathbf{x}_{m,i}$                  | mole fraction of the constituent $i$ in the liquid |                                        |
|                                     | phase                                              |                                        |
| $y, j$                              | coordinate axis (cross-machine direction)          |                                        |
| $\mathbf{Y}$                        | normalized $y$ -coordinate                         | [-]                                    |
| $y_{bfit}$                          | parameter of the fitting to determine $E_f$        | [kg H <sub>2</sub> O/m <sup>2</sup> s] |
| $y_i$                               | mass fraction of the constituent $i$ in the web    |                                        |
|                                     | ( $i = a, b, cw, f, l, air, v, dry, solids$ )      | [kg $i$ /kg $ds$ ]                     |
| $y_{m,i}$                           | mole fraction of the constituent $i$ in the        |                                        |
|                                     | gas phase ( $i = air, v$ )                         |                                        |
| $y_{mf}$                            | mass ratio of matrix to fibers                     |                                        |
| $z, k$                              | coordinate axis (thickness direction)              |                                        |
| $\Delta z_{ijk}$                    | thickness of each cell or RVE                      | [m]                                    |
| $\Delta \mathbf{z}_{ijk}$           | dimensionless thickness of each cell or RVE        | [-]                                    |
| $\mathbf{Z}^*$                      | dimensionless $z$ -coordinate at the paper/felt    |                                        |
|                                     | interface                                          | [-]                                    |
| $z_{ijk}$                           | vertical position within the web                   | [m]                                    |
| $\mathbf{Z}_{ijk}$                  | normalized vertical position within the web        |                                        |
|                                     | ( $z$ -coordinate)                                 | [-]                                    |

### Greek letters

|                      |                                                            |                                    |
|----------------------|------------------------------------------------------------|------------------------------------|
| $\alpha$             | ratio of the solid phase area to the total area of the RVE |                                    |
| $\alpha_i$           | area fraction of $i$ ( $i = s, l, g, f$ )                  | [-]                                |
| $\xi$                | constant in Eqns. 3.5a and 3.5b                            | [m.s <sup>-1/2</sup> ]             |
| $\varpi_l, \varpi_v$ | thermal diffusivity of liquid and vapor                    | [m <sup>2</sup> .s <sup>-1</sup> ] |
| $\varepsilon$        | strain                                                     | [-]                                |
| $\varepsilon_{ij}$   | strain of the $ij$ column                                  | [-]                                |
| $\varepsilon_{ijk}$  | strain of the $ijk$ element                                | [-]                                |
| $\varepsilon_y$      | yield strain                                               | [-]                                |

|                                           |                                                                      |                       |
|-------------------------------------------|----------------------------------------------------------------------|-----------------------|
| $\dot{\varepsilon}$                       | strain rate                                                          | [s <sup>-1</sup> ]    |
| $\varepsilon_{\max}$                      | strain at zero porosity                                              | [-]                   |
| $\sigma$                                  | stress                                                               | [MPa]                 |
| $\sigma_i$                                | stress applied on phase i (i = s, g, l)                              | [MPa]                 |
| $\sigma_{ij}$                             | stress applied on each ij column                                     | [MPa]                 |
| $\sigma_{ij}$                             | dimensionless stress applied on each ij column                       | [-]                   |
| $\sigma_{ijk}$                            | stress applied on each ijk element                                   | [MPa]                 |
| $\sigma_T$                                | total applied stress                                                 | [MPa]                 |
| $\sigma_T$                                | dimensionless total applied stress                                   | [-]                   |
| $\sigma_{ycw}$                            | yield stress of the cell wall material                               | [MPa]                 |
| $\sigma_1, \varepsilon_1$                 | amplitude of the stress and the corresponding strain                 | [MPa], [-]            |
| $\sigma_0$                                | maximum applied stress (also denoted as $\sigma_{\max}$ )            | [MPa]                 |
| $\mu_c$                                   | viscosity parameter in Eqn. 3.9                                      | [Pa.s]                |
| $\mu_i$                                   | dynamic viscosity of i (i = l, g, suspension, medium)                | [Pa.s]                |
| $\mu_f$                                   | fiber viscous parameter                                              | [Pa.s]                |
| $\mu_a$                                   | viscous parameter of the additive                                    | [Pa.s]                |
| $\mu$                                     | viscous parameter of paper                                           | [Pa.s]                |
| $\mu^*$                                   | parameter in Eqn. 3.60                                               | [Pa.s]                |
| $\mu_1^*, \mu_2^*$                        | parameters in Eqn. 3.61                                              | [Pa.s]                |
| $\mu_{rel}$                               | relative viscosity                                                   | [-]                   |
| $\mu_K$                                   | viscous parameter of the Voigt-Kelvin model                          | [Pa.s]                |
| $\mu_{ij}$                                | viscous parameter of the ij column                                   | [Pa.s]                |
| $\mu_{ijk}$                               | viscous parameter of the ijk element                                 | [Pa.s]                |
| $\mu_0$                                   | reference value for the viscous parameter                            | [Pa.s]                |
| $\mu_T$                                   | dimensionless viscous parameter                                      | [-]                   |
| $\mu_{ijk}$                               | dimensionless viscous parameter for the ijk element                  |                       |
| $\mu_{ij}$                                | dimensionless viscous parameter for the ij column                    | [-]                   |
| $\mu_i$                                   | dimensionless viscosity of i (i = g, l)                              | [-]                   |
| $\mu_A, \mu_B$                            | viscous parameters of the Voigt-Kelvin and Maxwell units             | [Pa.s]                |
| $\mu_{nylon}$                             | felt viscous parameter                                               | [MPa.s]               |
| $\Phi(\varepsilon)$                       | nonlinear strain function                                            | [-]                   |
| $\Phi(\varepsilon(\xi^*))$                | nonlinear strain function in Eqn. 3.83                               | [-]                   |
| $\Omega(F_{o.s.})$                        | function in Eqn. 3.9                                                 |                       |
| $\epsilon$                                | structural parameter in Eqn. 3.11                                    | [-]                   |
| $\epsilon'$                               | parameter in Eqn. 3.190                                              | [-]                   |
| $\rho_{rel}$                              | relative density                                                     | [-]                   |
| $\langle \rho_{rel}(\varepsilon) \rangle$ | relative density function                                            | [-]                   |
| $\rho$                                    | apparent density of the porous material                              | [kg.m <sup>-3</sup> ] |
| $\rho_i$                                  | density of i (i = f, composite, s, a, cw, b, p, v, g, l, air, fluid) | [kg.m <sup>-3</sup> ] |

|                                            |                                                                                  |                                        |
|--------------------------------------------|----------------------------------------------------------------------------------|----------------------------------------|
| $\rho_{dry}$                               | apparent density of the dry solid                                                | [kg.m <sup>-3</sup> ]                  |
| $\rho_i$                                   | dimensionless density of i (i = g, l, v, p, dry)                                 | [-]                                    |
| $\rho_{ijk}$                               | apparent density of the ijk element (also denoted as $\rho_{ijk}$ )              | [kg.m <sup>-3</sup> ]                  |
| $\rho_{p0}, \rho_{v0}, \rho_{l0}$          | reference values                                                                 | [kg.m <sup>-3</sup> ]                  |
| $\rho_{s,ijk}$                             | density of the solid phase in each ijk element (also denoted as $\rho_{s,ijk}$ ) | [kg.m <sup>-3</sup> ]                  |
| $\rho_{rel,ijk}$                           | relative density of each ijk element (also denoted as $\rho_{rel,ijk}$ )         | [kg.m <sup>-3</sup> ]                  |
| $\rho_{dry}^*$                             | dry basis density of the fibrous material for $P_t = P'_t$                       | [kg.m <sup>-3</sup> ]                  |
| $\rho_{f,nylon}$                           | specific density of the nylon fibers                                             | [kg.m <sup>-3</sup> ]                  |
| $\vartheta$                                | curve-fitting parameter in Eqn. 3.24                                             | [-]                                    |
| $\eta$                                     | parameter in Eqn. 3.24                                                           | [-]                                    |
| $\nu$                                      | lateral deformation of the cells                                                 | [-]                                    |
| $\tau^*$                                   | retardation or relaxation time                                                   | [s]                                    |
| $\tau$                                     | dwelt time of the pressing event                                                 | [ms]                                   |
| $\theta$                                   | dimensionless time                                                               | [-]                                    |
| $\theta'$                                  | dimensionless time defined in Eqn. 3.112                                         | [-]                                    |
| $\theta_m$                                 | fitting parameter in Eqn. 3.111                                                  | [-]                                    |
| $\theta_c$                                 | contact angle                                                                    | [°]                                    |
| $\beta$                                    | ratio of the area occupied by the liquid phase to the area of the fluid          | [-]                                    |
| $\beta_T, \beta_{yb}$                      | parameters in Eqn. 3.32                                                          | [°C], [-]                              |
| $\omega_1$                                 | angular frequency                                                                | [Hz]                                   |
| $\omega_1, \omega_2$                       | constants in Eqn. 4.8                                                            | [-]                                    |
| $\varphi_{tx}, \varphi_{ty}, \varphi_{tz}$ | total heat fluxes                                                                | [J.m <sup>-2</sup> .s <sup>-1</sup> ]  |
| $\varphi_{tx}, \varphi_{ty}, \varphi_{tz}$ | dimensionless total heat fluxes                                                  | [-]                                    |
| $\varphi_{vx}, \varphi_{vy}, \varphi_{vz}$ | total water vapor fluxes                                                         | [kg.m <sup>-2</sup> .s <sup>-1</sup> ] |
| $\varphi_{vx}, \varphi_{vy}, \varphi_{vz}$ | dimensionless total water vapor fluxes                                           | [-]                                    |
| $\varphi_{gx}, \varphi_{gy}, \varphi_{gz}$ | total gas fluxes                                                                 | [kg.m <sup>-2</sup> .s <sup>-1</sup> ] |
| $\varphi_{gx}, \varphi_{gy}, \varphi_{gz}$ | dimensionless total gas fluxes                                                   | [-]                                    |
| $\varphi_{lx}, \varphi_{ly}, \varphi_{lz}$ | total liquid water fluxes                                                        | [kg.m <sup>-3</sup> ]                  |
| $\varphi_{lx}, \varphi_{ly}, \varphi_{lz}$ | dimensionless total liquid water fluxes                                          | [-]                                    |
| $b_0, b_1, b_2$                            | coefficients in Eqn. 4.34                                                        | [-]                                    |
| $b_3, b_4$                                 | parameters in Eqn. 4.37                                                          | [-]                                    |
| $b_5, b_6, \varepsilon_{exp}$              | experimental parameters in Eqn. 4.38                                             | [-]                                    |
| $b_7, b_8$                                 | parameters characteristic of the felt (Eqn. 4.41)                                | [-]                                    |
| $\beta$                                    | generic property                                                                 |                                        |
| $\gamma$                                   | surface tension of water                                                         | [mN.m <sup>-1</sup> ]                  |
| $\phi$                                     | total porosity                                                                   | [-]                                    |
| $\phi_i$                                   | volume fraction of i (i = f, m, a, g, l, s, solids)                              | [-]                                    |

|                               |                                                                                 |                                       |
|-------------------------------|---------------------------------------------------------------------------------|---------------------------------------|
| $\phi_{eff}$                  | effective porosity                                                              | [-]                                   |
| $\phi_g^l$                    | gas saturation (also denoted as $S_g$ )                                         | [-]                                   |
| $\phi_i$                      | dimensionless volume fraction of i (i = g, l)                                   | [-]                                   |
| $\phi_{eff,ijk}$              | effective porosity of the ijk element                                           | [-]                                   |
| $\phi^*$                      | porosity at 0.2 kPa                                                             | [-]                                   |
| $\ell$                        | expansion ratio                                                                 | [-]                                   |
| $\Lambda$                     | angle formed by the two mean directions of fluid flow (Eqn. 4.10)               | [°]                                   |
| $\Lambda'$                    | angle between the mean direction of flow and the direction of fluid penetration | [°]                                   |
| $\Lambda_{silvy}$             | angle of the direction of fluid penetration                                     | [°]                                   |
| $\xi_l, \xi_g$                | tortuosities for the liquid and gas phases in the porous medium                 | [-]                                   |
| $\xi'$                        | tortuosity factor of the porous medium (Eqn. 4.11)                              | [-]                                   |
| $\xi_{silvy}'$                | tortuosity factor according to Eqn. 4.24                                        | [-]                                   |
| $\xi_x', \xi_y', \xi_z'$      | tortuosity factor in the three main directions                                  | [-]                                   |
| $\xi^*$                       | parameter in Eqns. 3.81 to 3.84                                                 |                                       |
| $\lambda_{pi}$                | thermal conductivity of paper in a given i direction                            | [W.m <sup>-1</sup> .K <sup>-1</sup> ] |
| $\lambda_{pi}$                | dimensionless thermal conductivity of paper in a given i direction              | [-]                                   |
| $\lambda_i$                   | thermal conductivity of i (i = g, v, air, l, dry, f, fluid)                     | [W.m <sup>-1</sup> .K <sup>-1</sup> ] |
| $\delta_f$                    | parameter in Eqn. 3.190                                                         | [-]                                   |
| $\delta_1$                    | phase lag or loss angle                                                         | [°]                                   |
| $\kappa^*$                    | parameter in Eqn. 4.25                                                          | [-]                                   |
| $\mathfrak{S}, \mathfrak{S}'$ | experimental parameters in Eqns. 4.57 and 4.58                                  | [kPa]                                 |
| $\wp, \wp_i$                  | coefficients in Eqn. 4.32                                                       | [-]                                   |
| $\Pi_0, \Pi'_0$               | parameters in Eqns. 4.61 and 4.62                                               | [-]                                   |
| $\varrho_1, \varrho_2$        | material-specific parameters in Eqn. 4.29                                       | [-]                                   |
| $\varrho_3$                   | material-specific parameter in Eqn. 4.30                                        | [-]                                   |
| $\varrho_4, \varrho_5$        | parameters in Eqn. 4.31                                                         | [-]                                   |
| $\varrho_6, \varrho_7$        | parameters in Eqn. 4.35                                                         | [Pa]                                  |
| $\varrho_8, \varrho_9$        | parameters in Eqn. 4.36                                                         |                                       |

## Subscripts

|     |                                                      |
|-----|------------------------------------------------------|
| 0   | initial value                                        |
| a   | additive                                             |
| air | air                                                  |
| b   | adsorbed                                             |
| cw  | cell wall material                                   |
| dry | dry solids (cell wall material + additive, or nylon) |

---

|       |               |
|-------|---------------|
| ep    | elastoplastic |
| eq    | equilibrium   |
| f     | fiber         |
| Felt  | felt          |
| fluid | fluid         |
| g     | gas           |
| h     | hydraulic     |
| in    | ingoing       |
| ini   | initial       |
| l     | liquid        |
| m     | matrix        |
| out   | outgoing      |
| p     | pore          |
| sat   | saturation    |
| st    | structural    |
| T     | total         |
| v     | vapor         |
| vis   | viscous       |
| voids | voids         |

### Upperscripts

|    |               |
|----|---------------|
| el | elastic       |
| ep | elastoplastic |
| F  | felt          |
| P  | paper         |
| pl | plastic       |

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# Chapter 1

## Introduction

### 1.1 Paper History - a brief perspective

What is paper and what are its origins?

Written communication has been the center of civilization for centuries. Most of our important records are on paper. Although writing has been around for a long time, paper hasn't. In fact, putting thoughts down in written form wasn't always easy and practical. Early, people discovered that they could make simple drawings in the walls of caves, which was a great place for recording thoughts, but it wasn't portable. One can imagine spending hours scratching a message into a heavy clay tablet and then having to transport it. That is exactly what the Sumerians did around 4000 B.C. Although this form of written communication was now portable it still wasn't practical because of its weight.

For centuries, people tried to discover better surfaces on which they could record their thoughts. Wood, stone, ceramics, cloth, bark, metal, silk, bamboo and tree leaves were all used as a writing surface at one time or another. Undoubtedly, of all the writing and drawing materials that people have employed down the ages, paper is the most widely used around the world. Its name derives from the material used by the ancient Egyptians, Greeks and Romans: papyrus. About 5000 years ago, Egyptians created "sheets" of papyrus by harvesting, peeling and slicing the plant (*Cyperous papyrus*) into strips; the strips were then layered, pounded together and smoothed to make a flat, uniform sheet. Papyrus is, in fact, one of the predecessors of paper produced by beating and pressing. Those sheets are known by the generic term "tapa" and found extensively in nearly all cultures along the Equator belt. The oldest papermaking technique, and one still

practised in the Himalayas and in South-East Asia, leaves no doubt as to the origin of the tapa technique. Although papyrus sheets were similar to paper in terms of function, being laminated sheets they were technically more like a mat and therefore not the same as the papers of today. No major changes in writing materials were to come for about 3000 years.

Paper, as it is known today comes from another source, China (see Figure 1.1). The person credited with inventing paper is a Chinese man named Ts'ai Lun. He experimented a wide variety of materials and refined the process of macerating the fiber of plants until each filament was completely separate. The individual fibers were then mixed with water in a large vat. Next, a screen was submerged in the vat and lifted up through the water, catching the fibers on its surface. When dried, this thin layer of fibers became what today is called paper. It wasn't until the 3rd century that the secret art of papermaking began to creep out of China, first to Vietnam and then Tibet. Word was then passed along to Korea, Samarkand (Uzbekistan), Baghdad (Iraq) and Damascus (Syria). Chinese papermaking techniques were introduced to Japan in the year 610, where paper is still made by hand on a large scale in the old tradition, preferably from the fresh bast fibers of the mulberry tree.

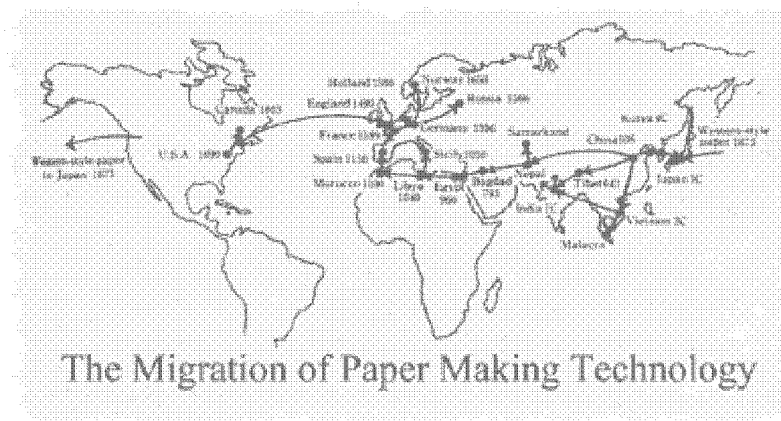


Figure 1.1: The migration of paper technology in the early days.

The Arabs, in the course of their eastern expansion, became acquainted with the production methods of the new writing material near Samarkand, and paper mills were subsequently set up in Cairo and later in Morocco. Finally, when the Arabs from North Africa invaded Spain and Portugal they brought the technology

with them and so papermaking entered Europe in the 12th century. In Europe, the use of papyrus had dropped out in the 9th century. The preferred medium for the artists and literati of the time was the smooth and lustrous parchment. However, parchment, made from animal skin, was extremely expensive when compared to the raw material used by the Arabs. Owing to the lack of fresh fibers, the material used by the Arabs was almost entirely rags. The defective processing equipment produced a poorly ground pulp. Using this method, with screens made of reeds, the Arabs made thin sheets and "coated" them on both sides with starch paste. This gave Arab paper its good writing properties and fine appearance. In Italy, papermakers tried to improve the Arab technique; their efforts did not affect the raw material, *i.e.* the rags, but certainly its preparation and the actual papermaking process by inventing the paper press (screw press) with slides for feeding in the material.

In the course of the rapid expansion of trade in the late Middle Ages, more and more merchants dealt in the commodity called "paper" that was of growing importance for the public service and for intellectual life. Around 1450, Johannes Guttenberg, a German, invented the printing press. Books and other important documents could now be reproduced quickly. This method of printing in large quantities led to a rapid increase in the demand for paper. It is not surprising, therefore, that the birth of modern paper and printing industry is commonly marked from this date.

Technical progress continued in the 17th century mainly by introducing a new method to improve paper smoothness and the invention of a much more efficient beater, the so-called "hollander". The tremendous upsurge in papermaking in and after the 16th century soon led to a serious shortage of raw materials and to regulations governing the trade in rags. The demand for paper also created the need for greater efficiency in production. In the late 18th century the labors of Nicholas Luis Robert resulted in the creation of a machine that could produce a seamless length of paper on a endless wire mesh with squeeze rollers at one end. Perfected and marketed by the Fourdrinier brothers, the new machine made papers soon replaced traditional single sheets made by hand. The systematic search for substitute materials met with little immediate success. Straw was certainly propagated as a raw material, in view of the aggravated situation following the introduction of the first paper machines from 1825 on, but failed to make headway on quality grounds.

Shortly afterwards other types of paper machines appeared, like the machines which filled wire moulds transported on an endless chain and couched them on an endless felt, and the cylinder machine (Dickinson). Flat screen and cylinder machines, made during the 19th century, were then extended to include a dryer section. This soon led to a considerable widening of the paper web and to an increase in production speeds.

The history of paper industry in the 19th and 20th centuries can be broken down into five periods, each marked by definite trends.

In the first stage (from approximately 1800 to 1860), all work sequences previously performed by hand were mechanized. This was true for rag preparation, the use of fillers, pulp beating, the paper machine with its various parts, and the machines required for finishing the paper (headbox, wire section, press section, dryer section, units for reeling, smoothing and packaging).

In the second stage (from approximately 1840 to 1880) efforts were made to obtain rag substitutes on an industrial scale (groundwood pulp and chemical pulp) and the development of appropriate industrial plants (groundwood and chemical pulp mills).

The third stage (from approximately 1860 to 1950) was marked for the enlargement of the web width, an increase in working speeds, the introduction of electric drive, further improvements to various machine parts, the development of machines designed specifically for the production of particular paper and board grades (*e.g.* Yankee cylinder, multi-cylinder machines). Web working width grew from 85 cm (1830) to 770 cm (1930), while production speeds rose from 5 m.min<sup>-1</sup> (1820) to over 500 m.min<sup>-1</sup> (1930).

The fourth stage (1950 to 1980) which was still dependent on the old methods as far as the mechanics were concerned, brought unprecedented changes in papermaking. Alongside further increases in web width and working speeds, the changes included the use of new materials (thermomechanical pulp, de-inked recovered paper, new fillers, process chemicals and dyes), new sheet forming options (*e.g.* by twin-wire formers), neutral sizing, greater stress and ecology (closed loops) and, most of all, automation. The operational impact of these changes resulted in: specialization in certain paper grades (LWC - light weight coated paper); corporate mergers, company groups with their own raw material supply and trading organizations; shutdowns of unprofitable operations.

The fifth stage (from 1980 on) leads into the future. The evolution of new sheet-forming principles (with fluid boundaries between paper and non-woven fabrics) and chemical pulp processes, but also the situation on the global market (increased demand, above all in the Third World, trends in chemical pulp prices, location problems) are again raising capital intensity and encouraging the formation of big company groups with international operations. Simultaneously, however, there are definite opportunities for smaller local firms satisfying specific needs [14].

### *2000 & beyond*

The new Millennium will be dominated by the tremendous progress that has been made in computer science and nanotechnology, thus triggering a complete change in our commercial and private communications and information behavior. As these new technologies develop where does the future of paper lay? Clearly, there will be a huge amount of data being generated electronically, but the issue is how to preserve it? The difficulties of data storage over a long period of time are well known (*e.g.* the durability of disks; frequent changes of hard and software; electronic breakdowns; *etc.*). Once again paper offers the most convenient and durable storage option. Only tiny segments of paper use, such as, for example, the printing short-lived handbooks and encyclopedias, will be definitely affected by the advance in technology. Reading a book will remain a great pleasure into the future, and paper, as a ubiquitous material with its many uses, will continue to play a preponderant role. And many artists, especially those fond of Paper Art, will continue to express themselves by using this most versatile material.

## 1.2 The papermaking industry

### 1.2.1 The importance of the sector

The pulp and paper industry is a vital manufacturing sector that meets the demands of individuals and society. Paper is an essential part of our lives and culture. People use it to store and communicate information (newspapers, books, business documents and writing paper), to transport and protect goods (bags, sacks, packaging), for personal hygiene (tissues, napkins, nappies, *etc.*) and in medicine (a variety of hospital uses). Electronic communication and information on paper complement each other. The presence of paper products is thus evident

in the everyday life of each and every citizen [14].

### **Role of paper in the information society**

Electronic media has shown its power. Paper will, however, continue to play an important role in communication. Newspapers, magazines, inserts and flyers will continue to be important means for advertising. The consumption of office papers, such as copy paper, is stimulated by increased use of faxes and personal computer printers. Also the trend towards computerized home offices stimulates office paper consumption, and opens new distribution channels for paper.

Thus, printed and electronic media complement each other. New paper grades are needed and will be further developed to respond to the needs of electronic communication.

### **Role of paper in the packaging and distribution of goods**

The role of packaging for the consumer is to provide an efficient part of the logistics system. Packaging provides protection and handling properties which ensure the optimum use of resources, avoids quality degradation, and avoids spoilage of the packaged product. Packaging is also a presentational medium which includes carrying information about the packaged product.

A substantial proportion of packaging paper and board is used for the production of corrugated board, which, in turn, is used for the transport and display of goods. However, 3 % of all solid waste going to landfill originates from all kind of household packaging, while commercial and industrial packaging constitutes a further 3 % [9]. Much legislative effort has been put into trying to reduce this amount, and the paper industry and its costumers along the chain should actively participate in this. The second largest packaging grade consumed in Europe is cartonboard [9], be it based on primary or recovered fiber. The properties of cartons usually require them to be light, convenient and efficient for packaging and filling operations. This paper grade often has a high content of recycled fiber, more than half of the raw materials in the European carton industry come from recovered paper and board [9].



## Hygiene papers

This covers a wide range of tissue and other hygiene papers for use in households or in commercial and industrial premises. Close to 70 % of the raw material used in their production is recovered paper [9].

### 1.2.2 Pulp and paper consumption; history and forecast

Paper consumption growth is strongly correlated to general economic development. Strong economic growth spurs demand for paper. GDP (Gross Domestic Product) growth correlates well with the demand for packaging grades, while advertising and private consumption correlates with the demand for graphic and hygiene papers. Also, the level of economic development and demographic factors determine the level of consumption of paper products. High per capita GDP generally means high paper consumption [9].

Between 1980 and 1996, world paper consumption grew by 3.3 % annually. Up to the year 2015, paper consumption is forecast to increase somewhat more slowly, by 2.8 % annually (Figure 1.2) [13]. In Europe, the growth forecast is close to the world average, contrary to North America, which is considered to be a more mature market with the world's highest per capita paper consumption. In Asia, excluding Japan, the annual growth forecast is 4.5 %, and in Eastern Europe 4.2 %.

It is worth noting that Asia, despite large capacity increases in the region, is expected to be increasingly dependent on net imports of paper, *i.e.* packaging grades. However, for particular paper grades, such as fine paper, Asia may well become a net exporter. The Nordic countries are net exporters within Western Europe while the rest of Western Europe is a net importer [9].

The pulp and paper industry has increased its performance for the last two decades, although the final period shows a slight cyclic behavior. In comparison with the previous two years, 2001 proved to be a difficult one for most paper and board producers in the CEPI region, as well as for some other world producers. Figures 1.3 and 1.4 are concerned to the global situation of the world pulp and paper industry, although major attention is given to Europe and in particular to the CEPI region.

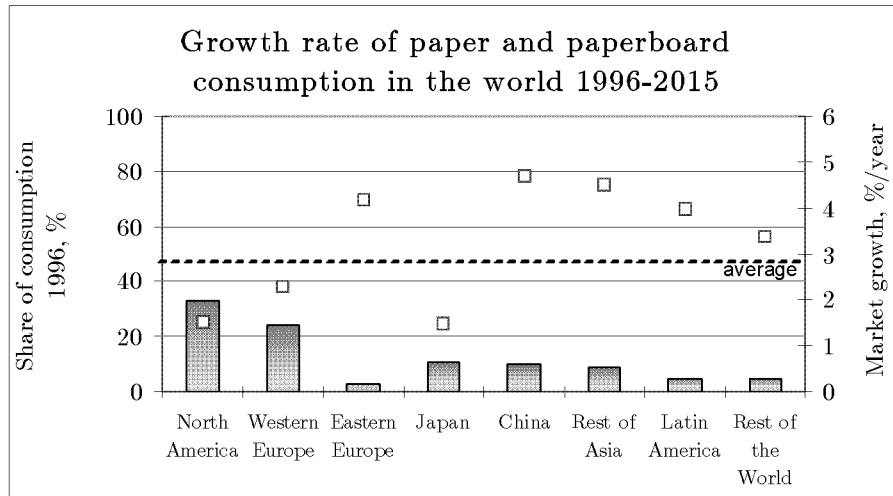


Figure 1.2: Growth rate of Paper and Paperboard consumption in the world 1996-2015. White squares correspond to market growth. Source: Jaako Pöyry Consulting [9].

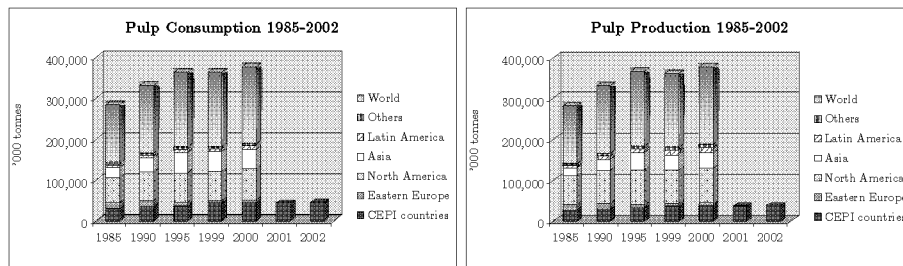


Figure 1.3: Pulp consumption and production in the CEPI region from 1985 to 2002 [13],[15].

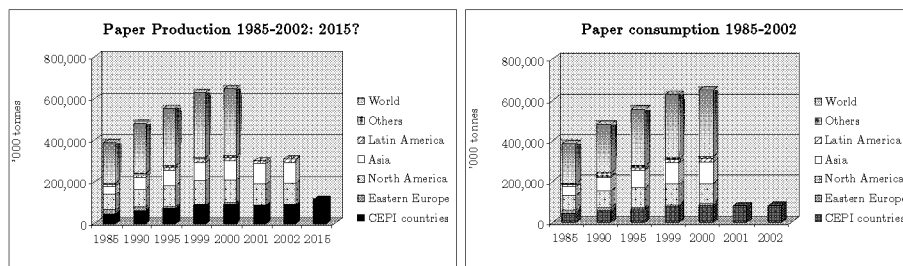


Figure 1.4: Paper production (2015 forecast) and consumption in the CEPI region from 1985 to 2002 [13],[15].

In Western Europe, 88.2 million tonnes of a wide range of paper and board grades were produced in 2001, a decrease of 2.7 % over 2000 [13] (see Figure 1.5). However, despite this decline, the overall level of production remains high compared to that in most other regions of the world. The average annual increase in paper production since 1998 has been around 2.5 %.

When looking at the output performance of different grades, an inconsistent picture emerges. Although overall output of graphic grades declined by 4 %, newsprint production rose by 1.3 %. Production of uncoated graphic grades fell by 3 %, whilst output of coated grades fell by 7.9 %. Mechanical grades achieved better comparative output levels than woodfree grades. Production of packaging grades and carton board fell 1.7 % and 1.8%, respectively, with case materials virtually unchanged. Output of wrappings fell by 3.7 %. Hygienic paper manufactures increased their output by 1.3 %. Output of pulp also fell in 2001. Total production, of both integrated and market pulp, decreased by 3.6 %. The fall in chemical pulp output was 1.7 %, whilst production of mechanical and semi-chemical pulp declined by 4.1 % [13].

The overall consumption of paper and board in CEPI in 2001 fell by 3.8 % from its year 2000 level. At the same time GDP increased by 1.6 % (Eurostat EU 15). The slowing down of the European economy, beginning towards the end of 2000, was reflected in the pulp and paper market through 2001 and to the present year of 2005 [13].

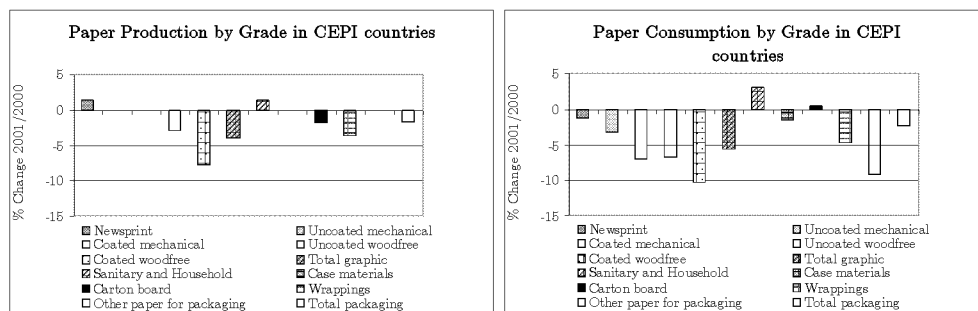


Figure 1.5: % Change 2001/2000 in paper production and consumption by grade in the CEPI area [13].

As in 2000, there was no great divergence in consumption trends between the major sectors, although on this occasion the trends were consistently downwards rather than upwards. Overall consumption of pulp fell by 4.1 % in 2001.

CEPI member countries account for more than 27 % of world paper and board production, slightly behind North America (34 %) and Asia (29 %). In volume terms, graphic paper grades account for 50 % of the Western European paper production, packaging paper grades for some 40 %, and hygiene and speciality papers for 10 % [18] (see Figure 1.6). Newsprint corresponds to around 25 % of total graphic paper production in the CEPI region [13]. The electronic age has brought with it the need for more, not less graphic paper.

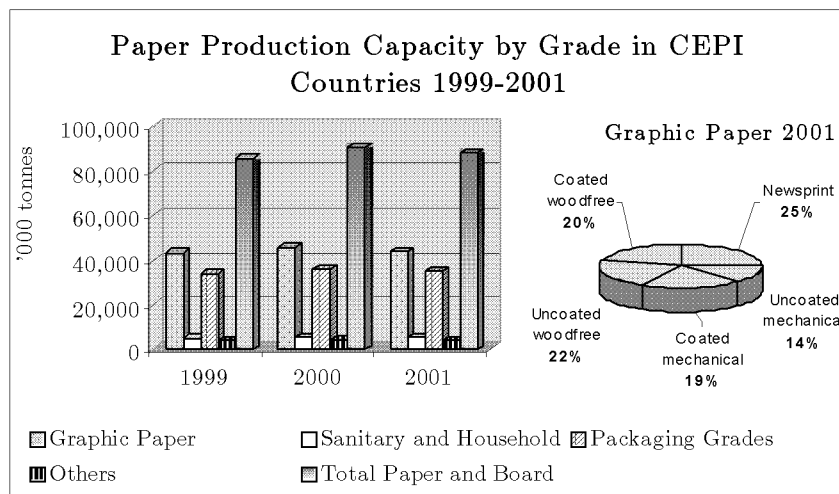


Figure 1.6: Paper production by grade in CEPI countries [13].

To end with, forecasts (source: Jaako Pöyry [13]) indicate that from 1998 to 2015 there will be an annual increase of 2.8 % in the consumption of paper and board globally. It is clear, therefore, that despite the growth of alternatives to paper like electronic media, their roles are complementary and that graphic, packaging, tissue and speciality papers will continue to play a major part in the everyday life of European citizens.

### The Portuguese pulp and paper industry

In the past decade, the Portuguese pulp and paper factories have managed to significantly strengthened their position in the European market. This was mainly accomplished by assuming an ever growing conscious position facing the new challenges presented by the market regarding paper quality and specifications according to its end use diversity. Moreover, the Portuguese paper industry has

long assumed its responsibilities in respect of the environmental impact resulting from its activity, having invested, in the period between 1988 and 1997, about €190 million in projects to reduce the environmental effects caused by its manufacturing plants, such as gaseous emissions, liquid discharges, solid waste and noise. The response to the new challenge presented by the Directive for the Integrated Prevention and Control of Pollution (IPCP) has been assumed, together with the rest of the European paper industry.

Although this is one of the national sectors in which Portugal has important competitive advantages, there are a series of problems that give rise to concern for the development of the sector at long term, namely the forestry policy, the availability of raw materials for industrial supply, and the certification of sustainable forestry management. Concerned about the existence of raw materials of sufficient quality and quantity for industrial production of pulp and paper, since 1984 the Portuguese paper industry companies have regularly carried out forestry inventory work to obtain and make strategic information available on the eucalyptus and wild pine forests, in order to prevent disruptions in industrial supply.

The essential raw material in the production of Portuguese paper is pulp, the majority being of eucalyptus and pine national species, and to a less extent recovered paper. The consumption of pulp as a raw material in papermaking has increased significantly in recent years along with a less evidenced growth in recovered paper consumption. In 2001, there was a change in the trend towards an increase in the consumption of recovered paper when a recycling paper mill, which was the largest user, ceased its industrial activity (see Figure 1.7). This situation has reduced the Portuguese paper industry's participation in the effort to use recovered paper, as stated in the European Declaration on Recovered Paper signed by the Confederation of European Pulp and Paper Industry (CEPI).

The production of uncoated printing and writing paper has been growing and is based on virgin eucalyptus pulp, not recovered paper. As a result, the relative consumption of recovered paper will not tend to rise. The potential consumption of recovered paper in Portugal, therefore has limitations, given the high relative weight of the production of uncoated printing and writing paper in the range of paper products manufactured in Portugal.

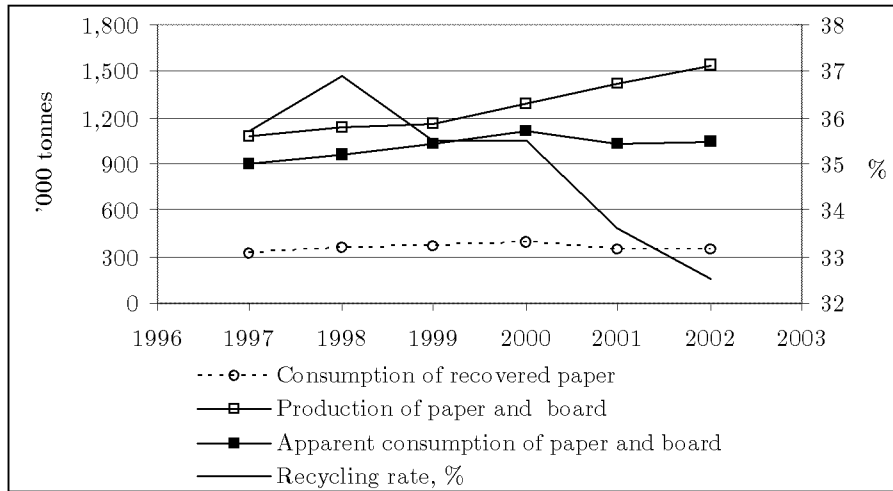


Figure 1.7: Production, consumption and recycling rate of paper in the Portuguese paper industry sector from 1997 to 2002 [8].

Paper production in Portugal grew 82 % between 1990 and 2001. This was more accentuated in 2000 and 2001, thanks to the installation of a new production line for printing paper at one of the national largest paper mills. A total of 1.418 and 1.537 million tonnes of paper were produced in 2001 and 2002, respectively, which corresponds to a 8 % increase in production and represents a good performance in the European context (see Figure 1.8). This growth is due essentially to a 24 % increase in the production of paper and board for printing, which is certainly significant if one considers that CEPI's forecast for Europe in 2001 was a 4 % decrease in the production of these types of paper.[8]

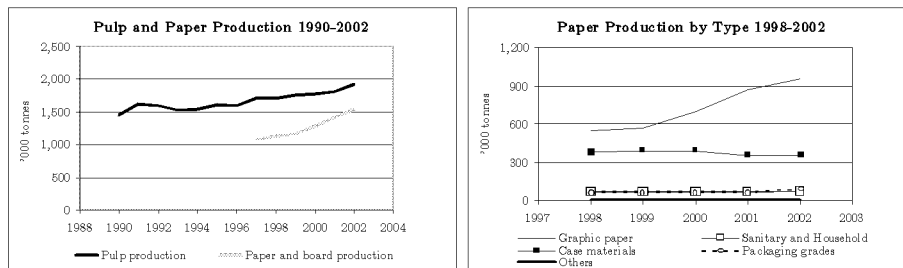


Figure 1.8: Pulp and paper total production from 1990 to 2002 and paper production by type from 1998 to 2002 in the Portuguese industry [8].

## **The future of paper**

In an age of computers and websites, it is easy to overlook some of the enduring qualities of paper. It is portable, disposable, recyclable, economical and versatile. In developing countries, population increases and a rising standard of living will result in a tremendous demand for paper, packaging and fiber. In developed countries, the continuing need for “hard copy” suggests a prominent complementary role for paper even as the information highway develops into the 21st century.

At the same time, shifts in paper consumption and paper products are expected. For example, the demand for varieties of printer paper and value-added papers will certainly increase while the demand for cheaper, lower grades may decrease.

The viable future of world’s pulp and paper industry depends mainly upon four interrelated factors:

- products that are second-to-none: companies are working now to ensure that they can offer the right products to the right markets and keep the industry competitive;
- access to world markets: the sustainable future of pulp and paper industry is not just a question of products but also a question to overseas markets;
- industry innovation: in the future, the search for new products and new markets will also be accompanied by a dynamic and proactive research effort into better, cleaner and more competitive ways to make pulp and paper products;
- global approach to sustainable forest practices.

It is generally acknowledge that the pulp and paper industry has the potential to become one of the first truly sustainable industries in the world. There are individual programmes at industry level for environmental protection, initiatives at international, national and regional level regarding certification of forests, and increasing recycling and recovery rates. All these demonstrate that the industry is making progress and taking its responsibility to improve its environmental performance extremely seriously.

### **1.2.3 Main concerns of the industry**

The pulp and paper industry is part of an important sector, which includes the woodworking industries, the printing and converting industries as well as distributors and forestry activities. Forestry is, in its turn, an integral part of the

forest-based industries as forests provide raw material for the industry. Forestry can, therefore, be regarded as the first stage of a “forest-based industry chain”. Forests thus need a thoroughly management system.

### **Environmental Issues**

The paper industry has long been aware of its environmental responsibilities and has substantially decreased its impact on the environment for several decades. *The great challenge of today is to keep progressing to ensure that every individual part of the paper production process is environmentally sound.* However, these efforts can only be continued as long as they are technically, environmentally and economically acceptable and do not jeopardize industry competitiveness.

**Sustainability - a positive development for the paper industry** Sustainable development dominated the agenda for most of the 1990s. Governments and industry finally realized that not only would they have to provide the goods and services required by society in a cost-effective way, but they would need to do it without diminishing the world’s natural resources for future generations.

The United Nations Conference on Environment and Development (UNCED), held in Rio in 1992, determined that there were three basic, equally weighted interrelated pillars of sustainability: *economic* - economic growth is vital for technological development and the investment required to improve social services; *environment* - industrial growth and consumption should advance in a way that does not diminish the world’s natural resources; *social* - involves concepts which defend that people should be included in discussions and decisions that will impact on their communities.

The impact that this focus on sustainable development has had on the pulp and paper industry cannot be underestimated. Because of its dependence on the forest for its primary raw material, the industry has had a much higher profile throughout the 1990s than before. During recent years, the focus has increasingly shifted to how raw materials are produced by the forest industry. Forest management has continuously improved, and the European pulp and paper industry today is committed to integrating sustainable forest management as part of society’s shift towards overall sustainable development. The management of forests focuses not only on maintaining the biodiversity of forests, but also on guaranteeing the future availability of both environmental and socio-economic benefits



to society, and the economic value. The pulp and paper industry recognizes that sustainability depends on achieving a high environmental performance throughout the papermaking cycle, from forest to final disposal of the used product, but maintaining competitiveness in an increasingly global market.

The pulp and paper industry believes that an efficient and cost-effective post-Kyoto strategy not only needs to be global, but also requires to be defined in close cooperation with all actors concerned. It is also essential that the efforts and resources devoted are not only developed in Western Europe, but are worldwide and that all sectors and actors within society contribute to meeting the targets.

Research, development and innovation is the key to many of the challenges the pulp and paper industry is facing today. Each year, some 1,700 man-years are devoted to pulp and paper research in the European Economic Area (EEA) countries (source: COST 1996 [9]) in institutes and universities. Some of the recent pulp and paper-oriented R&D needs are repeated below [9]:

- eco-efficient processes;
- use of advanced simulation and visualization technologies in industrial processes;
- less capital-intensive production systems;
- energy efficiency in the production systems;
- reduced water consumption through water management and closed loop technologies;
- new biological processes and products, including development of functional enzymes;
- resource-efficient use of renewable materials in packaging, including safety issues.

The progress in environmental protection and in scientific knowledge has led European Union (EU) authorities to adopt a new environmental approach based on two principles [9]:

1. the need to integrate the environmental dimension in any EU policy as recognized by the Maastricht Treaty in 1993 and as strengthened by the Amsterdam Treaty;
2. the need for a greater dialogue between governments, enterprises and the public, to enhance efficient implementation of environmental protection measures. The development of the Integrated Pollution Prevention and Control (IPPC) Directive and the encouragement of voluntary agreements between industry and authorities belong to this trend.

**European declaration on paper recovery** Products from the forest, including paper, form part of an integrated carbon cycle based on the photosynthetic conversion of water, carbon dioxide, nutrients and solar energy into renewable woody biomass. After paper products have been consumed, they can start a new life when separately collected as a secondary raw material. This cyclical process means that the forest is a renewable source of raw material and the eco-cycle is closed and balanced. Based on the idea of this closed loop, the European Declaration on Paper Recovery deals with important aspects of the paper and board life-cycle, from raw materials, auxiliary materials, processes and production, to collection and recycling.

Paper recycling in Europe has increased markedly throughout the 1990s. The amount of paper collected and recycled at the end of the decade is roughly two thirds more than at the beginning. This means that the recycling rate (percentage of recovered paper use compared to total paper consumption) was 48.7 % in 1999, compared to 38.8 % in 1990 [12]. Initially modest, the recycling rate achieved 52.7 % in 2002, and is expected to rise up to around 56 % in 2005 [17]. This scenario makes the paper industry one of the leading recycling industries in Europe. The Signatories firmly believe that the European Declaration will not only help to stimulate the European Paper and Board Industry and Recovered Paper Collectors/Merchants to pay even more attention to environmental interests, but also to encourage other members of the Paper Chain as well as consumers to actively contribute to the achievement of higher collection and recycling levels.

Taking into account the expected increases in paper and board consumption, the ambitious target of a 56 % recycling rate for the year 2005 would mean that the amount of paper and board recycled would be at least 25 % higher than it was in 2001. In real terms, an additional 10 million tonnes or more of recovered

paper will be voluntarily recycled by the European Paper and Board Industry by the year 2005, increasing the total amount of paper collected and recycled per year from 38 million tonnes to approximately 48 million [12].

However, as the consumption of paper is expected to increase in the coming decades, the need for fresh wood fiber will grow as well, even though the collection of recovered paper and paper recycling will continuously rise. For that reason, due attention is also paid to the improvements of the quality of recovered paper, which enforces its character as a secondary raw material. Since recovered paper and board currently accounts for about 40 % of the fiber raw materials used for paper and board making in Europe, it is easy to see why the industry does not consider recovered fibers as waste [9]. Once it has been collected, used paper and board is sorted and graded according to strict standards that define its quality, composition and purity.

Regarding recovered paper as “waste” hampers the positive developments seen in paper recycling and is counterproductive. The positive definition awarded to recovered paper is therefore of vital importance to the papermaking sector, particularly since the paper and board industry is capital intensive and investments have to be made in a long-term basis.

In the following figure (Figure 1.9), a “switching table” for recovered paper and paper and board grades is shown. For reasons of specific end use and market demand for grade characteristics, one cannot put whatever recovered paper grade into whatever paper and board grade, the possible combinations are limited.

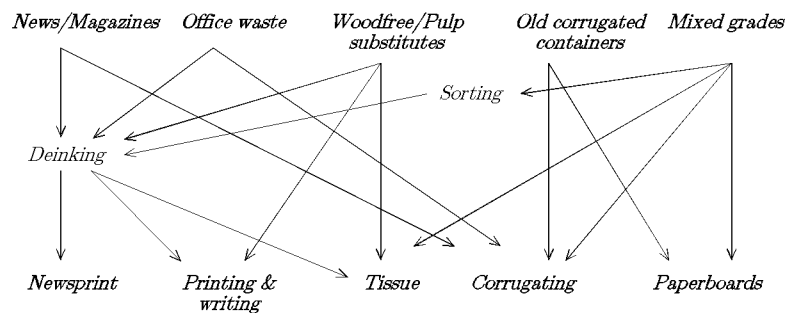


Figure 1.9: Recovered paper: main end uses (adapted from [10]).

Paper and board can even be seen as prompting environmental consciousness,

since it is the first industrial material to engage consumers in wide-scale collecting and recycling, thereby avoiding recyclable paper and board products from ending up on landfill sites. In this way, paper recycling also contributes positively to climate change.

This positive impact can be further improved by increasing recycling, and incinerating used paper that cannot be recycled with energy recovery. This must of course remain technically and economically viable as part of the forest and paper cycle.

**Recycling and paper products** Wood and paper products are used and reused by society for long periods of time. This long-term use represents an expanding reservoir of carbon removed from the atmosphere. The industry's positive contribution towards reducing greenhouse gas emissions (methane from landfills) by using fibers that can be economically recycled should be encouraged, although the technical limitations related to reusing the same fiber must be recognized. Paper cannot be recycled indefinitely, the fibers weaken every time and need to be replaced. Some grades of paper are more suited to recycling than others, and finally, not all paper grades can be made from recovered fibers. Virgin pulp will always remain essential to paper and board production because the loop requires a constant flow of fresh fibers.

Recycling is an industrial process and as such creates residues, be they *used fibers, inks, colors or foreign materials*, which have to be used or disposed off by paper and board mills. Higher collection and recycling levels inevitably lead to an increase in residues, in sorting as well as in recycling processes. Expensive disposal of these residues is becoming burdensome for some mills, which, in turn, hampers the economic viability of paper recycling. Mills are constantly finding environmentally and economically acceptable solutions to this problem. They can be used for example as a soil additive or building material. More and more mills are able to use their residues to generate some of their energy requirements. Research is ongoing, but optimal solutions depend on technological, economic and environmental factors. Experiences need to be shared and promoted throughout the industry.

**Alternative papermaking fibers** For a long time European forests have been an important resource for mankind; previously to source wood, livelihood

and industrial development; and nowadays to provide the foundation of sustainable development of society.

Fibers are the major component of wood and have a phenomenal importance to paper, without them both wood and paper would no longer exist. However, in response to concerns about sustainability an effort is being made to promote the use of alternative fibers to produce paper. Alternative fibers incorporate a whole array of crops and plants for production of papermaking fibers. Non-wood fibers are made all over the world. Cotton, one of the first papermaking fibers, holds the largest share of non-wood fiber production by far. Europe has several cotton paper producers. Cotton and rags are still used in most of the world's banknote and currency paper printing, and the highest end of the text and cover markets (wedding and invitation printing, government declarations, *etc.*).

The rest of the fibers are fighting for second place. Sugar cane (bagasse), bamboo, hemp and straw (rice, wheat and corn) all have positions in several market segments. Kenaf, straw, blue grass, banana, cigar, and others yet untried have had some exposure, but they need more dedicated production for distributors to regularly stock.

Though it is a small, niche area of paper consumption, alternative fibers papers are growing in acceptance and use. Paper qualities continue to improve. Performance has been proven in most printing presses. Availability is reasonable, but prices are higher than wood pulp based papers, and probably will be until proper volumes are in place.

**Climate change and energy** The forest and paper industry recognizes the challenge facing all governments, industries and citizens around the world: the potential warming of the climate as a result of greenhouse gas emissions. Climate change is an environmental issue as well as an important economic, political and trade issue which requires adopting the most cost-effective, equitable and least disruptive solutions in order to reduce atmospheric greenhouse gas concentrations.

Managed forests, an important element of the Kyoto Protocol, provide a powerful mechanism to remove carbon dioxide from the atmosphere. The amount of carbon stored in trees and forest soils is increased, and the industry is able to provide society with more natural carbon-based products. In addition, more biomass fuels are available for energy production.

The Intergovernmental Panel on Climate Change (IPCC) estimates that 12

to 15 % of the projected emissions from fossil fuels up to 2050 could be offset by measures to increase the amount of forested land [9]. Carbon is more efficiently sequestered in growing trees and is estimated that, at the expected rate of utilization and planting, the annual removal of carbon by forests in the CEPI area will increase by approximately 60 % between 1990 and 2010 [11].

It should not be assumed that the pulp and paper industry *significantly* contributes to an increase in emissions. In Europe, for example, the European Commission has estimated that industrial emissions are likely to decrease 12 % between 1990 and 2010, while emissions from transport are expected to increase by 39 % and emissions from households by the same amount, over the same period.

**The forest and paper industry's carbon cycle** Forests play a crucial role in the global carbon cycle (see Figure 1.10). Managed forests, improvements in their productivity and the creation of new forests provide a powerful means for removing CO<sub>2</sub> from the atmosphere. Through sustainable management, the forests and forest products can make a positive contribution towards reducing the risk of greenhouse effect and changes in the climate.

There is growing interest in using forests as renewable energy sources as a substitute for fossil fuels. The pulp and paper industry uses wood in an eco-efficient manner, initially by using it to make useful products and then by using the residues and by-products from the pulping process to generate energy. Seen from the product's side, the raw material, wood from forests, is used in the sawmill industry and the pulp industry. Stemwood is primarily used by the sawmilling and plywood sector. Sawmilling produces sawn timber, for the furniture and building industry, and wood chips, saw-dust and cut-offs for the pulp industry, the particle board industry, and as bio-fuels in the energy sector.

Roundwood from thinnings and lower quality wood are used, together with sawdust and chips, for pulp production. Residuals from the pulp mills, mostly bark and spent liquor, are used for energy generation, mostly within the mills but also in some cases, for sale.

Pulp is turned into paper and board. Downstream industries to the paper industry are the printing, publishing, packaging and converting industries. The final products, be they newspapers, magazines, office printings, books, transport or consumer packaging are mostly capable of being recovered and can be recycled as new raw material in the paper industry or used to generate energy.

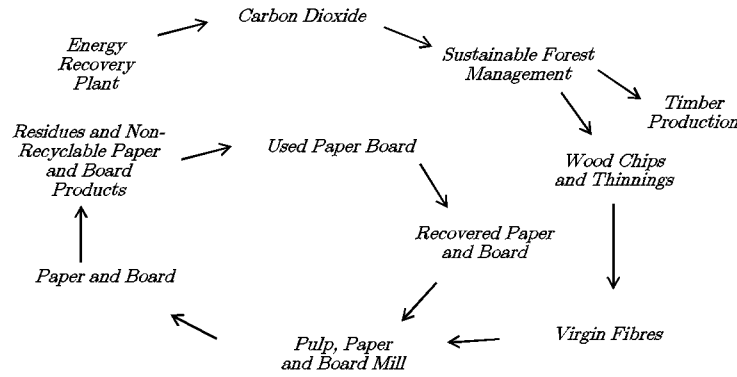


Figure 1.10: The paper and board industry's carbon cycle (adapted from [17]).

Hygiene products are generally not recycled but fit into the eco-cycle as they are biodegradable.

Primary and recycled fiber are complementary resources, as the later can be used in products that are less demanding in quality, whereas products which require specific properties need a high proportion of primary fiber. The paper cycle therefore depends on new fibers replacing exhausted fibers and being recycled in their turn.

**The paper production process and energy efficiency** The paper industry is a substantial producer and consumer of energy, and has already been using energy efficiency strategies for a long time. This has allowed the industry to significantly reduce its emissions of carbon dioxide in the production process. Greenhouse gas emissions in the European pulp and paper industry declined by 25 % per tonne between 1990 and 2001 thanks to a greater energy efficiency in the manufacturing processes, switching to lower carbon emitting fuels, and an even greater use of biomass fuels [16].

At the same time, production of paper products has increased over the past decade in line with higher population and living standards. So, while the absolute emissions of greenhouse gases have increased along with the greater use of energy, there has been a reduction in greenhouse gas emission on a per tonne basis [17]. The industry is one of the main producers and consumers of bio-fuels. Its production and consumption of bio-fuels is increasing, be it wood waste from forests, bark, sawdust, recovered spent liquors or other bio-fuels such as sludges. These bio-fuels are carbon dioxide neutral, since they are wood-based and, when

sustainable forest management is practised, are cycled back into the new forest growth.

The current proportion of total energy use derived from biomass fuels ranges from 18 to 56 %, depending on local circumstances. Combined heat and power (CHP) or co-generation is the simultaneous production of electricity and thermal energy. In some cases, with the sale of electricity and heat to the power grid, it has proven to be energy efficient and is increasingly applied in industry. A CHP unit supplying electricity and heat to an industrial site will use around 30 to 40 % less primary fuel than conventional separate generation. Part of the forest and paper industry's CHP production is based on bio-fuels. In Europe, for example, the production of primary energy by CHP plants, as a whole, has allowed savings of some 30 to 35 % of primary energy as compared to that produced by conventional plants [17].

Energy saving, be it primary energy (biomass, fuel oil, gas and coal) or electricity is, more than ever, a major concern of the pulp and paper industry. Depending on the paper grade and production process, the pulp and paper industry is energy intensive, it can represent up to about 25 % of its manufacturing costs. As a result this has always been a major incentive for the industry to improve energy efficiency [15].

### **1.3 Research and development in a high-tech industry**

Any perception that paper, by its nature, is a low-tech product is misleading. Substantial development work has been undertaken to create the pulp, paper and board qualities of today, emphasizing factors such as printability, machine runnability, opacity, low grammage and barrier properties. High-tech has played an important role in this respect. The large volumes of the products and the necessary quality control require specific machinery with a strong high-tech character.

Modern paper machines are giant tailor-made units which need highly sophisticated control equipment and process computers. The same is true for the equipment and process control of a modern pulp mill. Intensive research has been undertaken by the suppliers of machinery and control equipment to further



improve process control, machine efficiency and paper quality.

Europe presently holds a leading international position in terms of pulp and paper technology. This is evidenced by the fact that not only do some European pulp and paper companies rank among the largest and most advanced in the world but also that some of the world's leading suppliers to the pulp and paper industry are Europe-based.

Within Europe, the largest research institutes are to be found in Finland, Sweden, France and Germany. Through EU Framework Programme for Research and several COST Actions, the research contacts within the European infrastructure are considerable. In addition, substantial development work has been undertaken in many research institutes based in Canada and in the EUA.

The research work, carried out either within the industrial infrastructures or inside the academic institutions, has shown to be an important mean of industrial and technical development in the field of papermaking.

### 1.3.1 The industrial papermaking process

The combined use of high- or low-tech special machines is required for the production of paper. The exact construction and combination of the different parts of the paper machine depends on the type of product generated by the process, as well as the type of fiber used. Although there is no such thing as a standard paper mill, the steps in the papermaking process can in principle be divided in the four main areas of “*stock preparation*”, “*papermaking*”, “*coating and laminating*”, and “*finishing*”:

#### Stock preparation

Recovered paper is delivered to the paper mill in dry form, as is chemical pulp as a general rule, while wood pulp, which is generally produced in the same plant, is pumped to the stock preparation section in the form of a fiber/water slurry. The recovered paper is firstly pre-heated and then dissolved in water before it enters the stock preparation section; while chemical pulp fiber is dispersed in water and then enters a multiple-stage purification process in which fibers are mechanically treated in a refiner in order to increase strength and improve sheet-forming properties.

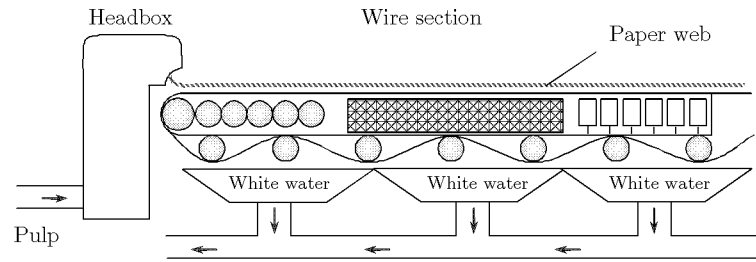


Figure 1.11: The wire section of a typical paper machine.

At this stage a diversity of agents may be added to the mixture, which serve to enhance paper quality according to its end use, as well as to increase productivity. Fillers such as kaolin clay and calcium carbonate (CC), alkyl ketene dimer (AKD) as an internal sizing agent, dry strength additives such as cationic starch (CS), and polyamide-epichlorohydrin (PAE) resin as a wet strength agent, among several others are presently used.

### Papermaking

This is the consolidation stage by excellence. Therefore, this paragraph is devoted to the description of the main steps of papermaking in which dewatering and consolidation of the paper web take place, namely formation, pressing, drying and calendering.

- Formation

The function of the headbox, which precedes the formation section, is to evenly spread the highly diluted fiber mixture over the formation fabric. With a Fourdrinier type of machine the mixture runs through a slit onto a flat, constantly revolving wire mesh or sieve, the wire section (see Figure 1.11). The fibers deposit themselves next to and on top of one another on the wire as water runs through it or is sucked off from below. It is worth noting that water removal is pressure driven, which means that vacuum is used to enhance dewatering as it increases pressure gradient between the two faces of the paper web. What is also true is that with the increasing demand for paper, machines run faster reducing the time available for dewatering. Therefore, water removal is also carried out by pressing the paper web at this stage.

The porosity and organization of pore space in paper, resulting partially from the formation process, will affect its performance in various applications. In fact, the entrapment of small particles, such as fines, and the absorption of polar and non-polar fluids, such as water, coating colors and printing inks, will be dependent on the pore size distribution. According to the work of Ollson and Pihl (see [21]) the organization of pore space, which determines the process of capillary penetration, implies corresponding effects in printing and coating.

- Pressing

In the press section, the web arriving from the former is compressed along several press nips, which operate at increasing nip loads [57]. A typical paper machine consists of three or four press nips [28]. To increase the extent of pressing, the three press nips configuration together with a fourth press nip has become almost standard on new printing paper machines [53], [57]. In the fourth nip the direction of water removal and the side in contact with a smooth roll are the reverse of those in the third nip, thus increasing paper quality, especially in terms of z-direction density distribution and surface smoothness [53].

Pressing technology has undergone a rapid evolution in the recent years in the stride to improve press section efficiency. Increased scientific understanding of the fundamental phenomena involving wet pressing has been an important step to further improve the paper machine press section. As water is expressed from the interfiber space and the fiber walls and pressed into the felt, where it is partially retained, felt design improvement has been decisive for the conceptual progress of recent paper machines. Here, a number of process alternatives, ranging from enhanced dewatering capacity felts to double felted press nips or elongated press nips are good examples. Probably one of the most important new developments in the press section has been the substitution of traditional roll press nips with a press shoe. Moreover, the shape of the pressure pulse can be controlled and the residence time is increased, thus resulting in significant dryness increase especially for flow-controlled nips [72]. The implementation of extended nip presses in the industry has shown to be beneficial in terms of final paper properties and paper machine runnability.

Extensive description of press section operation and development throughout the years will be given in more detail in a following section of this thesis.

- Drying

The dryer section of a paper machine consists of up to 100 heated drying cylinders in which water is progressively removed. The now stronger paper is at first guided over the cylinders with the help from felt sheets but later it threads itself over the heated cylinders. Several other techniques, such as microwave or infrared are employed to further increase the drying capacity of the paper machine or simply to correct the humidity profile of the sheet. It is worth noting that as the sheet is being consolidated water is leaving the larger pores followed by the smaller ones in which capillary forces are significantly higher. At the same time, small particles of fines and fillers are filling in the empty pores to some extent, inducing the formation of new fiber-fiber bonds thus making paper more resistant.

Additional machine fittings in the dryer section can bring about special effects. An example of such a fitting is the size press (consisting of two smooth rollers) with which a durable solution of either starch or a synthetic-based material is applied to the pre-dried paper web. In this way for instance, the surface strength (the *tearing strength*) of the paper can be increased.

- Calendering

Calendering can be performed on-line as a part of the papermaking process or off-line as a separate operation. Some paper machines have as an extension to the dryer section, a calender, which may consist of several rollers arranged vertically one upon the other (the so-called supercalender). By running the almost dry paper web between the rollers under high pressure and speed, the fibers are flattened out in the thickness direction giving a smoother surface and a more compacted structure. Although microslip between the paper and the calender roll result to an extent in shear forces that could possibly be responsible for the glossy appearance of the sheet, it is today generally accepted that gloss is mainly a result of replication of the smooth surface of the steel or cast iron roll into the paper [59], [54]. However, calendering may lead to deterioration in the mechanical properties, *e.g.* the bending stiffness of the paper sheet.

In calendering, there are basically three kinds of processes: machine or hard-nip calendering, soft-nip calendering and supercalendering. In hard-nip calendering paper is passed through two metal rolls forming a hard nip, where the load can be considered to be more or less supported by the thicker areas, *i.e.* fiber

flocs, of the paper. These stress concentrations can thus lead to local variations in gloss. Supercalendering is performed by passing the paper sheet through a stack of rolls vertically arranged, which gives paper superior printing properties than those obtained with a hard-nip calender.

In a soft-nip calender one of the rolls is covered with a polymeric material and the other non-covered roll is heated to a high temperature (see Figure 1.12). The paper obtained in this process presents smaller variations in gloss and porosity but with a less even thickness profile, for the stress concentrations are reduced. In fact, this is a consequence of load distribution over a larger area due to the deformation of the polymer cover.

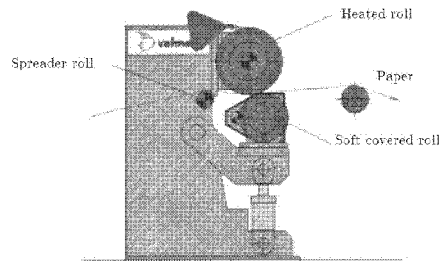


Figure 1.12: Soft-nip calender equipped with a hard heated roll and a soft covered roll (adapted from [59]).

Increasing the residence time, by changing the length of the nip, even smaller variations in gloss and porosity could be achieved. The extended soft nip (see Figure 1.13) can be seen as an extension of the soft-nip calendering process, as now paper is pressed against the heated steel roll.

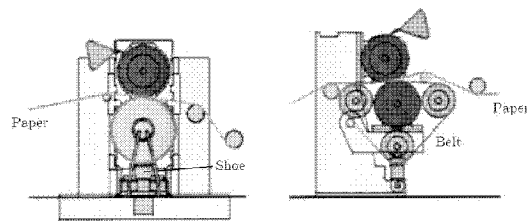


Figure 1.13: Extended nip calender using a shoe press (left) or a belt (right) (adapted from [59]).

More recently, soft-nip and supercalendering have been combined, allowing the use of higher pressures than in a traditional soft nip calender by using smaller rolls. The development of this concept was also based on the use of lower temperatures than those required in a traditional soft-nip calender [23].

#### Coating and laminating

The end-user sometimes demand that some of the raw paper have its surface further improved, which may be achieved by coating. During this process the raw paper is coated with a colored substance consisting of pigments and binders, resulting in a sealed paper surface. A subsequent smoothing of the paper surface may be achieved with the help of another calender, the so-called “supercalender”, in which the paper runs between several rollers of different hardness and material giving the paper its smoothness and gloss. To meet the needs of the recently widened packaging industry a further improvement may be obtained by coating the paper with a synthetic material, as for instance plastic, to make it waterproof or aroma proof. Laminating, which means combining paper with board, paper with paper, or synthetic materials or metal foil with paper or board, is also considered to be a form of surface improvement.

#### Finishing

At this stage paper gets its final appearance before being shipped out to individual consumers and downstream industries. Normally, paper is not used in the full width or length in which it leaves the paper machine or the coater. In the finishing process, the rolls of paper are cut into smaller rolls by a reel cutter, or if needed for quality printing paper is cut by a cross-cutter into format-cut sheets and then placed in piles on palettes and packaged.

### 1.3.2 Pressing technology development

As it was previously mentioned, the production of paper is mainly a question of removing as much water as possible from the pulp at the lowest possible cost. During papermaking, water removal takes place in three stages, namely in the wire, press and drying sections (Figure 1.14).

When the pulp enters a typical paper machine, it contains about 99 % water, the rest being cellulose fibers and chemical additives. Once in the paper machine

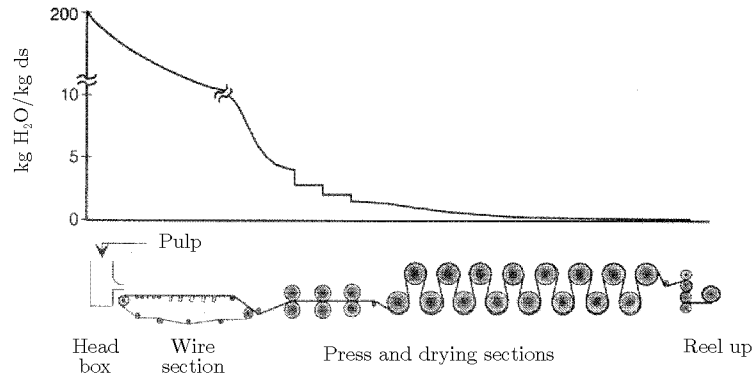


Figure 1.14: Water removal along a Fourdrinier paper machine (adapted from [28]).

water removal is accomplished in three sequential steps. In the first step, the *wire section* or *formation*, the water is removed by gravitational forces or with the aid of suction boxes. As the pulp slurry is squirted onto a plastic screening cloth, the fibers orient themselves in the same direction as which the wire is moving, and attractive forces among the cellulose fibers are developed at the end of the filtration process. After the wire section, the dryness of the paper is approximately 20 %. The following step is in the *press section*, where the dewatering process continues here by mechanical pressure. When the fiber web leaves the press section, its dryness has increased to 35-50 %. The paper then enters the *drying section*, which is comprised of several rotating heated cylinders, and most of the remaining water is evaporated from the paper. After this section, the dryness has increased up to about 90-95 %. Even though the water removal in the drying section is relatively modest this is by far the largest energy user, making mechanical dewatering a much more cost-effective process than evaporation. Also, the demand for higher productivity led to a significant increase in the speed of the paper machine which, in its turn results in higher water content after the press section and higher strain is put on the dryer section. As a result, a considerable effort has been made over the last thirty years, by researchers and paper makers, to increase the efficiency of the press section, which means developing novel consolidation processes that potentially improve machine runnability and paper properties at the most cost-effective way.

### Former process alternatives and future trends

The different techniques and concepts can be roughly divided into three categories: pressing/wet pressing, hot pressing, and high intensity pressing and drying processes. Each of these concepts is associated with different press configurations that were developed and substantially improved throughout the years. Typical operating conditions are to be found in Tables 1.1, 1.2 and 1.3.

A number of process alternatives, ranging from plain to extended press nips and more recently high-temperature processes, have been introduced throughout the years. The first generation of press sections was based on the so-called “*plain presses*”, where water was removed from the paper web by means of a set of plain cylinders operating in counter-current. The increasing demand for higher productivity levels soon showed that faster paper machines were necessary, as those used up to that point could not hold for higher speed and load mainly because water was not allowed to escape from the nip at a sufficiently high rate. An attempt to solve this problem was the introduction of suction cylinders which allowed water to flow easily from the paper web through the felt and finally to the core of the cylinder. This system reduced the water flow resistance (the hydraulic pressure created inside the paper web and the felt is no longer a limiting factor), therefore achieving higher yield levels. However, the so-called “*suction press*” presents some drawbacks: the drilled surface of the cylinder may induce cracks and other damages in some fragile points of the cylinder; the applied pressure cannot exceed a certain level under the risk of inducing shadow marking on the paper surface. In addition, it is a very energy-demanding and noisy system.

Afterwards, a novel concept was implemented in the former plain presses, which consisted of placing a very porous fabric between the cylinder and the felt. The main purpose of the fabric is to retain the amount of water extracted from the felt during the pressing event, after which felt and fabric must be separated in order to avoid or at least minimize the risk of rewetting.

The use of “*grooved presses*” date from 1964 as it was invented by Beloit (“*Venta Nip Beloit*”). The main feature of this type of press is that one of the cylinders is provided with helicoidal grooves that collect water extracted from the felt. The water removal is assisted by gravitational forces and/ or by a vacuum system. It allows the use of high pressures but some marking may arise on the side in contact with the grooved surface of the cylinder. “*Blind drilled presses*”



are thought as an improvement of the former presses. The helicoidal grooves were replaced by a set of different sized drilled surface with a substantially higher water storage capacity. The drawbacks are the same as those for “*grooved presses*”.

The increasing demand for higher grammage papers, such as carton board, has encouraged the development of “*double-felted presses*”. High-grammage paper grades present low water permeability, therefore, the use of two felts improve water removal as the dwell time in the press nip is increased and, on the other hand the mean path water has to go through within the paper web is decreased to half the distance. The main disadvantage of the process is that its use reduces the real pressure inside the nip, thus increasing the risk of rewetting.

Moreover, the common use of a double-felted nip soon showed to be inappropriate for printing and writing paper grades of low specific surface density, as rewetting occurred on both sides of the paper web thus limiting water removal efficiency. On the other hand, the former uncovered cylinders were responsible for sticking and delamination problems, for that they were replaced by ceramic-covered cylinders.

Table 1.1: Typical operating conditions for wet pressing (adapted from Paulapuro, 2000, Paulapuro and Nordman, 1991, Lange, 1991 and Pikulik et al., 1995).

|                          |                          | Conventional<br>pressing | Double felted presses/<br>High-diameter cylinders | Shoe presses |
|--------------------------|--------------------------|--------------------------|---------------------------------------------------|--------------|
| Mechanical pressure      | $\text{kN.m}^{-1}$ (MPa) |                          | 200 - 400                                         | (5.5 - 17)   |
| Temperature              | $^{\circ}\text{C}$       |                          |                                                   | 30           |
| Nip width                | cm                       | 8 - 12                   | 25 - 29                                           |              |
| Maximal outgoing dryness | %                        | 40 - 45                  |                                                   | $\geq 50$    |

Heating the web in the press section has also demonstrated to be a beneficial way to increase the dewatering efficiency in the press section. *Steam showers*, *infrared radiators* and “*steam heated cylinders*” are commonly used to increase the temperature of the sheet during wet pressing [57]. The combination of steam showers and a heated press roll have also been installed in some paper machines [57]. The technique of using steam boxes or “*steam heated cylinders*” to heat the paper web is also used in the so-called hot pressing process.

Heating the paper web, either before or inside the press nip, decreases water viscosity, thus facilitating the water flow throughout the paper web. In addition, a higher densification degree is attained due to the softening of the cellulose fibers

[2]. The implementation of these methods showed to reduce dryer section steam consumption while allowing to obtain a drier and stronger sheet at the end of the press section [57].

In the 1980s a new concept arises with the development of the so-called “extended nip presses”, or ENP. This category includes the terms “*high-impulse presses*”, “*long-nip presses*” (LNP), “*wide-nip presses*” and “*shoe presses*” (Figure 1.15), and the common feature to all is the increased time of contact between the paper web and the pressing element. Except for the “*long-nip presses*”, which are equipped with two high-diameter cylinders ( $>1300$  mm) covered with a soft elastomeric material, the bottom press roll is replaced with a concave press shoe that allows to control the shape of the press pulse, which in addition to the increased residence time leads to a significantly higher dryness, especially for flow-controlled nips (this concept will be further explained in the text) [72]. In the lower element, a dense and flexible belt is passed over the stationary shoe and moves along the machine direction.

In a conventional press the load experienced by the paper web is around  $200\text{--}300\text{ kN.m}^{-1}$ , but in a shoe press it reaches easily something like  $1000\text{ kN.m}^{-1}$ . Moreover, the nip length in conventional roll nips is typically between 20 and 60 mm, whereas shoe press nip lengths are normally in the range of 150 to 300 mm [26], which roughly corresponds to a nip dwell time between 12 and 50 ms on modern machine speeds.

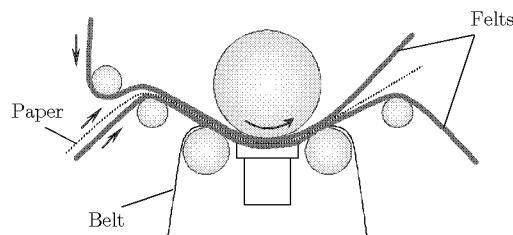


Figure 1.15: Design of a shoe press nip (adapted from [76]).

Presently, shoe presses have become standard elements of modern press sections thus consolidating their position in the manufacture of heavy grades such as linerboard, fluting, pulp sheets and recently in other board grades as well as in light weight grades [27], [56].

Table 1.2: Typical operating conditions for hot pressing (adapted from Paulapuro, 2000, Paulapuro and Nordman, 1991, Lange, 1991 and Pikulik et al., 1995).

|                          |                     | Conventional<br>hot pressing | Pre-heating<br>of the sheet                                      | Heated cylinder<br>presses | Pre-heating of<br>the sheet + heated<br>cylinder presses |
|--------------------------|---------------------|------------------------------|------------------------------------------------------------------|----------------------------|----------------------------------------------------------|
| Mechanical pressure      | kN.m <sup>-1</sup>  |                              |                                                                  |                            | > 150                                                    |
| Temperature              | °C                  |                              |                                                                  |                            |                                                          |
| — paper sheet            |                     | < 100                        |                                                                  |                            |                                                          |
| — cylinder               |                     |                              |                                                                  |                            | 85                                                       |
| Maximal outgoing dryness | %                   |                              | T < 80 °C:<br>dryness is a<br>linear function<br>of temperature. | 48 – 51                    | 51                                                       |
| Machine speed            | m.min <sup>-1</sup> |                              |                                                                  | 1 800                      | 1 320                                                    |

In some emerging techniques such as *press drying*, the *Condebelt process* and more recently *impulse drying*, higher levels of dryness are possible, as temperatures above 100 °C are produced inside the paper sheet thus promoting dewatering.

In press drying the paper web is dried under restraint due to the application of pressure in the thickness direction during the drying process. In addition, paper is in contact with a heated surface, allowing the wet web temperature to rise well above 100 °C [47]. As pressure levels range from 0.1 to about 0.4 MPa, the majority of water is removed by evaporation rather than by means of compression [20].

Press drying is a batch process initially used to fabricate hardboard, and despite the attempts to make it a continuous process it is not yet commercially available given the difficulty of reproducing static press drying conditions in a dynamic apparatus [20].

Afterwards, Lehtinen proposed a process in which the paper web is transported between two rotating impermeable steel bands, drying the paper web under mechanical pressure. The upper band is steam-heated and the lower cooled by water. The water vapor formed near the hot surface passes through a permeable felt in contact with the cold band where it condenses [30]. This technique, known as the Condebelt process, is already installed in two commercial paper mills, one in Finland and one in South Korea. According to Retulainen and Ojala, both mills report good runnability and improved strength properties for

the Condebelt-produced paper compared to conventional-produced paper [30].

Impulse drying will be discussed in more detail later in this dissertation. For the meantime, however, it is important to clarify some aspects related to the common terminology used in the analysis of some pressing events as well as to exemplify some basic engineering parameters and concepts presently used in different paper machines (see Table 1.3).

Table 1.3: Typical operating conditions for high-intensity pressing and drying (adapted from Paulapuro, 2000, Paulapuro and Nordman, 1991, Lange, 1991 and Pikulik et al., 1995).

|                           |                          | Press drying  | Condebelt<br>drying | Impulse drying<br>(one felt only) |
|---------------------------|--------------------------|---------------|---------------------|-----------------------------------|
| Mechanical pressure       | MPa                      | 0.1 – 0.4     | 0.02 – 0.5          | 1 – 5                             |
| Temperature               | °C                       |               |                     |                                   |
| — paper sheet             |                          | < 100         |                     | 100 – 200                         |
| — cylinder                |                          | 100 – 250     | 120 – 180           | 150 – 500                         |
| Dwell time                | ms                       | 200 – 300     | 250 – 10 000        | 5 – 50; 15 – 100                  |
| Machine speed             | m.min <sup>-1</sup>      |               | 100                 | > 800                             |
| Drying rate per unit area | kg / m <sup>2</sup> h    | 25 – 120      | 100 – 400           | 500 – 8 000; 2 000 – 8 000        |
| Specific energy use       | kJ / kg H <sub>2</sub> O | 2 500 – 3 500 | 2 200 – 3 000       | 550 – 1400; 500 – 2 200           |
| Maximal outgoing dryness  | %                        | 40 – 45       |                     | ≥ 50                              |

The overall-aim of developments in the press section is to improve the energy efficiency of web consolidation while enhancing the finished product properties. Due to the intense competition between paper industry suppliers, technology in the pressing and drying sections is likely to continue to advance at a fast pace.

## 1.4 Impulse technology

### 1.4.1 Introduction

The demand to produce more environmentally friendly paper products requires the world industry to put a great deal of effort into more energy-efficient production lines. This is especially true for the world pulp and paper industry. Paper manufacturing is an expensive process associated with very high investment and operation costs. Being the most important process in paper production, dewatering of the cellulose fiber suspension is responsible for the major operation costs. Even though the water removal in the dryer section is relatively modest, up to

about 1 %, the costs for this last per cent are many times higher than those for removing the other 99 %. Moreover, the investment cost is proportional to the number of cylinders installed in the dryer section of the paper machine and in some installations more than 100 cylinders are used. Therefore, a small improvement of the process towards a decrease in energy consumption can, however, easily lead to lower costs or higher productivity keeping the same product quality.

The most obvious goal driving the development of high-intensity pressing and drying techniques is the quest for higher drying rates and more efficient mechanisms of water removal. One such process seems to be impulse drying which combines wet pressing and drying into a single operation. In fact, the introduction of impulse drying in paper manufacturing has generally been expected to offer several advantages over conventional paper technology. Impulse drying has been postulated to be economically advantageous since it uses less energy, although of higher grade such as electricity, gas or high-pressure steam, than conventional drying because the increased amount of water removed in the improved press section may not need to be evaporated in the drier section, which now may use less cylinders. Sprague [66] suggested that impulse drying would probably work well for initial solid contents of 20-50 % replacing one or two presses in the press section. Designing more compact and shorter machines would mean substantial savings in investments [57], [4].

### 1.4.2 The impulse drying concept

In its present form the process has been developed from the original ideas proposed by Gottwald *et al* [24] and Wahren [73], although for different construction solutions. In the early seventies, Wahren, then working at STFI/KTH (Swedish Pulp and Paper Research Institute/Royal Institute of Technology, Sweden), installed a heating element in a falling-weight press, and realized how difficult it would be to get insight of the transport mechanisms involved as the paper web dried extremely fast. This finding suggested that the transfer of heat from the hot surface to the paper web was a matter of utmost relevance.

Some years later, while working at KMW (Swedish Equipment Manufacturers), Wahren focussed his attention on the drying section as he was looking for an effective way of limiting the capital involved in this section of the paper machine. The main goal was to find out how to get the required evaporation heat into the paper web in the most effective way. He then came up with what seemed to be

the solution: “Press hard against a moist surface, and the heat transfer rate will greatly increase. Steam will be formed at the junction between paper and heated surface, so you press harder than the sum of the developing steam pressure and the pressure required for mechanical compression. Steam expands rapidly. Pre-pressing removes any air from the web and enables the steam to move through the web at high speed. Pressing renders the web less porous, so the steam can only move in the direction of the felt, and so perhaps displace water from the web! In addition, water may be pressed out of the fiber walls, but it will be sucked back into them as soon as the pressure is reduced. It is improbable that this water will be sucked back in when steam is flowing past the fibers.” [37].

It was only in 1977/1978 that Wahren applied for a patent on the subject and in 1979 started working at IPC (Institute of Paper Chemistry, USA) where the name “Impulse Drying” first came up.

From 1979 onwards, systematic research on impulse drying was carried out at IPST (Institute of Paper Science Technology, former IPC). The first readings from an experimental program performed with a falling-weight press on bleached kraft paper ( $45 \text{ g.m}^{-2}$ , 140 mL CSF, 25 % and 45 % ingoing dry content), showed that water was removed extremely fast from the paper sample and increases of 10 to 20 % in solids content could be obtained for a nip dwell time of 4.5 ms, depending on the ingoing solids content of the paper samples. Their results also showed that increasing the dwell time to 12 or even 15 ms was not highly effective for porous and thin sheets. For a denser web, however, an extension of the residence time to 12 ms showed to improve the water removal effect, although the drying rate was lower than that for light-weight sheets [1].

Although the results may lead to some discussion, they show that pressing in a high-temperature nip results in more than just evaporation. Evaporation rates alone cannot explain the dryness level attained with the short nip times used. At that time, Wahren and Arenander pointed out that the high temperature of the moving brass block of the static press used caused the surface of the paper to be subjected to a new water removal mechanism in which both mechanical and thermal effects play a role.

As above mentioned the concept of impulse drying was first suggested in a Swedish patent application by Wahren [73]. Instead of conducting heat through thick dryer cylinders, heat was transferred rapidly from a hot surface to the paper web using high pressure. The high heat flow to the paper web generates steam

in the vicinity of the paper web surface and the idea was that the formed steam would pass right through the paper web and drag the remaining free liquid water with it to a “permeable surface” on the other side of the paper web. According to Wahren and Arenander, it is not likely that a classical conduction-evaporation process alone results in so high water removal rates, because it would take longer for such a mechanism to operate. Instead, they suggested the following three mechanisms:

1. the hydraulic pressure gradient at the paper/felt interface;
2. the conduction heat from the hot surface to the paper surface, causing generation of steam;
3. transport of interstitial water out of the sheet by means of the steam-generated pressure gradient or steam flow through the sheet.

These mechanisms would result in extremely high water removal rates and energy efficiencies. The concept today is somewhat different to Wahren’s idea, even though the basics are the same. The original idea was to press the paper web at a high pressure and a high temperature using a short dwell time. Typical operational parameters would be a peak pressure of 2-8 MPa, a temperature of 150-480 °C and a dwell time of 5-15 ms. Temperatures of 200-350 °C and average pressures of 1.6-3.2 MPa are now being used. The contact time in the press nip is 15-50 ms depending on the machine speed and the press nip length (250-300 mm).

A development of impulse drying is to increase the dwell time even further, to super-elongated press nips. A conventional press nip with a nip residence time of only a few milliseconds is too short to take maximal advantage of the effects of high pressing temperatures. It is therefore proposed that impulse drying should be used in the form of a longer nip dwell time or a so-called shoe press [28]. For effective dewatering and densification, exposure times of 20-50 ms are required [66]. Recent research from IPST by Larsson and Orloff [32] demonstrates improved water removal and paper properties. Since the technique is most suitable for long dwell times, shoe presses are used [28].

The patent introduced by Wahren [74] reported that the roll must be heated by hot combustion gases or by an external circulation of a heating fluid. However,

for higher heat transfer rates it is suggested that the hot press roll must be heated using either electric induction or gas energy [65], [28], [30]. Sparkes and Poirier [65] explained that electric induction heating is also cleaner and easier to control compared with combustion.

The theory proposed by Arenander and Wahren trying to explain the high dewatering rate, supporting the existence of a steam-pulse effect, has raised some criticism among researchers. Experiments trying to verify the presence of a steam pulse have been made [77], but the actual mechanism is still not understood in detail.

The principle for impulse drying equipment is shown in Figure 1.16. The sheet is pressed between a moving felt, which acts as a water reservoir, and a smooth heated roll [71]. A cool press roll backs the felt.

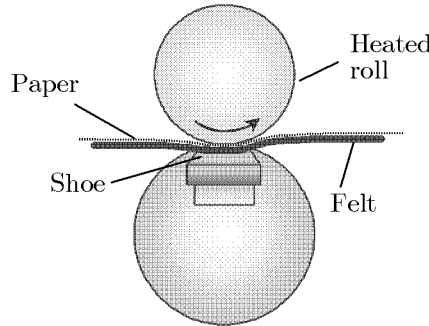


Figure 1.16: Design of an impulse drying press nip.

On the basis of their findings, Arenander and Wahren [1] proposed that the process proceeds as follows:

1. in the first part of the nip, the wet web is subjected to a compressive load and heat is transferred from the heated surface into the proximate layers of the web. This initial part of the drying event may be considered as a consolidation strategy which enhances dewatering by volume reduction and temperature effects on compressibility and water viscosity;
2. if the boiling point of the water at the actual hydraulic pressure is reached, some steam is generated near the hot surface; the only potential outlet for the expanding steam is through the sheet and toward the felt due to the steam pressure gradient established between the top and the bottom of the sheet; at this moment, the voids in the web are completely or partially filled



with water, except for a growing layer of pressurized steam close to the hot surface;

3. if the steam actually flows through the sheet it may drag some interstitial water out of the web and into the felt; while in wet pressing the water in the fiber walls and lumens is transferred to the inter-fiber space and then out of the web and into the felt having the liquid pressure gradient as the driving force, in impulse drying the situation is different: once water has been squeezed out of the fiber walls, it becomes accessible to removal either by steam rushing through the web or evaporation.

As has been shown above, the dewatering mechanisms on impulse drying technique are a complex subject, which is still not understood in detail. As different results and theoretical views have been reported in this field, it is important that further work could clarify the complex mechanisms of dewatering by impulse drying. The heat and mass transfer mechanisms operating in such complex event will be further explored throughout the present manuscript.

### 1.4.3 Dryness and energy efficiency

Impulse technology combines wet pressing and drying into a single operation by pressing the sheet in a nip formed between a felt-covered shoe and a solid roll, externally heated to temperatures above 200 °C. The basic effects of temperature are well known since the 1950s: most literature studies show that water removal due to elevated temperatures increases linearly with the increasing heat transfer to the web, which in its turn presents a linear correlation with the pressing temperature [43], [30]. This technology results in post-nip dryness increases of 2-20 % over the reference pressing technology, and the magnitude of such increase depends largely on the paper grade, *i.e.* lightweight papers experience the highest increases [43]. Then, in the drier section of the paper machine the paper web is dried to its final dryness of 90-93 %. In this section the water is removed by evaporation from the web by means of steam-heated cylinders (steam with saturation temperatures of 80-150 °C). Drying the paper web in the dryer section from dryness of 40-45 % to over 90 % is very expensive because it requires a large amount of energy. Normally about 25-40 % more energy than the latent heat of vaporization is used. The drying rate is mainly affected by the temperature of the cylinder surface and the wet bulb temperature of the air.

The dryness level of paper exiting an impulse drying unit depends on the following variables:

- Machine variables** (*e.g.* roll surface temperature, press load, machine speed). Experiments carried out by Larsson [30] showed that the water removal increases with increasing heat transfer because of hot pressing effects and more water being vaporized. A high press load increases water removal because more water is pressed to the press felt. The author also pointed out that the difference in water removal for different press loads was fairly constant with increasing roll surface temperature which suggests that the total amount of steam formed is not affected by the pressure, from what he concluded that the difference in water removal is only due to differences in mechanical pressure and not in the amount of formed steam. Since the energy transferred to the paper web is approximately proportional to the square root of the dwell time, a higher machine speed should result in a lower moisture ratio change. However this was not always reported from the experimental work by Larsson: no difference in moisture ratio was observed between  $600 \text{ m.min}^{-1}$  and  $800 \text{ m.min}^{-1}$  as the small difference in dwell times was not enough to show any difference in moisture ratio change. The experiments with  $300 \text{ m.min}^{-1}$  showed contradictory results, *i.e.* when an uncovered cast iron roll was used the energy transferred to the paper web was significantly higher than those for lower machine speeds; on the contrary, a ceramic-covered cylinder allowed a much smaller moisture ratio change at the same machine speed. Phelan and his co-workers [55] showed that the heat transfer to the paper web is proportional to the thermal mass (*i.e.* thermal conductivity divided by the square root of the thermal diffusivity) of the roll cover. This author reported a ratio of the thermal masses of 1.4, which means that the cast iron roll transfers much more energy to the paper web than the ceramic-covered roll.
- Paper variables** (*e.g.* ingoing moisture ratio, compression properties, fiber furnish, sheet formation, refining degree, grammage and, fines content and distribution) [67]. For instance, a trend of decreasing water removal for decreasing ingoing moisture ratio has been reported by Larsson [30] and Lavery [35]. As the heat transfer to the paper web is also dependent on the ingoing moisture ratio, because the physical properties governing the

heat transfer inside the paper web are the heat conductivity and the heat capacity of the fiber-water mixture, a dryer web means poor heat transfer capability, thus lower water removal is expected. It is also worth noting that free water outside the fibers is removed by pressing and consequently, the heat transfer inside the paper web is poor. On the contrary, water bound to the fiber structure is not so easily removed, thus a lower water removal level is expected for higher refining degrees (as refining increases fibers hydration level). As for the influence of grammage on water removal rate per unit area, some contradictory results can be found in the literature. Krook's experimental study showed no clear difference in heat transfer between 60 and 150 g.m<sup>-2</sup> and a dwell time of 50 ms. The results were in agreement with results reported by Larsson for 60 and 96 g.m<sup>-2</sup> and dwell times between 25 and 33 ms since the temperature gradients were not fully developed in the thickness direction of the paper[30]. On the other hand, a study by Macklem and Pulkowski in a laboratory rig at a press temperature of 260 °C and a dwell time of 67 ms, showed that the heat transfer to the paper web increases with grammage thus influencing the water removal rate per unit area. The increase in water removal rate per unit area for higher grammage could be explained by the extended dwell time since more water is removed by both mechanical and hot pressing effects. For short press nips, however, the heat transfer is of minor importance since there is no sufficient time for heat to propagate in the thickness direction, whereas wet pressing effects seems to play an important role. If the same power is transferred to different grammage paper webs the amount of water removed is higher for higher grammage, due to wet pressing, as more water is available to be removed (assuming equal moisture ratios).

- **Felt variables** (*e.g.* compression properties, flow resistance, uniformity and moisture) [5], [30]. The use of dry felts results in poorer dewatering than when they are slightly moist. This is likely due to different dynamic compression behaviors of the felt or to modifications in its water absorption properties [5]. The common drawback with the current press felts is the lack of high-temperature resistance, which is required for impulse drying [46]. Besides high temperature-resistance, felts will need to improve sheet release properties for good runnability and impart a smooth surface to the sheet [66]. The surface must also promote and allow water to penetrate as

the sheet is being dewatered [4]. In addition, the body of the fabric must provide sufficient void volume to readily accept and hold the water removed from the sheet as well as rewetting resistance [66], [4]. In the past 20 years, considerable efforts have been made to develop new fabrics that can fulfil these requirements.

As impulse drying has been reported to improve water removal in the press section, it is therefore expected to improve over-all energy efficiency in paper-making. In this new technology, energy is used initially for sensible heating of the wet sheet, later for heating the dry fiber and finally for evaporating the water that leaves as steam. However, in this process, liquid-phase water removal may account for 80-90 % of the total water removed, decreasing specific energy consumption [66], [38].

Typically, the drying section represents approximately 75 % of the energy required for making paper [39]. Using impulse drying this amount can significantly be reduced. An energy balance of an impulse drying unit implemented in a complete drying process, showed that only 61-66 % of the required energy input is used to achieve the same increase in solid contents compared to conventional pressing and drying [71]. As it was already discussed, this percentage depends on machine, paper and felt variables.

If electrically driven impulse drying was introduced in paper industry, the consumption of thermal energy would decrease, whereas the consumption of electrical energy would increase. Although the electricity used to heat the press rolls is more expensive than steam used in conventional drying, there will be an appreciable over-all energy saving [62]. In fact, the real cost savings will depend on the relative price of electricity and boiler fuels.

Moreover, the introduction of impulse drying in paper mills will result in a decrease in emissions of nitrogen oxides (collectively known as NO<sub>x</sub>) and carbon dioxide (CO<sub>2</sub>) due to the decrease in the use of primary fuel, leading to a more environmentally friendly paper production.

During the past thirty years, much effort has been devoted to improving dewatering in paper production. Although in a developmental stage, the technology of “*impulse drying*” has proven to increase dryness in a somehow energy efficient manner. And this is a matter of utmost importance as the economical impact of the implementation of an impulse unit in a paper machine depends on whether

the use of energy is compensated or not with the increase of product properties. In a recent study, Stenström [69] compared the total specific energy use of both a traditional press section (with three nips) followed by a cylinder dryer, and two traditional press nips followed by an impulse unit and a cylinder dryer. From his findings, one may say that a paper machine equipped with the impulse unit would need to have a post-press dryness of about 73 % in order to match the energy consumption of a traditional system pressing from 35 % to 42 % dryness. Furthermore, this showed to be feasible only for low grammage paper grades as the higher consumption of energy for the case of high grammage is not economically viable for the moment [40].

In their work, Larsson and Stenström, [34], two types of energy efficiency have been defined for the impulse unit. The first is the total specific energy use (TSEU) which measures an overall efficiency and is calculated as the total power input divided by the total water removal. The second calculation of energy efficiency is the impulse specific energy use (ISEU) calculated as the heat transferred to the paper web divided by the water removal caused by the elevated temperature. The water removal caused by the elevated temperature is defined as the total water removal subtracted the water removal at wet pressing conditions. The water removal caused by the elevated temperature can in its turn be divided in two mechanisms: hot pressing and vaporization. Hot pressing is defined as the water removal to the press felt due to changes in the compressibility of the paper web and the physical properties, such as the viscosity and the surface tension of the liquid water. In their findings it was emphasized that the ISEU value should be compared with the latent heat of vaporization. It was then found that at lower temperatures the value is higher than the latent heat of vaporization because most of the heat is used to heat up the paper and not so much to remove water from the paper. At higher temperatures the ISEU value showed to be lower than the latent heat of vaporization because water is removed as steam and due to hot pressing. The ISEU is thus a measure of how efficient the impulse drying mechanism is compared to vaporization of water.

In Larsson *et al* [34], it was shown that the water removal due to wet pressing was lower for lower ingoing moisture ratios, which could explain the increase in TSEU. Since the same type of pulp and degree of refining was used in all experiments, it was believed that the decrease in water removal is coupled to the water retention value (WRV), since there is a lower amount of water in between

the fibers which results in a decrease in water removal. Like the TSEU value, the ISEU value also depended on the ingoing moisture ratio. As for the TSEU value, the breakpoint was observed at 1.35 kg H<sub>2</sub>O/kg ds. This trend was confirmed by Macklem and Pulkowski [43] who studied the dependency of the specific energy use on the ingoing moisture ratio in a laboratory rig. For a grammage of 60 g.m<sup>-2</sup> pressed at 260 °C, the specific energy use increased with a decrease in the ingoing moisture ratio. The specific energy use increased from 1000 kJ/kg H<sub>2</sub>O at 1.9 kg H<sub>2</sub>O/kg ds to about 2000 kJ/kg H<sub>2</sub>O at 0.8 kg H<sub>2</sub>O/kg ds. At higher water removal rates the ISEU was constant in the interval of 1500 to 2250 kJ/kg H<sub>2</sub>O. This means that the water removal mechanism is the same and that it is more energy-efficient than vaporization at higher rates of water removal. The reason was believed to be the influence of hot pressing. At lower water removal rates the water removal is close to that of wet pressing and the heat supplied is used to heat up the fibers and the water, which results in a higher ISEU value. Also, for ingoing moisture ratios higher than 1 kg H<sub>2</sub>O/kg ds, Lavery reported a specific energy use of 1000-2100 kJ/kg H<sub>2</sub>O for impulse drying of newsprint (60 g.m<sup>-2</sup>). For linerboard (127 g.m<sup>-2</sup>) the specific energy use was reported to be 1250-1750 kJ/kg H<sub>2</sub>O. All these numbers seem very promising for the Impulse Technology process. Unfortunately the conditions are different for full-scale impulse units where there are more heating losses which are not accounted for in the calculations, except for those of Larsson .

When plotting water removal due to the elevated temperature versus the amount of power transferred to the paper, Larsson [30] found a linear regression. The linearity suggests the mechanism to be entirely dependent on the amount of energy transferred to the paper, *i.e.* combined vaporization with hot pressing. Larsson advanced that, had another water removal mechanism (*e.g.* vapor front displacement) been involved, the water removal rate per unit area due to the elevated temperature would not have increased linearly with the heat flux. Rather it would have increased faster than the heat flux, which was the idea of the vapor front. That is, an enhanced liquid water removal rate per unit area would occur with a very small increase in heat input. No trend suggesting such mechanism was observed by Larsson.

The suggested water removal mechanism, a combination of hot pressing and vaporization, was confirmed by Macklem and Pulkowski [43] who have reported an energy balance for a 110 g.m<sup>-2</sup> hand sheet pressed in a laboratory rig during

67 ms at 260 °C. Macklem and Pulkowski found that the water removal difference between wet pressing and impulse drying was 39 g.m<sup>-2</sup>. To heat up this amount of water to 100 °C and vaporize it equalled to the amount of heat transferred to the hand sheet. This result led the authors to conclude that the water removal mechanism is a hot pressing mechanism combined with evaporation.

It should also be remembered that the overall energy efficiency, which may be given by the TSEU value, of an impulse unit depends on several factors, as reported by Larsson [30]. Moreover, the ISEU value is a measure of how efficient impulse drying is compared to vaporization of water, and it also depends on variables such as roll surface temperature and ingoing moisture ratio of the paper web:

- **Ingoing moisture ratio:** a decreasing trend of the total energy use for higher ingoing moisture ratios was observed. The impulse drying specific energy use showed the same tendency. In Larsson *et al* [31], when plotting TSEU and ISEU against ingoing moisture ratio, it was shown that both TSEU and ISEU decreased to a certain level corresponding to 1.35 kg H<sub>2</sub>O/kg ds. This was suggested to be related to the water retention value; lower amount of free water in between the fibers results in a decrease in water removal by wet pressing and more energy is needed to remove the water inside the fiber walls. Similar results were published by several other authors [43], [36].
- **Grammage:** a decreasing trend of TSEU for higher grammages was observed. Indeed, in heavy-weight paper most of the water is removed by wet pressing, which results in a lower TSEU value. The ISEU value was not affect by grammage [34].
- **Press load:** as it was shown by Larsson *et al* a high press load increased the water removal rate per unit area due to wet pressing, thus it is expected a low TSEU value for high press loads. On the other hand, as the press load did not affect the water removal due to the elevated temperature, the ISEU value is also not influenced by the press load[34].
- **Roll surface temperature:** According to Larsson's experiments carried out for 60 g.m<sup>-2</sup> paper and a press load of 600 kN.m<sup>-1</sup> at different roll surface temperatures, impulse drying showed to be more energy-efficient

at lower temperatures. At these temperatures wet pressing is more dominant, resulting in a low TSEU value between 800 and 2500 kJ/kg H<sub>2</sub>O. At temperatures above 200 °C the TSEU value ranged between 2000 and 2800 kJ/kg H<sub>2</sub>O, slightly higher values than those obtained by Lavery and Macklem and Pulkowski: 1000-2100 kJ/kg H<sub>2</sub>O and 600-2000 kJ/kg H<sub>2</sub>O, respectively [36], [35], [43]. At lower temperatures the ISEU value is higher than the latent heat of vaporization because most of the heat is used to heat up the paper web and not so much to remove water from the web. At higher temperatures, however, water is removed as vapor and also due to hot pressing effects, so the ISEU value is lower than the latent heat of vaporization [34].

In spite of the potential benefits of this technique and after thirty years from its conception by Wahren [73], the process is not commercially available yet. However, there are some problems associated with impulse drying that must be solved for its effective implementation. These problems are *web delamination* as it exits the press, *two sidedness* of the dried light-weight sheets, *brightness* and *opacity losses* and *sticking* of the sheet to roll surfaces. The following section is devoted to improve insight into the most common runnability problems faced by the modern paper machines, and the main effects of impulse drying on paper properties.

#### 1.4.4 Runnability problems and technical solutions to prevent or minimize them

According to some authors, [3], [19], [61], and many papermakers, the industrial implementation of impulse drying has been postponed due to two important runnability problems, namely delamination of the paper web and web sticking to the heated roll surface.

##### The delamination process during impulse drying

Delamination, *i.e.* a strength reduction in the thickness direction of the sheet, has been the main cause preventing the industrial implementation of the impulse drying technology. It is generally accepted that delamination occurs when the force dissipated by the flow of steam generated inside the paper web is greater



than the z-directional strength of the wet web [19], [33], [49], [50]. The mechanism by which the paper web delaminates has been the subject of many experimental studies, and the following conclusions can be drawn: apparently, the heat transferred from the heated roll surface to the paper web increases its temperature during its stay in the nip. Once the sheet leaves the nip, the pressure decreases suddenly. This causes the water, at 100 °C or over, to flash due to the pressure decrease. Depending on the amount of water evaporated, this phenomenon can cause severe damage to the sheet, known as delamination. Several types of delamination problems can be observed, such as complete delamination, delamination bubbles at the felt side, and a reduction in z-directional strength and compression strength. Crouse *et al* [19] have observed four modes of delamination on the paper:

- complete delamination (occurs when delamination happens in the central portion of the sheet thickness and leads to its complete destruction);
- blisters on the heated and felt sides (large or small bubbles formed near the extreme layers of the sheet);
- fiber picking on the heated side (leads to peel off of a skin layer on this side of the sheet);
- internal delamination (occurs in the core of the sheet but is harder to be visually detected).

Delamination is usually characterized by studying the evolution of one or more strength properties with increasing temperature. It can then be defined what is known as the critical delamination temperature, *i.e.* the hot roll temperature at which the measured strength property starts to decrease upon further increase of the pressing temperature. Physical tests such as Scott Bond and STFI compression strength can be used to detect internal delamination. A decrease of sheet density can also be interpreted as a sign of the onset of delamination [40]. Moreover, air permeability, tensile and burst strengths may also be affected for a delaminated sheet [49], [41], [61].

Many attempts have been made to relate the tendency to delaminate to the permeability of the web [48]. Although there are a number of published works reporting the permeability of impulse pressed papers [35], [48], [29] using both dried

and never-dried samples, the results vary greatly and is therefore difficult to draw any firm conclusions regarding the delamination process based upon those results. With dried samples permeability was found to decrease with increasing pressing temperature; according to Burton [6] this was caused by possible densification and stratification of the web thus decreasing its local porosity. Stratification was defined by MacGregor as the uneven densification of the web in the thickness direction due to hydrodynamic forces [42]. On the contrary, Boerner (see [40]) found no change in permeability for never-dried samples taken before and after an impulse drying nip, which suggests that impulse drying does not affect the structure of the web. Szikla and Paulapuro [70] also state that the changes in web structure due to the hydrodynamic forces present during wet pressing do not result in a stratified web structure until after drying. Lucisano [40] reported a decreasing trend in air permeability, for dried samples, with pressing temperature up to 200 °C and then it became essentially constant. The author suggested that the air has an open conductive pathway from one side of the paper to another created by delamination; the reduction in permeability with increasing pressing temperature reflected the fact that the paper densifies with increasing pressing temperatures by reduction in interfiber spacing. The results obtained for water permeability of never-dried samples are not so easy to explain. At low temperatures, below 90 °C, the permeability of the web was found to be essentially constant and independent of pressing temperature. After this, permeability quickly rose to a maximum at temperatures around the atmospheric boiling point of water. Above 100 °C, a linear trend with increasing temperature was observed in the region where delamination first occurred. Under each mechanical loading, the thickness of the compressed sheets was nearly uniform and did not present any systematic variation with temperature. The author assert that the increase in water permeability with pressing temperature can be related to damage occurring in the cell wall material during the delamination event due to flashing of hot liquid water in the fiber walls and lumina (water is likely to be permeating through the cell wall material to a greater extent than in the external pore space).

Press temperature, load, nip residence time, pulse shape, the nature of roll surface material and felt moisture content are variables that can affect delamination [5], [49]. The research carried out in recent years with the purpose of eliminating or at least to minimize the risk of delamination in impulse drying has resulted in a number of rules of thumb, some of which are summarized here. A

classification between fiber/web-related parameters and machine parameters is presented. In addition, phenomena of interest in the loading phase of the nip are separated from those relevant during nip unloading.

The phenomena taking place during the loading phase of the impulse drying event is expected to greatly depend on the thermal properties of the paper web, which in their turn affect the web and fiber structure. Fiber type, water content and initial temperature of the web will certainly lead to different compression behaviors of the network. For example, the critical delamination temperature decreases significantly if the web is heated prior to the impulse nip [58]. This may be related to the fact that the compression properties of the web are enhanced due to temperature effects, which results in a more compacted network and therefore less interfiber space is available for water to flow through the paper web and into the felt. Additionally, some machine-related parameters, such as roll surface temperature and press load have a large influence on the delamination tendency. The use of non-porous materials, with low thermal mass, to be used in the construction of the heated cylinders has been suggested for delamination control [40]. Suitable materials for that purpose are ceramics, polymers, inorganic plastics, glass, composite materials and cermets [40]. The press load influences delamination both through the shape of the pressure profile and through the absolute level of mechanical loading. Larsson and Stenström [33] reported that the risk of delamination could be reduced if a low linear load could be maintained in order to keep the vapor pressure low enough not to destroy the paper sheet. The pressure profile must be set accordingly, *i.e.* it has to prevent the increase of the hydraulic pressure (pressure carried by the water). A low hydraulic pressure is obtained by lowering the applied press load, which leads to a low temperature profile in the web and then the corresponding vapor pressure is not sufficient to induce web delamination.

Other method suggested in literature to inhibit delamination is to control the decompression process of the sheet by means of a slow depressurization during nip opening [51]. Maintaining the pressure after nip opening for a longer time seems to be a better approach when compared with that involving the increase of ambient pressure, because raising the ambient pressure is more difficult to implement due to the need of more advanced equipment [46]. However, the application of a controlled decompression during the nip opening will force the use of higher

residence times. Orloff *et al* [51] supported the idea of using higher ambient pressure to prevent delamination, as they recognized that the ultimate cause of delamination was flashing of subcooled water upon unloading of the impulse nip. From their experiments they found that the ambient pressure did not need to be as high as the saturation pressure for water evaporation at temperatures close to that of the heated roll surface. They came to the conclusion that the method worked not by preventing flashing of water into steam, but rather by limiting the grad forces experienced by the top layers of the paper sample.

Another technical solution for delamination prevention is the use of a porous pressing surface in replacement of the solid surface of the hot pressing roll. Stenström [68], suggested that the high-pressure vapor developed in the hot nip could diffuse into the porous layer, without disrupting the paper. Additionally, the porous layer tends to reduce the heat transfer between the press roll and the paper web. However, such a porous roll configuration was difficult to put in practice. Another disadvantage of the process would be the possibility of shadow-marking and an uneven pressure distribution on the paper surface.

It was also reported that using two impulse units, the second nip appeared to heal the delamination [25]. Apparently, repeated pressure application reduces delamination damage and gives higher dryness.

Chemical additives are thought to prevent delamination since it influences the porous structure of the paper and its strength in the wet state. Westman *et al* [75] suggested that adding a chemical system comprising a polymer component and micro- or nanoparticles to the papermaking stock improves the runnability of the process by increasing the critical delamination temperature and Scott Bond values. Mesic [45] did not find any significant effects on the critical delamination temperature. Instead, he found out that carboxymethylcellulose and chitosan increased that critical temperature due to hydrogen bonding interactions.

## Sticking

Runnability problems associated with web sticking on the hot roll have been observed in certain temperature regions [61]. Rigdahl *et al* [61] detected adhesion of the paper web to the heated roll in temperatures between 140 and 180°C. The sticking phenomenon is more likely to happen in this temperature range due to the thermal softening of the wood polymers [61]. The wood polymers are

a solid at low temperatures, but they soften with increasing web temperature [71]. At sufficiently high temperatures, it appears that the fast evaporation of the water keeps the surface of the polymers again solid, preventing the web from sticking to the heated roll [71]. Roll temperature appears to be an important factor affecting the adhesion, but web sticking also depends on machine speed and ingoing solid contents of the web [61]. Impulse drying temperatures should be kept above the sticking region but at levels lower than the critical temperature for delamination [61]. However, these conditions may in some cases overlap and to prevent the web from sticking at low temperatures the roll should be coated with a special non-stick surface. For example, Orloff and Lindsay [48] applied a polymeric release agent to the ceramic roll to overcome any tendency to sheet sticking. The method also allowed to achieve lower heat transfer rates, which reduced the risk of delamination [37].

#### 1.4.5 Enhanced paper properties

Enhanced strength properties are of utmost importance for the economical assessment of impulse technology since it needs to compensate for the economical disadvantage of high grade energy consumption.

It was early recognized that since press drying makes the paper more dense, it has the potential to produce good paper bonding and strength even with pulps that normally give only low strength papers. The same seems to be true for impulse drying.

However, it is still unclear whether the improved mechanical properties are only due to the increased density or if some additional effects are present. Back, suggested that, with the exception of a minor amount of auto cross-linking (indicated by an improvement in wet strength) the increase in dry strength is due to an increase in interfiber bonding area [3].

The ability of pulp fibers to form fiber-to-fiber bonds is an important characteristic, which strongly influences the structural, mechanical and optical properties of paper. The formation of fiber-fiber bonds depends mainly on wood species, and/or pulping method, fines content, amount of bonding agent, chemical modifications of fibers, refining and consolidation process [64]. Impulse drying subjects the paper sheet to more intense operating conditions than those in a conventional process. High temperatures improve fiber flexibility and conformability, explaining the greater sheet densification obtained by impulse drying.

Laboratory experiments in platen press simulators, performed by Burton [6], Burton and Sprague [7] and Rudman and Orloff [63], showed that impulse drying generates a unique density profile in the thickness direction of the web, as the well-known stratification phenomena on the felt side of the sheet was accompanied by the development of a high-density region at the surface in contact with the hot pressing platen. This resulted in a “U”-shaped density profile with local maxima at both paper surfaces [40]. Cross-sectional solidity profiles were evaluated from micrographs of paper cross-sections using an image-analysis technique [59], and a comparison of some typical profiles of oven- and freeze-dried samples was made. It was shown that the drying history affected the measured solidity profiles: in all non-delaminated oven-dried samples a parabolic profile was observed whereas an essentially uniform profile was found for freeze-dried sheets. The solidity profiles before and after the impulse nip were remarkably similar but shifted towards higher solidities, with no sign of stratification. Further, the measured profiles were found to translate uniformly towards higher solidities with increasing pressing temperature. Asymmetric profiles were detected only after the onset of delamination. On the basis of these findings, Lucisano [40] advanced with the argument that for non-delaminated impulse pressed sheets, the resulting parabolic solidity profile is a phenomenon resulting from capillary forces present during oven-drying and not a result of hydrodynamic forces induced onto the fibers during the pressing event. No clear evidence was found to justify the hypothesis of heat-induced stratification due to lignin-softening suggested by Burton and Sprague [7]. A combination of surface density and mid-sheet bulk can be advantageous in developing several physical properties. In some cases, however, the nonuniform density may be a disadvantage [66].

The thermal softening of cell wall material is responsible for the increase in smoothness on the heated roll side of the sheet. The improvement in surface smoothness is clearly one side, since for the surface of the paper in contact with the felt either it decreases or remains constant [61], [44]. Paper is calendered in order to obtain a smoother surface and thereby better printing properties [60]. However, paper is also permanently compressed during the calendering operation, and this means that its mechanical properties may be affected in a negative way [60].

Uneven printing ink absorption is a quality defect for printing paper. For grades where equal smoothness is required on both sides, three alternatives are

suggested in the literature [22], [57]:

- the use of a smoothing press roll in the final press position;
- the application of a soft nip in the dryer section or calendering section, to smooth the opposite side of the sheet;
- the installation of a second impulse drying unit, where the geometry of the two stacks is arranged in such a way that both paper sides are exposed to the hot roll.

Among these alternatives, the third one is likely the most effective and practical for most applications because a second impulse drying unit may eliminate the need for calendering [4]. The sheet becomes, in all properties, less two sided and generally prints better [25], [4].

In fact, different research institutions have been studying the effect of a second impulse drying unit to reduce two sidedness. In a study conducted at IPST, it was demonstrated that the roughness difference between the two sides was significantly reduced in a second nip operated at the minimum pressure required to sustain impulse drying [25], [4]. During 1996-1997, STFI in Stockholm also equipped its research paper machine EuroFEX with two impulse units [61]. In fact, the press section consists of one roll press followed by two SymBelt presses (*i.e.* shoe presses). The rolls in the shoe presses are inverted in relation to each other, the shoe being in the bottom position in the second press and in the top position in the third press.

Several other paper properties are influenced by the impulse drying operating conditions. A brief summary based in the experimental investigation carried out by Mendes *et al* [44] is presented here:

- as expected, the reduction observed on the thickness induces an increase of sheet density;
- air permeability of the impulse dried sheets was reduced in all cases (60 and 80 g.m<sup>-2</sup> beaten at 25 and 40 °SR) when compared with the ambient pressed handsheets. This behavior can be explained by the increase in density;

- the stiffness of the paper pressed at 80, 150, 200, 250 and 350 °C, for different grammages and beating degrees studied here, was lower than that of paper sheets pressed at room temperature. Stiffness is proportional to the in plane elastic modulus, and to the third power of the sheet thickness. Thus, although the increase of the pressing temperature increases the in plane Young's modulus, at the same time it decreases the thickness resulting in a decrease of the paper stiffness;
- the consolidation achieved allowed better fiber-to-fiber contacts, thus creating more bonded areas. Consequently, higher internal cohesion strength was observed;
- an improvement of burst and tear index was also observed;
- roughness is a property that affects the printing and converting qualities of a paper sheet. The impulse drying produces more closed sheet surfaces, which resulted in a decrease of the surface roughness and an increase in surface smoothness. However, at some pressing temperatures some delamination was detected. Some paper sheets made from bleached *Eucalyptus globulus* kraft pulp present visually small blisters on the hot side surface of the sheet. In fact, paper sheets of 60 g.m<sup>-2</sup>, beaten at 40 °SR and pressed at 250 °C, and samples of 80 g.m<sup>-2</sup>, beaten at 40 °SR and pressed at 150, 200, 250 and 350 °C, were visibly delaminated on the heated surface. These observations are in agreement with the increase on roughness or the decrease on smoothness on the side of the paper sample contacting the heated plate. *This means that high temperatures can be used for lower grammages and beating degrees without occurring the delamination phenomenon;*
- at a pressing temperature of 350 °C, the *Eucalyptus globulus* paper sheets suffered a decrease in brightness;
- there were no major effects in most physical properties for paper made from *Pinus pinaster* pulp. This furnish was found to exhibit more problems of delamination even at the lowest grammage and refining degree. *Therefore, impulse drying was more effective on papers made from Eucalyptus globulus pulp than in the sheets of Pinus pinaster pulp.*



The use of impulse drying will allow the reduction on fiber use or the substitution by lower grade furnishes of lower cost to meet product specifications [66]. Alternatively, a lower pulp beating degree can be used to achieve the same paper strength than in a conventional process. According to the IPST team, impulse drying could be used to reduce fiber usage by about 10 %, while maintaining strength properties [52].

In this novel consolidation process in which water is removed from the paper web by the combined action of mechanical pressure and intense heat in a short residence time in the impulse nip, the response of the sheet is affected by fiber type, shape size (packing density), stiffness, compression resistance, previous process history (drying) and network formation [20]. Taking into account all these factors, more research is needed before reaching the capacity of predicting the properties of paper sheets prepared from a given furnish associated with machine parameters.

## 1.5 Summary of the literature

1. Although the potential benefits of impulse drying have been debated over the last thirty years, its industrial acceptance has been prevented by some difficulties in controlling the physical aspects of the web under these intense conditions [39]. In fact, delamination has been one of major obstacles to the commercialization of impulse drying. However, over the past few years, much progress has been made towards solving sheet delamination problem, which makes the commercialization of impulse drying almost a reality.
2. There is a large body of information available in the literature on the water removal and heat transfer mechanisms involved in such a complex process. Nevertheless, more experimental work is necessary in order to get insight in the heat and mass transfer phenomena and quality changes of the sheet. Improved mathematical descriptions for the heat and mass transfer as well as for the stress-strain behavior exhibited by the fiber network (*i.e.* wet paper) would be of great help to understand the mechanisms by which paper consolidates and dries by impulse drying.

## 1.6 Objectives and thesis lay-out

Impulse technology is seen as a promising web consolidation technique that combines the effect of mechanical pressure and intense heat to remove water from a paper web. Over a number of years, this novel technique has been developed and improved in terms of press nip design and control of the physical aspects of the paper sheet that might turn it less susceptible to delamination. Many methods have been tried to prevent delamination, and much of this work has been focused on the understanding of the complex interactions of heat with water in the compressible porous structure of the paper sheet. Delamination has been known to occur almost since the inception of the impulse drying concept [1], and it was believed that it could be overcome by proper control of the ingoing sheet characteristics and dryer parameters. Although this was partially accomplished, the operating window was still somewhat restrictive, which impelled several institutions and industrial companies to work jointly on the development and implementation of the impulse drying technique, and considerable effort has been made in the last few decades to get more insight on the mechanisms by which the paper web consolidates.

The central issue of this work has been the study of the impulse drying process in the paper production, with special emphasis in the dewatering and consolidation mechanisms involved in the press section of the paper machine. As mentioned above, a deep knowledge of the interactions between heat and water is of utmost importance to control and optimize this operation in order to improve paper quality and to reduce the operational costs. The development of theoretical models based on the many physical, chemical and mechanical phenomena that are involved in this operation, constitutes an attempt to understand and quantify the most diverse interacting phenomena. As repeatedly mentioned in the literature, the complexity of this operation arises from the fact that all those phenomena are coupled. It is advanced that the main mechanisms involved are the heat and mass transfer with phase change, and the rheological behavior of the fibrous material. Bearing this in mind, the specific objectives of this thesis are:

1. to develop a theoretical model able to describe the pressing/drying process at high temperatures, taking into account all the physical phenomena in-

- volved (conductive and convective heat and mass transfer with phase change), as well as the chemical aspects;
2. to validate the mathematical model by comparing the results from the simulation runs, with data obtained in a lab-scale platen press;
  3. to develop a lab-scale platen press in order to simulate press nips similar to those used in the impulse drying process, and to record temperature, pressure and displacement data;
  4. to get a deep insight into the mechanical behavior of both paper and its supporting material in the press nip, the felt, when submitted to the extreme operating conditions of impulse drying;
  5. to evaluate the water removal efficiency under conditions of interest for high-intensity processes;
  6. to experimentally determine the influence of temperature, peak pressure, nip residence time, and physical properties of the material, on its mechanical response inside the press nip;
  7. to investigate the influence of some chemical additives, usually used in the papermaking industry, on the performance of paper pressed from room temperature up to 350 °C.

Finally, this thesis is divided into six chapters, briefly described in the following paragraphs.

**Chapter 1** focus four main areas that characterize the papermaking industry and its development throughout the years. A brief historical perspective is given by highlighting the most important and decisive stages of the art of making paper. Then, economical, social and environmental issues related to the sector are presented and discussed. The extensive research work carried out by the industry and several educational institutions is described and the major achievements are enumerated. The final section is dedicated to the description of the impulse drying concept and the runnability problems inherent to the process, as well as to the technical solutions found so far.

As one of the main goals of this work was to experimentally characterize the changes in web properties such as density and moisture ratio during impulse

drying, a laboratory press was adapted to meet the requirements of the research. **Chapter 2** therefore describes the experimental program carried out in the platen press, covering different operating conditions in terms of temperature, peak pressure and nip residence time. This research also evaluated the effect of some paper parameters such as grammage, refining degree, moisture ratio and pulp furnish on the mechanical behavior of paper. For this purpose, paper samples from bleached kraft pulp of *Eucalyptus globulus* and unbleached kraft pulp from *Pinus pinaster* were prepared and submitted to impulse drying, where temperature, pressure and thickness recordings were obtained. These results were then used to validate the theoretical models developed both for paper and felt. Additionally, a set of impulse drying trials were performed with paper samples with different wet end additives, namely cationic starch, polyamide-epichlorohydrin resin, alkyl ketene dimer and calcium carbonate, in order to infer about their influence on the mechanical response of the material being pressed, and also on the water removal efficiency of the process. This last parameter was also evaluated for the different operating conditions.

Finally, it is presented a study based on the thermal mechanical analysis of paper samples of different pulp furnishes and moisture contents. The main purpose of this investigation was to determine the possibility of a glass transition of paper components in the temperature range of the impulse drying tests, which could produce a significant change in the materials response to compression.

In **Chapter 3**, a mathematical model for high-temperature pressing of paper is developed. Prior to the description of the model, the fundamentals of wet pressing are presented as a basis to the understanding of high-intensity drying of paper. The water removal and heat transfer mechanisms involved in impulse drying of paper are focused, together with the major factors that might affect those same mechanisms, namely temperature, press load, machine speed, moisture ratio and grammage.

Then a brief review on the existent rheological models for paper is presented. A deeper insight in this field is given in **Appendix A**. In addition, a number of mathematical models of wet pressing based either in experimentally determined data and empirical relationships or in physical laws that could describe the behavior of the material in a more realistic way, are described together with the recent developments of high-intensity pressing models.

Afterwards, a rheological model based on the theory of cellular solids is pre-

sented for paper. This new approach intends to describe paper as a cellular material, highlighting its nonlinear behavior when submitted to compression. Paper is then treated as a viscoelastoplastic material, and its elastic and viscous properties are estimated as a function of its components rheological properties according to the rule of mixtures. The model was used to predict the evolution of paper strain and density for a given peak pressure and pulse shape imposed in a typical impulse drying event, and it constitutes the starting point to the development of the global mechanical model. **Appendix C** contains a brief description of the cellular solids theory, giving special emphasis to the mechanical behavior of foams and honeycomb-like materials.

Finally, an unsteady state simultaneous heat and mass transfer model is presented, where the complex mechanisms involved in the dewatering process of paper are included. A global model that integrates all the mechanisms involved in the process is then presented. The model performance was evaluated using the typical operating conditions used in impulse drying. A brief description of the main wet pressing models is presented in **Appendix B**, and serves as a basis to the development of heat and mass transfer models for high-intensity drying processes.

**Chapter 4** is dedicated to the study of the supporting felt. This chapter summarizes three experimental studies focusing on the dewatering performance and rheological behavior of felts designed for impulse drying. The study is divided into three separate but interrelated parts: (i) the first part deals with an experimental investigation of felt permeability and compressibility. This preliminary study aims to give some insight into the consolidation process of the felt when subjected to the same operating conditions as those used in impulse drying; (ii) a mathematical model for the rheological behavior of the felt is derived and compared with the experimental results from dynamic compression trials; and (iii) computer simulations of the pressing event are presented, aimed at showing how the dewatering process takes place within the fabric. The objective of the work reported in this section was then to specify the role of felt in the water removal process taking place during the impulse drying of paper.

Additionally, **Appendix D** and **E** contain information related to the analysis of the experimental data.

Then, **Chapter 5** describes a global three-dimensional unsteady state model

for the high-temperature pressing of paper and felt. The validation of the model is accomplished by comparing the results from the simulation runs to the experimental data obtained with the laboratory platen press. Finally, some major conclusions of the present work and recommendations for future research are drawn in **Chapter 6**.

The printed version of this thesis is accompanied by a CD-ROM, which contains additional material that cannot be reproduced by any means. It includes mathematical details, computer code (see **Appendix F**) and other background information that could not be included in the main text, *i.e.* all the appendices previously mentioned, as well as some additional experimental results.

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## Chapter 2

# Experimental

*“Measure what is measurable, and make measurable what is not so.”*

Galileo Galilei (1564-1642)





## **Part I**

### **Impulse drying analysis**



## 2.1 Introduction

The most extensive experimental research in the field of impulse drying has been performed on delamination and heat transfer. Other areas covered in the literature are dewatering, rheology of the paper fiber network, influence of operating parameters such as temperature, press load and machine speed, as well as paper and felt properties on the performance of the process. The mechanisms of impulse drying have been widely discussed in the literature since the technique was conceived in the early '70s, yet no clear picture has emerged. From the theory of a steam front developed within paper near the hot roll surface and able to displace any unbond water from the wet web, to the idea of a hot pressing process combined with flashing of superheated water, and even to the combination of these two main phenomenological approaches put forward in the literature, experimental and theoretical studies have been manifold.

Impulse drying is similar in nature and mode of operation to traditional wet pressing technologies. The main feature of impulse drying, that sets it apart from conventional processes, is the simultaneous action of intense thermal energy and mechanical pressure to enhance sheet consolidation and dewatering. This is also true for press drying. Yet, Sprague [59] argues that the differences in operating conditions, dewatering mechanisms and technical challenges towards an industrial installation are so important that impulse drying and press drying are to be treated as distinct processes. In spite of the differences, it is clear that most phenomena discussed in connection to press drying, and even to wet pressing, have some relevance in the investigation of the physics of impulse drying. For that reason it is instructive to present a brief review of technological advances of lab-scale presses since the wet pressing era till the emerging impulse drying technology.

### 2.1.1 Lab-scale developments and achievements: bibliographic review

In the past forty years, different research projects have been carried out around the world covering wet pressing technology and related issues as well as high-intensity drying processes. The possible process conditions in which impulse drying technology may be applied were initially explored using static presses.

Different paper grades such as linerboard, tissue and writing paper, newsprint and LWC were tested in order to investigate the effect of pressure and temperature profiles on both water removal rate and paper properties. In addition to noting the various effects of these two operating parameters on paper properties it was found that the operating window was restricted by the risk of sticking at temperatures between 100 and 200 °C [34]. High water removal rates were observed for all paper grades covered by the research, and a strong evidence of density increase was reported for impulse drying compared to conventional drying processes [34].

A recent study by Reverdy-Bruas [54] highlighted the influence of the applied pressure and fiber furnish on both compressibility and porosity of saturated hardwood and softwood bleached paper samples for two different refining levels. The experiments were carried out on a compression device designed to measure the steady-state value of both transversal and in-plane water permeability of paper. The samples were pressed from 0.1 to 3.5 MPa between two permeable plates at room temperature and the web thickness was continuously recorded by eddy-current displacement transducers. The experimental results indicate that water movement inside and out of the pulp fibers effected the compression behavior of the fiber network. In fact, softwood paper samples tend to be compressed to a higher extent due to the also higher water retention value of its fibers compared to that of hardwood fibers. In addition, higher porosity levels were reported for hardwood paper samples [54]. Although of extreme relevance to determine the water permeability of paper, this type of devices cannot represent the real operating conditions to which paper is subjected in a press nip of a modern paper machine.

Many designs of laboratory platen presses based upon wet pressing of a stationary paper web are available in the literature. Chang [15], studied the compression behavior of a paper web placed between a solid plate and a felt using an air pressurized camera to exert pressure on the web. The thickness of the paper web plus felt was recorded and web thickness was calculated by subtracting the separately measured felt thickness at the corresponding pressure level. Two major problems were detected in his experimental evaluations, the inaccuracy in the felt thickness calculation and the unknown interaction in the felt/sheet interfacial layer. However, what really stands out of Chang's work is the attempt to study

the hydraulic pressure in the sheet during the pressing operation.

Almost at the same time, Wahren and Zotterman at FPPRI (Finish Pulp and Paper Research Institute) used a press simulator built to create fast sinusoidal pulses. As shown in Figure 2.1, the felt is fixed to the bottom surface of the falling part and the paper sample is placed on the stationary head, which has a solid pressing surface. After bouncing, the anvil is caught by a special mechanism at a safe distance from the sample, therefore ensuring that the felt is in contact with the paper web only during the press pulse. The removed water is transported through the felt into the grooves of the pressing head.

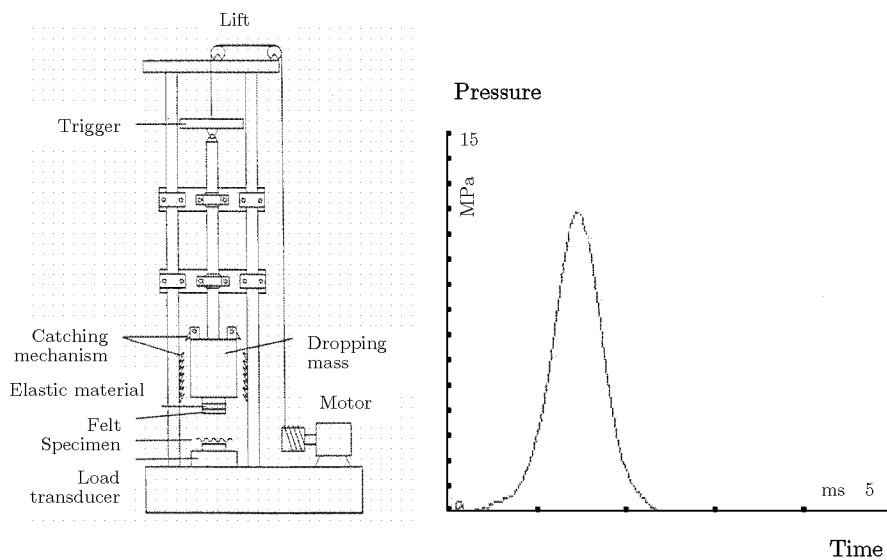


Figure 2.1: Schematic drawing of the Wahren-Zotterman type press simulator; typical pulse made by a Wahren-Zotterman type press simulator (adapted from [61]).

The mass of the dropping part together with its velocity at the moment of bump determines the kinetic energy, which then determines the impulse of pressing. The strength and dwell time of the force pulse created between the dropping and the stationary heads are then a function of kinetic energy and velocity of the dropping mass and compression properties of the system taking part in the bump. A higher velocity yields a higher peak pressure and a shorter dwell time. A peak pressure of about 22 MPa can be obtained when the dwell time is 1.5 ms and the sample size is 35 cm<sup>2</sup> [61]. A softer nip can be generated by placing a suitable rubber sheet behind the press felt. A typical pulse made by the FP-

PRI's Wahren-Zotterman type simulator is presented in Figure 2.1. This device simulated the complete press cycle, including compression, pressure release and final separation.

Ceckler *et al* [14] also studied the compression event of a paper web placed between a solid plate and a porous plate, which allowed to obtain a more accurate evaluation of the web thickness and dryness. The pressure release or plate separation phase was not studied by Ceckler *et al* [14]. As with Chang [15], pressure oscillations were observed during the first 5 ms of the pressing event.

All the press simulators built to that time, including the ones at FPPRI, have been platen press type devices. Regarding mechanical simulation of wet presses the pioneering work was performed at KMW (Sweden) and at the Institute of Paper Chemistry (USA) in the end of the '70s. Further refinements were carried out later at STFI (Sweden) and at the University of Maine (Orono, USA). In these press simulators the paper web is pressed between two parallel plates and the pressure pluses generated are very similar to that of true presses. However, the events in true presses and simulators differ from each other in one respect: in true presses the different points of the web along the machine direction are in different phases of pressing, therefore, systematic gradients exist in the web in the machine direction. In the simulators the same load is concentrated simultaneously over the whole sample. This brings about the question of how important is the role of in-plane water flow inside the paper web. According to a general view the water flow out of the web is mainly transversal although the in-plane water flow cannot be neglected [61].

### **Stratification: density profile measurements**

In the platen press equipment used in the previous studies, as well as in some other experimental work performed later by Ellis [19], Carlsson [13], Jantunen [24], Burton and Sprague [12], Springer *et al* [60], Burns *et al* [8], El-Hosseiny [18] and Szikla [61], a wet pulp web was placed between a smooth solid surface and a rough permeable surface. The dynamic compressibility of the wet web was evaluated based on the applied stress and the recorded web thickness. However, this type of arrangement, as shown in Figure 2.2, has some critical points as pointed out by Vomhoff [65]. During the pressing event the water flow through the wet web exerts primarily viscous forces onto the fiber network, which results in

a structural stress onto the fibrous structure. This structural stress accumulates and thus increases in the flow direction, creating an uneven compaction of the web in the thickness direction, commonly known as stratification and first defined by MacGregor [42]. The highest compaction of the material is found near the porous plate. Through the years, stratification has been predicted in models by Westra [68], Jönsson and Jönsson [26], and was also experimentally observed by some researchers like Wicks [69], MacGregor [42], Burton and Sprague [12], Szikla and Paulapuro [62], and Burns *et al* [8].

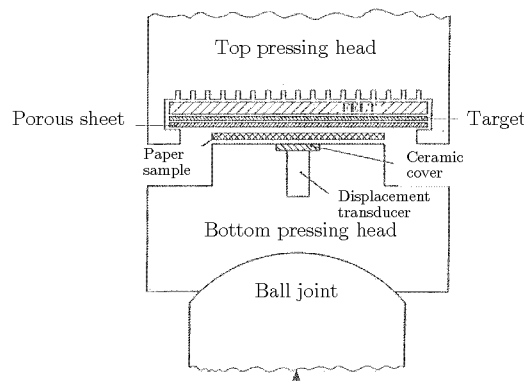


Figure 2.2: Schematic drawing of the thickness measuring system used by Szikla (adapted from [61]).

The process of stratification is defined as the development of a z-direction density profile resulting from the redistribution of sheet fiber and filler caused by fluid shear forces, but it can be avoided if no water flow occurs in the fiber network during the compression event [65]. To accomplish that, both Ellis [19] and Szikla [61] used unsaturated wet webs when investigating the dynamic compressibility. The paper webs were pressed to maximum compression without reach saturation. Szikla observed, in contrast to Ellis, a dependency of the compressibility on the stress rate and relates this phenomenon to the flow of water within and out of the fiber wall; this influence has been mentioned also by others [25], [66], [51], and is supported by the fact that a considerable amount of water is pressed out of the fiber wall at the compression levels obtained in wet pressing [13], [30]. It is worth noting, however, that under unsaturated conditions the compressibility of the fiber network is changing with increasing dryness, which may be an important limitation to obtain reproducible experimental conditions.

Wicks (i) pressed five  $60 \text{ g.m}^{-2}$  handsheets together in a roll press nip, separated them after the press nip, and measured the dryness and density of the individual handsheets [69]. Szikla and Paulapuro (ii) embedded samples in epoxy resin after wet pressing, and then used an image analysis technique to measure the density distribution over a cross section of the sample [62]. Burns *et al* (iii) embedded metal targets at different levels in their samples during forming. By measuring the movements of the individual targets during the pressing experiments, they were able to study thickness changes of the layers within the sheet. They could then calculate the densities of the different layers in the sheet during pressing [9].

Despite the three different techniques used, all the researchers came to the same conclusion: higher sheet densities are found close to the permeable surface where the water is removed. Vomhoff [65] came to the same evidence when some years later, trying to illustrate the wet pressing process, was able to visualize the stratification during the dynamic consolidation of a paper model. The paper model consisted of 10 rectangular layers of foam rubber, each with a thickness of 3.2 mm and a density of  $43 \text{ kg.m}^{-3}$ . In order to make density gradients visible, the layers were dyed alternatively black and white. The paper model was compressed using a hydraulic press controlled by a MTS equipment operating in a deformation control mode. From the experiments, Vomhoff observed that the layers were compacted in succession starting with the layer next to the permeable press surface. Moreover, the extent to which the different layers were compacted was dependent upon the compression and permeability properties of the model material and on the compression rate. Unfortunately, the effect of temperature on the compression behavior of paper webs was not the subject of Vomhoff's study.

### **Density and strength properties**

In the late '80s, in an attempt to simulate the high-intensity pressing conditions used in the impulse drying technique, tests were performed on a dynamic laboratory press at IPC. The reported paper properties were comparable to those obtained from the earlier static press tests [12]. Meanwhile, at Paprican a semi-continuous press was being used to evaluate the energy consumption during impulse drying experiments. The average power requirement reported was only 65



% of the theoretical requirement for heating the web up to 100 °C to obtain a similar solids content through evaporation. Other results from Paprican show the same trends in paper properties as those earlier reported by IPC, *i.e.* increased density combined with improved tensile strength and a decreased scattering coefficient. The increase in tensile strength is less than that obtained from the static press tests.

Property improvement, strongly influenced by density development was reported by Burton and Sprague [12]. The density profile measurements have considerably increased the understanding of the dynamic physical processes which occur during impulse drying. Figure 2.3 shows density measurements over a typical impulse drying event for a 173 g.m<sup>-2</sup> handsheet, originally at a moisture ratio of 1.4 kg H<sub>2</sub>O/kg ds impulse dried at 315 °C, and density profile measurements taken over a single wet pressing event.

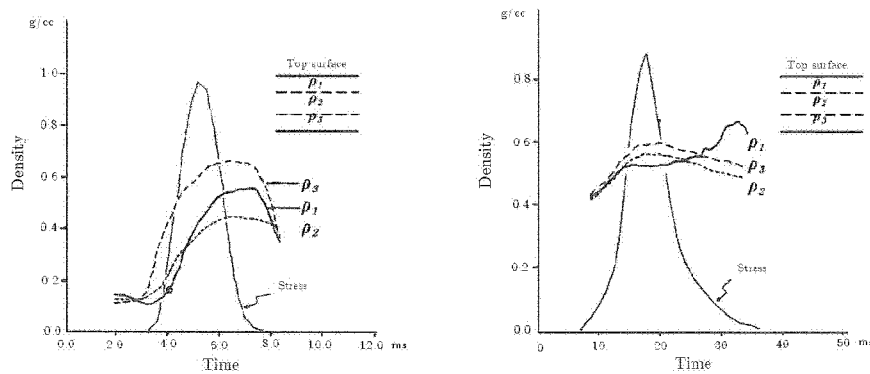


Figure 2.3: Density-time relationships for each of three sheet thickness regions taken over an impulse drying event. Basis weight = 173 g.m<sup>-2</sup>, ingoing moisture ratio = 1.4, freeness = 735 CSF,  $P_{max} = 4.14$  MPa; impulse drying temperature = 315 °C. (adapted from [12]).

### The physics of wet and impulse pressing: experimental highlights

By observing the response of the sheet structure within the nip, much can be inferred about wet pressing and impulse drying fundamentals. The above mentioned authors [12] suggested the following explanation for the density profiles obtained in their experiments:

- Wet pressing results

Since the sheet is initially saturated, pressurization of the liquid water begins immediately. The region next to the ceramic porous plate (see Figure 2.2) densifies first, followed by the middle region as the hydraulic pressure gradient increases in magnitude towards the press surface. Since the flow from the press surface encounters the greatest cumulative flow resistance, and the flow from the exiting region the least, it follows that the region near the porous plate densifies at the highest rate, followed by the middle and press surface regions, respectively. Moreover, the rapid increase in the measured density of the press surface region is considered an artifact of crushing that results from the radial flow of both water and fibers out of the press nip. This is apparently attributed to the very high moisture of the sheet which caused a large hydraulic pressure in the press surface region that could not be reduced through the transverse flow of water from the sheet.

- Impulse drying results

Initially, the sheet densifies uniformly as it would during wet pressing. Since it is at a low moisture ratio, there is little fluid resistance to compression resulting in an even density profile. Near saturation, the densities of the individual layers begin to develop to different magnitudes. The lower regions continue to densify beyond the saturation point, reach a maximum density near the peak applied pressure and then begin to expand. Steam pressure measurements at the hot surface region indicate a significant resistance to compression which leads to a near constant density over the central part of the nip. As the applied pressure is reduced, the steam pressure drops and the previously steam-filled structure begins to collapse and densifies.

The intense dewatering and densifying forces of impulse drying result in high average sheet densities and nonuniform z-direction density profiles. Measurements of the density distribution of impulse-dried sheets by other means such as scanning electron microscopy, demonstrated that much of the density profile developed dynamically was retained in the fully dry sheet [11]. However, these findings have been a matter of some controversy, as it will be further highlighted in the text.

In related work, other researchers have attempted to characterize the delamination event by changes in the web permeability. There are a number of published works reporting the permeability of impulse pressed papers using both dried and never-dried samples. The reported data is sometimes controversial which makes it difficult to draw a firm conclusion regarding the delamination process. However, some results brought some insight into the stratification event and its relation to the impulse drying process. As previously mentioned some authors attributed stratification to hydrodynamic forces developed in the thickness direction of the web within the press nip. It was also found a decrease in local porosity of the post-dried impulse pressed webs, which could be related to its permeability and tendency to delaminate [42], [12]. A contradictory result was found by Boerner however [7]. With never-dried samples he observed no changes in permeability for samples taken before and after the impulse nip. This implies that impulse pressing causes no significant change in web structure. Moreover, Szikla and Paulapuro [62] suggested that the changes in web structure due to hydrodynamic forces present during wet pressing do not result in a stratified web structure until after drying. They observed that freeze-dried sheets pressed under the same operating conditions as those sheets that were dried in a drying-drum at 65 °C did not display the same z-direction density gradient. The outer layers of the freeze-dried samples remained bulkier than the inner parts. Further, they advanced the idea that the densification effect of wet pressing is primarily attributable to the improvement of the fiber bonding conditions. The essential difference between a web dried by evaporation and a web dried by sublimation of ice is that in the latter case far fewer bonds are formed between the fibers [62].

Further, Lucisano and Martinez [37] found no evidence that either wet or impulse pressing induced stratification in non-delaminated sheets. In their experiments paper samples were obtained before and after the impulse nip of STFT's research paper machine, EuroFEX, and then they were cross-sectioned and imaged in order to determine the solidity profile. Additional experiments were performed by simulating impulse pressing on a lab-scale platen press in which the pressing head was heated to temperatures used on the research paper machine, *i.e.* temperature was increased stepwise from 40 °C to 290 °C. The first observation to draw was that non-delaminated freeze-dried samples were substantially thick than those oven-dried, indicating an important action of capillary forces [37]. Also, freeze-dried samples presented an essentially uniform profile, whereas

a parabolic profile was found for all non-delaminated oven-dried samples, regardless of the drying strategy. Moreover, the density profiles were similar for samples taken before and after the impulse nip. The second observation made was that the measured profiles moved uniformly towards higher solidities with increasing pressing temperature. Asymmetric profiles were observed only after the onset of delamination. On the basis of their findings, Lucisano and Martinez advanced the argument that capillary forces present during oven-drying were responsible for the resulting parabolic profiles, and not the hydrodynamic forces induced onto the fibers during the pressing event [37].

### **Interfacial phenomena**

Apart from the relevance of the water flow through the porous media and the consolidation behavior of the fibrous network, special attention has been paid to the possible effect of the non-uniform compaction of the web, which is induced by applying the load onto the web by means of a rough permeable contacting surface: the felt. Felts have been shown to play a critical role in the success of the impulse drying process. Felts for impulse drying must meet the same mechanical and chemical resistance requirements as felts for conventional press sections but must survive the extreme temperature conditions. Among several features, the felt should distribute the applied load into a fairly uniform pressure over a sufficiently large paper surface area. Moreover, it should constitute a rather soft press transfer medium, that will adjust to the somewhat irregular thickness of the web, and in a similar way, it should transfer the pressure between the web to be compressed and the water receiving structure, like drilled holes, grooves or a coarse fabric. Although recent works tend to show that felt permeability in modern pressing techniques is not a major factor for the efficiency of the process, and may thus be neglected [22], the structure of the felt remains at the forefront of pressing physics because of its water stock capacity, the problems of rewetting and, as mentioned previously phenomena related to the uniformity of pressure application. According to Vomhoff [65], a non-uniform stress application results in a heterogeneous flow inside the web. He observed that, compressing the web non-uniformly with parts of the paper model (as described earlier) penetrating into the “surface-pores” of the felt model, a significant reduction in required compression stress was achieved. Figure 2.4 illustrates the hypothesis on the interaction between web and felt and its influence on the flow inside the web.

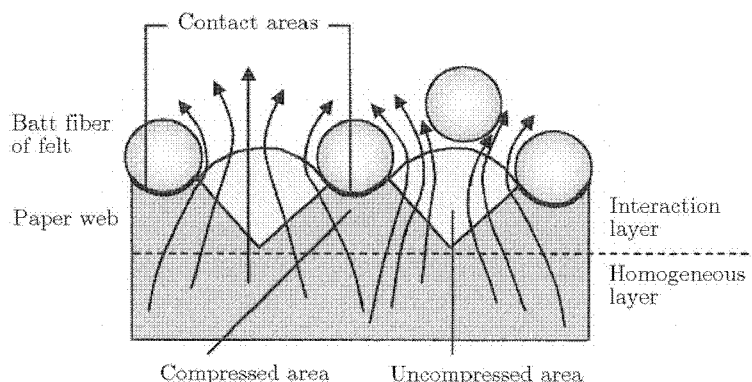


Figure 2.4: Hypothesis on the interaction between the felt and the web and its influence on the water flow inside the web (adapted from [65]).

Here the web was divided into two layers, the interaction and the homogeneous layer. While in the region below some imaginary separation line the web can be assumed to be compressed homogeneously, in the interaction layer the regions below a contact surface are compressed to a higher extent than those between contact areas. Towards the center of the web, the applied stress is spread from the contact points sideways and the web is compressed more and more evenly. Furthermore, in the interaction layer, the water flow in the web occurs predominantly in the uncompressed and highly permeable areas between the contact areas. Being a boundary effect, the influence of the non-uniform compression should decrease for increasing web thickness [65].

The influence of the contact material, *i.e.* the felt, on the web permeability was studied by Vomhoff. In his experiments water was pressed through a sandwich consisting of two identical contact materials with a paper web of defined grammage in between. The permeability was evaluated based upon the measured steady-state volumetric water flow rate and the pressure drop over the permeability cell. Six contacting materials were used: a sintered plate, a coarse wire and four different felts (extremely coarse and extremely fine felts, both with respect to batt fiber diameter and base weave). It was then observed that at an identical grammage, the permeability was several orders of magnitude larger when the web was compressed between the wires, *i.e.* when the more “open” structure was used. Despite choosing extremely different felts, the difference in permeability was at the limit of significance. In fact, at lower web grammage

the size of the batt fibers appeared to control the permeability, with coarser batt fibers giving higher web permeabilities. For higher web grammage, however, the difference in permeability was less discernible. The results also suggested that the interaction between the web and the rough contacting surface influenced the flow through the compressed fiber network, especially at low grammage, and that the flow was not homogeneous over the entire fiber network. Moreover, Vomhoff suggested that interactions between the web and the rough contacting surface should also be relevant during highly transient pressing processes. It should also be pointed out that the paper web is usually compressed between two surfaces with a different structure and, therefore, the flow situation might differ from that presented above. Irrespectively of the effects on the flow through the paper web, the asymmetry between the two contacting surfaces of a typical impulse event results in a very smooth surface (the one in contact with the hot pressing surface) and a rougher surface (the one in contact with the felt). Being so, impulse technology could be useful for qualities that require one smooth surface only and, at the same, it could be used to correct undesired two-sidedness by installing two impulse units inverted with respect to each other.

### **On heat transfer in impulse drying: from experimental to theory**

Apart from the work devoted to investigate the influence of hot pressing, and in particular of impulse drying, on the physical and mechanical properties of paper, the heat transfer from the heated pressing roll into the paper surface and through the thickness of the web towards the press felt has always been a matter of extensive research. The central question being asked here is, what is the net result of the research so far in terms of insight? Experimental research in heat transfer is vital in the attempts to understand the mechanisms behind impulse drying in the sense that it serves as a basis for defining models of the process. The development of these models could ultimately be defined for the purpose of preventing surprises in the event of future scale increases or changes in paper production using impulse technology.

Knowledge of the temperature gradient achieved in the paper and the heat transferred at different roll temperatures and pressures during high-intensity pressing conditions is important for design purposes and it has been the subject of several studies since the early 80's.

Impulse drying is characterized by high peak heat fluxes followed by a gradual decrease [49]. These high heat fluxes and water removal rates experienced during the impulse event suggest that the mechanisms that control dewatering differ substantially from those of conventional pressing and drying operations.

Explanations for such high water removal rates are manifold, but an analysis of the literature published in the field suggests that three modes of water removal can take part in the impulse event, as already reviewed in **Chapter 1**:

1. *Hot and superhot pressing*, *i.e.* dewatering by volume reduction, enhanced by temperature effects on network compressibility, water viscosity and capillary pressure. The water inside the web is considered to be in the liquid state, even if temperatures exceed 100 °C;
2. *Evaporative dewatering*, in which thermal energy is used to evaporate water. Here, two modes of liquid-vapor phase change are considered: traditional evaporation or drying, and flashing. *Drying* refers to the use of evaporation to remove liquid water from a solid matrix by supplying enough thermal energy to overcome the latent heat of evaporation of the liquid phase. *Flashing* or flash evaporation is another mode of evaporation in which the liquid water is exposed to a pressure lower than the saturation pressure at its temperature. In contrast with other modes of evaporation for which heat is supplied to the liquid from the outside, sensible heat stored in the liquid as superheat is converted into latent heat of evaporation during flashing. The theory of a flash evaporation taking place in the final phase of the impulse event, when the applied pressure is reduced, following a hot pressing process, was suggested by Macklem and Pulkowski to explain the dewatering process present in impulse drying. Their interpretation was later adopted by Larsson to explain his own experimental data [31]. It is worth noting that, according to the interpretation suggested by Macklem and Pulkowski, all or almost of the water trapped in the web remains in the liquid state in spite of the high temperatures recorded in direct experiments. Opposing evidence was presented by other authors, [72], [35], [53], who suggested that a complex *heat-pipe* mechanism advancing through the paper sheet was responsible for the high heat fluxes, *i.e.* the vapor formed close to the surface would be transported to spots cold enough for condensation to take place. Lindsay and Sprague [36], proposed that a resupply of

water to the region near the hot surface via a capillary wicking mechanism would be responsible for the temperature gradient in that region, thus explaining the high heat fluxes in the final step of the impulse event. Besides capillary wicking they also pointed out that the water located in the lumen of the fibers close to the hot surface could be insulated, making the heating and boiling of the water very slow. Capillary forces, gravity and gradients in saturation pressure drive the motion of the fluids. This results in the latent heat of evaporation being transferred between the ends of the porous media via the motion of the fluid [39];

3. *Steam-assisted displacement dewatering* in which liquid water is displaced by the action of a vapor phase. The existence of a steam front or not has been a matter of great controversy since the impulse drying concept emerged in the late 1970s. According to this theory, the resulting steam pressure hypothetically developed in the initial portion of the nip is expected to act as an extra dewatering force, displacing the free liquid water from the wet web into the felt. Moreover, a positive thermal effect is assumed as the heat transfer between the steam, the fibers and the remaining liquid water results in an effective heat-up of the sheet. Arenander and Wahren [3], Devlin [17], and Rudemiller [55], report indications that such a vapor-phase displacement mechanism drives water from the sheet due to volume expansion upon phase change [39].

The main purpose of the vast experimental work published in the field of impulse drying was to gain insight into the commonly accepted non-conventional heat and mass transfer mechanisms. The most accurate and updated temperature and heat flux measurements in paper webs subjected to impulse drying, at least to the author's knowledge, have been performed since the mid 1990s. According to several authors, the two opposing theories to explain the high heat fluxes observed in impulse drying found experimental evidence in works developed by Devlin [17], Lavery [33], Burton [10], Lindsay and Sprague [36], Ramaswamy and Lindsay [53], Zavaglia and Lindsay [72], and more recently Krook *et al* [29], Larsson [31], and Lucisano [39]. In spite of the effort to clarify the complex mechanisms of heat and mass transfer involved in impulse drying it is still difficult to draw a firm conclusion on the subject. The following paragraphs summarize some of the most



relevant experimental studies focusing on the role of phase change phenomena in the physics of impulse drying.

### **The role of phase change phenomena: experimental research**

In order to simulate impulse drying, Krook *et al* [29] used a MTS platen press with an electrically heated pressing head. The heat transferred to the web and the temperature gradients inside a sheet during impulse drying were investigated. They measured temperature in the z-direction by placing micro thermocouples between three thin sheets that were placed on top of each other. It was further shown that the temperature measured between three discrete paper webs give the same result as in a single homogeneous web of the same grammage.

Two sets of experiments were performed by Krook *et al* in order to investigate the influence of peak pressure and platen press temperature, from which it was concluded that at lower temperatures there is not much influence of the peak pressure on the web temperature. Basically the same web temperature is reached even if the peak pressure is increased from 0.5 to 8 MPa. At higher pressing temperatures, however, the temperature profile observed in the thickness direction of the web suggested that peak pressures higher than 1 MPa lead to web temperatures well above 100 °C. The authors advanced the idea that at lower peak pressures the load is mainly taken up by the fiber network, thus resulting in a hydraulic pressure close to the atmospheric pressure which prevents temperature to exceed 100 °C. Increasing the peak pressure would increase the hydraulic pressure enough to allow the wet web to be heated well above 100 °C.

In fact, if the hot surface temperature is higher than the saturation temperature corresponding to the resulting hydraulic pressure, the paper web will be heated to the saturation temperature, and a further increase of the hot surface temperature will therefore not result in a higher web temperature, as long as liquid water is present. However, if the applied pressure is increased, it would produce a higher hydraulic pressure inside the web thus increasing the corresponding saturation temperature. In this case, the web would be heated further to the new saturation temperature, water would evaporate and keep the web at that temperature as long as liquid water is present. But, increasing the applied pressure does not increase web temperature as it would be expected. Krook *et al* advanced two possible reasons for this: either the resulting hydraulic pressure was close to atmospheric, which means that even at 8 MPa the applied pressure

was mainly taken up by the fiber network, or the peak pressure had passed before the web was heated to 100 °C. The main idea to retain here is that as long as liquid water is present temperatures above 100 °C are only expected in the region of the web closest to the hot surface.

As for the heat transfer issue, Krook *et al* [29] measured peak heat fluxes in the range 2-8 MW.m<sup>-2</sup> at surface temperatures ranging from 100 to 300 °C, which they found to be in accordance with the literature. As expected, heat is transferred very rapidly to the web in the beginning of the nip due to the temperature gradient between the hot surface and the upper surface of the wet web. As heat is transferred from the hot platen to the web faster than it is further transported to the interior of the web, heat is accumulated in the region of the web closest to the hot surface thus allowing the web temperature to quickly reach a temperature close to that of the hot platen. This can explain the high heat fluxes in the first milliseconds of the pressing event followed by a gradual decrease.

Almost at the same time, Orloff *et al* [50] used a lab-scale device named “High Ambient Pressure Impulse Dryer” (HAPID) to simulate impulse drying. Most of the focus of that work was to control the cause of delamination, which the authors believed to be flash vaporization at the nip opening. In fact, they advanced the idea that water in the web exists as a subcooled liquid just prior to the nip opening. They further suggested that as the nip is opened the web continues to be heated while experiencing a sudden pressure release, which leads to a rapid flashing of the subcooled liquid to vapor.

In that exploratory work they hypothesized that reduction of the pressure differential between the inside and the outside of the web and suppression or reduction of vapor formation during the nip opening would prevent delamination. This goal was achieved by pressurizing the atmosphere surrounding the sheet with compressed nitrogen after the close of the nip but before nip opening. Therefore, their results directly support the flash vaporization theory for delamination and suggest methods for opening the process operating window of impulse drying technology. In a particular way, the work points out that by sufficiently increasing the ambient pressure at the nip opening, the press roll surface temperature can be increased without inducing web delamination, therefore resulting in increased water removal.

More recently, Lucisano, Mazzatorta and Martinez [41] performed an investigation of steam forming during an impulse drying event by conducting two different, yet complementary studies. In a first study, they measured the transient temperature profiles of wet paper webs subjected to a compressive load in a heated platen press, by placing thin thermocouples inside the samples at different elevations through the paper web. The initial temperature of the platen press was set from 150 to 300 °C, the length of the pressure pulse varied from 100 ms to 5 s, and the initial dryness of the paper webs was held constant at approximately 30 %. For longer pulses, *i.e.* 5 s they observed four distinct regions in the measured temperature profiles: (i) initially the sheet was heated to 100 °C, whereupon (ii) the temperature remained constant at the atmospheric boiling point of water until the felt side of the sheet reached 100 °C. After that, (iii) the temperature increased again until (iv) an almost stationary condition was reached just before nip opening. In light of their findings, they concluded that conduction was not the primary mechanism by which heat was being transferred in the initial portion of the nip, as they measured a heat flux with essentially no gradient temperature between the heated platen and the upper surface of the paper web. They further suggested a heat-pipe mechanism, *i.e.* a convective mode of heat transfer to be dominant in that region. However, with faster compression rates, they saw no evidence of such mechanism. Instead, they speculated that web stratification or viscoelastic effects induced an increase in the hydraulic pressure which, in its turn, would tend to shift the boiling point of water and prevent steam generation. In summary, the authors believe that for short pulses the hydraulic pressure in most of the sheet is high enough to prevent steam generation and water is present in the liquid phase until the pressure is released.

Also, with platen temperatures greater than 200 °C and nip dwell times shorter than 500 ms, they observed a sudden increase in temperature when pressure was released from the paper sample. The same qualitative trends were observed when experiments were later repeated with more realistic pressing conditions (pressing dwell times reaching down to 25 ms and pressure profiles resembling more those used in real press machines).

The goal of their subsequent work was to investigate both the course of events at the interface between the wet sheet and the pressing surface, and the existence of liquid displacement and its role as an additional dewatering mechanism.

The authors performed visualization experiments using a modified platen press and STFI's FlashLab, a laboratory device for flashing studies in water-saturated porous media [40].

Traditionally, it has been assumed that steam would form when the web comes in contact with the hot surface and that it could assist dewatering by displacing unbound water [67], [17]. Opposing evidence was suggested by Lucisano *et al* when performing visualization tests in a platen press analogous to those traditionally used for studies of impulse technology [40]. The main feature of their visualization apparatus is the replacement of the heated steel platen that was normally located above the sample by a removable 10 cm diameter by 1 cm thick borosilicate safety sight glass mounted from below. Once uniformly heated to nearly 220 °C in a furnace, the glass platen was placed on the apparatus, whereupon the pressing head with the attached 60 g.m<sup>-2</sup> paper web was lowered into place so that a high-speed camera was activated, and the pressing event was initiated (see [45] for more details). The maximum applied pressure was approximately 8 MPa and residence times from 25 to 250 ms were experienced. Images from short press pulse experiments suggest flashing only at the end of the nip since no evidence of steam bubbles generation was observed prior to that moment. On the other hand, an increase in nip residence time showed a more dramatic pattern of events for the impulse experiments, since bright spots (possibly bubbles) appeared soon after loading and increased in density across each image taken throughout the event [40]. In light of their findings they suggested that no significant in-nip steam generation takes place for short press pulses and that this type of phenomena might only be seen for pulse lengths well beyond those encountered in industrial pressing conditions.

The mechanism of dewatering upon unloading of the hot press nip was characterized with experiments performed on STFI's FlashLab. The core of the apparatus is a pressurized sample holder equipped with transparent windows for direct visual inspection. The structural and hydraulic pressure in the sample can be set independently of each other and the temperature can be set up to 180 °C (see [38] and [41] for more details). The sample holder was loaded with a 7-8 cm thick fiber cake with 20 % solids content of softwood bleached kraft pulp beaten to approximately 20 °SR. Prior to the experiments, the system was pressurized to 0.7 MPa and heated for 2 hr to a maximum sample temperature of 150 °C.

Flashing was initiated by a sudden release of the pressure in the expansion tank and flashing-induced phenomena were recorded on a digital videocamera focused on the inspection window of the sample cell. The results of these flashing experiments showed, according to the authors, that displacement of liquid water by action of an expanding steam layer can play an important role in the physics of dewatering in an impulse nip. In these experiments, steam generated by flashing could be vented through the cold surface only, which caused three phenomena to occur: (i) initially, the expanding steam chamber on the top of the fiber cake compressed the spring supporting the wire; (ii) additionally, the fiber cake was consolidated by volume reduction due to the vapor pressure; finally, (iii) liquid water was displaced from the fiber cake by the expanding steam layer. Additionally, Lucisano *et al* [41] suggested that flashing of water, together with steam expansion in the opening press nip, could explain the large temperature peaks observed during their platen press experiments, since hot liquid water is displaced through the wet web towards the felt, thereby heating up the sheet.

Lucisano *et al* proposed that this mechanism should be termed “*flashing-assisted displacement dewatering*” since it differs from the steam-assisted displacement of liquid water originally proposed by Wahren [67] because of the different driving force [40].

## 2.2 Materials and methods

### 2.2.1 Design of a laboratory press

Many experimental studies of dewatering and consolidation of wet paper webs have been performed using laboratory platen presses. Here, the web remains stationary as it is pressed between the movable pressing head and the bottom plate. Laboratory presses in which the paper web passes dynamically through the press nip have been used, at least to the author’s knowledge, in studies of separation rewetting [1], [27], and web delamination [27]. In fact, both studies were performed at the Royal Institute of Technology, in Stockholm, using the so-called KTH-press in which the shape of the pressure pulse is determined by a changeable press shoe acting against a rotating press roll. Such experimental conditions are more representative of an industrial impulse drying event as the water flow patterns within the sheet, both in the cross and in the machine di-

rection, are generally assumed to be more resembling of those observed in real paper machines. However, platen presses have gain acceptance in a vast amount of experimental studies of heat and mass transfer phenomena, which is due to its less complex structure and easy fitting of sensors and control devices. It is, however, worth noting that invaluable research work has been performed in pilot-scale presses. Here, the different mechanisms taking place in the impulse drying event represent more accurately what happens in a real paper machine. Nevertheless, experiments at pilot-scale were not within the scope of the present work.

In the present study, one of the goals was to develop a laboratory press, allowing the investigation of the dynamic behavior of wet and water saturated paper webs submitted to the extreme temperature and load conditions typically used in impulse drying. In order to simulate pressing conditions as close as possible to those of an industrial pressing event, and measure some dimensional changes in such paper samples, it was essential to have a very sensitive control/acquisition system. Therefore, a hydraulic press (see Figure 2.5) available in the laboratory was modified and equipped with a high-precision measurement system. New sensors were placed on the press and the control software was optimized to the purpose of this work. The following paragraphs summarize the most important features of the laboratory press and the main decisions taken concerning the choice of equipment and sensors that were introduced in the apparatus in order to allow correct measurement of temperature, pressure and displacement of the pressing block.

### **The hydraulic system**

The laboratory press was designed to simulate press nip dwell times as low as 30 milliseconds. Longer press pulses can also be performed in order to test some different experimental conditions. The hydraulic system is controlled by an Apple Macintosh II fx computer using LabView<sup>®</sup> 2.0. Therefore, the press pulse is software controlled and a specific data acquisition system records the applied load, displacement of the heated plate, and temperature both in the paper sample and in the heated pressing block.

The force acting on the sample is generated by a fast response hydraulic system equipped with a double-effect cylinder of 63 mm diameter and a maximum stroke length of 155 mm. The gear pump provides a maximum pressure of about

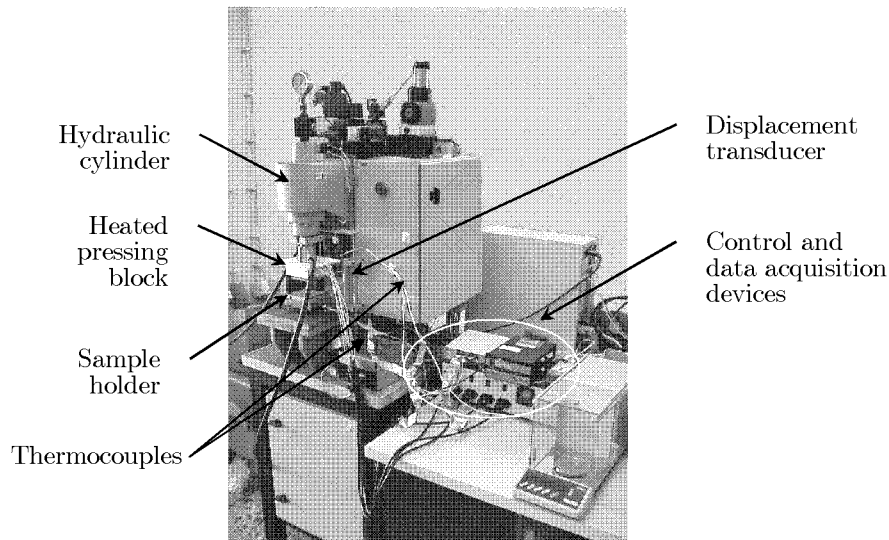


Figure 2.5: General view of the laboratory press machine.

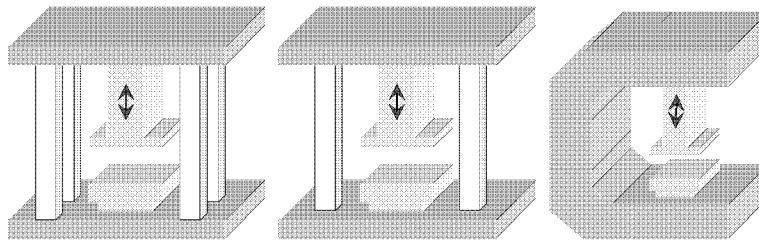


Figure 2.6: Schematic view of different structures for a pressing device: 4 columns, 2 columns or C-shaped structure.

15 MPa, which means that the applied force can, theoretically, reach 46 kN. By security reasons, however, the manufacturer limits that value to 35 kN.

### The structure of the press machine

In terms of structure there are basically three solutions, as illustrated in Figure 2.6. A pressing device with a structure of 4 columns is, beforehand, the most appropriate for high capacity press machines due to its stability and stiffness. Perfect parallelism between the top and bottom plates must however be assured at the risk of failure and fracture of the structure.

On the other hand, C-shaped designs are widely used in small to medium capacity presses due to its low cost and fairly accurate performance. In this case,

however, it is advisable to use tools, *i.e.* sensors, with flexible unions to the hydraulic piston and precisely guided.

The laboratory press used for the present work has a C-shaped design. Therefore, the structure was expected to deform in a similar mode to that illustrated in Figure 2.7. In a previous study performed by Mendes [46], the dynamic behavior of the structure was characterized by evaluating the dynamic response of the machine to an impulse-like stroke. This analysis is of utmost importance since the vibrational frequency of the structure must differ significantly from that used to collect the experimental data. Mendes observed a vibrational frequency of about 1.8 kHz by using an accelerometer from Brüel & Kjær (see Figure 2.8), which means that the working conditions are quite different from that value, as required.

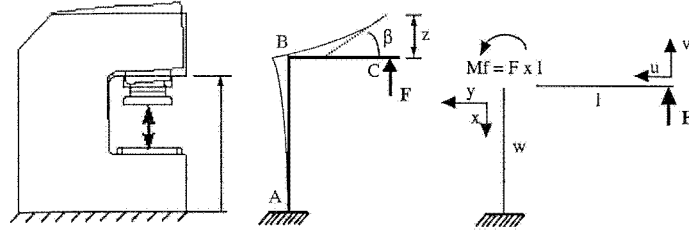


Figure 2.7: Schema of the press design and the consequent structure deformation (adapted from [46]).

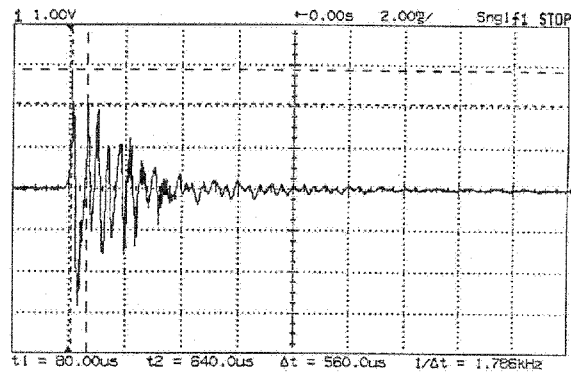


Figure 2.8: Vibration of the press structure when subjected to an impulse-like stroke. Data is presented as the output voltage measured by the accelerometer with a gain of 10 mV/m/s<sup>2</sup> (taken from [46]).



A more detailed discussion of issues related to press structure and hydraulic system dynamic responses will be presented in a subsequent section dedicated to signal processing and filter design methodologies.

### The test cell

All of the experiments in this study were performed on the laboratory press described above. Apart from the computer controlled hydraulic cylinder, the pressing head (see Figure 2.9) is composed of three subsystems: a cooling system with circulating water, a heating system composed of four cartridge electrical heaters and a control and data acquisition system. The pressing head consists of a very smooth stainless steel solid plate, contacting directly the paper sample, mounted on a heated aluminium plate. This block is heated up to 350 °C by means of a set of electrical cartridge heaters (model No. CIR-1037/240. 1/4" diameter, 300 W, high watt density cartridge heater from OMEGA<sup>®</sup>) disposed in a way that assures the even distribution of temperature in the surface of the plate (see Figure 2.10). The temperature is monitored and controlled using a PID temperature controller (model No. ICN77R352 from Newport<sup>®</sup> with output control by solid state relays of 1A at 120/240 VAC), allowing to stabilize the temperature of the aluminium plate at the required setpoint in no more than 45 minutes. At first the temperature was monitored at two different points of the stainless steel plate in order to verify the heat distribution near the surface contacting the paper sample. It was verified a fairly even temperature distribution near that surface, and the temperature control was then possible using but one thermocouple type E (model No. CHCO-032 from OMEGA<sup>®</sup>). The contact plate has a square cross-section of 56.25 cm<sup>2</sup> (see Figure 2.11), exactly the same size of both paper sample and felt, which requires a perfect alignment of the top and bottom plates of the test cell.

A cooling system was placed above the heated plate (see Figure 2.12) in order to minimize the effect of temperature on the hydraulic cylinder and valve system of the press. This was even accomplished by placing an insulating board (Duratec 750 plate from Amidata, SA) on the top of the aluminium block, which also prevents major heat losses from this side of the pressing head.

Being a platen press, the paper sample remains stationary as it is pressed between the upper impermeable surface and a porous material, the felt, under which exists a 2 mm thick sintered stainless steel lamina with pores of 200 µm

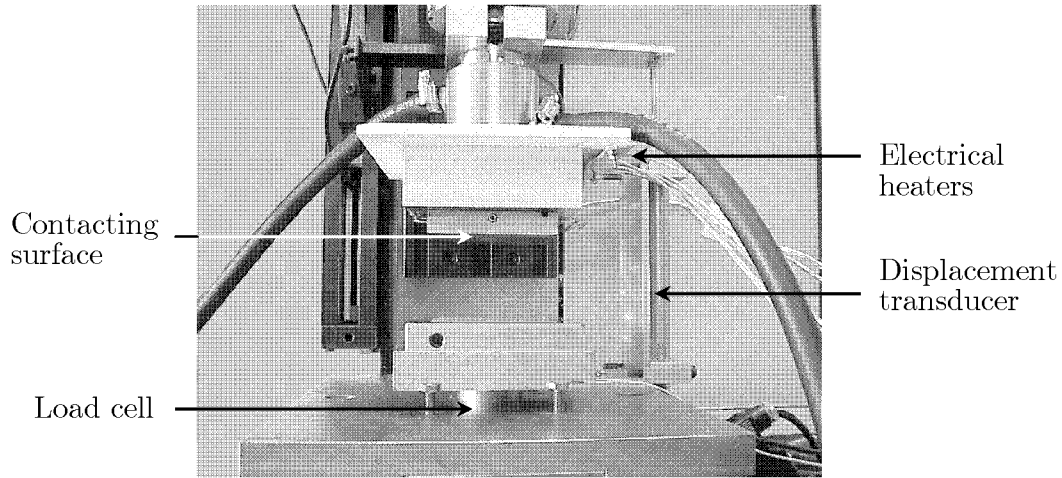


Figure 2.9: Photography of the test cell (closer view).

(*material*: stainless steel AISI 316L with the following physical and mechanical properties in the range 20-100 °C: density  $8027 \text{ kg.m}^{-3}$ , coefficient of thermal expansion  $16.5 \text{ }\mu\text{m/m.}^\circ\text{C}$  and modulus of elasticity in tension 200 GPa; *quality*: SIKA - R200; from GKN Sinter Metals Filters, GmbH). During the compression, a temporary hydraulic pressure is generated in the compressed area in both paper and felt samples causing an in-plane as well as transversal water flow into the sintered metal plate. Therefore, special attention must be paid to the selection of the material the plate is made of, as well as to its structure. In summary, the plate must have a structure open enough to allow the water and air to escape from the sample, but having an external surface as plain as possible in order to assure an even compaction of the samples. In addition, the structure must withstand loads as high as those typically used in impulse drying events.

The design of the plate that holds the former lamina was developed bearing in mind the stability of the system and the homogeneity of pressure application. Therefore it has a pattern of parallel bars separated by 3 mm thick grooves in order to facilitate water and air that eventually reach the bottom side of the porous structure (see Figure 2.13).

The collector plate is placed on a stainless steel block in which a load cell was fitted. The load applied to the set consisting of paper and felt was then measured by means of a miniature quartz load washer from Kistler<sup>®</sup>. Quartz load cells are piezoelectric force transducers of extremely high resolution and have an inherently

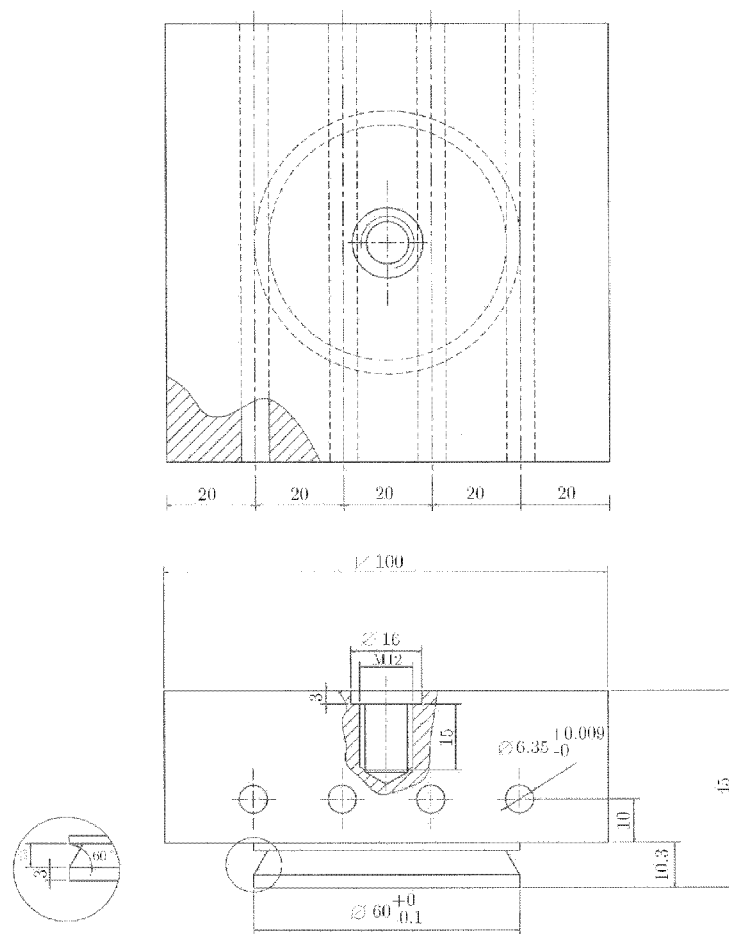


Figure 2.10: Design of the heated aluminium plate. The inset shows details of the fitting for the contact plate illustrated in Figure 2.11.

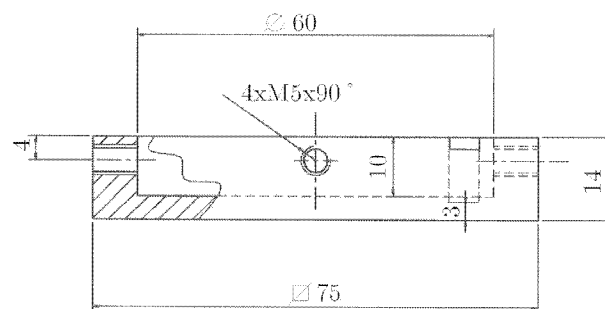


Figure 2.11: Design of the contact plate.

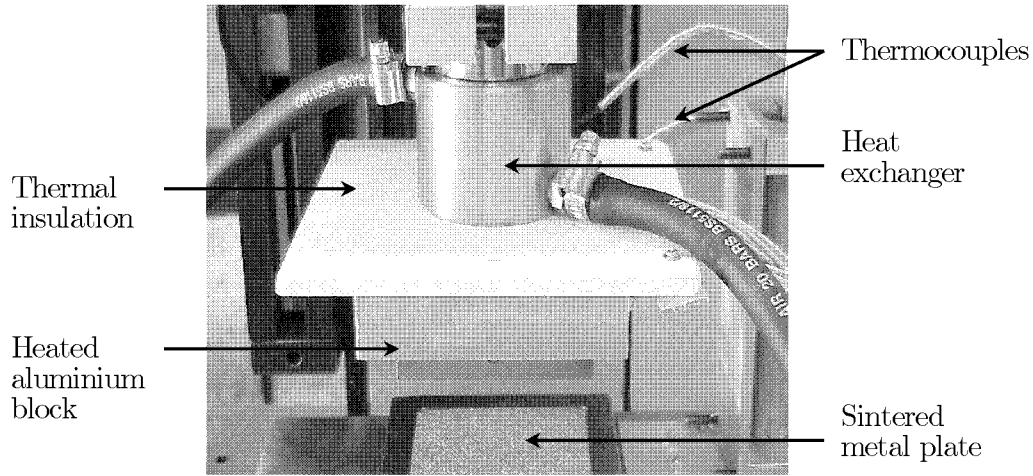


Figure 2.12: Photography of the test cell (top view) and some of its components.

high rigidity which allows them to be fitted in measuring devices without altering the mechanical behavior of these significantly. Thanks to their high rigidity, load washers are suitable for measuring rapidly varying forces, which is the nature of an impulse drying event. However, in order to have accurate values a correct placement is required, *i.e.* the contact surfaces for the load washer must be flat, finely machined and rigid to assure an even distribution of the force. Taking all these details into account the selected load transducer was the 9051A, from Kistler<sup>®</sup>. This quartz load washer has a linearity error lower than 0.4 % of the full measuring range of 0-120 kN. The sensitivity for full scale output is  $-4.32 \text{ pC.N}^{-1}$ .

In principle a quartz load cell measures not the absolute amount of force but only changes of force. Attention was also paid to the operating temperature. If the temperature of the transducer changes during the measurement, an error signal must be expected; and it is caused by mechanical stresses due to thermal expansion. In the present case, this temperature problem was naturally overcome because the transducer was carefully placed away from the heating font.

In this study, the laboratory press was also equipped with a linear variable displacement transducer (LVDT) which allowed to measure the thickness of the paper web or/and felt throughout the compression event. The displacement transducer used is an LD300-50 type from OMEGA<sup>®</sup> which has a linearity error of 0.25 % of the total stroke, *i.e.*  $\pm 50 \text{ mm}$ . For LVDTs the resolution is usually

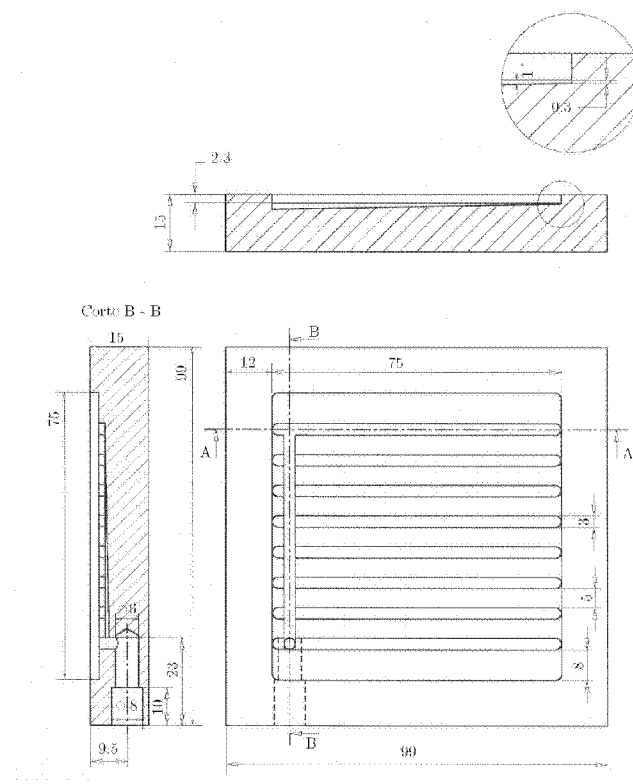


Figure 2.13: Design of the collector plate. The inset shows the slope of the parallel grooves in order to facilitate water removal.

restricted by the resolution of the measuring instruments. Apart from that, the intrinsic resolution of the transducer may be calculated as 0.0005 % of full range, which means a resolution of  $0.5 \mu\text{m}$ .

Because only one displacement transducer is being used, instead of three placed at  $120^\circ$ , it is imperative to verify the parallelism between the top and bottom plates of the test cell. The simplest way to do so is to run an experiment placing a white paper sample underneath a carbon paper and check the uniformity of the imprint on the white paper. As illustrated in Figure 2.14, at first the two plates were not parallel as the imprint was non-uniform. The problem was overcome by rotating the sintered metal plate by  $180^\circ$ . Observing then the imprint to the right in Figure 2.14 it is reasonable to assume an even pressure application. It is, however, worth noting that being a C-shaped press an inherent error exists when measuring the displacement of the pressing head, but that is more notorious during the first 2 ms of the pressing event, after which the force is redistributed over the entire contact surface.

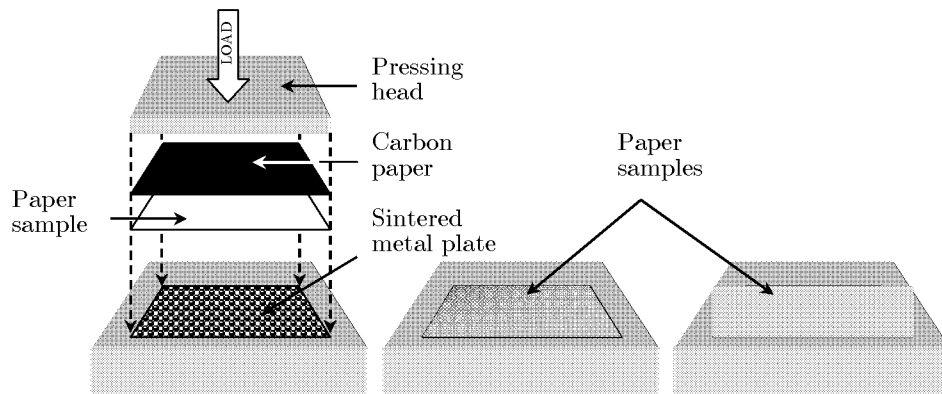


Figure 2.14: Schema of the experimental procedure to investigate the uniformity of pressure application (center: non-uniform imprint; right: uniform imprint).

Despite the uniformity of pressure application being assured, it is important as well to guarantee the good repeatability of the measurements performed. Bearing this in mind, the transient stress profiles were measured, here defined as the force applied on the test cell divided by the cross section of the contact surface, during an impulse experiment without felt and paper sample. The gist of the study was to identify the influence of load and temperature conditions on the dynamic behavior of the press itself. The forms of the stress profiles shown in Figures

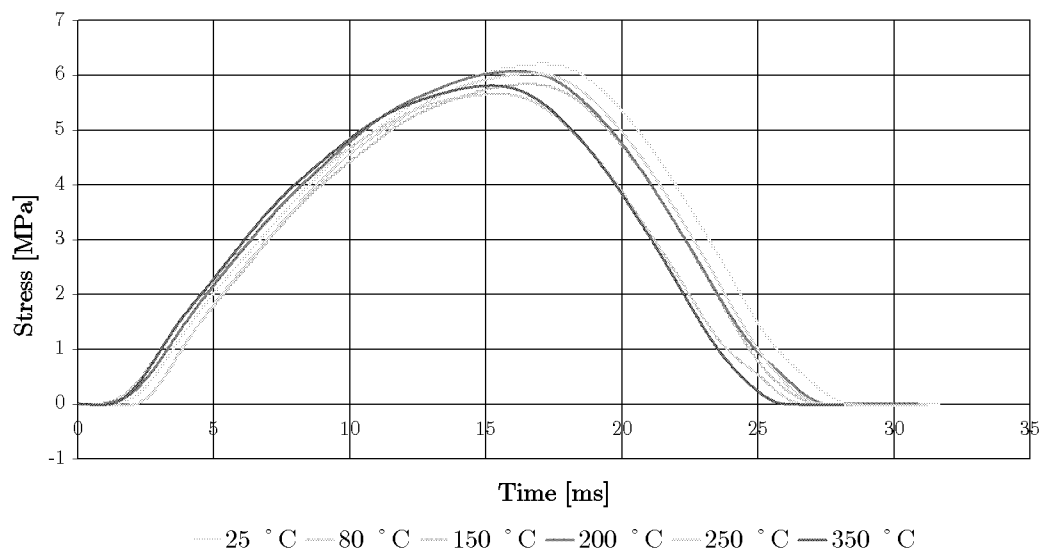


Figure 2.15: Experimental stress pulses obtained at a peak pressure of about 6 MPa. Data refer to blanc trials performed at different operating temperatures.

2.15 and 2.16 are representative of all cases tested and qualitative similarities among those profiles were found. It is believed that the main discrepancies may be attributed to the fact that for each set of experiments the pressure on the gear pump had to be set manually, which could give rise to differences in the maximum applied force. Consequently, the response of the valve system of the press varies according to the applied pressure, which results in different pulse lengths. This is even more evident if, for each experiment the applied stress is normalized by its maximum value, and divided the dwell time by its corresponding value at that point, as shown in Figure 2.16. The stress profiles are then almost identical.

This behavior suggests the applied stress profile to be almost independent of temperature, at least concerning blanc trials. It should also be noted that the main temperature effect is observed at the core of the test cell, *i.e.* the heated aluminium plate and the contact plate, for the mechanical and physical properties of both aluminium and stainless steel vary with temperature. Therefore it is not surprising that different levels of compression are attained when performing blanc trials at temperatures from 25 to 350 °C. For this very reason, blanc trials were performed previous to all sets of trials at a given operating temperature.

The results of the displacement of the pressing head for blanc trials are shown

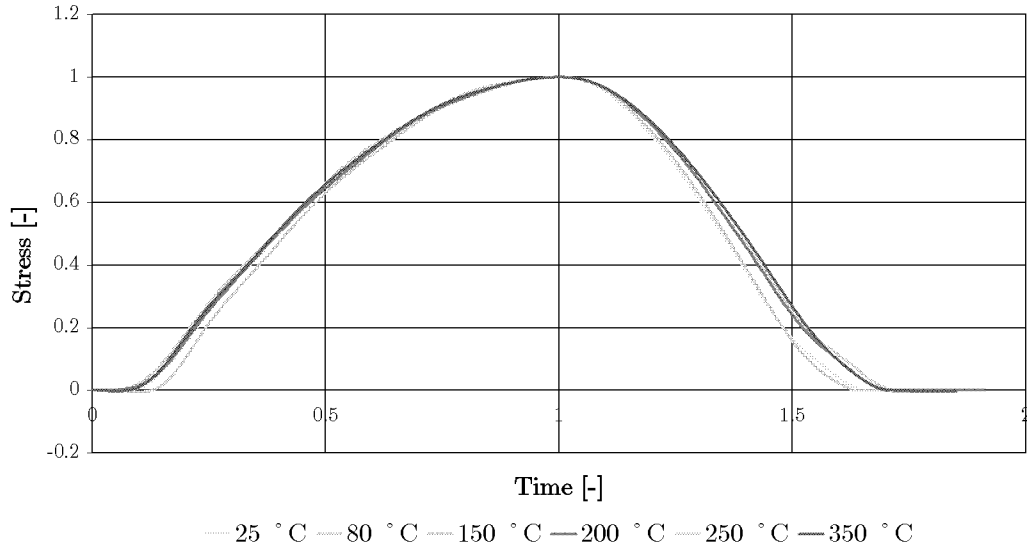


Figure 2.16: Normalized stress pulses obtained in blanc trials (data from Figure 2.15 were used).

in Figure 2.17. The strain of the test cell, here defined as the deformation divided by its corresponding value at the point of maximum force is plotted against dimensionless dwell time, for different pressing temperatures. Figures 2.18 and 2.19 report the strain profiles obtained at 25 and 250 °C.

The strain levels achieved at temperatures ranging from 25 to 350 °C basically follow the same trend: a fast increase in strain followed by an almost flat profile and a gradual recovery of strain at the end. It is worth noting at this point that all strain profiles seem to be incomplete as the strain level should decay to zero at the end of each experiment. This is not expected to happen, however, because the end of the experiment is defined by a given stress level under which the contact between the plates of the test cell is no longer assumed.

In addition, the difference between the trends observed in Figure 2.17 is ascribed to the different loading conditions used for each experiment, as well as to temperature effects. The findings of Figures 2.18 and 2.19 are in agreement with what was previously stated. In fact, plotting the strain measurements obtained for different experiments performed at the same temperature and load conditions no significant discrepancies are observed. As shown in Figure 2.18, the forms of the strain profiles obtained at 25 °C are very similar and no major strain deviations are observed. As for higher temperatures, the scenario remains, *i.e.* at 250



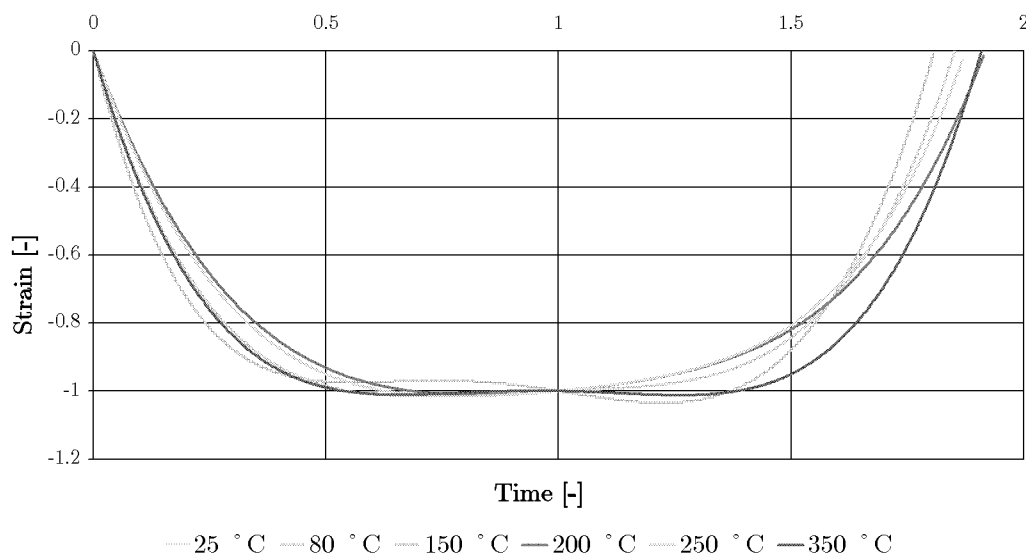


Figure 2.17: Strain evolution obtained for blanc trials performed at 25, 80, 150, 200, 250 and 350 °C. The corresponding stress profiles are represented in Figure 2.16.

°C the strain profiles follow the same trend (see Figure 2.19).

In summary, the results of these experiments show good repeatability if the experiments are performed in exactly the same loading conditions. Obviously, this is not something easy to accomplish and proper data treatment must be carried out in order to compare results from different experiments.

Finally, micro thermocouples type E (model No. CHCO-001 from OMEGA<sup>®</sup>) were used to measure the temperature inside the wet paper samples. These thermocouples have a diameter of only 25  $\mu\text{m}$  which is in the same order of magnitude as a single cellulose fiber, thus ensuring that they would not take up any load during the impulse event or create additional resistance to heat or mass transfer in the web. Additionally, the very small size of the junction point of these thermocouples ensured a sufficiently low time constant, which is particularly important in fast processes as those concerning the impulse drying technology.

### The data acquisition system

In this study an acquisition unit was used to collect the data from transient temperature profiles of wet paper webs undergoing compression at different loading

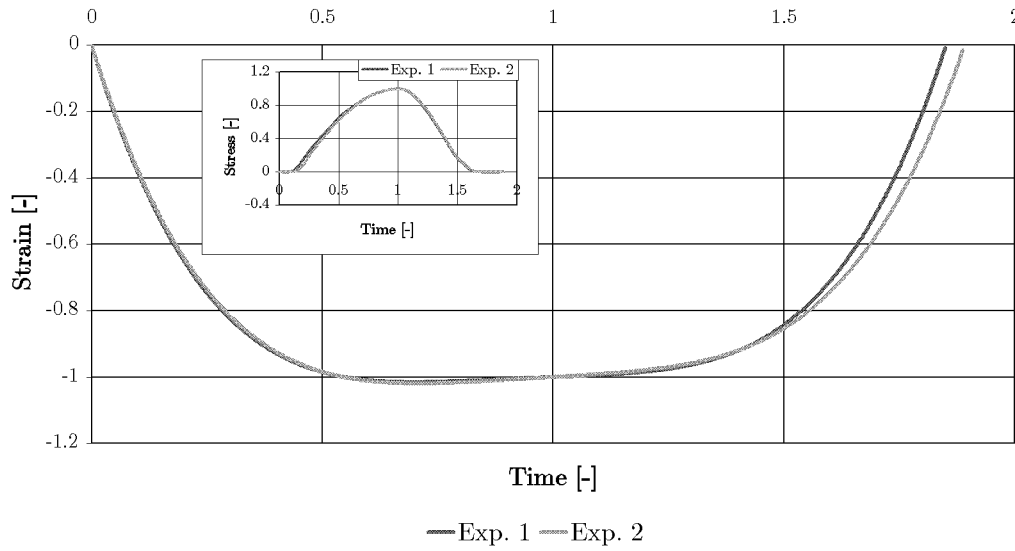


Figure 2.18: Strain evolution obtained for two blanc trials performed at 25 °C. The inset shows the corresponding stress pulses applied during the impulse event.

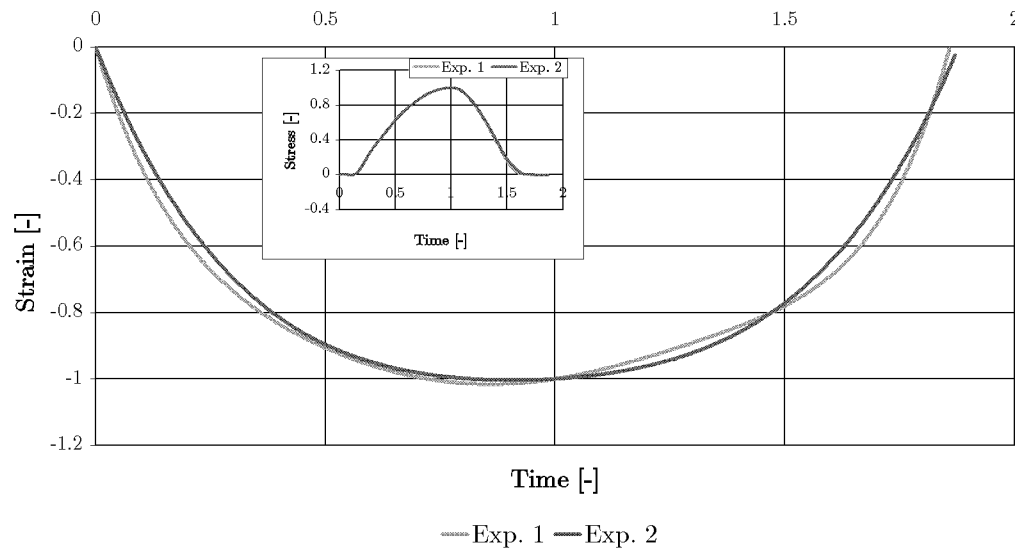


Figure 2.19: Strain evolution obtained for two blanc trials performed at 250 °C. The inset shows the corresponding stress pulses applied during the impulse event.

conditions. Investigating the physics of impulse technology also requires the measurement of dimensional changes of the paper web when subjected to different levels of stress at a given operating temperature. Additionally, other properties such as dry mass and water content of the paper samples are required in order to infer about water removal efficiency.

The temperature data, compensated for the cold junction, and the load and displacement transducer signals were collected on a personal computer via a high-speed data acquisition device from National Instruments using the Labview<sup>®</sup> 5.0.1 platform. As the process is too fast, the NI PCI-6040 E (former PCI-MIO-16E-4) board was selected for this task. With 500 kHz single-channel sampling, 250 kHz multichannel scanning, one is able to acquire all the channels at about 30 kHz, which is two orders of magnitude higher than the sampling rate. This means that one can get about 1000 points per channel within 30-50 ms.

Finally, a SCB-68 shielded connector block is used for signal connection to the 16 analog inputs of the data acquisition board. This block provides rugged, very low noise signal termination and is equipped with a cold-junction temperature sensor for use with thermocouples. However, cold-junction compensation is accurate only if the temperature sensor reading is close to the actual temperature of the screw terminals of the connector block. Therefore, the SCB-68 board must be kept away from temperature gradients such as those caused by the heating elements of the test cell.

### 2.2.2 The experimental procedure

The majority of the experimental work presented in this study was carried out on the laboratory press that has been described previously. The purpose of the study was to acquire, process and organize pressure, thickness and temperature measurements during impulse drying of 60 and 80 g.m<sup>-2</sup> isotropic handmade paper sheets made from *Eucalyptus globulus* and *Pinus pinaster* pulps. In order to simulate impulse drying operating conditions the webs were placed in the test cell and compressed between a smooth non-porous surface on one side and a high temperature-resistant industrial felt (from Albany Nordiskafilt AB, Halmstad, Sweden) on the other (Figure 2.20). Uniaxial compression tests were conducted at temperatures ranging from room temperature to 350 °C. The pressure pulses applied by the hydraulic press machine can vary greatly in shape, peak pressure

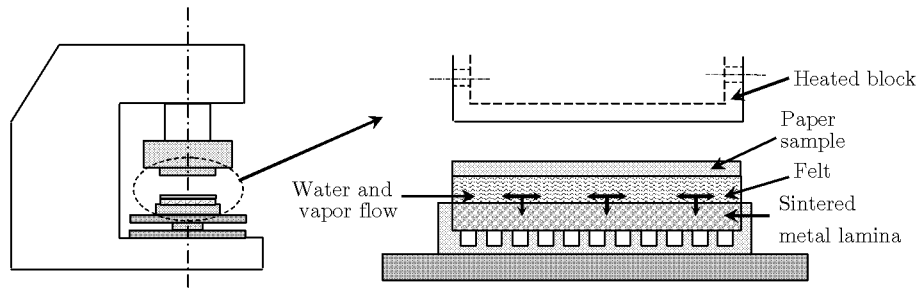


Figure 2.20: Schematic drawing of the laboratory press in the configuration used for the impulse drying experiments. The inset shows the water flow pattern and the samples arrangement within the press nip (taken from [48]).

and pulse length. Although the objective of the research was the investigation of paper performance when subjected to impulse drying, a complementary study was done concerning the influence of pulse length and shape on the mechanical response of paper. In that sense, the experimental trials were performed at peak pressures of about 6 MPa in two separate time scales: (i) 25-30 ms, in order to simulate roll-like press pulses and (ii) 75-200 ms, closer to the so-called extended press nips. The response of the web thickness to the pressure pulse was recorded as a function of time. The temperature both on the heated plate and inside the mat consisting of paper and felt was also monitored. Additionally, part of the work was dedicated to the study of water saturated paper samples which were compressed in the same test cell in a slightly different configuration, as it will be explained further ahead in the text.

The following sections intend to give a more detailed description of the experimental work performed.

### Preparation of the samples

Two sets of additive-free paper samples of both pulps were prepared: wet and water saturated samples. Furthermore, this work also concentrated on the study of wet paper samples behavior, when impulse dried, in the presence of some wet end additives used nowadays in the paper industry. Among several additives and fillers used in the industry, some were selected and studied in order to infer about the possibility of inducing cross-linking reactions during impulse drying of paper, and therefore influence its response to the high-intensity conditions inherent to the process. The selected additives were calcium carbonate (as a filler), cationic

starch (as a dry strength additive), alkyl ketene dimer (as an internal sizing agent), and finally, polyamide epichlorohydrin resin (as a wet strength additive).

**i) Additive-free paper samples** The two sets of paper samples used in the experimental trials were made of (i) bleached *Eucalyptus globulus* kraft pulp from Soporcel S.A. (Figueira da Foz, Portugal) and (ii) unbleached kraft pulp with approximately 90 % *Pinus pinaster* fibers and 10 % *Eucalyptus globulus* from Portucel Tejo (Rodão, Portugal). This last furnish is referred throughout the text as unbleached *Pinus pinaster* kraft pulp.

Before sheet forming the pulps were disintegrated for 20 minutes in a Valley beater, then refined to Schopper-Riegler degrees of 25 and 40 °SR. The *Eucalyptus globulus* pulp suspension was diluted to a stock concentration of 0.8 %, *i.e.* 8 g of oven dried (o.d.) fibers per liter of water. After being beaten, the *Pinus pinaster* pulp was disintegrated once more using a standard laboratory disintegrator (Frank 95568). In fact, the pulp suspension of 2 L containing 24 g of moisture-free pulp was disintegrated at 30 000 revolutions for about 10 minutes. Then, the pulp was diluted to 0.2 g.L<sup>-1</sup>. This second disintegration step and the dilution of the pulp were carried out in order to avoid partial flocculation during sheet formation. Throughout this work, deionized water was used for all operations. [47].

After being made with a 56.25 cm<sup>2</sup> squared area in a static sheet former, the paper samples were enclosed in plastic bags and placed inside a box having multiple thin compartments allowing the stocking of the samples in the horizontal position. These wet paper samples, which should keep an acceptable water content, *i.e.* between 60 and 70 %, were kept in a refrigerator at 5 °C for no more than 24 hours after being prepared. Part of these samples were impulse dried according to the test conditions listed on Table 2.1, the rest being soaked in water and kept apart to perform a different set of experiments. The mechanical behavior of water saturated paper samples submitted to the same pressure pulses as those impulse dried, was also investigated.

**ii) Samples with calcium carbonate (CC)** The filler used was precipitated calcium carbonate slurry from Inapa (Setúbal, Portugal) with a solids content of 30 %. The retention aid used for filled paper was polyethylene-imine based poly-electrolyte (PSK), supplied by BASF Portuguesa Lda (Lisbon, Portugal).

Five liters of 0.8 % bleached *Eucalyptus globulus* kraft pulp beaten at 25 and 40 °SR were mixed with 15 % of calcium carbonate solution (w/w based on o.d. pulp) and maintained under constant stirring (1200 rpm). After homogenization of the furnish, 0.5 % (w/w based on o.d. pulp) of PSK was added and the ensuing suspension was mixed for further 5 minutes. Sheets of 80 g.m<sup>-2</sup> and both refining levels were then formed. [47]

**iii) Samples with cationic starch (CS)** The cationic starch used was based on potato starch modified by alkyl chains bearing quaternary ammonium groups with a degree of substitution 0.034 (CBond 35804). The material was obtained from Sarcot S.A. (S. Mamede Infesta, Portugal). 2 % of cationic starch (w/w based on o. d. pulp) was added to five liters of 0.8 % *Eucalyptus globulus* pulp suspension beaten at 25 and 40 °SR. The mixture was then stirred at 1200 rpm for 20 minutes. Finally, sheets of 80 g.m<sup>-2</sup> were formed. [47]

**iv) Samples with AKD** The AKD emulsion, Raisafob 9132, was provided by Raisio Chemicals (Maia, Portugal). The AKD used was branched fatty acid type with melting point close to room temperature. The AKD emulsion with particle sizes in the range of 0.25 to 1.15 µm was constituted by 13.4 % (w/w) AKD and 5.2 % (w/w) emulsifier-stabilizer, mostly cationic starch. Cationic starch acts both as a stabilizer for AKD emulsion and as a retention agent.

The AKD sized handsheets were prepared by adding 0.15 % of AKD (w/w based on o.d. pulp) to a pulp suspension of 0.8 % consistency. The mixture was stirred at 700 rpm for 5 minutes, after what 80 g.m<sup>-2</sup> handsheets were prepared. [47]

**v) Samples with polyamide-epichlorohydrin resin** The wet strength resin employed in the experiments was a commercial polyamide-epichlorohydrin resin, Maprisine 748 from Raisio Chemicals (Maia, Portugal). 0.5 % of PAE resin (w/w based on o. d. pulp) was added to five liters of 0.8 % *Eucalyptus globulus* pulp suspension beaten at 25 and 40 °SR. Before sheet forming, the mixture was stirred for about five minutes at 1200 rpm in order to accomplish the adsorption of the resin. Handsheets of 80 g.m<sup>-2</sup> were then prepared. [47]

After being prepared by Mendes [47], at the University of Beira Interior, all the paper samples were conditioned and sent to the Faculty of Engineering of Porto University in order to be submitted to impulse drying.

## Impulse drying experiments description

**i) Wet paper samples** Investigating the physics of impulse technology through the inspection of the local temperature of the paper sheet provides some interesting clues on the mechanisms of phase change active in an impulse nip. The temperature profile inside a paper sheet subjected to a very long, low pressure pulse is well known and presents clear indications of the phase transition from liquid water to steam, *i.e.*, if the hot surface temperature is higher than the saturation temperature corresponding to the resulting hydraulic pressure, the paper web will be heated to the saturation temperature, and a further increase of the hot surface temperature will therefore not result in a higher web temperature. However, if the applied pressure is increased, it would produce a higher hydraulic pressure inside the web thus increasing the corresponding saturation temperature. In this case, the web would be heated further to the new saturation temperature, water would evaporate and keep the web at that temperature as long as liquid water is present. On the other hand, if a high pressure is applied to the system, the hydraulic pressure generated inside the paper sheet will be significantly increased thus resulting in a higher saturation temperature.

In this part of the study, the transient temperature and thickness profiles of both wet paper and felt, undergoing compression at a peak pressure of about 6 MPa, were measured. The experimental conditions were such that the pulse length was varied between approximately 30 ms and 75-200 ms. Thin, micro thermocouples were carefully placed at different elevations within the mat (paper and felt) allowing the local temperature to be recorded as a function of time in a range of temperatures from 25 to 350 °C. The temperature was recorded at the paper/felt interface and on the top surface of the paper web (Figure 2.21). This last sensor was initially used to set the moment of contact between the surface of the heated pressing head and the web. However, as it was extremely difficult to place the micro thermocouple and even harder to keep it in the correct position without damaging the metal junction, the procedure was abandoned, at least in respect to this issue. Additionally, blanc tests as well as tests with the felt only were carried out for each set of experiments, *i.e.* for every temperature and loading conditions.

In the very beginning of the experiment, both paper sample and felt were weighted. After stabilizing the temperature in the heated plate, the paper sample

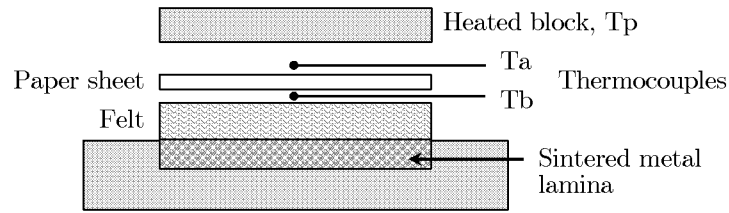


Figure 2.21: Two thermocouples were embedded in the mat consisting of a felt and a paper sample ( $T_p$ : temperature of the heated block;  $T_a$ : temperature at the top surface of the paper sheet;  $T_b$ : temperature at the paper/felt interface).

was placed on top of the felt, pressed and immediately weighted, as well as the felt. After pressing, the paper samples were dried under restricted shrinkage in an oven at 105 °C for about 10 minutes, after what they were stored in plastic bags and sent to University of Beira Interior for characterization. Part of the samples were retained and further dried at 110 °C till no mass variation was observed. This experimental procedure allows us to determine the initial and after pressing water content of the samples and thus infer about the water removal efficiency of the process.

Approximately one thousand experiments were performed using the platen press which resulted in an extensive database to use for validation of theoretical models of heat and mass transfer, as well as mechanical behavior of the webs under study. The main operating conditions are summarized on Tables 2.1 to 2.6 and emphasize the vast range of temperatures and pulse lengths tested in order to evaluate the influence of such parameters on the behavior of paper and felt.

Table 2.1: Impulse drying tests performed with additive-free paper samples of hardwood and softwood kraft pulps. All the tests were performed at a peak pressure of about 6 MPa.

| Pulp furnish           | Refining level [°SR] | Additive content [w/w o.d. pulp] | Grammage [ $\text{g.m}^{-2}$ ] | Pulse shape | Pulse length [ms] | Temperature [°C]           |
|------------------------|----------------------|----------------------------------|--------------------------------|-------------|-------------------|----------------------------|
| Bleached hardwood pulp | 25, 40               | -                                | 60, 80                         | roll        | 30                | 25, 80, 150, 200, 250, 350 |
| Bleached hardwood pulp | 25, 40               | -                                | 60, 80                         | roll        | 30                | 25, 80, 150, 200, 250, 350 |



Table 2.2: Impulse drying tests performed with paper samples of hardwood kraft pulps with calcium carbonate. All the tests were performed at a peak pressure of about 6 MPa.

| Pulp furnish              | Refining level<br>[°SR] | Additive content<br>[w/w o.d. pulp] | Grammage<br>[g.m <sup>-2</sup> ] | Pulse shape | Pulse length<br>[ms] | Temperature<br>[°C]   |
|---------------------------|-------------------------|-------------------------------------|----------------------------------|-------------|----------------------|-----------------------|
| Bleached<br>hardwood pulp | 25                      | 15 % CC                             | 80                               | roll        | 30                   | 25, 80, 150, 200, 250 |
| Bleached<br>hardwood pulp | 40                      | 15 % CC                             | 80                               | roll        | 30                   | 25, 150, 200, 250     |

Table 2.3: Impulse drying tests performed with paper samples of hardwood kraft pulps with cationic starch. All the tests were performed at a peak pressure of about 6 MPa.

| Pulp furnish              | Refining level<br>[°SR] | Additive content<br>[w/w o.d. pulp] | Grammage<br>[g.m <sup>-2</sup> ] | Pulse shape | Pulse length<br>[ms] | Temperature<br>[°C]        |
|---------------------------|-------------------------|-------------------------------------|----------------------------------|-------------|----------------------|----------------------------|
| Bleached<br>hardwood pulp | 25                      | 2 % CS                              | 80                               | roll        | 30                   | 25, 80, 150, 200, 250      |
| Bleached<br>hardwood pulp | 40                      | 2 % CS                              | 80                               | roll        | 30                   | 25, 80, 150, 200, 250, 350 |

Table 2.4: Impulse drying tests performed with paper samples of hardwood kraft pulps with alkyl ketene dimer. All the tests were performed at a peak pressure of about 6 MPa.

| Pulp furnish              | Refining level<br>[°SR] | Additive content<br>[w/w o.d. pulp] | Grammage<br>[g.m <sup>-2</sup> ] | Pulse shape | Pulse length<br>[ms] | Temperature<br>[°C]        |
|---------------------------|-------------------------|-------------------------------------|----------------------------------|-------------|----------------------|----------------------------|
| Bleached<br>hardwood pulp | 25                      | 0.15 % AKD                          | 80                               | roll        | 30                   | 25, 80, 150, 200, 250, 350 |
| Bleached<br>hardwood pulp | 40                      | 0.15 % AKD                          | 80                               | roll        | 30                   | 25, 80, 150, 200, 250, 350 |

Table 2.5: Impulse drying tests performed with paper samples of hardwood kraft pulps with polyamide-epichlorohydrin resin. All the tests were performed at a peak pressure of about 6 MPa.

| Pulp furnish              | Refining level<br>[°SR] | Additive content<br>[w/w o.d. pulp] | Grammage<br>[g.m <sup>-2</sup> ] | Pulse shape | Pulse length<br>[ms] | Temperature<br>[°C]    |
|---------------------------|-------------------------|-------------------------------------|----------------------------------|-------------|----------------------|------------------------|
| Bleached<br>hardwood pulp | 25                      | 0.5 % PAE                           | 80                               | roll        | 30                   | 25, 150, 200, 250, 350 |
| Bleached<br>hardwood pulp | 40                      | 0.5 % PAE                           | 80                               | roll        | 30                   | 25, 80, 150, 200, 250  |

Table 2.6: Experiments performed for longer press pulses with additive-free paper samples made from hardwood kraft pulps. All the tests were performed at a peak pressure of about 6 MPa.

| Pulp furnish           | Refining level<br>[°SR] | Grammage<br>[g.m <sup>-2</sup> ] | Temperature<br>[°C]   | Pulse length<br>[ms] |
|------------------------|-------------------------|----------------------------------|-----------------------|----------------------|
| Bleached hardwood pulp | 25, 40                  | 60, 80                           | 25, 80, 150, 200, 250 | 75, 120, 200         |
| Bleached hardwood pulp | 25, 40                  | 60, 80                           | 350                   | 75                   |

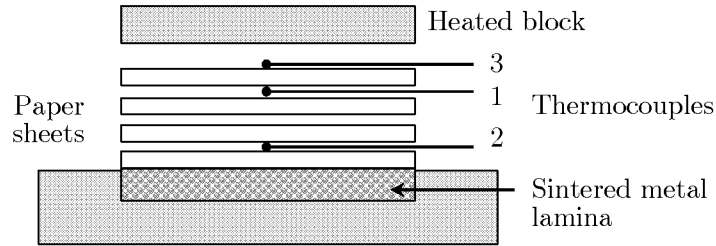


Figure 2.22: Schematic illustration of the sheets with inserted thermocouples forming a saturated paper web of total grammage 240 or 320 g.m<sup>-2</sup>.

**ii) Water saturated paper samples** The paper furnish used in this part of the work was bleached kraft additive-free pulp from *Eucalyptus globulus*, and the samples were prepared using the experimental procedure mentioned above for additive-free paper sheets. After being in the refrigerator, the samples were immersed in water at room temperature for about 15 seconds in order to assure that they were saturated. This is easily achieved due to the high water content of the samples (60-70 %).

The same platen press was used to investigate the temperature gradients inside a saturated paper sheet during impulse drying. The temperature in the z-direction was measured by placing micro thermocouples between four thin sheets that were placed on top of each other (Figure 2.22).

At this point it was assumed that the temperature measured between four discrete paper webs give the same result as in a single homogeneous web of the same grammage [28]. In other words, it seems there is no significant heat flow resistance increase in the interface between the sheets and the method is widely accepted. Handsheets with grammages of 60 and 80 g.m<sup>-2</sup> were made from pulps beaten to a Shopper-Riegler degree of 25 and 40 °SR. The total grammages corresponded to 240 and 320 g.m<sup>-2</sup> respectively when a stack of four sheets were

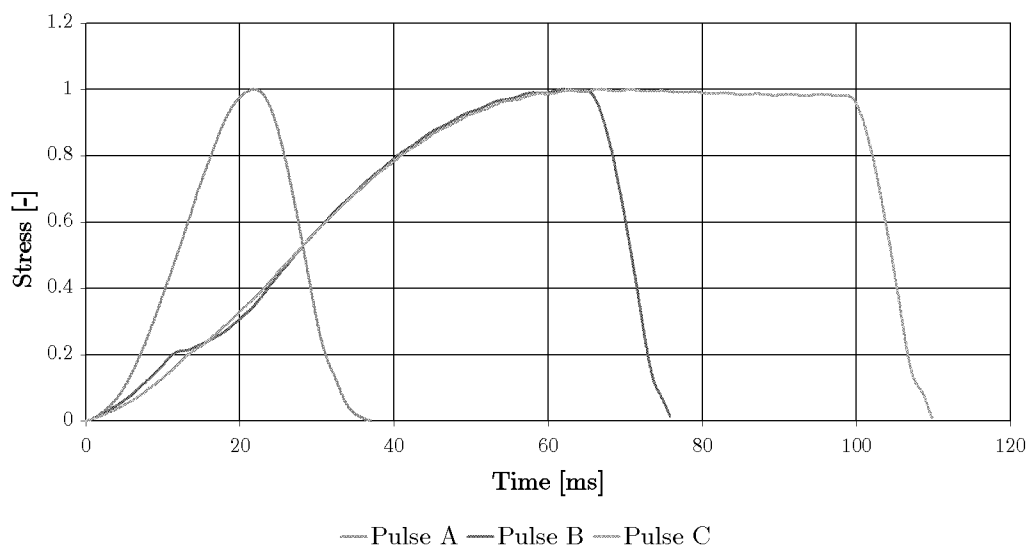


Figure 2.23: Pressure pulses applied to water saturated paper samples; Pulse A (roll-type press pulse): 38 ms, Pulse B (roll-type press pulse): 76 ms, Pulse C (extended press pulse): 111 ms; the pressure pulse represented by Pulse A is presented here for comparison only; the pressure profile corresponding to a dwell time of 2 000 ms is not presented.

piled up. The pressing head initial temperature was set from 25 up to 350 °C and the nip residence time was approximately 75, 120 and 2 000 ms as summarized on Table 2.7. The peak pressure was about 6 MPa and the pressure profiles were similar to those illustrated in Figure 2.23 (Pulses B and C).

Table 2.7: Experiments performed for longer press pulses with water saturated paper samples made from hardwood kraft pulps. All the tests were performed at a peak pressure of about 6 MPa.

| Pulp furnish           | Refining level<br>[°SR] | Grammage<br>[g.m <sup>-2</sup> ] | Temperature<br>[°C] | Pulse length<br>[ms] |
|------------------------|-------------------------|----------------------------------|---------------------|----------------------|
| Bleached hardwood pulp | 25, 40                  | 4 × 60, 4 × 80                   | 25, 80, 150         | 75, 120, 2000        |
| Bleached hardwood pulp | 25, 40                  | 4 × 80                           | 250                 | 2000                 |
| Bleached hardwood pulp | 25                      | 4 × 80                           | 350                 | 2000                 |

## Signal processing and filter design methodologies

Electromagnetic noise was, at the beginning, a problem in the laboratory. In an attempt to reduce this interference, all the thermocouples, cables and boards were shielded. Two more measures were taken to minimize this undesirable noise: the use of software filtering and acquisition at high sampling rate (30 000 samples/s). While acquiring at such high frequencies it is obvious that a proper signal filter must be used to minimize the influence of magnetic and electric noise.

The goal of filter design is to perform frequency dependent alteration of a data sequence. For this purpose Infinite Impulse Response (IIR) or Finite Impulse Response (FIR) filters can be applied. The primary advantage of IIR filters over FIR filters is that they typically meet a given set of requirements with a much lower filter order than a corresponding FIR filter. For IIR filters, however, the phase distortion is usually highly nonlinear, whereas in the case of FIR filters, it is possible to design linear phase filters that, when applied to data, simply delay the output by a fixed number of samples.

In the present study a Matlab<sup>®</sup> 5.0 was used to process the pressure, displacement and temperature data, prior to filtering. This allows for a noncausal, zero-phase filtering approach (via the `filtfilt` function), which eliminates the nonlinear phase distortion of an IIR filter. The `filtfilt` function uses the information in the signal at points before and after the current point to eliminate phase distortion. Within the classical IIR filters, it is also possible to find the lowest filter order that meets a given type of performance specification.

Bearing all this in mind, the Butterworth filter was chosen among the classical IIR filters. This filter is characterized by a magnitude response that is maximally flat in the passband and monotonic overall. For data sampled at 30 000 Hz it was designed a 5th-order lowpass Butterworth filter with cutoff frequencies of 150, for temperature and displacement data, and 400 Hz for pressure, as illustrated below. The terms C1 to C4 correspond to the output signals of transducers measuring the temperature at the surface of the heated plate, the heated plate/paper interface, and at positions 1 and 2 inside the paper web, as illustrated in Figure 2.22. In addition, C5 and C6 represent the load cell and displacement sensor output signals, respectively.

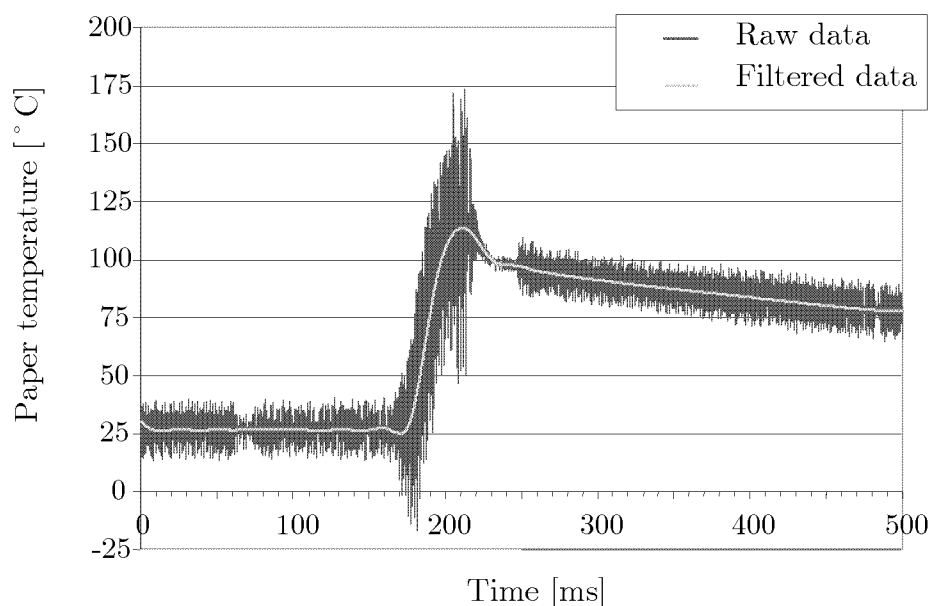


Figure 2.24: Internal web temperature during impulse drying of hardwood bleached kraft paper in the laboratory press. The temperature of the heated plate was set to 200 °C, the peak pressure was 6.2 MPa, the web grammage was 60 g.m<sup>-2</sup> and the refining level 40 °SR.

```
[b,a]=butter(5,150/15000);
[c,d]=butter(5,150/15000);
[e,f]=butter(5,400/15000);
C1f=filtfilt(c,d,C1);
C2f=filtfilt(c,d,C2);
C3f=filtfilt(c,d,C3);
C4f=filtfilt(c,d,C4);
C5f=filtfilt(e,f,C5);
C6f=filtfilt(b,a,C6);
```

The cutoff frequencies were selected based on frequency domain analysis of output signals from temperature, displacement and force measurements. As it can be seen in Figure 2.24, the thermocouple signal is far from being *clean* without filtering. Nevertheless, a quite acceptable temperature profile is obtained with this procedure.

By its turn, the load cell has almost no noise but it has a very fast response. This means that at the beginning of the plate impact the load cell starts to feel

the pressure, and consequently the oscillating movement of the press machine structure. Figure 2.25 shows the vibrational behavior of the structure obtained by Mendes [46], in which three phases are clearly visible: (i) the impact moment, characterized by a slight initial oscillation, (ii) the contact period, where a near steady signal is observed, and (iii) a decompression phase characterized by a quite violent oscillation followed by damping with similar extent to the contact phase.

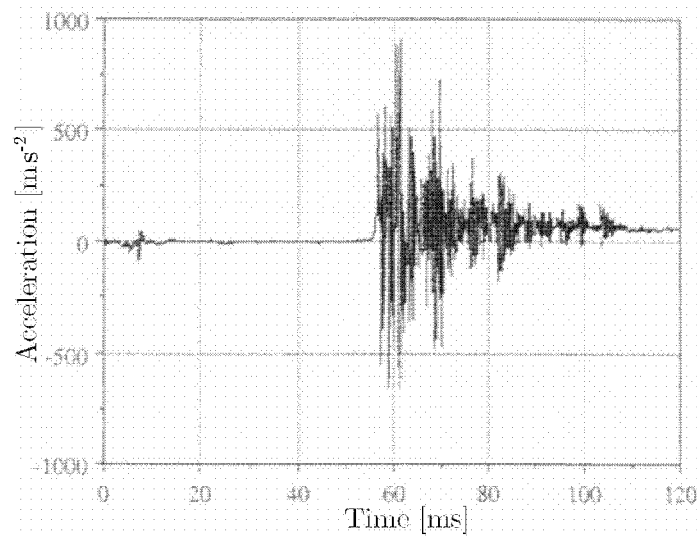


Figure 2.25: Vibration of the press structure when subjected to an impulse-like stroke (adapted from [46]).

For the reasons presented above, a 150 Hz cutoff frequency produced a ripple in the beginning of the plate impact and at the end of the event. Therefore, a 400 Hz cutoff frequency was used for the load cell output signal.

### Thickness-direction profiles and stress-strain diagrams

Although some temperature and stress-strain profiles are presented in this section, a deeper exploitation will be performed and presented on **Chapters 3** and **4** concerning the detailed study of both paper and felt samples. There, a comparison between experimental results and predictions from theoretical models will be presented and evaluated. Meanwhile, some typical profiles are illustrated on Figures 2.26 to 2.29.

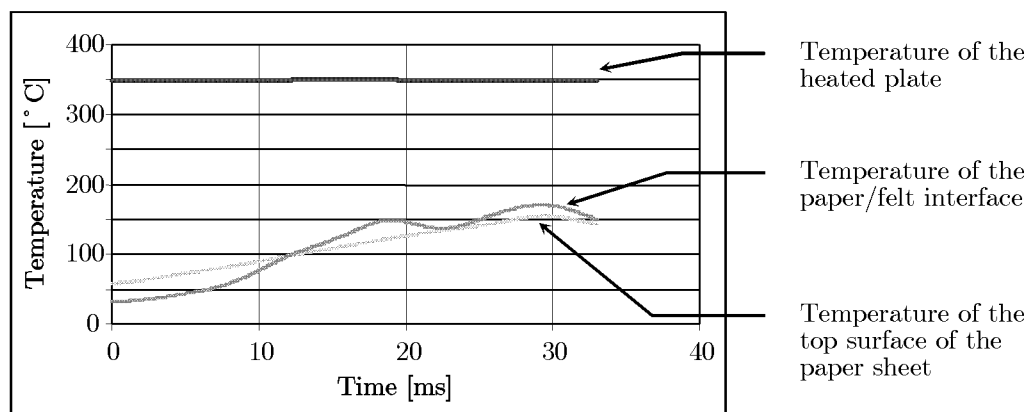


Figure 2.26: The heated plate temperature and interface temperatures during an impulse drying event. Pulse length: 33 ms; peak pressure: 5.2 MPa; temperature of the heated plate: 350 °C; grammage: 60 g.m<sup>-2</sup>; refining level: 25 °SR.

**Temperature profiles** The forms of the temperature profiles shown are representative of all cases tested. On Figure 2.26 it can be observed that in the interface paper/felt the temperature rises above 100 °C. This temperature profile is achieved for low grammage paper sheets, in which the heat front moves easily towards the felt. Figure 2.27 shows the different temperature profiles for a 60 g.m<sup>-2</sup>, 25 °SR additive-free *Eucalyptus globulus* paper sheet.

Figure 2.27 gives a general insight of the temperature profile inside the nip at five different pressing temperatures. It is observed an increase of temperature in the paper/felt interface from room temperature to about 50 °C when a wet paper sample is pressed at 80 °C. A very marked increase is observed for higher temperatures for which there is an upper limit of 150 °C, approximately.

**Stress-strain diagrams** Figure 2.28 illustrates the pressure profiles obtained for a given set of experiments performed at 350 °C, while the stress-strain relation is presented on Figure 2.29 for the same paper samples.

### Water removal evaluation

Since the most important process in paper production is dewatering of the cellulose fiber suspension, one of the objectives of the present study was to measure the increase in dryness experienced by the different paper grades during impulse drying. The difference between the ingoing and outgoing dryness of the samples

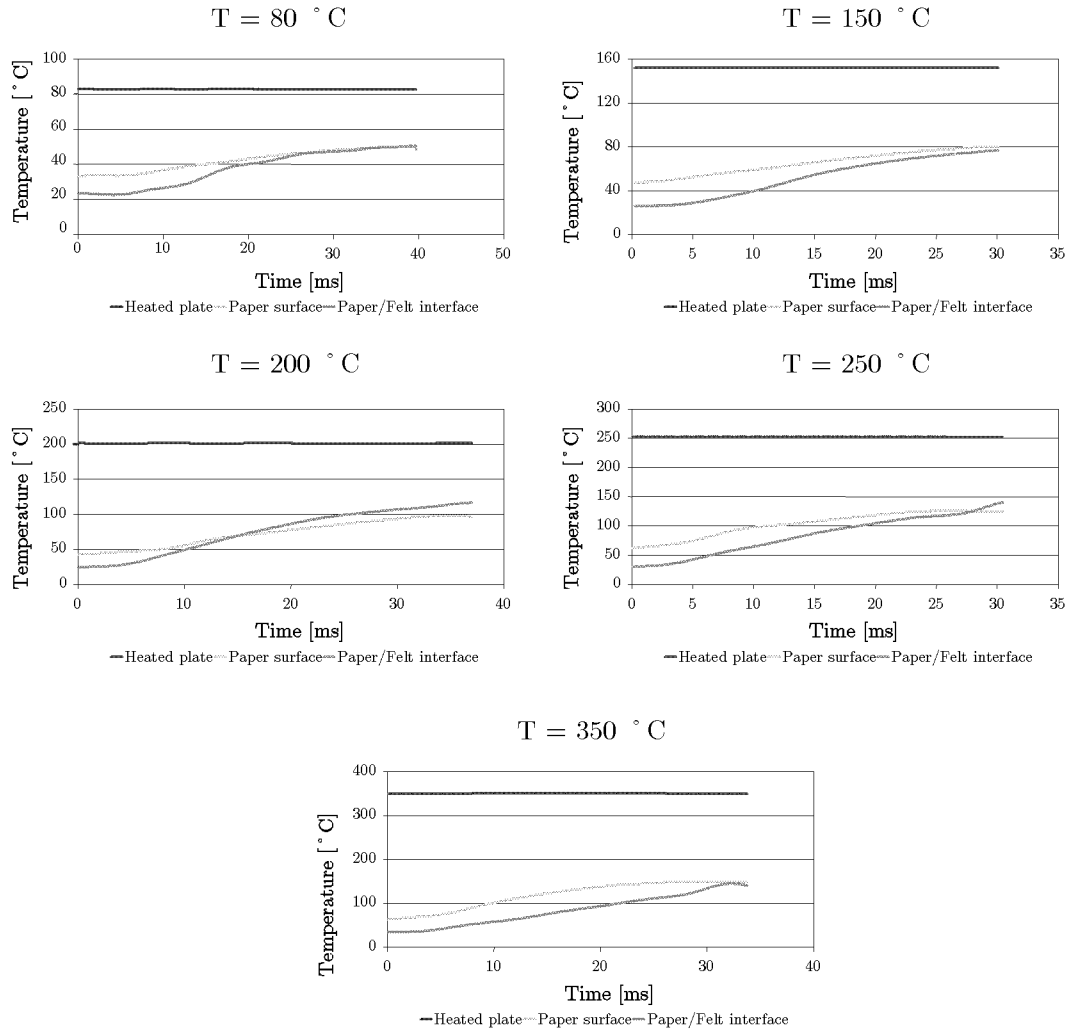


Figure 2.27: Time evolution of temperature for a  $60\text{ g.m}^{-2}$   $25\text{ }^{\circ}\text{SR}$  (additive-free *Eucalyptus globulus* pulp). Temperature of the heated plate from  $80$  to  $350\text{ }^{\circ}\text{C}$ .



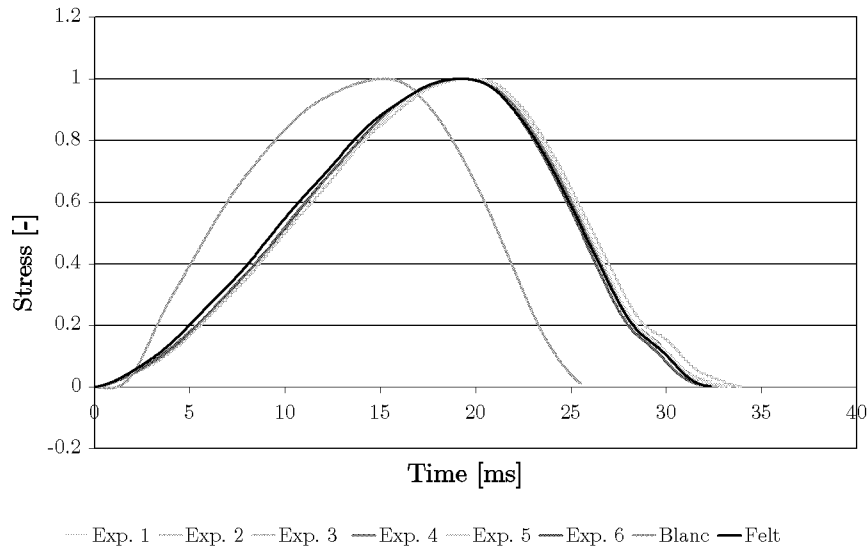


Figure 2.28: Time evolution of pressure obtained for  $80 \text{ g.m}^{-2}$  paper samples made from *Eucalyptus globulus* pulps refined at  $25^\circ\text{SR}$  and pressed at  $350^\circ\text{C}$ . Nip length 30-35 ms. A felt and blanc tests were also performed at the same pressing temperature.

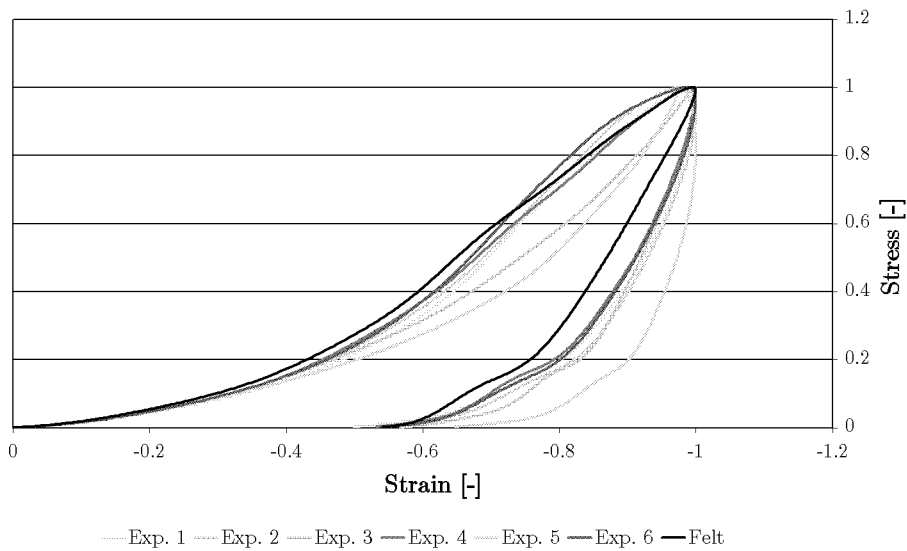


Figure 2.29: Stress-strain diagrams obtained for  $80 \text{ g.m}^{-2}$  paper samples made from *Eucalyptus globulus* pulps refined at  $25^\circ\text{SR}$  and pressed at  $350^\circ\text{C}$ . Nip length 30-35 ms. A felt test was also performed at the same pressing temperature.

was determined under different temperature conditions and furnish properties, so that the effect of variables such as moisture ratio, refining level and type of pulp on water removal rate could be studied. Here, dryness is defined as the percentage of dry mass of fibers to the total humid mass of the wet sample. Moreover, gain in dryness is taken as the increase in dryness in respect to the corresponding ingoing dryness of the sheet.

The paper sheets were produced from softwood (*Pinus pinaster*) unbleached kraft pulp and hardwood (*Eucalyptus globulus*) bleached kraft pulp with two different grammages, 60 and 80 g.m<sup>-2</sup> and two refining degrees, 25 and 40 °SR. In addition, sheets with additives were also investigated. The samples were made and then impulse dried according to the experimental procedure used for wet paper samples described above. All the paper samples were dried using the standard press pulse of Figure 2.15. Dewatering results for the operating conditions tested are given in Figures 2.30 to 2.40. Caution must be taken, however, if an attempt is made to transfer the results to real roll press nip conditions. Even taking precautions for the correct handling of the sheets immediately after the press pulse, the degree of rewetting resulting from the post-nip contact between paper and felt, is still largely unknown.

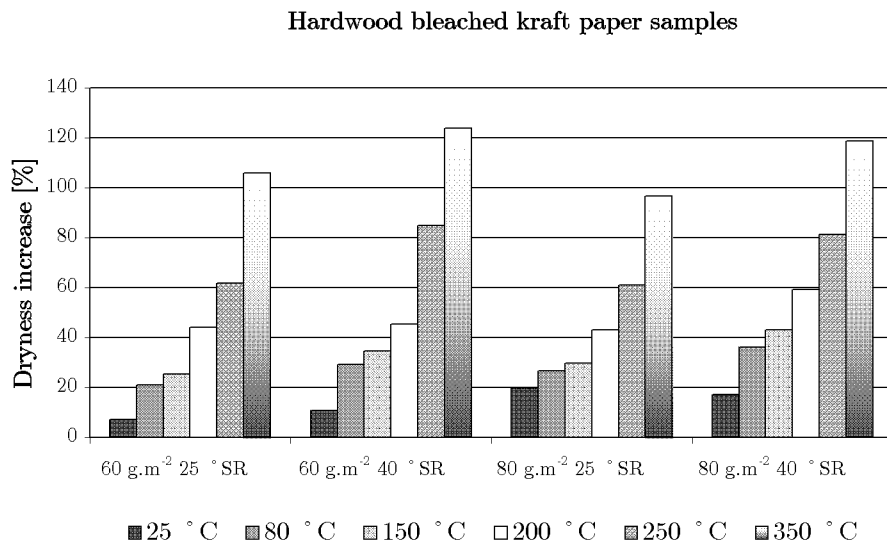


Figure 2.30: Dryness increase for bleached kraft samples of *Eucalyptus globulus* submitted to a press pulse of 6 MPa at 25, 80, 150, 200, 250 and 350 °C. Mean nip length: 38 ms.

Despite some experimental error due to the extremely difficult handling of the samples and variability of the samples properties, it was observed a very similar behavior for different degrees of freeness and grammage. Figure 2.30 shows in some extent the influence of Schopper-Riegler degree and grammage on dryness increase. It seems there is almost no dependence of dewatering rate on the refining level and grammage, as the water removal rate depends mainly on the roll surface temperature, the press load and the ingoing moisture content [31].

A continuous increase of gain in dryness was observed with increasing temperature of pressing. Figures 2.30 and 2.31 clearly show the influence of this parameter.

The heat transfer between the top plate and the paper surface is dependent on the *temperature difference*, the *contact area* and the *time of contact*. In fact, the supplied heat to the paper web surface is transferred from the surface by conduction, with the liquid water flow, by water phase change and with the vapor flow. The compression and the multiphase flow enhance the heat transfer from the surface into the paper web, but as the heat transfer inside the paper web is slow, the temperature difference between the top plate and the surface of the sheet decreases. Therefore, the heat flux to the paper web also decreases. In addition, the dwell time affects the heat flux to the paper web as the heat transfer from the sheet surface to its inner part is slower than that supplied by the heated block. This means that, the temperature difference between the top plate and the paper web surface decreases with increasing dwell time. Thus the heat flux also decreases with increasing dwell time. Moreover, the heat transfer rate inside the paper web determines the amount of heat transferred to the paper web [31]. Since the physical properties governing the heat transfer inside the paper web are the heat conductivity and the heat capacity of the fiber-water mixture, a dryer web means poor heat transfer capability. In conclusion, if the same pressing conditions are maintained, a higher temperature difference does mean a higher amount of heat transferred to the paper web and, consequently, a superior water removal.

The general tendency of the gain in dryness for sheets made from softwood unbleached kraft pulp is not so clear as in the case of hardwood bleached paper samples (Figure 2.31). Apart from the fiber structure, the total transport length, the number of fiber segments and the area of hydraulic contacts are important. In fact, collapsibility, conformability, and flexibility of wet fibers, together with

swelling, determine the densification of paper structure in pressing and drying. Conformable fibers can bend and match the shape of each other to give a dense and well-bonded network. The conformability of fibers depends on their *cross-sectional dimensions* and *internal and external fibrillation*, *chemical composition* and *morphology of the cell wall*. In fact, wet fiber flexibility can assess fiber conformability, and it decreases rapidly with increasing fiber thickness. Moreover, pulp beating which results in higher fibrillation of the pulp fibers has a positive effect on fiber flexibility which probably come from an increase in the porosity or delamination of the cell wall. Beating loosens the structure of the fiber wall (internal fibrillation) and surface (external fibrillation). It can also break fragments from the fiber wall. Internal fibrillation corresponds to a partial delamination of the fiber wall which increases the swelling degree, flexibility and conformability of the wet fiber wall. This improves inter-fiber bonding and strength properties of paper. External fibrillation is visible when fibrils spread out from fiber surfaces, and enhances sheet consolidation and bonding between fibers. Fines, resulting from the beating process also play an important role in dewatering. There are two types of chemical pulp fines, the primary and the secondary fines. Primary fines are present in unbeaten pulps. Beating creates secondary fines. These include lamellar and fibrillar parts of the fiber wall. The primary fines content of chemical pulps is typically less than 2 %, but beating can increase the total fines content to 15 %. Fines improve sheet consolidation and bond formation because they have a large specific surface area. Although fines are expected to increase the ease with which steam is transported out of the paper web, they might also clog the pores through which steam is expected to escape.

The bleaching process directly affects the chemical composition of the pulp. Not only it enhances the brightness of the pulp but alters also the mechanical properties of wet and dry fibers. The bonding ability of fibers may improve and tensile strength deteriorate in bleaching.

In summary, fiber and pulp properties that enhance fiber conformability also induce sheet consolidation, which in part decreases the path length for water to escape from the wet paper web.

The influence of each of the previous parameters may partially explain the results shown in Figure 2.31.

*Pinus pinaster* has longer fibers than *Eucalyptus globulus*. Longer fibers not only produce stronger paper but also tend to create a more open paper struc-

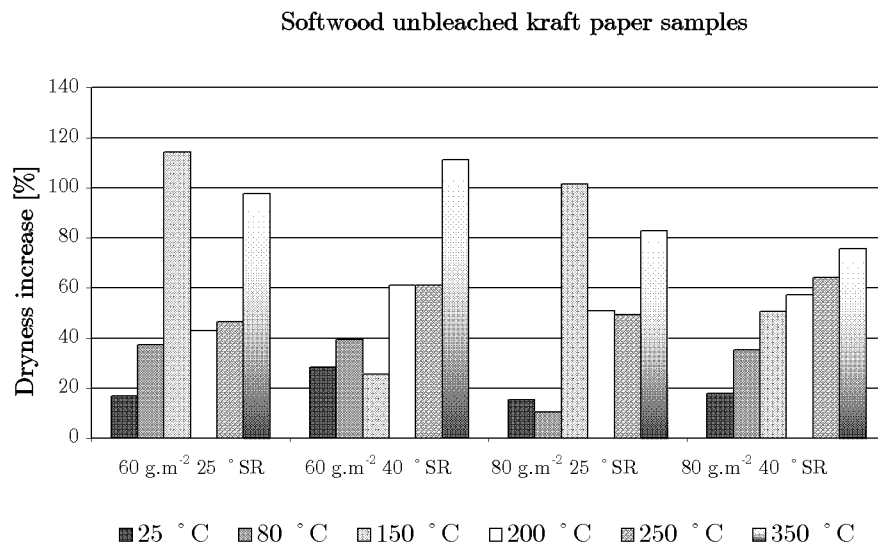


Figure 2.31: Dryness increase for bleached kraft samples of *Pinus pinaster* submitted to a press pulse of 6 MPa at 25, 80, 150, 200, 250 and 350 °C. Mean nip length: 36 ms.

ture than sheets made with short fibers. In addition, longer fibers easily form macroscopic flocs of entangled fibers during the sheet forming process, thereby producing a sheet with a relatively non-uniform mass distribution and hence a poorer quality of appearance [57].

Fibers having a thick cell wall and high coarseness tend to be rigid and inflexible, while fibers exhibiting a thin cell wall and low coarseness are more collapsible and flexible, which improve their possibilities to form fiber-to-fiber bonds. Therefore, *Eucalyptus globulus* fibers have a higher ability to promote bonding within a paper sheet than *Pinus pinaster* fibers.

From Figures 2.30 and 2.31 one may infer that sheets made from *Pinus pinaster* unbleached kraft pulps are less promising in terms of water removal efficiency. In fact, softwood fibers are less conformable and the paper web offers more mechanical resistance to compression when impulse drying is applied. In fact, *Pinus pinaster* fibers present higher length, width, wall thickness and coarseness than *Eucalyptus globulus* [2],[20], [56]. These properties may explain to some extent the better results achieved with impulse drying using hardwood pulps (*Eucalyptus globulus*).

Another remark, which is worth to note, concerns the fact that unbleached *Pinus pinaster* kraft pulps are expected to form a more open network structure which partially explains a marked tendency for delamination [47]. Some signs of internal delamination were observed and confirmed by the reduction in internal cohesion strength observed by Mendes [47]. In fact, when the transversal sections of paper sheets were observed by metallographic microscopy, the paper samples of 60 g.m<sup>-2</sup> beaten at 25 °SR and pressed at 150 °C clearly shown an internal delamination. This fact is in agreement with a reduction of about 40 % on the internal cohesion strength [47]. The same seems to have occurred for 80 g.m<sup>-2</sup> paper samples with a refining level of 40 °SR.

The most common way to measure water removal efficiency is to calculate increase in dryness points. Unfortunately, the outgoing dryness can only be used as an efficiency parameter when the ingoing dryness is constant. The reason for this is that for the same dryness increase, very different amounts of water may be removed out of the sheet, *i.e.* a 1 % dryness increase at 30 % outgoing dryness means higher water removal than 1 % at 40 %. The total water removal rate per unit area,  $WR_{tot}$ , was then used as an efficiency parameter, being defined as

$$WR_{tot} = \frac{\dot{m}_{tot}}{A} = \frac{\Delta MR \cdot Gr}{\Delta t} \quad (2.1)$$

where  $\dot{m}_{tot}$  is the total water removal rate,  $A$  the contact surface area of the web,  $\Delta MR$  the difference in moisture ratio,  $Gr$  the grammage and  $\Delta t$  the dwell time.

The dryness increase was plotted for different grammages of paper samples pressed at different temperatures. Observing Figures 2.30 and 2.31 no clear tendencies can be drawn for the influence of grammage on dryness increase. If, however, the total water removal rate per unit area is used, the result is altogether different (Figure 2.32).

For the same refining level, sheets of 80 g.m<sup>-2</sup> experience a higher water removal, and this tendency is even more pronounced at higher temperature of pressing and refining level. In fact,  $WR_{tot}$  clearly increases with temperature and refining level, following the same trend as dryness increase, but the main idea to retain here is that sheets with the same moisture ratio and higher grammage have more water available to be removed. One may then say that the  $WR_{tot}$  does not depend on sheet grammage but on the amount of water inside the paper web (Figure 2.34). Results reported in the literature are similar to those obtained in

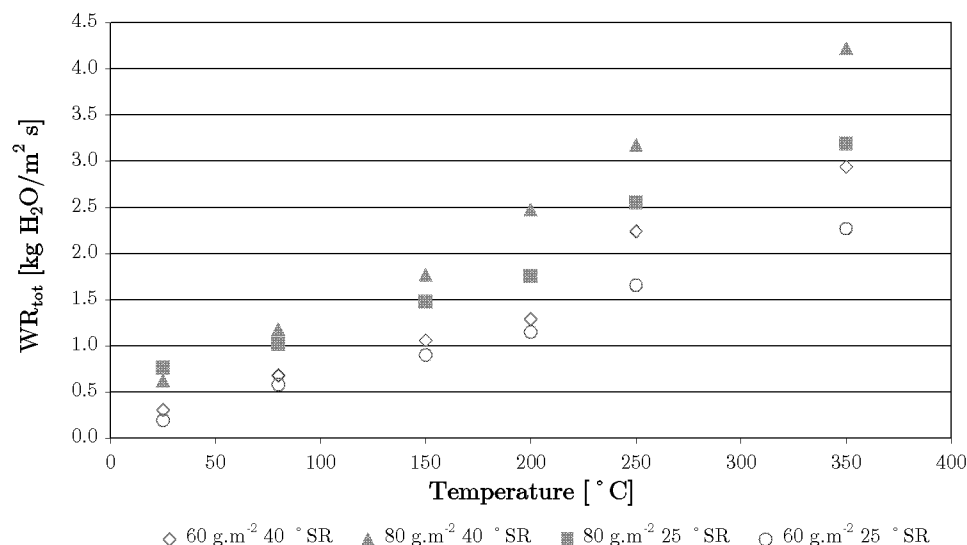


Figure 2.32: Total water removal rate per unit area as a function of temperature for hardwood paper samples of different grammage and refining level.

the present study. In fact, in laboratory experiments conducted by Larsson and Stenström at a press temperature of 300 °C and a dwell time of 40 ms the  $WR_{tot}$  was 2.0 kg/m<sup>2</sup>s for 54 g.m<sup>-2</sup> and 3.2 kg/m<sup>2</sup>s for 84 g.m<sup>-2</sup> [32]. In results by Macklem and Pulkowski [43] handsheets were pressed at 260 °C for 67 ms. The  $WR_{tot}$  was 1.5 kg/m<sup>2</sup>s for a 60 g.m<sup>-2</sup> paper and for a 100 g.m<sup>-2</sup> paper it was about 1.8 kg/m<sup>2</sup>s.

The analysis is not so easy for the *Pinus pinaster* paper samples. These samples do not present a clear tendency when the  $WR_{tot}$  is plotted against temperature and for different grammages and refining degrees, with the exception of 80 g.m<sup>-2</sup> 40 °SR paper sheets (Figure 2.33). Although water removal remains higher for heavy weight sheets pressed at temperatures ranging from room temperature to about 150 °C, the results become scattered for higher temperatures. Still, paper sheets beaten to a higher extent present higher water removal rates per unit area, which follows the trend presented by *Eucalyptus globulus* paper. The behavior of *Pinus pinaster* paper samples is ascribed to some runnability problems with the platen press for sheets pressed at 150 °C and above. No attempt was made to further investigate the data scatter.

Figures 2.34, 2.35 and 2.36 reinforce the conclusions presented above, *i.e.* water removal rate per unit area depends greatly on ingoing moisture ratio. A trend

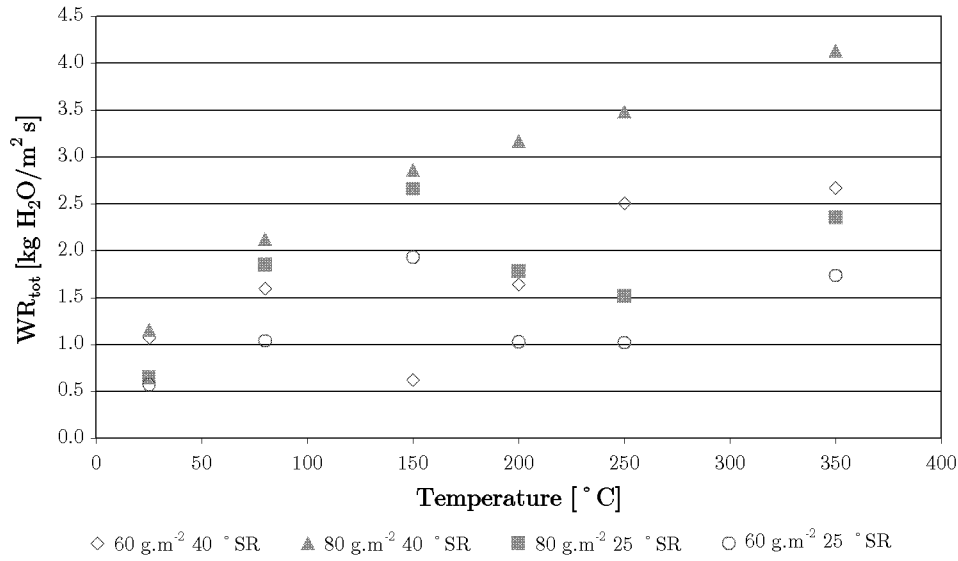


Figure 2.33: Total water removal rate per unit area as a function of temperature for softwood paper samples of different grammage and refining level.

of decreasing water removal for decreasing ingoing moisture ratio is observed. As explained above, the heat transfer inside the paper web is also dependent on the ingoing moisture ratio. The lower heat transfer in the paper web explains the decrease in water removal for lower ingoing moisture ratios. In addition, if the ingoing moisture ratio is close to the water retention value, it could be expected that water removal would be less as most of the water is bound to the fiber structure and is therefore not so easily removed without heat. This may explain the increasing slope of the trend lines observed in Figures 2.34, 2.35 and 2.36 for increasing press temperatures, *i.e.* at higher temperature and ingoing moisture ratio, the amount of water in the interstitial space (not bounded) is higher and easily removed due to pressing and temperature effects. Another remark, which is worth to note, is that high water removal rates achieved for higher Schopper-Riegler degrees and grammage (corresponding to a higher amount of water) are also confirmed in the following figures.

As previously mentioned, the performance of the selected additives was also tested and some important conclusions can be drawn. Paper sheets containing 15 % (w/w based on o.d. pulp) calcium carbonate exhibited additional difficulties in terms of delamination and sticking to the press plate. Two reasons could be appointed to explain this behavior: (i) the lower porosity of the paper sheets con-



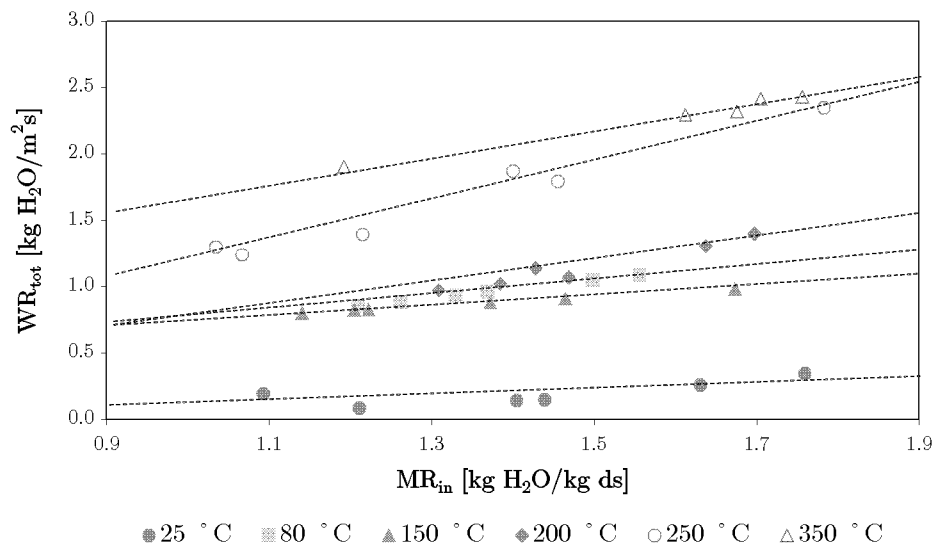


Figure 2.34: Total water removal rate per unit area versus ingoing moisture ratio for  $60 \text{ g.m}^{-2}$  *Eucalyptus globulus* paper at different temperatures. Refining level: 25 °SR.

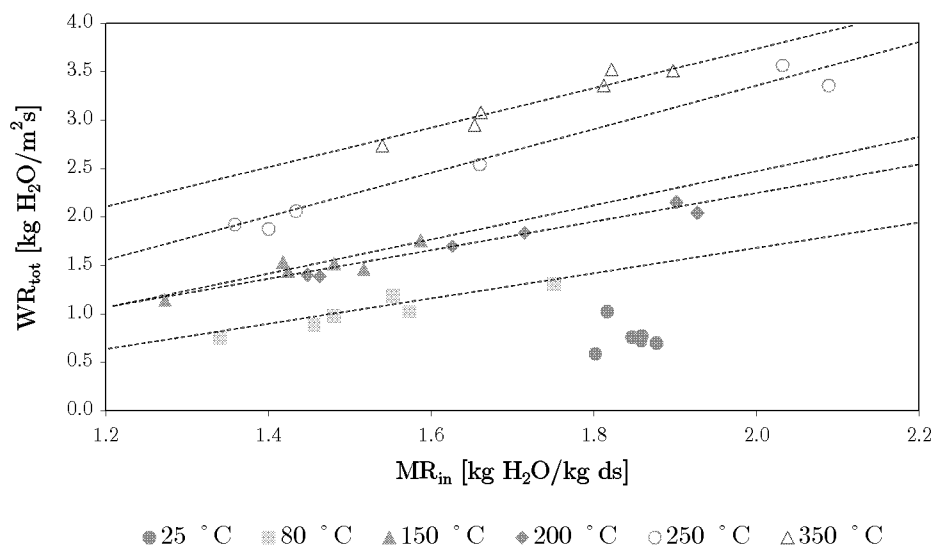


Figure 2.35: Total water removal rate per unit area versus ingoing moisture ratio for  $80 \text{ g.m}^{-2}$  *Eucalyptus globulus* paper at different temperatures. Refining level: 25 °SR.

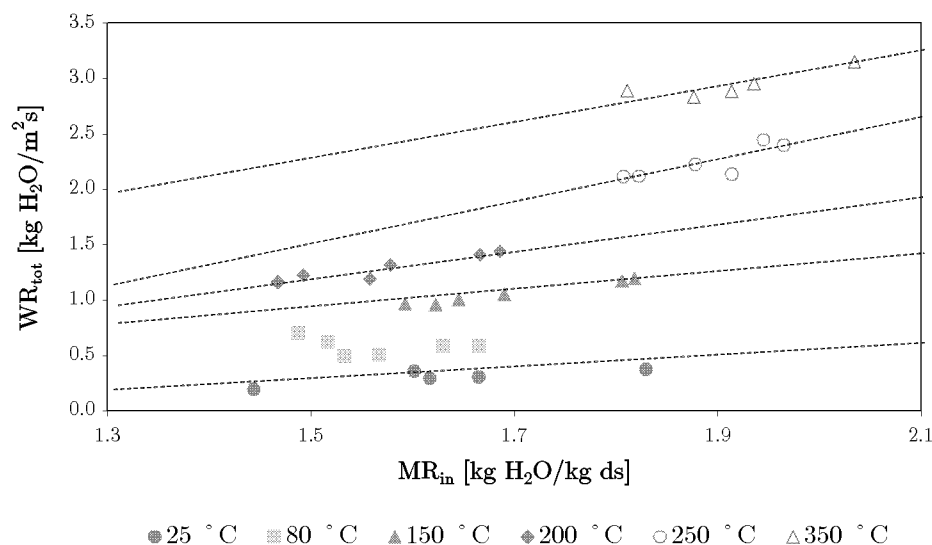


Figure 2.36: Total water removal rate per unit rate versus ingoing moisture ratio for 60 g.m<sup>-2</sup> *Eucalyptus globulus* paper at different temperatures. Refining level: 40 °SR.

taining calcium carbonate and (ii) the lower number of bonds between fibers due to the presence of the filler. The presence of fillers makes the network structure less open, which difficulties the water and steam movement inside the paper web. Moreover, as the number of bonds between fibers is low, the structure is not so strong and tends to delaminate.

In fact, paper samples beaten at 25 °SR and pressed at 80 and 150 °C stuck to the press plate. The same behavior was observed for paper sheets beaten at 40 °SR and pressed at 25 and 80 °C. Moreover, it was detected for sheets beaten at 25 °SR and pressed at 200 and 250 °C large and small bubbles on the felt side surface of the sheet [47]. Paper samples beaten at 25 and 40 °SR and pressed at 350 °C presented complete delamination, where the sheet practically splits apart.

Concerning paper sheets beaten at 40 °SR, when pressed at 150, 200 and 250 °C, exhibited clear tendency for delamination. Paper samples pressed at 150 °C presented small blisters on the felt side, whereas the samples pressed at 200 and 250 °C exhibited large bubbles on the press side surface. Only the paper sheets beaten at 25 °SR and pressed at 25 °C presented an appropriate appearance.

Visual inspection of the pressed samples confirms delamination for sheets beaten at 25 and 40 °SR, which explains, at least in part, the inferior performance

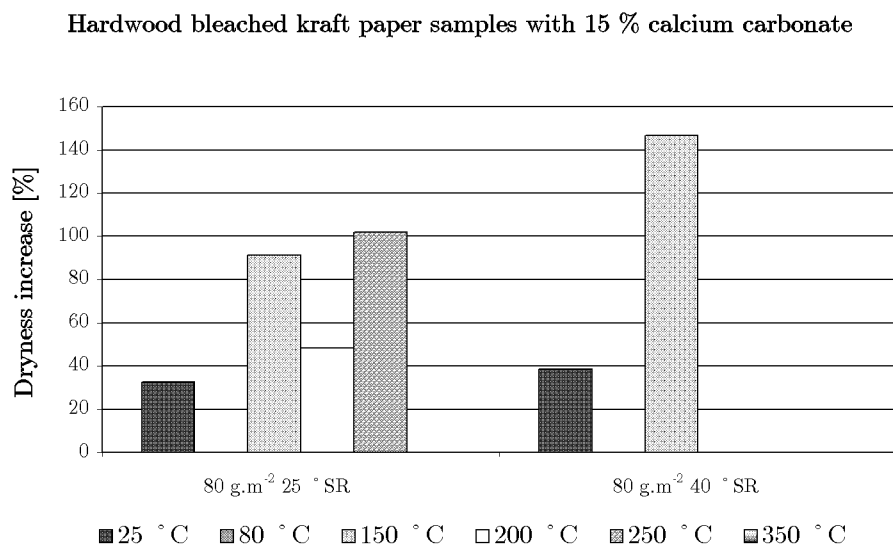


Figure 2.37: Dryness increase for bleached kraft samples of *Eucalyptus globulus* with 15 % calcium carbonate submitted to a press pulse of 6 MPa at 25, 80, 150, 200, 250 and 350 °C. Nip length: 30-40 ms.

of the calcium carbonate containing paper sheets (Figure 2.37).

As expected, paper sheets containing cationic starch shown tendency to stick to the top plate of the press. The sticking phenomenon is probably due to the gluing effect that cationic starch exhibits. For this very reason, some paper sheets could not be recovered after the pressing event and the corresponding water removal evaluation was not performed (Figure 2.38).

Cationic starch paper sheets having a beating level of 40 °SR presented sticking at 80 and 200 °C and almost complete delamination was observed in sheets pressed at 150, 250 and 350 °C. For the lowest beating degree, delamination was only observed in paper sheets pressed at 250 and 350 °C, but paper samples pressed at 80 °C stuck to the press plate.

The different behavior exhibited by the two beating degrees can be explained by the decrease of air permeability with increasing beating level. As the air permeability is lower, and consequently that of water, water is partially trapped inside the web being unable to flow easily towards the felt surface. In non-delaminated and non-stuck cationic starch paper sheets beaten at 25 °SR, the impulse drying technique enhances web consolidation, which results in an increase of density [47].

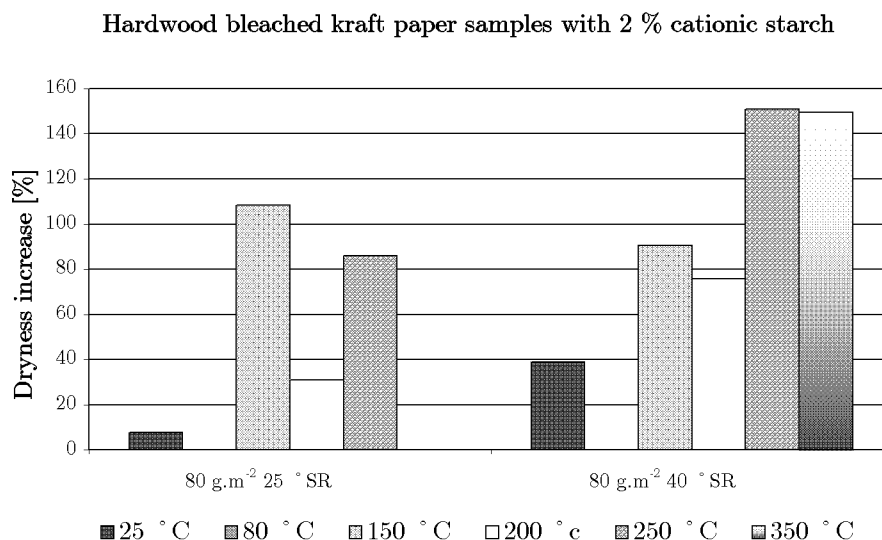


Figure 2.38: Dryness increase for bleached kraft samples of *Eucalyptus globulus* with 2 % cationic starch submitted to a press pulse of 6 MPa at 25, 80, 150, 200, 250 and 350 °C. Nip length: 30-40 ms.

Higher air permeability was observed in cationic starch containing-paper sheets pressed at room temperature when compared with additive-free paper sheets impulse pressed at the same temperature [47]. These results are attributed to the flocculation that cationic starch induces in the paper samples. Therefore, it is not surprising that cationic starch-containing sheets present higher water removal rates per unit area, at room temperature, than additive-free paper samples with the same grammage, refining level and fiber type. This is also observed at higher pressing temperatures, but due to sticking and delamination problems.

Increasing pressing temperature compensates the higher air permeability and roughness in papers containing cationic starch pressed at room temperature. Also, impulse drying produces more closed cationic starch containing-sheet surfaces, which results in an increase of smoothness, density and strength. During impulse pressing, the delamination and the sticking of paper sheets containing cationic starch were also smaller for sheets prepared from pulps beaten at 25 °SR than for those made with pulps beaten at 40 °SR, as already mentioned. It is believed that the temperature effect on paper made from pulps of higher refining level, having a higher amount of water, facilitates delamination as water and steam tend to be trapped inside the paper web.

The performance of *Eucalyptus globulus* samples containing 0.15 % of AKD is somehow similar to that of additive-free paper samples (Figure 2.39). The impulse drying produced more closed sheet surfaces for sized papers made from *Eucalyptus globulus* beaten at 25 °SR, which resulted in a decrease of the gain in dryness compared to 40 °SR paper (Figure 2.39). A less opened surface prevents steam to leave the paper web during the decompression phase of the impulse event, which contributes to a lower dryness increase. Apart from the surface problem, the web consolidation followed almost the same trend observed for 25 and 40 °SR additive-free paper samples pressed in the same range of temperature. This fact lead to a more pronounced dryness increase for paper made from highly beaten pulps, which are more conformable and thus less resistant to compression and dewatering.

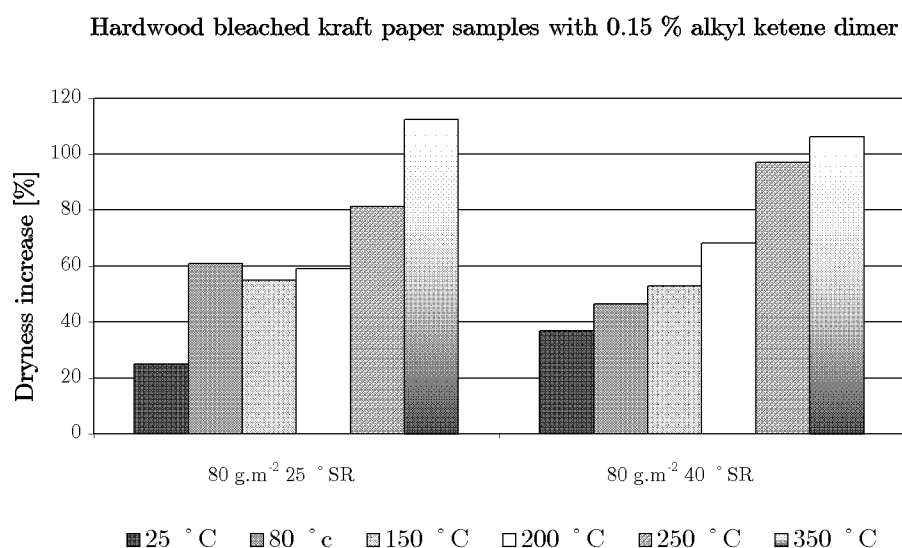


Figure 2.39: Dryness increase for bleached kraft samples of *Eucalyptus globulus* with 0.15 % alkyl ketene dimer submitted to a press pulse of 6 MPa at 25, 80, 150, 200, 250 and 350 °C. Nip length: 30-40 ms.

Dewatering also plays an important role in AKD retention degree within the fiber network. Mendes [47] investigated the AKD retention values for 25 and 40 °SR paper samples impulse pressed at temperatures from 25 to 350 °C. The author concluded that the lower values of retention at higher temperatures are the main reason for lower sizing on impulse pressed papers beaten at 25 °SR. For a pressing temperature of 25 °C, the AKD retention was 74 %, whereas only

approximately 24 % of AKD was retained in handsheets pressed at 80 °C. In sized paper sheets beaten at 40 °SR, the sizing results follow the same trend.

A likely explanation for the decrease on AKD retention with increasing pressing temperature is the mechanisms of dewatering on impulse drying technique. Higher temperatures and pressures used in this process allow that high amounts of water be squeezed out of the paper web in a space of milliseconds. The applied pressure results in a pressure gradient in the thickness of the paper causing compression and a water flow towards the press felt. The water flow is enhanced since the viscosity of the water and surface tension decrease and the compressibility of the paper web is improved with higher temperatures. These effects, in concert with a possible steam pressure gradient, create a larger water flow through the paper web, which can be responsible for dragging some AKD particles out from the sheet and into the backing felt.

In summary, it seems that the low AKD retention may be the reason for the similarities between the performance of AKD-sized and additive-free paper samples made from *Eucalyptus globulus* pulp. Being so, the effect of temperature is comparable to that observed in additive-free samples, *i.e.* it changes the dewatering ability by enhancing water viscosity and fiber conformability.

Paper sheets treated with the PAE resin presented some problems of delamination and sticking. In fact, paper sheets beaten at 25 °SR and pressed at 80 and 150 °C stuck to the platen press. Moreover, paper beaten at 25 °SR and pressed at 250 °C as well as paper beaten at 40 °SR and pressed at 250 and 350 °C exhibited complete delamination. Delamination was however more pronounced for 40 °SR paper and pressed at higher temperatures.

As expected, impulse drying was found to affect positively the curing rate of the wet strength resin [47]. However, this effect was not high enough to prevent delamination, which was observed at some pressing temperatures especially with sheets made from highly beaten pulps. On the other hand, when delamination was not observed, impulse drying was found to enhance paper performance (Figure 2.40). In fact 40 °SR paper experienced higher dryness increase when pressed at 25, 80, 150 and 200 °C than its additive-free paper counterpart.

According to Back [4], if PAE resin reacts inside the press nip, it results in considerable moist web strength, especially in the z-direction. In the present study, however, the nip length is too short to allow the binder to react deeply and to prevent delamination. It seems that the higher dryness increase observed

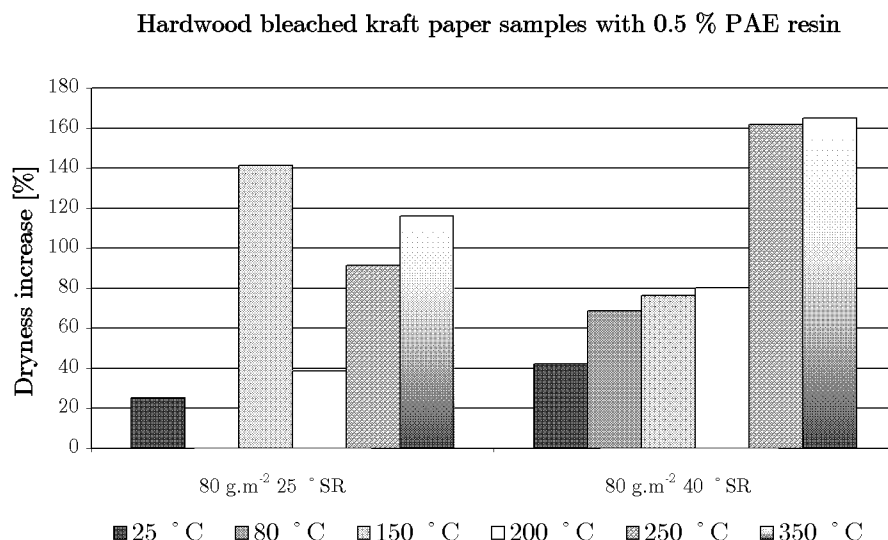


Figure 2.40: Dryness increase for bleached kraft samples of *Eucalyptus globulus* with 0.5 % PAE resin submitted to a press pulse of 6 MPa at 25, 80, 150, 200, 250 and 350 °C. Nip length: 30-40 ms.

for 40 °SR paper samples pressed at 250 and 350 °C results from loss of fiber mass at the moment of delamination (Figure 2.40).

Beating enhances significantly the tensile performance of PAE containing paper sheets [47]. Actually, paper sheets beaten at 40 °SR and pressed at 25 °C have better dry and wet strengths than those beaten at 25 °SR and pressed under the same conditions [47]. This could be attributed to the higher surface area available for resin adsorption (*i.e.* higher resin retention) for the case of higher beating level. Therefore, it could be expected that paper made from highly beaten pulps have better performance, even at higher pressing temperatures. However, this is only true for modest temperatures, *i.e.* from 25 to 200 °C, which may be attributed to a late development of the resin cure.

On the contrary, the wet strength showed a gradual increase for papers made with furnish beaten at 25 °SR and pressed at 25, 150, 200 and 350 °C [47], which may explain the absence of delamination and also the attainment of acceptable levels of water removal. It should be pointed out that this set of samples stuck to the platen press at 80 and 150 °C, which enhanced the performance at 150 °C in terms of water removal.

**Conclusions** A result of utmost importance was the achievement of a significant increase in dryness of the fiber webs coming out of the pressing unit working at these high temperatures and submitted to peak pressures of 6 MPa.

It was found that the water removal rate per unit area is a strong function of the heat transfer to the paper web and the ingoing moisture ratio. The water removal increases with increasing heat transfer due to hot pressing effects, *i.e.* it enhances water flow by decreasing its viscosity, and increases fiber flexibility and conformability which improves sheet consolidation. A high ingoing moisture ratio also increased the amount of water removed because more water was pressed towards the felt.

At high working temperatures some delamination problems were observed. It is well known that this phenomenon occurs during decompression, or after the press nip. According to several authors, it is affected by some parameters such as temperature, grammage, pulse shape and pressure. The true is that when superheated water flashes to vapor and forces its way out, the web delaminates. In addition, paper made from *Eucalyptus globulus* pulp presented a better performance than its *Pinus pinaster* counterpart when submitted to the extremely high intensity pressing conditions of impulse drying. As for additive-containing paper sheets the water removal evaluation is much more of a problem than for the remaining cases, mainly due to their tendency to delaminate or stick to the press plate.



## Part II

# Complementary experimental study



## 2.3 Application of thermomechanical analysis to the study of temperature dependent softening of the moist paper components

Throughout the nineteenth and twentieth centuries, the advanced technologies in all countries have made increasing and insistent demands to better understand the properties of materials, to measure them, and to make an increasingly better fit between these properties and the functional requirements of manufacturing processes. In this sense, one has assisted to a large development of paper industry in the last few decades. It is believed that there is a great need to better understand the actual demands made by the process, *i.e.* stresses, strains, and so forth, and how they are conditioned by time, temperature and moisture.

Thermal analysis plays a major role in the characterization of composite materials such as paper, in the sense that it encompasses a family of measurement techniques that record the response of the material being heated or cooled. Thermomechanical analysis (TMA) measures dimensional changes of the sample when subjected to a static load. In this study a thermomechanical analyzer was used to determine the mechanical behavior of the wet paper web when subjected to low loads. The softening temperature of paper was obtained by continuous heating of the sample. The dependency of this property on moisture was also studied. The main objective was to infer about paper performance within the temperature range usually used in the impulse drying.

### 2.3.1 Introduction

In response to the demands to better understand the properties of paper and to make a better fit between these properties and the functional requirements of its manufacturing processes, papermaking has moved towards an increasing number of measurements, both off-machine and on-machine, during the last 30 years; particularly the measurements related to the determination of the mechanical properties of the wet and dry webs.

There is a great need to truly understand the actual demands made by the process, and how paper properties are conditioned by temperature, moisture, pH, and charged particles in the medium or the atmosphere.

It is known that some properties of raw materials such as particle size dis-

tribution, fiber stiffness and type of fiber (either beaten or unbeaten) affect web compressibility. Grammage and sheet structure are also important in this respect. The magnitude of the effects often depends very much on the water content of the web and on the speed of compression [63]. The compressive pressure applied to a paper web is balanced by two components, one arising from the stiffness of the fiber network and the other from the flow of water during compression. So, the total pressure can be divided into structural and hydraulic components. The moisture content has a very pronounced effect on the dynamic compressibility of paper webs. Below fiber saturation point the resistance to compression is not detectable up to a relatively high density. Beating also have a significant effect on the dynamic compression of chemical pulps (it increases the hydraulic pressure created in the web), and the effect is largely dependent on the moisture content. The chemical and mechanical pulps respond to changes in speed of compression in a very similar way. A higher compression speed always results in a higher resistance to dynamic compression and the effect is more pronounced at higher moisture contents. On the other hand, several studies made at the Swedish Pulp and Paper Research Institute (STFI) [64] showed that for short load pulses mechanical pulps are more compressible than chemical pulps, while the opposite phenomenon occurred for longer pulses .

For most polymeric materials it is recognized that higher temperature and addition of plasticizers may speed up processes such as creep or relaxation [44]. When a constant stress is suddenly applied to a material, the strain may immediately reach a certain level but thereafter it may increase with time. Loading in which stresses are constant but strains increase with the duration of load application is referred to as creep loading. By contrary, when a constant strain is applied to a solid material, a stress can be immediately observed. However, the level of stress decreases with the duration of time. This phenomenon is referred to as stress relaxation. On a logarithmic time scale, material behavior at high temperatures will be more or less identical to long-term behavior at a lower temperature. It is therefore relevant, in a discussion of time-dependent properties of paper, to consider the influence of temperature and moisture. Water is recognized as the most efficient plasticizer for cellulosic materials, and it may lower the glass transition temperature of the polymer [44]. So, in long-time experiments it is important to assure that environmental conditions are stable and well known.

As for most polymeric materials, paper composition also plays a major role

when studying its mechanical behavior. The basic constituent of paper is the pulp fiber. Bleached chemical wood pulp is almost pure cellulose, whereas unbleached pulp also contains hemicelluloses and lignin. On the other hand, the composition of wood itself also depends on the species. So, wood like *Eucalyptus globulus* has between 15 and 24 % of lignin whereas *Pinus sylvestris* presents a lignin content of 24-35 % [23]. A polymeric material may possess both crystalline and disordered or amorphous regions or states. The crystalline phase is associated with a melting point, but for some polymers, such as cellulose, this temperature is so high that they decompose before they melt. The amorphous phase, however, does not have a melting point and can be associated with two states: at high temperatures the polymer is rubbery or liquid like, whereas at temperatures below the glass transition point,  $T_g$ , its behavior is very similar to inorganic glasses, showing hardness, stiffness and brittleness. In a completely amorphous polymer there is a large reduction of the elasticity modulus when crossing its glass transition point [44].

The distribution of cellulosic polymers on the fiber wall is responsible for its mechanical resistance. The crystalline phase is mainly formed by cellulose, which increases the cohesion between fibers. Hemicelluloses are smaller and their distribution ensures a certain elasticity to the fibers. This wood component makes an amorphous matrix and, as it is hydrophilic, it allows for the hydration of fiber walls [23]. In this sense, it is of great importance to refer that *paper behavior changes with temperature as its components properties are temperature-dependent*.

Since hemicelluloses, lignin and disordered part of the cellulose all to various extent absorb water, a softener for these polymers, their glass transitions will depend on their water content. The lignin and hemicellulose are amorphous and essentially thermoplastic, while the cellulose is semicrystalline with disordered areas and crystallites arranged systematically. These disordered areas are regarded as amorphous although they might not have a perfect disorder. For an amorphous polymer the main softening, the glass transition, is of prime importance since many properties, and especially the elastic modulus, change drastically while the material transforms from a glassy to a rubber-elastic state. The term *glass transition temperature* is used here as the point at which the material exhibits a decrease in its mechanical properties. The correct definition of the term has been a matter of some controversy, as it depends on the measurement method and the

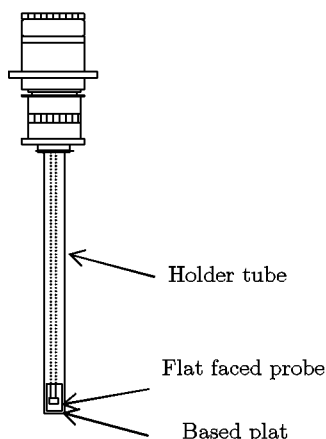


Figure 2.41: TMA sample holder assembly (adapted from [58]).

time-scale of the experiment. Nevertheless, the term is usually accepted.

For the reasons pointed out in the previous lines, the range of temperature in which the mechanical behavior of paper and of its components might change during the impulse drying event was investigated under the influence of moisture ratio, temperature of pressing and time-scale of the experiments.

### 2.3.2 Experimental procedure

To obtain the mechanical response of specific paper web samples, as described below, some measurements were made on a SETARAM TMA 92 12 module at a sampling rate of 1/3.6 Hz. A 7 mm diameter flat-faced probe of fused silica was used [58]. A simplified explanation of the TMA technique may be described as follows. A stainless steel crucible of 8.5 mm diameter was used to test all paper samples. The sample to be investigated is placed onto the base of the crucible, then it is placed on the base-plate of the holder tube and a suspended quartz probe is lowered down and positioned so that it just touches the top surface of the sample. Thereafter, the probe is loaded with some finite weight. The TMA sample holder assembly, as illustrated in Figure 2.41, is then placed into a furnace unit and the vertical movement of the quartz probe is continuously monitored. Probe displacement profiles are subsequently analyzed.

For experimental determination of the above mentioned characteristics, two fiber types were tested: *Eucalyptus globulus* and *Pinus sylvestris*. All samples

were made from bleached kraft pulps, and the tests carried out took into account different moisture contents, grammages, and also two different network structures, isotropic and anisotropic. It is also worth noting that in either case the refining level was 25 °SR.

The paper samples were stored in plastic bags inside a refrigerator and later circular samples with a diameter of 7 mm were made. One sample of each hand-sheet was kept for moisture content calculation.

### Experimental determination of glass-transition temperature

Typically, TMA tests are run in a heating mode at some controlled heating rate. To determine the glass transition temperature, some experiments were carried out at constant load (150 g), and the temperature program was as follows: an initial temperature of 25 °C, and continuous heating at a rate of 90 °C.min<sup>-1</sup> and a final temperature of about 250 °C. The stress applied on the sample is given by the force divided by the cross-sectional area of the specimen ( $\simeq 3.8 \times 10^{-5}$  m<sup>2</sup>), *i.e.* 38.7 kPa.

It was necessary to measure the initial thickness of each sample, and for that purpose a micrometer was used. The strain was then calculated as the difference between the final and initial thickness of the sample at each measurement point, divided by its initial value.

The characteristics of the samples used in the present work are summarized on Table 2.8.

Table 2.8: Paper samples characteristics.

| Pulp<br>furnish | Fiber type    | Refining level<br>[°SR] | Grammage<br>[g.m <sup>-2</sup> ] | Moisture<br>ratio | Web structure | Initial thickness<br>[μm] |
|-----------------|---------------|-------------------------|----------------------------------|-------------------|---------------|---------------------------|
| Bleached        | E. globulus   | 25                      | 60                               | 0.86              | Isotropic     | 240                       |
| hardwood pulp   | E. globulus   | 25                      | 60                               | 1.83              | Isotropic     | 240                       |
|                 | E. globulus   | 25                      | 60                               | 2.97              | Isotropic     |                           |
| Bleached        | P. sylvestris | 25                      | 60                               | 0.82              | Isotropic     | 240                       |
| hardwood pulp   | P. sylvestris | 25                      | 60                               | 1.71              | Isotropic     | 240                       |

### 2.3.3 Results and discussion

The definition of glass transition temperature is difficult to establish because this phenomenon takes place within a more or less large range of temperatures, and

this same range depends on the output variable and on the employed method [71].

For the polymeric wood components the dry glass transitions occur at rather high temperatures (Figure 2.42), at which decomposition rates are significant. Therefore, a very high heating rate ( $90\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ ) was used to determine the glass transition which is not usually accepted for this purpose.

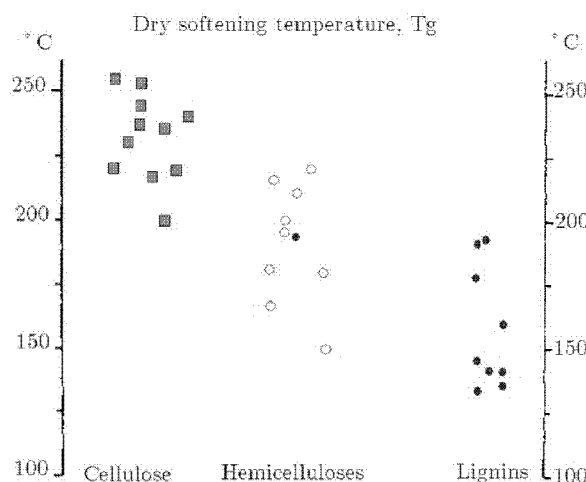


Figure 2.42: Published main softening temperatures,  $T_g$ , of the wood components at completely dry conditions (adapted from [5]).

As illustrated on Figure 2.42, for cellulose the measured transition varies between 200 and 250  $^{\circ}\text{C}$ . Although the scattering might be due to variations in crystallinity, it is also due to the various methods used, their definition and the time-scale of the experiment. Although none of the measurements definitely prove that the softening noticed is due to a glass transition, this is generally accepted to be the case [5]. For the hemicelluloses the observed glass transitions vary over a span of 150 to 220  $^{\circ}\text{C}$ . This may be attributed to differences in chemical composition among the native hemicelluloses. For native lignin an overall glass transition as high as 205  $^{\circ}\text{C}$  is suggested [5]. However, in lignin, the plasticizing effect of water has a limit at a glass transition of about 80-90  $^{\circ}\text{C}$  at water contents as low as 5 % [21]. Additional water is probably not part of the homogeneous phase, and thus does not result in further softening of the lignin. The plasticizing effect of water on hemicellulose has been demonstrated by Cousins [16], who found a typical glass-rubber transition at 20  $^{\circ}\text{C}$  at a moisture content of about 25 %.



In wood pulp fibers, the cellulose microfibrils are believed to be disturbed from their crystalline order in certain regularly occurring zones. Such disordered zones consist mainly of tie molecules between the cellulose crystallites, and this implies a restricted chain mobility which shifts the  $T_g$  to higher temperatures or higher moisture contents and also broadens the transition region compared to that of a completely amorphous material.

The qualitative behavior of the studied paper samples over the whole temperature range is in accordance with what would be expected. The glassy state is associated with a low volume coefficient of expansion. At the glass transition temperature, the curve of specific volume versus temperature changes in slope to resemble that of a liquid [44]. This phenomenon may be explained in terms of free volume, that is, the volume of the material unoccupied by polymer molecules. The free volume is approximately constant up to the glass transition point, but above this temperature it expands, which has the effect of increasing the rate of expansion to that more typical of a liquid. In Figure 2.43 it can be observed a soft increase of samples thickness and a great expansion at the transition point. Near the end of the experiment there is a little reduction of samples thickness as the load is still being applied and the material is now more conformable.

From Figure 2.43, some interesting observations can be drawn. It is worth noting that the y-axis represents the thickness variation with respect to each former experimental determination, which means that what is illustrated in Figure 2.43 is in fact the relative expansion of the web. This is done in order to have a better visualization of the transition point. Plotting the dynamic position of the flat-faced probe that contains the paper sample against the time-scale of the experiment a very smooth slope followed by a sharp increase is observed. When comparing the trends illustrated in Figures 2.44 and 2.45, one may see great similarities. In fact, if a polymer is completely amorphous, the specific volume follows the line A-D in Figure 2.45. In the region C-D the polymer is stiff and brittle, but beyond  $T_g$  it softens and changes from a glassy to a rubber-elastic state. On the other side, there would be the ideal crystalline polymer. When temperature increases its specific volume raises along the line H-B-A and no glass transition is observed due to the absence of disordered chains in the structure. Close to the so-called melting point,  $T_m$ , the material starts to collapse and behaves as a liquid, which explains the sharp increase of specific volume.

It is then suggested that the paper used has a very high percentage of crys-

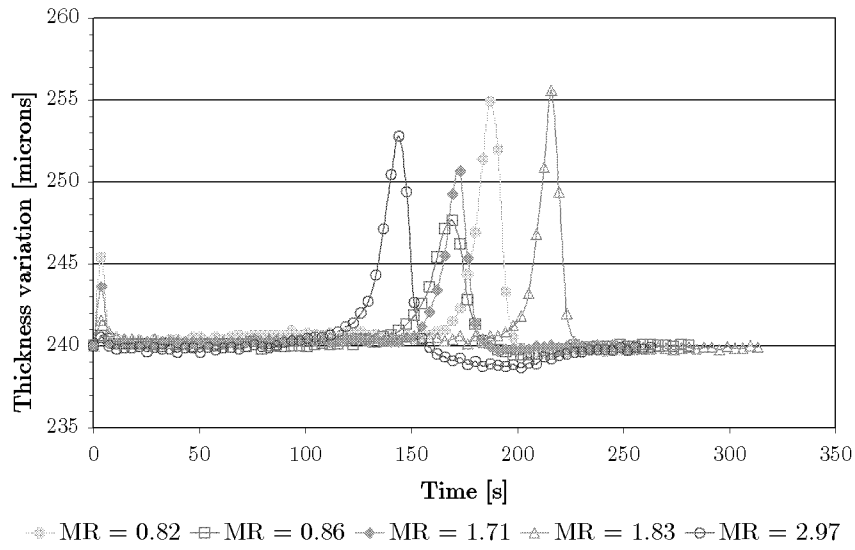


Figure 2.43: Paper thickness evolution obtained at a constant load of 150 g and heating rate of  $90\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ . The paper samples are made from 25 °SR bleached kraft pulps of *Eucalyptus globulus* and *Pinus sylvestris*. MR (kg H<sub>2</sub>O/kg ds.) represents the ingoing moisture ratio of the web. The y-axis represents the thickness variation with respect to each former experimental point, i.e. the relative expansion of the web.

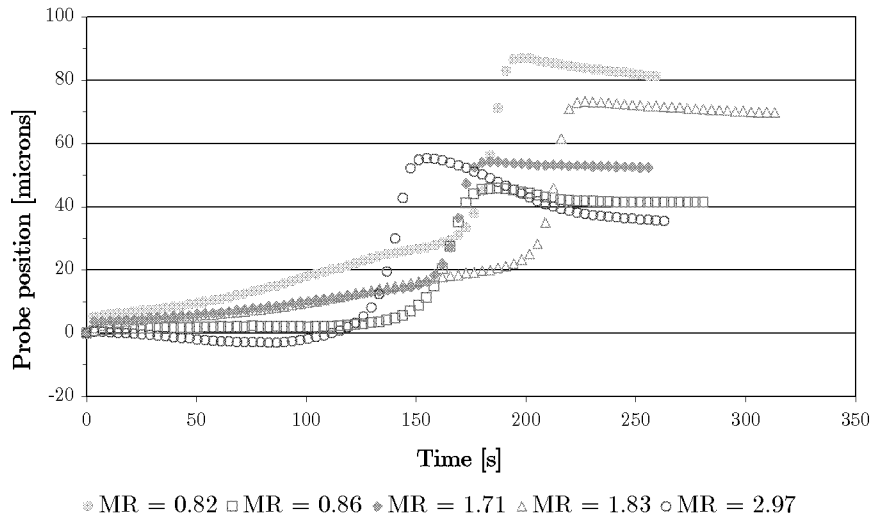


Figure 2.44: Typical diagram used to determine the glass transition temperature. Here, the x-axis contains the time-scale of the experiment instead of temperature for a clear visualization of the softening event.

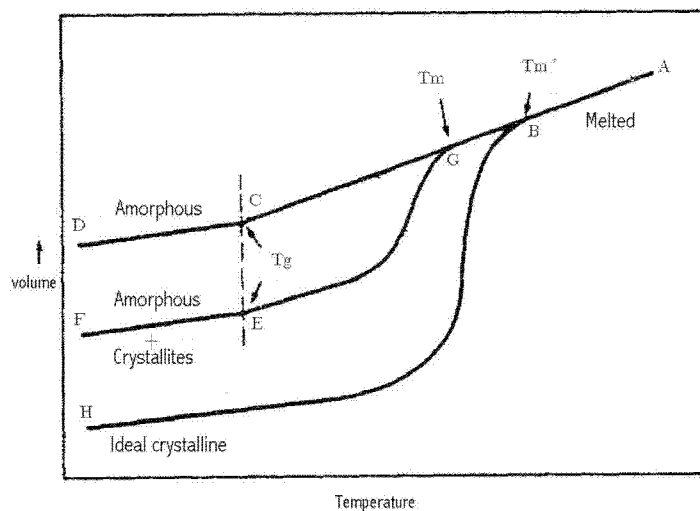


Figure 2.45: Schematic variation of specific volume of a polymer with temperature: i) amorphous polymer, ii) semi-crystalline and iii) ideal crystalline (adapted from [52]).

talline material. In fact, it is a semi-crystalline material, which contains zones mainly amorphous with a corresponding glass transition temperature, and highly oriented areas corresponding to crystallites which have a typical melting point. It is then suggested the term softening temperature for the temperature range in which the material expansion takes place.

If, on the other hand, strain (here defined as the relative expansion of the web divided by its initial thickness) is plotted against temperature, a temperature span from about 25 to 100 °C is observed, which reflects the kinetic nature of the transition phenomenon (Figures 2.46 and 2.47). In addition, a glass transition temperature from 194.4 to 217.6 °C was obtained for paper samples made from 25 °SR bleached *Eucalyptus globulus* kraft pulp with moisture ratios ranging from 0.86 to 2.97. The plasticizing effect of water lowering the glass transition temperature was also observed for bleached *Pinus sylvestris* kraft paper samples. The moisture sorbed into the wood polymers is intimately mixed with these polymers and acts as a softener for them. The water interferes with the interaction forces, bonding, between the wood polymer chains and thus increases their mobility.

Glass transition temperatures of 209.0 and 216.4 °C were obtained for paper made from softwood kraft pulp beaten at 25 °SR. These and the previous values

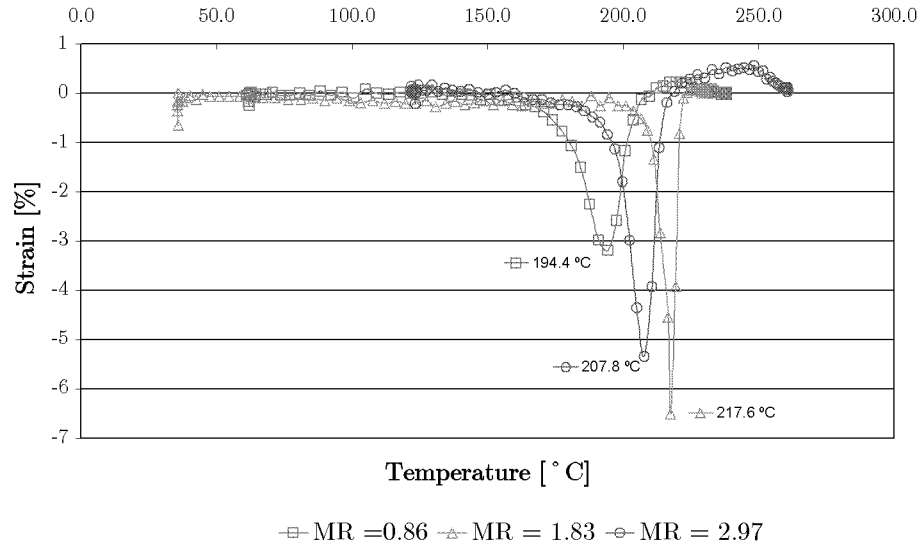


Figure 2.46: Strain-temperature profiles obtained for paper made from hardwood kraft pulp of different ingoing moisture ratios. Strain is here defined as the symmetric value of the relative expansion of the web divided by its initial thickness.

for glass transition temperature are in agreement with those reported in the literature. The scan of all samples was carried out using wet sheets, *i.e.*, with moisture content higher than 60 %. It is well known that this level of moisture plastifies strongly lignocellulosics thus reducing its glass transition temperature. In fact, it was reported that the glass transition temperature of pulps containing only 10 % of water was as low as 5 °C [70].

Both species present a very similar behavior, *i.e.*, their glass transition temperature shows a decrease when moisture increases. This effect can be explained if one takes into account that during beating the water content within fiber walls increases. In this sense, the expansion occurs more rapidly when the water content is higher, *i.e.*, at lower temperature. The presence of water have such a decisive effect due to water viscosity dependence on temperature [63]. It should also be pointed out that the obtained values of  $T_g$  for both species are only comparable to those corresponding to dry conditions, as the paper samples were almost dry due to the high heating rate. It is also noteworthy that the high heating rate affected inevitably the glass transition temperature, as the movement of amorphous and crystalline components greatly depend on their thermal history. The changes on the molecular level brought about by the changes in temperature

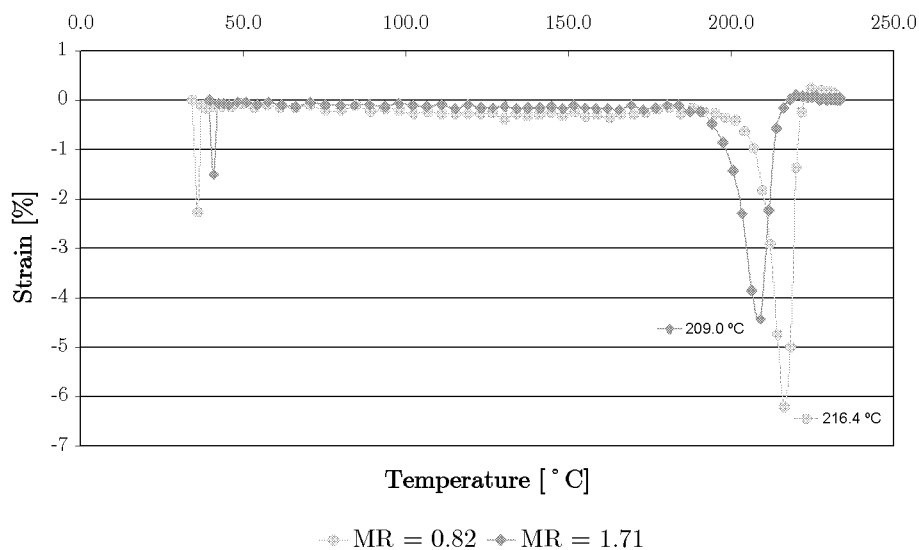


Figure 2.47: Strain-temperature profiles obtained for paper made from softwood kraft pulp of different ingoing moisture ratios. Strain is here defined as the symmetric value of the relative expansion of the web divided by its initial thickness.

and moisture content naturally influence the physical properties of the wood fiber and paper materials. With increasing temperature, the molecular mobility of the wood polymers increases, leading to an expansion of the solid and also resulting in a gradual diminishing of the elastic modulus. At the softening temperatures of the wood polymers, the molecular mobility increases drastically leading to a higher thermal expansibility but more importantly it leads to a drastic reduction in the elastic modulus. On the other hand, it is clear that higher moisture contents shift the softening region to lower temperatures. These effects of water have been described by Batten *et al* as an effect on the hydrogen bonds in the cellulose system, the more pronounced effect of water at higher moisture contents being attributed to a cooperative breakage of the hydrogen bonds [6].

### 2.3.4 Conclusions

Thermal mechanical analysis shows that glass transition temperature decreases with moisture content, and its experimental determination depends on the method used and time-scale of the experiment. A higher heating rate will inevitably produce higher glass transition temperatures. Nevertheless, the main idea was to

perform the TMA tests in the same conditions as those of impulse drying experiments, in order to infer about paper performance inside the press nip.

Paper is envisaged as a viscoelastoplastic material. In that respect, it is quite similar to many polymers. The softening of the amorphous components of the fiber wall, hemicelluloses, lignin and amorphous cellulose control the viscoelastic properties of paper. Moisture strongly influences the softening of paper as it affects the softening temperature of paper components. The viscous behavior of paper arises from the fiber wall structure where crystalline and amorphous regions mix. Amorphous materials have a glass transition temperature, below which they are glass-like, rigid, stiff, and brittle. Above that point, they soften and become increasingly fluid-like. In wood fibers, hemicelluloses, lignin and amorphous cellulose are thus the components whose flow is responsible for the rheology of paper. Although cellulose and hemicellulose soften even at room temperature in the presence of moisture, lignin, which does not readily absorb water, softens at approximately 115 °C in moist conditions, as reported by Back *et al* [5].

Because these components were in a fluid-like state during the impulse drying experiments, the sheet was compressed further than would be possible using conventional pressing and drying. This compression brings the fibers into intimate contact, in the presence of moisture, which promotes bonding. In fact, paper samples made from bleached *Eucalyptus globulus* or unbleached *Pinus pinaster* pulps presented a moisture ratio between 1.50 and 2.33, approximately. At such high moisture levels, and bearing in mind the operating temperature used in impulse drying, the fibers are more conformable as the glass transition temperature of hemicelluloses and amorphous cellulose has been overcome. In the particular case of unbleached paper samples, it is likely that lignin overcomes its glass transition point within the press nip as the temperature inside the paper web may in some cases evolve from room temperature, at which lignin is in the glassy-state, to temperatures well above  $T_g$ .

In conclusion, one may expect that no glass transition of the material will take place within the range of temperatures in the press nip, except maybe for the unbleached paper samples pressed under certain operating conditions.

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## Chapter 3

# Mathematical Model for High-Temperature Pressing of Paper

### 3.1 Consolidation mechanisms involved

The most important process in paper production is dewatering of the cellulose fiber suspension. This suspension entering the **forming section** has a fiber concentration less than **1 %**. Most of the water is removed on the wire section due to the gravitational force, as well as vacuum pumps and hydraulic pressure difference between the paper web and the forming fabrics. The dryness of the paper web going out the **wire section** is in the range **20-25 %**.

In the **press section**, which follows the wire section, water is removed by mechanical pressure. Normally, the press section consists of two to four press nips, where the paper web is pressed between two permeable felts or between a felt and a solid surface. Here, water is expressed from the interfiber pores and fiber walls and absorbed into the felt [27]. The dryness is usually in the range **35-50 %** after the paper web leaves the press section.

After the press section the paper web is dried to its final dryness of **90-95 %** in the **drier section**. In this section water is evaporated from the paper web by means of steam-heated cylinders. The paper web is pressed against the cylinder using a fabric, but the pressure is not very high.

Approximately 99 % of the water is removed in the forming section, but the

largest amount of energy is consumed in the dryers [115]. Further, the dryer section is the most capital intensive portion of the paper machine. As a result, a great deal of effort has been put into minimizing and optimizing the dryer section over the last twenty years. One such area rich in development is in the press section, where higher dewatering rates, with improved paper properties can be achieved using a somewhat recent technique, impulse drying. But first, some fundamental aspects of wet pressing will be discussed as a basis to the understanding of impulse drying.

### **3.1.1 Fundamentals of wet pressing**

There is a large body of literature on wet pressing; almost all of it deals with water removal and much of it is empirical in nature. Though one has been forced to infer what happens inside a roll press nip by making observations from the outside, the quantitative and qualitative knowledge of the water removal process has improved greatly over the years. There have been some direct experimental measurements of several important variables inside the nip (applied pressure, fluid pressure, and midnip roll separation), but only at the system boundaries (the roll surfaces). Direct data is still lacking on other important variables inside the nip such as localized pressure gradients, sheet thickness and sheet dryness, localized deformation, a good definition of the interfacial region, direct measurements of parameters in the thickness direction, and thermodynamic properties. In this learning process, paper property development is expected to receive equal, if not greater, attention.

#### **Early work**

Campbell [24] introduced concepts from soil mechanics, which form the basis for many later wet pressing studies. His much underquoted paper seems to be the first to discuss or imply the following fundamental concepts:

- the separation of the total applied press load into the mechanical and hydrodynamic pressure components;
- the variation of sheet density in the thickness direction;
- the dependence of water removal on the product of applied pressure and pressing time (later given the name “press impulse”);



### 3. Mathematical Model for High-Temperature Pressing of Paper 159

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- machine-direction pressure gradients resulting from roll geometry, accompanied by an explanation of “crushing”.

Several attempts were made after Campbell’s work to develop a theory of wet pressing, but the first advance came from the work of Bergström (see [15]). After performing a large number of wet pressing experiments with a platen press, he concluded that water must be removed on the compression side of the nip — something unquestioned today, but contrary to views of the time. He also added another new concept — that some water could perhaps return to the paper from the felt in the expanding nip. He envisioned this to occur as a combined result of surface tension and suction forces arising from both expanding structures. Besides rewetting, Bergström discussed the variation in sheet density through its thickness as a result of the division between hydrodynamic and mechanical pressures, as predicted by Campbell. Lastly, he believed that the felt should have high permeability to water even when subjected to high pressure, and it should have a pore size small enough for the water to remain in the pores when the sheet expands and tries to pull it back. Almost all these ideas remain valid today.

Almost at the same time, Wahlström [193], [194] made the first successful attempt at bringing together all the reasonable postulations then known into a comprehensive theory of wet pressing. Bergström and Wahlström had theorized and demonstrated the benefits of minimizing the pressure drop along the flow path. To accomplish this it was necessary to avoid nip saturation — condition where all voids in the paper, felt, and press roll vents are filled with water at some point into the nip — which was thought to create longitudinal flow in the sheet and in the felt.

Some time later, Wrist [206] gave an excellent critical review of the fundamental understanding of wet pressing. His work includes one of the first specific references addressing the importance of felt uniformity during the compression phase of pressing. He pointed out the need to greater fundamental understanding of fluid flow through rapidly compressed networks, network mechanics, and pressure distributions in deformable nips. He also called for direct experimental evidence of the fluid pressure distribution, and studies of splitting as a possible mechanism for rewetting.

Asklöf *et al* [9] presented work dealing with platen pressing of wet webs. They were among the first to provide data that flow resistance in the paper web was a significant factor in its water removal.

At the 1968 International Water Symposium, Wahlström [195] presented his next review of wet pressing research on which he modified his earlier stands on rewetting by (i) including the possibilities of rewetting both by a suction process and by Wrist's film splitting mechanism [206]; (ii) viewing the capillary transfer mechanism as being so rapid compared to the nip expansion time that it could be considered essentially time independent; and (iii) stating that rewetting was probably an interfacial, not a bulk flow phenomenon. He still maintained his view that rewetting was controlled mainly by the capillary structure of the paper and felt and their respective wetness, adding for emphasis that "capillary transfer in the expanding part of the nip was firmly established as present for all press conditions".

Wahlström was one of the first advocates of double felting as a way to simultaneously reduce the effects of sheet flow resistance and slightly increase the nip residence time. Double felting was later combined with large press rolls, soft covers, and high loads and implemented as "high impulse" pressing.

Nilsson and Larsson [126] made one of the first references to water being pressed out from inside fibers. Using their previous work [9] and Wahlström's theory as a starting point, they mathematically modeled the static water pressure distributions in the sheet, both in the machine-direction and in the sheet thickness direction — something not done before.

Schiel [158] presented methods for approximating roll press nip geometry using the "effective roll radius" and the felt compression response. Combining this nip geometry with the press load and speed, he introduced the now-familiar term "Press impulse" which led him to the optimum pressure-time concept. He discussed at some length the important subject of how the press affected paper quality. He described three different kinds of crushing and made the interesting observation that paper became drier, but weaker. It is inferred from his writing that the fibers slightly displaced by fluid and mechanical shear forces create microscopic flow paths which allow easier exit of water but which also weaken the network bonding.

Heller *et al* performed a number of wet pressing studies using laboratory and pilot plant roll presses in the early 1970's. Their first paper, [66], has often been cited because they were apparently the first to report achieving 70 % paper dryness in a felted roll press. They proposed this dryness approached the "equilibrium fiber moisture content", a level beyond which was unavailable for

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removal by conventional pressing. In their work, these dryness levels could only be achieved by utilizing the most uniform press felt possible and pressing the unrefined sheet in a plain press with extreme maximum pressure (15 MPa) and time (500 ms).

At the 1977 Fundamental Research Symposium Carlsson, Lindström and Söremark [27] presented fundamental work on water removal from inside the fiber lumen and cell walls — something mentioned earlier in the context of wet pressing [126] but never actually investigated. Their work and experimental methods were motivated by the widely recognized work of Stone and Scallan (see refs. 1-6 in [27]) and convincingly demonstrated for the first time that water within the fiber was an important component of the water removal process.

Concerning the rewetting phenomena, some observations have supported the view that it is an insignificant factor in wet pressing, unless paper and felt are kept together for a long period of time (tens of milliseconds) after the nip. Thorne's studies have shown that the capillary suction of wet sheets is small and that capillary forces cannot yield large water flows in the fiber structure in the time the web spends in the nip [181].

According to Norman [129], flow and separation rewettings can be distinguished on the basis of mechanisms, and internal and external rewettings on the basis of location. Flow rewetting occurs when water flows straight from felt to paper. Separation rewetting can appear in connection with felt-paper separation, when water moves from felt pores onto the surface of the web. Rewetting is internal when it takes place within the nip and external outside the nip.

In addition, the felt may also affect water removal and paper properties as well. From the point of view of water removal from paper, the most important felt properties are probably uniformity of pressure application, permeability, and capacity to retain water in the pores. Unfortunately these properties are usually interdependent in felts and to change them independently is often impossible.

Smart [168] and Fekete [48] showed that the thickness of batt fibers on the paper side has the greatest effect on water removal. The type, coarseness, and compression of the base are of only marginal importance in this respect. They showed the felts have a very uneven surface, and from this it was concluded that the differences in the micro-scale pressure nonuniformity created by the felts are the main source of the differences in water removal. Another possible reason for the good performance of the felts made of thin fibers in the batt is that they have

higher flow resistance and higher capillary suction in the vicinity of the paper. This may give them a greater capacity to obstruct the redistribution of water from the felt to the paper at the exit of the nip.

**Hydraulic and structural pressures generated during compression of the wet web** It is convenient to think of wet pressing as a one-dimensional volume reduction process, with the sheet, felt, and water assumed to be a more or less homogeneous continuum. However, when visualized in the microscope, wet pressing is a far more complex process which combines important mechanical changes in the fiber network with three-dimensional, highly unsteady, two-phase flow through a rapidly collapsing interconnected porous maze.

In wet pressing, volume reduction, fluid flow, and static water pressure gradients are intimately interrelated. Classical Fluid Mechanics states that the static water pressure is reduced in the direction of flow by conversion into kinetic energy (water velocity). Some of the total energy available at each layer is lost to friction with the surrounding fiber and by microturbulence in the narrowing flow paths. This loss is associated with fluid shear stress. However, the water-filled fiber network should not really be considered a continuous confined system (*e.g.* water flowing in a pipe). The local velocity vector changes direction frequently as the water is forced to take a tortuous path around and along the rapidly collapsing fiber network in the general direction of the average static water pressure gradient.

Despite the simplifications offered by classical fluid mechanics, it seems safe to say that the static water pressure is highest at the smooth roll surface (if referred to a roll press), where water is not in motion relative to the fibers, and lowest at the felted side of the paper, where water velocity is highest.

In a roll press the largest static water pressure gradient is not directly downward — it is oriented slightly upstream and, coupled with significantly higher in-plane sheet permeability must create some longitudinal water flow component toward the nip entrance. This component is present to some extent in any roll press and is rarely mentioned in wet pressing discussions.

In summary, the roots of our understanding of wet pressing mechanisms go back to 1960. At that time Wahlström showed that water is removed from the paper web in the converging part of the press nip due to web compression, but that part of the expressed water returns into the web on the outgoing side of the

### 3. Mathematical Model for High-Temperature Pressing of Paper 163

nip due to capillary forces [193]. The essence of this statement is still considered to be valid and generally forms the basis of wet pressing. Another important pillar of wet pressing theories has been the division of the total applied load into *hydraulic* and *structural* components. The sum of the two pressure components has been considered to be constant in the z-direction and equal to the total applied pressure but the contribution of these components is considered to change in that, progressing in the direction of water flow hydraulic pressure decreases and structural pressure increases. This idea of separating the two components of pressure, originating from Terzaghi [180], was applied to the compression behavior of paper webs by Campbell [24].

Carlsson's and his co-workers' studies [27] at the end of the seventies revealed the important role of water held within fibers in wet pressing. These studies showed that water is already expressed from fibers at 20-25 % solids content, and as the compression progresses the proportion of water expressed from fibers makes an increasing contribution to the total amount of water removed from the web. Consequently, *flows within fibers must make a significant contribution to the structural pressure*. The hydraulic pressure cannot be defined simply as the pressure counteracted by flow resistance: the location of the flow taking part in the generation of hydraulic pressure must also be determined. Only the flows in the interfiber voids are responsible for the hydraulic pressure. The flows within fibers generate part of the structural pressure. The rest of the structural pressure is the result of mechanical stiffness (Figure 3.1).

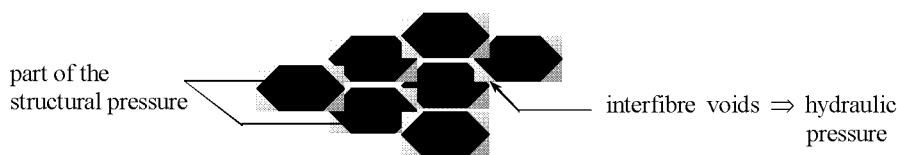


Figure 3.1: Contribution of water to the hydraulic and structural pressures.

Studies carried out at STFI and University of Maine at Orono (UMO) have revealed a lot of important details regarding hydraulic pressure generation. They have shown that hydraulic pressure is often a decisive factor in balancing compression pressure. A higher hydraulic pressure is generated when the grammage or the compression rate are higher, or if the beating of chemical pulp is increased [129].

It was gradually realized that the original definition of hydraulic and structural pressures was oversimplified. Classical wet pressing theory separates the total applied pressure into only two components — static water pressure and the network compressive stress (usually called mechanical pressure). The stress associated with the fluid drag force — here called fluid shear stress — and the static water pressure drop always appear together; one cannot exist without the other. The vertical component of fluid shear stress should be added to the fiber network stress to obtain the total compressive stress acting at each layer. Fluid stress is maximum at outflow side of the paper and nonexistent at the smooth press roll. It is also nonexistent after the point of zero hydrodynamic pressure since water flow has ceased. Fluid shear stress also has an in-plane component which must be taken into account when considering paper properties. Classical wet pressing theory only addresses water removal and does not consider the mechanical response of the fiber network.

Although the value of Terzaghi's principle as a tool for quantitative predictions has been questioned by Kataja *et al* [78], it still constitutes the basis of our understanding of pressing. Consequently, the operations of press nips are traditionally divided into two categories. In the first case, the press nip is considered to be compression controlled. Here, the mechanical stress in the fiber network is the dominating factor, and the maximum web dryness is determined by the applied pressure, and is independent of the pressing time. On the other hand, the nip is considered to be flow controlled when the viscous resistance between water and fibers controls the amount of dewatering. Here, web dryness increases with the residence time of the nip, and the fluid flow is proportional to the pressure impulse which is the product of pressure and time. Schiel's work [158] led to the conclusion that for many cases the problem was not in applying enough press load (this wouldn't bring much dryness improvement), but in applying enough pressing time. Wahlström also coined the well known terms “pressure controlled” and “flow controlled” pressing as a way to denote whether the water removal was restricted by fiber compression response or by fluid flow resistance inside the paper (see Figure 3.2). Thus, to increase the solids content in a fluid controlled press nip either the applied pressure or the nip residence time should be increased. The pressing of a wet web in a paper machine is often flow restricted.

It was then concluded that the moisture content of a wet sheet leaving a press nip depends both on the compressibility of the solid fibrous skeleton and

### 3. Mathematical Model for High-Temperature Pressing of Paper 165

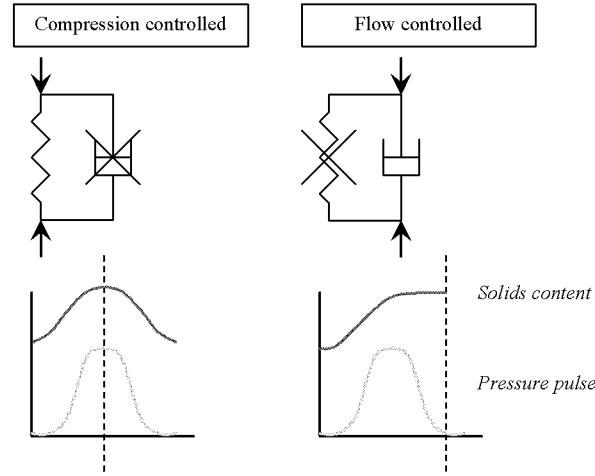


Figure 3.2: Schematic drawing of compression controlled and flow controlled press nips for an applied roll-like pressure profile (adapted from [26]).

on the resistance to flow in the porous space [193].

As a consequence of the applicability of Terzaghi's principle to flow-controlled press nips, the web layers closer to the felt are compacted first, with the higher density at the sheet-felt interface. MacGregor [107], [108] described this phenomenon as stratification and its existence has been observed in laboratory experiments [20], [21]. Moreover, the resulting density profile in the thickness direction of the sheet has been measured in dry paper by Szikla and Paulapuro [178], and Szikla [177]. Yet, a recent study performed by Lucisano shows opposing evidence to the existence of a density profile as it was previously reported by several authors. When trying to characterize the delamination process by the changes in transverse permeability and solidity profiles he found no evidence that wet pressing, and even impulse pressing, induced stratification in non-delaminated sheets and concluded that the parabolic solidity profiles observed were due to capillary forces present during oven-drying and not a result of hydrodynamic forces induced onto the fibers during the pressing event [105]. In addition, asymmetric density profiles similar to those described earlier by other authors were detected only after the onset of delamination (the layers near the hot surface present lower density than those at the paper-felt interface as a consequence of the damage induced by delamination at the top surface of the paper sheet) [105].

**Factors affecting the governing mechanisms of water removal in wet pressing**

According to Szikla, the role of various factors in dynamic compression is greatly influenced by the *moisture ratio* in the web, suggesting different governing mechanisms over different ranges of moisture ratio and/or density [177]. *Beating* of chemical pulp increases the resistance to compression when the moisture ratio is high. *Drying* and *removal of fines* from pulp have the opposite effect: they facilitate compression when the web contains a lot of water but make compression more difficult when the moisture ratio is low. Drying closes pores within the fiber material and makes external fibrils become attached to the fiber body. Fines are the furnish component with the largest surface area and the highest capacity to retain water per unit mass. *Fiber stiffness* can affect the compression when the moisture ratio is low. But in the range in which the stiffness of wood pulp fibers can be changed, it has no marked influence on compression when the moisture ratio is high and the compression is fast. An increase in *compression rate* yields a higher resistance to compression. This effect is stronger when the moisture content is higher. However, compression rate also exerts a clear influence at low moisture ratios, even when compression does not yield water removal at all. Raising the *grammage* increases the dynamic compression resistance at high moisture ratios but leaves the resistance unaffected at low moisture ratios [177].

In order to remove water by compaction from a web, the mechanical stiffness of the structure must be overcome and water must be transported.

The mechanical stiffness of a fiber mat is influenced by its moisture content. The mechanical stiffness reaches its maximum when all the water has been removed from the web, and decreases continuously as the moisture content increases. Therefore, the pressure carried by the mechanical stiffness of a saturated web during the compression cannot be higher than the pressure measured at the same density when an unsaturated web is pressed. The two values may be close to each other as long as significant water transport does not take place in the unsaturated web.

The experimental results obtained by Szikla [177] for 50 g.m<sup>-2</sup> sheets of mechanical or chemical pulps under dynamic load and ingoing moisture ratios in the range 2.0-4.0, showed that an increase in chemical pulp beating resulted in higher contribution from hydraulic pressure; an increase in fiber stiffness, the removal



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of fines and a decrease in compression rate all lowered the hydraulic pressure. His results also showed that flow in the interfiber voids plays an important role in the dynamic compression behavior of wet fiber mats. When the moisture ratio of the web is high and the compression is fast, as in paper machines, most of the compression force is balanced in the layers of the web close to the impermeable pressing surface by the hydraulic pressure. This is the case for low grammage webs (*i.e.* 40-50 g.m<sup>-2</sup>). The role of hydraulic pressure in balancing the compression force decreases as the compaction of the web increases.

Regarding the mechanisms of dynamic compression of wet fiber mats, the following conclusions can be drawn from the work of Szikla [177]:

- the mechanical stiffness of the structure must be overcome and water must be transported in order to bring about compression of a wet fiber mat. According to this, the force balance prevailing in pressing can be written in the following form:

$$P_t = P_{mec} + P_{flow} \quad (3.1)$$

where  $P_t$  is the total compressing pressure,  $P_{mec}$  the pressure carried by the mechanical stiffness of the mat, and  $P_{flow}$  the pressure required to transport water;

- the load applied to a wet fiber mat is carried partly by the structure and partly by the water in the interstices of the structure. The structure is formed by fiber material and water. *Water located in the lumen of the fiber wall and bound to external surfaces is an integral part of the structure.* The pressure carried by the structure is often called structural pressure,  $P_{st}$ , and the load carried by the water hydraulic pressure,  $P_h$ . The pressure carried by the mechanical stiffness of a fiber mat constitutes only a part of the structural pressure. Another part of the structural pressure is a result of water transport within the fiber material. According to this classification, the force balance can be written in the following form:

$$P_t = P_{st} + P_h = (P_{mec} + P_{fh}) + P_h \quad (3.2)$$

where  $P_{fh}$  is the structural pressure due to water transport within the fiber material. The structural pressure is equal to the pressure carried by the mechanical stiffness of the fiber material only when water transport within the fiber material is negligible. On the other hand, in most paper sheets there are large density ranges over which the pressure generated by the water transport within the fiber material plays a dominant role in forming the structural pressure;

- wet pressing of paper webs on paper machines starts at about 0.8 moisture content and finishes at 0.5-0.6 moisture content. In the early stages of wet pressing (down to about 0.75 moisture content) the flow in the interfiber channels is the main factor governing compression.

Quantitatively, Terzaghi's principle has to be used carefully in the case of highly deformable pulp fiber networks, as the hydraulic pressure is only effective on a share of the contact surface. Qualitatively, it helps to give an understanding of the balancing of pressures inside a porous medium [192]. In conclusion, Terzaghi's principle applies rigorously only to solid undeformable particles with point-like contact points (see Figure 3.3).

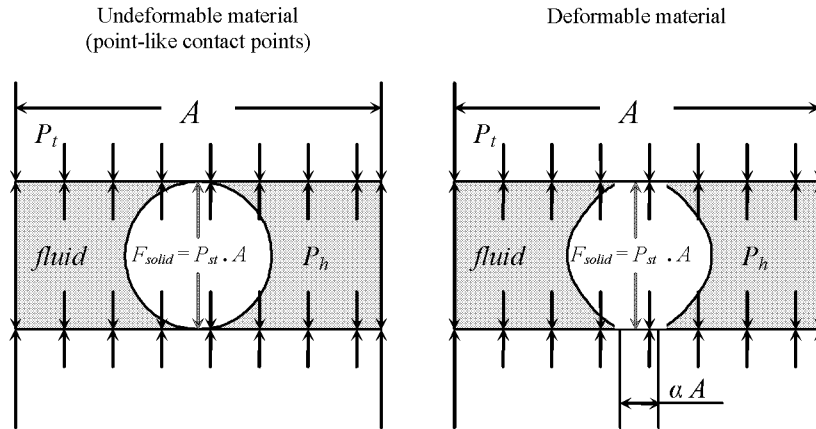


Figure 3.3: Porous medium compressed between two solid plates. The applied stress is balanced by the solid force,  $F_{solid}$ , and the hydraulic pressure.

In the case of a deformable porous material the hydraulic pressure is only effective on a share  $(1-\alpha)$  of the area  $A$ . So being, the stress balance may be written as:

$$P_t \cdot A = P_{st} \cdot A + P_h \cdot A(1 - \alpha) \quad (3.3)$$

$$P_t = P_{st} + P_h(1 - \alpha) \quad (3.4)$$

Szikla also pointed out that the main reasons for the strong resistance to water transport are the softness of the material and the large specific surface at solids contents characteristic of wet pressing. In fact, under a dynamic compressing load, the easily deformable material together with water bound to its surfaces can form a structure of very low permeability. Also, water must be transported in very narrow channels, and water bound to surfaces of solid material must also be set in motion in order to obtain a compression.

In conclusion, the dynamic compressing force is balanced in the paper web by the following factors:

- the flow resistance in the interfiber channels;
- the flow resistance within the fibers;
- the resistance against the separation of associated water from the fibers;
- and the mechanical stiffness of the fiber material.

### **3.1.2 Extended press nips and high-intensity drying of paper**

#### **The water removal mechanism**

A brief description of the heat and mass transfer mechanisms involved in impulse drying was already made in **Chapter 2** (see sections “The physics of wet and impulse pressing: experimental highlights” and “On heat transfer in impulse drying: from experimental to theory”). Nevertheless, it is worth mention some fundamental issues regarding transfer mechanisms at elevated temperature.

The driving forces of water removal mechanism in impulse drying are believed to be temperature and pressure. The applied pressure results in a pressure gradient in the thickness direction of the paper web causing a compression and a water flow towards the press felt. The water flow is enhanced since the viscosity

of the water and the surface tension decrease with increasing temperature. Also, the heat increases the compressibility of the paper web, which leads to a larger water flow.

The higher temperature of the press roll surface compared with that of the paper web causes a heat flux from the roll surface to the paper web surface. This heats up the water and the fiber network of the paper web, and when the temperature is equal to the saturation temperature corresponding to the local hydraulic pressure (*i.e.* the pressure carried by the water inside the paper web) vapor is formed. The moment of vapor formation can be controlled by means of achieving the right pressure profile (*i.e.* by controlling the hydraulic pressure) [132].

The controversial hypothesis of a vapor front displacing liquid water was suggested to explain the enhanced water removal to the press felt found by *Wahren* [196] and *Arenander* and *Wahren* [6]. The authors proposed that the generated steam gradient drags or pushes interstitial liquid water through the paper web to the press felt (see Figure 3.4).

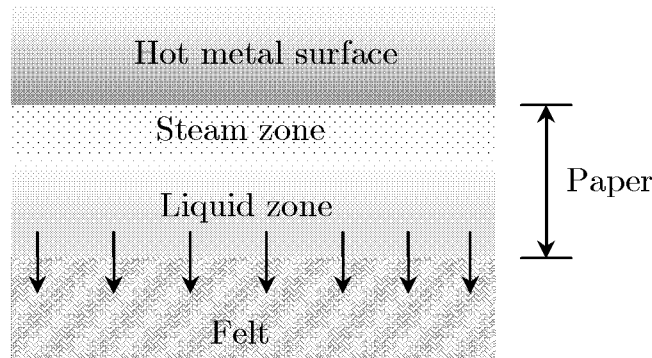


Figure 3.4: A one-dimensional displacement view of impulse drying, as suggested by *Arenander* and *Wahren* [6].

It has been hypothesized by the former authors that the improved dewatering efficiency at high roll temperatures is due to the compression of the wet web but also to the formation of a steam pressure gradient inside the web. The steam pressure gradient is seen by its inventor to be effective in expelling the liquid water from the web and into the backing felt [196]. In a subsequent paper, *Arenander* and *Wahren* [6] suggested that three mechanisms are operative in removing water from the sheet:

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- hydraulic pressure gradient at the paper/felt interface;
- heat transfer from hot roll surface to paper surface, leading to the generation of steam;
- removal of interstitial water from the sheet by means of steam pressure gradient or steam flow through the sheet. If the steam actually flows through the sheet and into the felt, then this flow may also drive interstitial water out of the fiber network. Water squeezed out of the fiber wall becomes accessible to removal by steam rushing through the network or may in part also be heated by the steam and evaporated.

Experiments were conducted on laboratory-scale equipment to validate the vapor front mechanism [99], [97].

Zavaglia and Lindsay [99] applied a flash X-ray visualization technique to track the motion of an X-ray-absorbing silver nitrate tracer solution added to the upper layers of a linerboard sheet during an impulse drying event. It was observed an absence of the tracer solution in the upper layers of the sheet, which suggested that an internal steam front was formed displacing the tracer away from the upper layers of the paper. Subsequent radiographs taken under more typical pressing conditions again show a low density region developing in the upper layers of the paper sheet. It was believed that the observed low density region represents a dry zone; a larger two phase zone containing both silver nitrate solution and steam could not be distinguished from a saturated zone. Therefore, some evidence was found confirming the mechanism of a vapor front displacing the liquid phase but the results were difficult to interpret. Later on, Lindsay used a pressurized gas chamber to displace water from handmade paper sheets and reports that dwell times of at least 50 ms are needed to displace liquid water. However, 50 ms is the upper limit of dwell times in modern paper machines and it may be questionable to extrapolate Lindsay's results to an impulse unit. Moreover, in his experiments the gas was applied directly, but in impulse drying the vapor pressure is built up over a period of time. So, it is likely that longer dwell times than 50 ms are needed.

Furthermore, the theory of a steam pulse effect has been speculated by some other authors that argue that impulse drying is nothing more than a hot pressing

due to the elevated temperatures combined with evaporation via flashing of superheated water [109]. According to the results of Macklem and Pulkowski [109], the energy used to heat up the paper web and evaporate water was equal to the heat transferred to the paper web, *i.e.*, the gain of impulse drying over wet or hot pressing is due to evaporative removal alone.

In order to explore water removal mechanisms, Lindsay [96] examined water removal amounts by wet pressing and impulse drying as a function of applied pressure. Measurements of water added to the felt by impulse drying and by wet pressing showed that about 90 % of the extra water removed by impulse drying in a  $250 \text{ g.m}^{-2}$  web (ingoing solids content about 35 %) is in liquid form. Improved liquid water removal was the explanation for energy savings in impulse drying, which contradicted the energy balance made by Macklem and Pulkowski [109], and is therefore consistent with the energy and mass balance measurements made by Lavery [92]. However, recent experimental studies conducted by Larsson [88] support the theory of Macklem and Pulkowski, which emphasizes the diversity of opinions and controversy of theories in this field. This issue will be discussed in more detail later on in the text.

As a sheet is compressed, its permeability decreases, making displacement of the fluid phase more difficult. On the other hand, the decreased thickness of the sheet increases the pressure gradient, partially compensating for the lower permeability. In impulse drying, improved thermal contact at higher mechanical pressures may improve heat transfer and further compensate for the lower permeability. According to Lindsay the small-dependency in the extra water removed by impulse drying may be due to several factors compensating each other, as discussed above. *But it also raises the possibility that a mechanism with less pressure dependency than displacement of the fluid may contribute to the extra water removal found in impulse drying.* The author advanced the hypothesis that the enhanced liquid water removal obtained in impulse drying is indeed due to the presence of a vapor phase, which in turn is expected to reduce rewet by suction, capillary forces and film splitting. In fact, the author suggested that capillary forces are responsible for the assumed mechanism of capillary resupply. In addition, mass and heat balances are still satisfied as water from the saturated zone is wicked back to the hot surface to undergo evaporation [96]. A model developed by Lindsay also predicts the flow of vapor in the gas phase, and shows that gas velocities are several times greater than the bulk liquid velocity as the

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evaporated fluid from wicking continually flows toward the cold zone where it condenses. The cyclic process of vaporization and condensation means that the total volume of vapor in the sheet at any time is much smaller than it would be if all the evaporated water had remained in the vapor phase.

Sparkes and Poirier [170] commented that the prevailing mechanism might well depend on the impulse drying variables. For example, at very high temperatures the dominant factor could be the vapor front mechanism, whereas to a high dry content paper web entering the nip the water removal is mainly accomplished by means of evaporation, behaving more as a conventional drying process [170], [171]. In a critical review of impulse drying, Back [11] also questions that steam formation can play a role in liquid water removal, claiming that the dewatering mechanism in impulse drying is the combination of “superhot wet pressing” and some evaporative drying on pressure deloading. Except for solid contents above about 70-80 % reached within the nip, Back [11] considers that a vapor phase can be formed near the press hot surface.

According to Macklem and Pulkowski [109], who determined that the mechanism of impulse drying was a “pressing/flashing drying” phenomenon, *i.e.*, hot pressing followed by flashing of superheated water, and whose findings were recently confirmed by Larsson and Stenström [90], the three water removal mechanisms present in impulse drying are (as already discussed in **Chapter 1**): (i) *wet pressing*, caused by the mechanical pressure gradient (which creates a water flow towards the press felt); (ii) *hot pressing* due to the elevated temperature (which increases the compressibility of the paper web and changes the physical properties of water, which in turn increases the water removal); and (iii) *evaporation* via flashing of superheated water.

More recently, Lucisano, Mazzatorta and Martinez investigated both the course of events at the interface between the wet sheet and the pressing surface, and the existence of liquid displacement and its role as an additional dewatering mechanism. Contrary to the idea of a steam layer formed when the web comes into contact with the hot surface, and thus assisting dewatering by displacement of unbound liquid water, these authors suggested that flashing of water, together with steam expansion in the opening press nip, could explain the results obtained in their platen press simulations. They observed that when sheets are unloaded, the specific volume of water on the hot side of the sheet

increases either by flashing or by expansion of steam formed in previous stages of the impulse event. Consequently, hot water is displaced through the wet web towards the felt, thereby heating up the sheet. The process continues until one of the following situations terminates it: (i) the press nip opens completely and vapor escapes towards the hot side of the sheet; (ii) the expanding vapor layer reaches the sheet-felt interface and it is vented to the atmosphere; (iii) a steady state is reached requiring no more expansion of the steam layer. Lucisano [105] then suggests that the presented mechanism is not dissimilar from that originally proposed for impulse drying by Wahren [196].

### **The heat transfer mechanism**

It is well known that cellulosic fibers and man-made polymeric filaments are relatively poor thermal conductors, yet the majority of drying systems in the paper industry continue to operate on the principle of conduction. Heat transfer can be increased by hot-gas impingement, through-drying, and radiant heating.

It is well established that the effective heat conduction from a hot metal surface to a fabric or paper sheet depends not only on the heated surface area but also on the effective physical contact area, and therefore sheet formation and smoothness. For tissue and products with a more open structure, additional energy by hot-gas impingement is mandatory for fast machines. Microwave and infrared are still too capital intensive. However, infrared radiant drying systems are becoming more acceptable, because they dry more than ten times faster than conductive units; infrared systems transmit heat into the sheet rather than relying solely on heat conduction from the outer surface.

Heat transfer is defined as energy transferred by temperature difference or gradient. In a vectorial sense, heat flows from higher-temperature regions to those of lower temperature. There are four basic heat transfer mechanisms: *conduction*, *convection*, *radiation* and *internal generation*. Conduction is the mechanism in which energy is transferred by atomic or molecular excitation from a higher- to a lower-energy zone. Most metals are good conductors because their atoms are more readily set in a vibration mode by thermal excitation. Most inorganic compounds and organic molecules, such as polymers, plastic and cellulose, are more difficult to set in a vibration mode and are poor conductors.

A second heat transfer mechanism is convection. For engineering purposes this



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is a subclass of conduction in a fluid where bulk motion or flow of the thermally excited molecules is the mechanism for transferring heated fluid to a colder region. The hot fluid must still transfer energy to a solid surface by molecular collision and then transfer it into the solid by conduction. Convection may be augmented by forced flow to increase the rate of molecular collisions.

A third mechanism is thermal radiation. Externally generated radiation from a hot body travels at the speed of light to the object and is absorbed by both the liquid or the solid substrate. The wavelength of the radiant energy must match the product's absorptivity for the best energy coupling and maximum heating and drying rate. Some substrates act as a window to radiant energy at specific electromagnetic wavelengths, and in many cases, hotter radiant heaters do not produce better drying rates.

Heat can also be transferred by internal thermal generation caused by radio frequency and microwave energy produced outside the substrate. These electromagnetic wavelengths only heat dielectric products. The thermal excitation is selective to small dipole molecules such as water, and therefore temperature and moisture profiles are uniform. This capital intensive method is most efficient when the moisture content is low, and it is frequently added to conventional drying processes.

*Simultaneous heat and mass transfer* occur in all drying systems. Some dryers or sections of a dryer are mass-transfer limited and are therefore constrained by the mass transfer rate of water to the web surface and into the dryer environment. Mass transfer requires a concentration gradient to effect a net transfer of liquid, just as heat transfer requires a temperature differential. In a liquid, molecular diffusion and turbulent mixing are the two basic mechanisms. In a porous web structure, additional mechanisms of capillary action, surface tension forces, wicking (movement along a fiber), and vaporization are very significant. In addition, if a phase change takes place a large quantity of thermal energy is required to separate water molecules as a liquid into those in the vapor state (latent heat of vaporization). This energy comes from the surface layers and therefore the surface temperature decreases. The effect, called evaporative cooling occurs, in all drying operations.

Bearing in mind all the possible mechanisms, understanding the mechanism of heat transfer in the impulse nip is a difficult task. Insight into this phenomenon can be gained by first examining a somewhat simpler, yet related, class of

heat transfer problems traditionally called “moving boundary problems”. Such problems are also referred to as “Stefan Problems”.

Stefan’s original work considered the heat flux in a medium that undergoes phase change at some fixed temperature,  $T_o$ , accompanied by the absorption or liberation of latent heat. If heat is transferred by conduction alone, the solution to Stefan’s problem in one dimension is given by [67]:

$$T_v(x, y) = T_H + \frac{T_o - T_H}{\operatorname{erf}\left(\frac{\xi}{2\sqrt{\varpi_v}}\right)} \operatorname{erf}\left(\frac{x}{2\sqrt{\varpi_v t}}\right) \quad (3.5a)$$

$$T_l(x, y) = T_{in} + \frac{T_o - T_{in}}{\operatorname{erf} c\left(\frac{\xi}{2\sqrt{\varpi_l}}\right)} \operatorname{erf} c\left(\frac{x}{2\sqrt{\varpi_l t}}\right) \quad (3.5b)$$

where  $T_{in}$  is the original temperature of the body,  $T_H$  is the temperature of the heated source,  $\varpi$  is the thermal diffusivity of each phase ( $v$  - vapor;  $l$  - liquid), and  $\xi$  is a constant related to the rate of growth of the moving boundary between the liquid and the vapor phases. Clearly, the form of these equations implies that the heat flux is initially high but diminishes with time,  $t$ . This analysis has been extended to a variety of problems [117] and has, in particular been applied to heat transfer problems with phase change in porous media [56], [33], [119], [201].

Under ideal conditions the heat transfer between two surfaces is dependent on the temperature difference, the heat transfer coefficient, the physical properties of the two materials, the contact area and the contact time. As it was mentioned previously one of the driving forces of dewatering in impulse drying is the temperature difference between the hot press roll surface and the moist paper web surface, as well as the ingoing moisture content and paper quality.

In impulse drying the temperature difference is dependent on how fast the energy is transferred from the press roll interior to the roll surface and into the paper web. Larsson [88] concluded that *the heat transfer rate inside the paper web determines the amount of heat transfer to the paper web*.

As for the heat transfer mechanisms involved in such a high intensity process several approaches have been made in the past twenty years. As soon as the paper web is brought into contact with the hot roll press surface heat starts to flow from the hot surface to the paper. The supplied heat to the paper web is transferred from the surface by conduction, with the liquid water flow, by water phase change (vapor formation) and with the vapor flow. The fluid transport

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through the porous medium can occur via a heat pipe mechanism or by the flow created by the squeezing action of the nip. The later mechanism has been considered in previous works associated with hot pressing [114], and several authors have speculated that a heat pipe may be an explanation for the high heat fluxes observed in impulse drying [98], [96], [139], [140]. Historically, the concept of a heat pipe was introduced by Grover *et al* [55], who showed that heat may be transferred in unsaturated porous media by internal fluid recirculation. For this to occur the temperatures at the boundaries of the porous media must be set such that: the liquid phase boils near the hotter end of the porous media and the vapor phase condenses near the colder end. Capillary forces and gradients in saturation pressure drive the motion of the fluids. This results in the latent heat of evaporation being transferred between the ends of the porous media via the motion of the fluid. This cyclic convective mechanism is extremely efficient and it can be used to transfer large quantities of heat with minimal temperature differences. The heat-pipe effect has been studied thoroughly in wet porous media by Udell [184], Udell and Jennings [188], Udell [185], [186] and Udell and Fitch [187] who investigated the thermodynamics of phase change in both homogeneous and heterogeneous solid matrices. A heat pipe is seen as an heterogeneous heat transfer device in which fluid is wicked through a porous medium from a cool to a hot region by capillary forces, and therefore the process of boiling and condensation allow heat to be transferred rapidly across large distances, greatly increasing the apparent thermal conductivity of the system.

In impulse drying, small capillaries with high capillary pressures may act as conduits for liquid to flow against a gas pressure gradient back to the hot surface, where it can boil and flow through the larger pores back toward the cooler saturated zone. A similar mechanism has already been observed in the cylinder drying of paper [40]. Such a process would allow boiling heat transfer to take place over a long period of time even though most of the liquid had already been removed from the hot surface.

Impulse drying is characterized by high peak fluxes followed by a gradual decrease. Heat flux curves calculated from temperature measurements, show that after the peak flux near the midnip a rather high heat flux is sustained throughout the pressing event. Lindsay [97] and Ramaswamy and Lindsay [140] argued that conduction alone could not explain the high heat fluxes observed in impulse drying, and that sustained heat fluxes of this magnitude would imply a contin-

uing phase-change process. They suggested though the heat pipe mechanism advancing through the paper sheet to be responsible for the high heat fluxes observed after the first heat flux peak. In addition, Lindsay and Sprague [98] had already proposed that a resupply of water to the hot surface via a capillary wicking mechanism could explain the high heat fluxes observed.

Rudemiller [147] and Lindsay [97] investigated the boiling heat transfer in a fibrous material. The purpose was to gain some insight into boiling heat transfer during impulse drying. The experimental conditions were not directly comparable to those in impulse drying, but the results indicated that the heat flux depends on pore diameter and the applied pressure. The contact coefficients in high-temperature pressing are expected to be quite high due to high pressure. Determining the heat transfer coefficients at these high temperatures is very difficult, and to the author's knowledge, no experimental investigations on heat transfer coefficients at high temperature have been carried out. By considering the magnitude of heat transfer coefficients in boiling heat transfer and conduction between two surfaces subjected to a high pressure, it was hypothesized that the contact coefficient could be in the range of  $10^4$ - $10^5$  W/m<sup>2</sup> °C. Vapor formation may influence the contact coefficient negatively by forming an insulating layer, which decreases the heat transfer. The vapor formation is controlled by the saturation temperature of the corresponding hydraulic pressure in the paper web. For example, vapor would form at 234 °C at a peak pressure of 3 MPa (if the hydraulic pressure at the paper surface is close to the applied pressure).

Finally, there are additional aspects regarding heat transfer that have not been considered. It has been assumed in previous works that heat is being transferred in the axial direction only [39], [87], [131], [130]. This however contradicts somewhat recent evidence that channelling may be present in the sheet due to uneven pressure application [46], [192] or by variations in the local grammage of the paper causing a free fluid channel [16]. Assessing these effects from temperature measurements is difficult if not impossible. However, measurement of local temperature histories within a sheet provides useful information.

Burton [22], reported a measurement of internal sheet temperatures at three different layers inside a linerboard sheet during a simulated impulse drying event. In spite of uncertainties in the data and its interpretation, the temperature history in each layer appears to be consistent with a displacement model of impulse drying, and according to the author, could be interpreted as evidence that a dis-

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tinct steam-liquid interface was moving through the sheet. Later, Sprague [172] used stacks of thin wet bleached kraft paper, each sheet having a grammage of  $50 \text{ g.m}^{-2}$ . Extremely thin thermocouples were sandwiched between the layers. During the impulse drying event with an MTS electrohydraulic press simulator, the temperature at each layer (including the felt-sheet interface) could be tracked in time. Tests showed that temperature propagation through a stack of thin sheets was essentially the same as temperature propagation through a single thicker sheet with the same cumulative grammage, indicating that *interface effects between the sheets were of minor concern*.

Measurements at three transverse locations show somewhat different trends. Here three  $50 \text{ g.m}^{-2}$  sheets have been stacked, and single thermocouples have been placed between the sheets. The temperature curve from the thermocouple closest to the surface does not show any intermediate plateau. The second curve, showing data from the interface between the middle and the bottom sheets, does show an S-shaped rise followed by a nearly flat region. The thermocouple at the paper-felt interface shows only a gradual temperature rise. These results have been interpreted, by their authors, in terms of the vapor-liquid displacement concept. The existence of plateau regions above  $100^\circ\text{C}$  is strong evidence for a two-phase zone where the vapor and liquid are in equilibrium at elevated pressures. The two-phase zone at any point may only be temporary, and as it is displaced or evaporated, a dry zone with higher temperatures follows. In some cases the two-phase zone is very thin or nonexistent, so a sharp steam-water interface may be a good description of the process. Regions of slow temperature rise, such as the paper-felt interface or the initial period of the S-shaped regions during the first few milliseconds of impulse drying, show the effect of transient conduction heating through a saturated liquid zone. The results also showed that conduction can account for the high observed heat transfer rates only during the first few milliseconds of impulse drying while the cellulose is still cool and the saturated zone is near the hot surface. Once a steam layer is formed, heat transfer into the sheet gives heat transfer rates far below those observed unless a supply of liquid is made near the surface for continued boiling.

These experimental results were then compared with two different mathematical models developed by Lindsay [96]. Both models predict similar trends in impulse drying, but MIPPS-II offers the advantage of dealing with a two-phase zone. According to Lindsay, a continued process of evaporation and condensa-

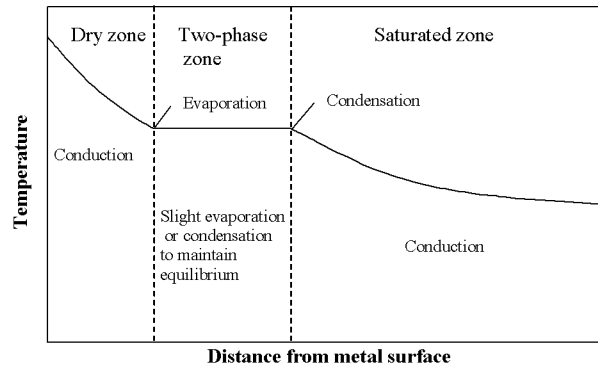


Figure 3.5: Temperature profile and associated heat transfer processes during impulse drying (based on numerical predictions from [96]).

tion in the web is envisaged to be the major heat transfer mechanism. Figure 3.5 illustrates the model predictions obtained by Lindsay [96], and will be described in more detail in a subsequent section of the present work.

As shown above, the dewatering and heat transfer mechanisms in impulse drying are a complex subject, which is still not understood in detail. As different results and theoretical views have been reported in this field, it is important that further work could clarify the complex mechanisms of dewatering by impulse drying.

## 3.2 Review of Previous Models Proposed for Paper

### 3.2.1 Mechanical models

In addition to the understanding of the many factors, which affect the constitutive behavior of paper material, a study of the current models for paper is also essential. This is so that one could appreciate the merits and beware of the deficiencies of contemporary models in comparison with each other. In the *continuum models* general approach is to treat paper or paperboard as a continuum of cell wall materials. The experimentally determined properties of the sheet are applied in finite element analysis or other general two- or three-dimensional constitutive models, such as the *hyperelastic model*, *composite laminate plate model*, and

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*mosaic model*, to predict the constitutive behavior of paper subjected to various loading conditions. Although the continuum approach is relatively easy to apply, it is more suitable for high-density paper material since its structure resembles more of a continuum of cell wall material.

In the *network models*, the constitutive behavior of paper material is derived from the properties and deformation of an elementary load-bearing unit in the fiber network. Therefore, this requires the knowledge of the mechanical properties of the load-bearing unit and its deformation behaviors when the sheet is subjected to applied loads. For example, in the micromechanics approach, one would determine the average fiber stress in a predefined fiber orientation. The sheet stress is then determined as the integral sum of the appropriate fiber stress components.

Paper material is a network of self-bonding wood fibers. It is used in many applications as load-bearing structure and packaging material. In the paper industry, paper and paperboard material are produced in sheet form. They are then converted to end products through various manufacturing processes such as bending, creasing, and scoring. The ability to model the response of paper and paperboard material subjected to various loading conditions greatly facilitates the product design and manufacturing processes.

In general, the constitutive models of paper and paperboard may then be separated into network and continuum models, as previously mentioned. The last ones do not consider the presence of voids, whereas network theories fall short when the fibers are too closely packed to act as elements of a network. According to Hollmark *et al* and Rigdahl *et al*, network models successfully predict elastic and post-elastic responses of low-density sheets (see [104]). However, these predictions require many geometrical and material parameters that are, sometimes, difficult to obtain. Structural analysis of composite materials is severely limited by the lack of constituent information. Micromechanics has been the traditional approach to achieving insight into constituent behavior in a composite material, but modeling micromechanical details in a structural application is frequently impractical.

Micromechanical methods have been used in analyzing fiber composites for more than thirty years. However, most often micromechanics is used to predict thermoelastic constants and other transport properties such as thermal conductivity. An example of that is the work performed by Foye (1993), Hart (1994),

Marrey and Sankar (1995) and Naik (1994) (see [207]). Dvorak *et al* [42] used micromechanics for predicting the yield surface of several metal matrix composites. Adams (see [207]), used micromechanical methods to predict the nonlinear temperature dependent stress-strain behavior.

Although micromechanical models have been successfully employed in predicting thermoelastic constants of fiber reinforced composite materials, their use for strength prediction under multiaxial loading conditions is not practical, according to some authors [207].

In the network models, paper and paperboard are treated as layers of fiber networks that are bonded at the fiber crossing sites. The constitutive behavior of the sheet is derived from the mechanical properties of its constituents and interaction mechanisms in the network structure. Although three-dimensional network models are available, they are computationally intensive to be of practical use. Therefore, in the past, the network model has only been applied in one-dimensional problems, *i.e.* uniaxial loading.

The continuum models, on the other hand, treat paper and paperboard as homogeneous plate like continuum. The macroscopic material properties are experimentally determined and are then used in two- and three-dimensional models for common engineering materials to describe the deformation of paper. The continuum approach provides a less calculation intensive alternative. However, it does not offer much insight on the relationship between the constitutive behavior of paper and the properties of the network constituents, the network structure, the papermaking process parameters, and environmental conditions. Since the continuum models do not explicitly address the factors that affect the constitutive behavior, the models do not provide any explanation to the orthotropic nature of paper material.

Regardless of the type of model, after an exhaustive literature review performed by Ramasubramanian and Wang [138], it is clear that the focus of constitutive modeling of paper material thus far has been mainly on the loading process. The unloading behavior after yielding has not been addressed. Wang [198] has modeled the unloading behavior of a sheet in a one- and two-dimensional problem using the same approach by Sinha and Perkins [166] for loading. The micromechanics model by Sinha [165], *i.e.* the asymptotic fiber and bond model was extended to address the unloading behavior of high-density paperboard ( $720 \text{ kg.m}^{-3}$ ) materials.



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The asymptotic fiber and bond model derives the sheet stress from the mechanical properties and interaction mechanisms of a representative load-bearing unit in the fiber network. At a given stress, the average fiber stress is calculated from the equilibrium condition of the load-bearing unit as a function of the fiber orientation angle. The sheet stress is then calculated by an integral sum of the appropriate fiber stress components of fibers in all orientations. In determining the average fiber stress, the knowledge of the micro-constituents and network properties, such as the fiber elastic modulus, fiber-to-fiber bond modulus, fiber orientation distribution, and so on is required. However, the measurements of these model parameters are difficult to accomplish and are not readily available. Therefore, uniaxial tensile tests were conducted on a sample stock so that the model could be fitted to the experimental data to obtain the model parameters. The extended model was then used to predict the permanent or plastic strains of uniaxially strained samples in the machine and cross-machine direction. Finally, the same combined continuum and micromechanics approach by Sinha and Perkins was used to model the unloading process of samples subjected to uniform loading on one surface.

Assuming that both fiber and bond behave elastically during unloading, the division of the final sheet stress by the elastic modulus provides the amount of elastic strain component, which is recovered upon unloading. This elastic strain component is then subtracted from the final sheet strain to obtain the permanent plastic strain, which remains after unloading. The model prediction of the plastic strain showed good agreement with experimental data for the machine and cross-machine direction. In a two-dimensional problem the unloading process is not so simple. Loading and unloading was applied in incremental steps. In the process, it was observed that over prediction of the yield point and stress-strain curve in the plastic region could result if the step size is not sufficiently small when the applied load is approaching the yield point.

As already mentioned in the thesis layout, in **Chapter 1**, a more detailed description of these rheological models is presented in **Appendix A**.

A quite different approach has been made by Lobosco [101] and Lobosco and Kaul [103], [102]. From their work two models of the stress-strain behavior of the fiber network in wet pressing were derived. The first model is based on the concept of strain-rate dependent plasticity, including a rate-independent elastic-

ity, following a phenomenological approach. Models of this kind are sometimes called elasto/viscoplastic models.

According to the authors, the stress-strain behavior of the fiber networks at high loads is rate dependent, and it is, at least partially, dependent on the intra-fiber water flow. Following the Perzyna's approach (see [101]), the authors decomposed the total strain rate into elastic (recoverable) and plastic (non-recoverable) parts. To avoid using the initial thickness of the material as the reference, the concept of modified strain was used:

$$\varepsilon = \ln \left( \frac{L}{L_i} \right) \quad (3.6)$$

where  $\varepsilon$  is the strain,  $L$  is the actual thickness of the web and  $L_i$  its value at zero porosity. The total strain rate,  $\frac{d\varepsilon_{ij}}{dt}$ , is then given by

$$\frac{d\varepsilon_{ij}}{dt} = \frac{d\varepsilon_{ij}^{el}}{dt} + \frac{d\varepsilon_{ij}^{pl}}{dt} \quad (3.7)$$

where  $\varepsilon_{ij}^{el}$  are the components of the elastic strain, and  $\varepsilon_{ij}^{pl}$  the components of the plastic strain tensor. These two components of the total strain rate were modeled independently. The sub-model proposed for the elastic strain follows a non-linear behavior, as in Eqn. 3.8:

$$\varepsilon^{el} = \ln \left[ 1 - A_2 \cdot \ln \left( \frac{\sigma/3 - A_1}{-A_1} \right) \right] \quad (3.8)$$

where  $\sigma$  is the uniaxial applied stress, and  $A_1$  and  $A_2$  are parameters. As for the rate-sensitive plasticity, Perzyna proposes that the plastic strain rate be expressed as a function of the normalized overstress,  $F_{o.s.}$ , according to:

$$\frac{d\varepsilon^{pl}}{dt} = \mu_c \langle \Omega_c (F_{o.s.}) \rangle \frac{\partial f}{\partial \sigma} \quad (3.9)$$

where  $\mu_c$  is a viscosity parameter,  $\langle \Omega_c (F_{o.s.}) \rangle$  is a function chosen to represent the results of tests under dynamic loading (see [101] for more details) and  $f$  is the dynamic load function.

The Perzyna model was validated by comparing predictions with experimental data obtained at temperatures in the range of 23-80 °C, and pulses with 25, 250 and 2500 ms and maximum peak pressure of 23 MPa. The model predictions were in good agreement with the experimentally observed fiber network rheological behavior over the entire range of peak pressure and pulse length. The agreement

was good also for different pulps (TMP and SBK), temperatures, and intra-fiber-water content.

The mechanical behavior of paper and paperboard under action of in-plane uniaxial and biaxial states of loading has been exhaustively investigated during the past few decades. However, it is perfectly clear that modeling the compressive behavior in the thickness direction of a paper sheet was somehow discarded. The development of a three-dimensional constitutive model for uniaxial loading in the thickness-direction of a paper web was the goal of the present work. The mechanical behavior of the backing material, *i.e.* the felt, was also taken into account. For this purpose the rheological responses of paper and felt were modeled using a phenomenological approach based on an assemblage of springs, dashpots and dry friction elements. The obvious nonlinear behavior of these materials was a matter of utmost importance regarding the formulation of a set of nonlinear constitutive relations for these media, which are based in the theory of cellular materials according to Gibson and Ashby [51]. The mechanical model for the felt material is presented in **Chapter 4**.

#### 3.2.2 Heat and mass transfer models

The transport mechanisms in high-temperature pressing are by nature very complex. modeling and simulation of transport processes in a rigid porous medium pose many problems and the situation is even more complicated if the medium is compressible. The coupling between heat and mass transfer is strong, making the material description complicated.

While the key to impulse drying is believed to be the creation of a vapor phase within the sheet, conflicting theories have been advanced, and even where there is consensus, much remains poorly understood. The difficulty of directly observing transport processes inside the nip, combined with uncertainties in interpreting experimental data, suggests that new tools are needed to supplement experimental studies. Numerical modeling is such a tool.

Mathematical modeling of drying has been developed in history with two at least partially distinct goals:

1. to understand the real nature of moisture flow inside a heterogeneous, hygroscopic porous medium and in the boundary layer between the medium

and the surrounding medium;

2. to quantify the details of the drying process for industrial needs.

Although wet pressing is not the subject of the present study, a brief description of the main wet pressing models is presented in **Appendix B**. These models constitute the basis of the development of more complex models that intend to describe what happens at high-intensity pressing conditions as those of impulse drying.

### High-intensity pressing models

A number of related numerical studies outside the paper industry have been published. Soil hydrology is generally concerned with heat transfer effects; displacement processes for the petroleum industry have frequently been modelled; models of heat pipes have been developed which are of relevance in understanding some transfer effects, although simultaneous displacement is not considered.

Phase-change problems in which a phase boundary moves have received much attention recently. This class of moving boundary problems requires unique and difficult solution methods. Analytical solutions are available only for the simplest cases, and may be impossible when physical properties change with temperature. In impulse drying, the vapor-liquid boundary moves not only because of phase-change but also because the liquid is driven out by the generated vapor pressure. Impulse drying is thus related to another set of moving boundary problems involving phase displacement in porous media.

In general, moving boundary problems require the simultaneous numerical solution of transport equations in two distinct phases which are coupled through boundary conditions at the moving phase boundary. The location of the interface is not known *a priori*, so iterative procedures may be required. Both finite-element and finite-difference techniques have been used. One-dimensional are most commonly treated, although many recent studies have been published with two and even three-dimensional solutions.

While numerical heat transfer studies of complex processes abound in the engineering literature, the only prior numerical investigation of impulse drying is found in the thesis of Pounder [137]. Pounder began with a two-zone model

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of displacement formerly developed by Ahrens [5], and extended it to a four-zone model including mat compressibility. The resulting model gave insight into the complexity of the impulse drying process and represented an ambitious first step in impulse drying modeling. While some aspects of the model are clearly successful (the incorporation of sheet compression, for instance), the treatment of the different zones seems to have resulted in a series of unrealistic predictions characterized by periods of linear change in time punctuated with discontinuities during the transition from one regime to another. Predicted heat transfer rates in particular did not agree well with observations.

A rigorous model for high-temperature pressing will involve the simultaneous solution of a wet pressing model and a heat transfer model. Such a model will be extremely complex and highly non-linear.

As previously mentioned, Pounder [137] and Ahrens [5] presented a model for high-intensity drying of paper, which could be applied to impulse drying conditions. The drying process is idealized in the sense that paper is divided in different zones. The different zones comprise different amounts of fiber, liquid water and water vapor. The model is based on solving the conservation equations of heat and mass in the different zones. Consequently, the model calculates the moisture content and other parameters as a function of time. The governing equations are combined with equations describing the applied pressure and the physical properties of liquid and vapor, as well as equations describing the thermal properties, compression and permeability of the paper. From their study it was found that in many cases the model predicted a higher degree of water removal than that observed in the experimental measurements.

Lindsay and Sprague [98] proposed a model called MIPPS I (“Moving Interface Problems in Porous Systems”), in which the impulse drying process is treated as a moving boundary problem. This approach originates from an early hypothesis stating that the enhanced water removal in impulse drying is due to a steam front displacing liquid water. One of the novel things about MIPPS I was the introduction of a capillary wicking mechanism to explain experimental results. The model describes the dynamic transport of heat and fluid flow in both vapor and liquid phases. The porous medium is considered rigid, isotropic and homogeneous. The impulse drying process is idealized in the sense that dewatering by compression of the paper has already taken place before the vapor zone begins to form in the sheet. Thus, the vapor-induced displacement of liquid

water should be regarded as an indication of additional dewatering. This means that impulse drying is viewed as a two-step process consisting of a wet-pressing stage and a vapor-liquid displacement stage. Vapor pressure acts to improve wet pressing once wet pressing starts to die down. In wet pressing, peak hydraulic pressures occur before mid-nip, and are dropping rapidly by mid-nip. The region of interest for the modeling, then, begins with the near-nip portion of the process in which the sheet has already been compressed and most of the water removal by compression has already occurred. This was shown to be consistent with experimental data taken at the Institute of Paper Chemistry showing that the intense heat transfer processes during impulse drying are not fully under-way until most of the sheet compression has occurred [92]. For simplicity, therefore, MIPPS I ignored the compression process early in the nip and assumes that the sheet has been compressed before the thermal process of impulse drying begins. At this stage the sheet was treated as a rigid, homogeneous porous medium. As heat flows into the liquid, a vapor phase forms, which forces the free saturated liquid into the felt below. Because water removal by compression has already occurred, the motion of the vapor zone through the saturated sheet was suggested to be an indication of additional water removal by displacement in impulse drying. These authors also introduced the hypothesis that resupply of liquid water caused by capillary wicking would help sustain the high heat fluxes observed in impulse drying.

In this first version of the MIPPS model, it was assumed that the steam-liquid interface was sharp. In reality, it is more likely that the two-phase zone has a varying saturation. Lindsay [97] then proposed a second version of the model, called MIPPS II. As previously, it is assumed that impulse drying begins when the paper is almost fully compressed. Lindsay claims that this assumption should not significantly affect the fundamental physics of the process. Vapor and liquid are assumed to be in equilibrium in the two-phase zone. The development of different three zones may then be observed:

- dry zone: close to the hot surface;
- wet zone: near the felt;
- two-phase zone: in between the other two zones.

The capillary wicking mechanism was abandoned, and a new parameter was introduced called the remaining saturation level. The physical meaning of this

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parameter may be interpreted as the water transported to the two-phase zone by capillary forces or water left behind in dead end pores.

Evaporation and condensation govern the heat transfer in the two-phase zone. Evaporation will occur at the dry interface and the condensation at the wet interface. This is a thermodynamic requirement, which must be fulfilled in order to maintain a constant temperature in the zone. The predicted temperature profiles showed a plateau of almost constant temperature. Lindsay stated that this plateau could be an indication of a two-phase zone. Experimental temperature profiles used for comparison in the study showed similar behavior, with a plateau of almost constant temperature.

The model was also used to predict the heat flux during impulse drying. Lindsay found that the predicted heat fluxes agreed well with the basic features found in the experimental investigations; a high peak flux followed by a gradually decreasing heat flux. However, the predicted heat fluxes were overestimated.

Almost at the same time, Ramaswamy [139] developed a generalized model for conventional and high-intensity drying. The model takes into account pressure-driven bulk flow of liquid and vapor, and is based on solving the fundamental equations for the conservation of mass and energy in non-compressible porous medium. The model proposed exhibits some similarities to MIPPS II. For example, it includes three different zones: a middle two-phase zone was present in which there was a negative liquid flux towards the hot surface and a positive vapor bulk flow; a dry zone close to the hot surface with high temperature, zero flux and constant pressure; and a wet zone close to the felt, with non-uniform saturation, almost constant temperature and varying pressure.

Ramaswamy states that conduction alone cannot explain the heat transfer under high-intensity conditions and that the observed behavior is due to a heat pipe mechanism advancing through the paper. The predictions are in line with Lindsay's findings that a vapor zone is created, which can displace the liquid water.

Bloch [15] used a singular approach based in the method of homogenization of the porous medium to describe the hot pressing and impulse drying of paper. The problem is analyzed at the microscopic scale and solved at the macroscopic level. The heat and mass transfer mechanisms (conduction, convection and phase change), and the analysis of paper and felt rheological behavior to compression

are taken into account in the development of the 2D and 3D models. In addition, paper and felt are unsaturated. Therefore a complex treatment of capillary forces is presented. According to the author, the water fills the smallest pores of the web, and the size of the pores is described by a density function for the hydraulic diameter. This analysis was later used in subsequent studies [57].

Unlike the earlier models based on the simultaneous solution of a wet pressing model and a heat transfer model, Riepen [144] chose a different approach, which included the compression of the paper. Pounder and Ahrens being the exception, had included the compression but in a simplistic way. Riepen's model EXPRESS-1 is a model capable of describing both wet pressing and impulse drying. The model includes the coupling of a wet pressing model and a heat transfer model, and it describes the transport of mass and energy through the paper. The liquid flow through the porous medium is assumed to obey Darcy's law.

Conduction and convective heat transfer are considered in the model. At the roll-paper interface, perfect contact is assumed, which means that the heat flux depends on the thermal properties of the roll material and the paper web.

In the solution of the equations, a finite-volume approach is used. One of the great advantages of EXPRESS-1 is the possibility of studying flash expansion during nip opening, providing information in the study of delamination. The model calculates the heat transfer from the heated roll to the paper, the temperature distribution in the press roll, and it also has the capability of predicting the outgoing dryness for a certain pressure curve and roll temperature.

The model was validated against an impulse drying experiment performed with the experimental paper machine EuroFEX. The predicted outgoing dryness was found to be in reasonable agreement with experimental data.

Riepen presents an interesting discussion about the possibility of steam generation during compression. The local hydraulic pressure can be predicted as a result of solving a wet pressing model. If the temperature is higher than the saturation temperature for the local hydraulic pressure vapor may form. This would be especially likely at low pressures, and could be one explanation of the enhanced dewatering in impulse drying. The steam could increase the hydraulic pressure and thus the hydraulic pressure gradient, which is the driving force in the dewatering process [144].

Woods, Bloom and Orloff [205] have derived a model for flash evaporation



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during nip opening in impulse drying. The aim was to increase the understanding of the mechanisms operating during delamination. Delamination occurs when excessive heat is transferred to the web, causes internal vapor pressure to increase to a level at which the fiber network can no longer withstand the increasing pressure difference.

Nilsson and Stenström (see [125]) presented a model based on conductive heat transfer in a non-compressible medium. One of the main purposes was to investigate whether a sheet of paper can be treated as a semi-infinite body. If it can, then a simple analytical solution of the constitutive equations of the model could be used. The model was used to predict the energy transfer under various conditions. In comparison with experimental data obtained by Krook and Stenström [87], good agreement was found when the applied pressure was low and the temperature moderate. Less good agreement was found for higher pressures. A larger discrepancy was observed when comparing the model with data from the EuroFex paper machine. It was also concluded that the paper could only be treated as a semi-infinite body at grammages above  $110 \text{ g.m}^{-2}$  considering the assumptions used in the model. The authors believed that the discrepancy was due to the high degree of compression of the paper. In fact, when compression is significant, a larger convective flow is induced in the paper, and thus a larger deviation is to be expected when comparing the model with data collected at high pressures.

The overall conclusion from their first study was that a simple heat transfer model can be used to simulate the heat transfer as long as the temperature is moderate and the pressure does not exceed 0.5 MPa. Higher pressures require a more advanced model that includes compression.

Consequently, their first model was extended to include compression and convective heat transfer, and dynamic thickness measurements were used to derive the required model parameters such as dewatering, compressibility, moisture content and thermal conductivity. The new model is based on solving the energy equations for a compressible medium, and paper is treated as a two-phase medium of cellulose fibers and water where the cellulose and water constitute a homogeneous matrix. The model is limited to the compression phase without phase change and no structural aspects of the paper were considered in the model.

The predicted temperature profiles were compared with experimental profiles obtained during high-temperature pressing under different conditions and it was

concluded that the model reproduced experimental data well when the peak pressure was high and the grammage low (*i.e.* 60 g.m<sup>-2</sup>). The reason for the less good agreement at low pressures could be that boiling occurred close to the hot surface, which is in fact likely to happen even at low hydraulic pressure. As for the grammage effect, a feasible explanation could be that the non-uniform consolidation of the web is more noticeable at higher grammages. As the model assumes uniform consolidation (which means that there are no moisture, porosity or density gradients) it is likely that a somewhat poorer agreement is thus to be expected.

In conclusion, and according to the authors, the ability of the model to predict internal temperature profiles at elevated temperatures reinforces the assumption that impulse drying is a process with enhanced wet pressing due to the increased web temperature followed by flashing of superheated water. In addition, conduction and convection are always present (and the transport mechanisms involved in impulse drying can occur simultaneously in different parts of the web), regardless of the temperature and pressure, but the convective heat transfer is very low and of minor importance.

However, efforts to model the flash evaporation process in impulse drying are few, as it constitutes an extremely difficult task. The key to understand delamination lies in understanding how the flash evaporation process interacts with the fiber network and that is the fundamental step to make impulse drying an industrially accepted technology.

More recently, Gustafsson and Kaul [57] presented a general model of wet pressing at high temperatures. The hydrodynamic model can simulate changes in the solids content and structural properties of the fiber web as it passes through the press nip. The model can also predict the effects of changes in operating variables, such as the hot roll temperature, peak pressure, pressure pulse shape and machine speed, and the state of the ingoing web and felt properties. In addition, the fiber web rheology is described by the model suggested by Lobosco and Kaul, here modified to incorporate the temperature dependency of the strain rate.

The model includes the rate dependency of the fiber network stress and thus takes into account the flow resistance of the intra-fiber water, something not done in previous works. The predictive capability of the model is good within the range of temperatures and linear loads studied by the authors.

### **3.3 A proposed model for the consolidation of paper in impulse drying**

#### **3.3.1 Introduction**

Paper is a medium consisting of the interactive components water, fiber and air. These components are comprised of viscous and elastic elements, with the viscous elements characterizing the degree to which the medium components move or change position with time when subjected to a stress, and the elastic elements characterizing the structural integrity of the medium.

In the present work, special emphasis will be given to some aspects related to time-independent mechanisms, the mechanical response of paper to compression in the thickness direction, which takes into account elastic as well as plastic strains, and finally, the material viscous behavior will also be examined. During the compression process the material is in an unsteady state resulting in a continuous changing of internal conditions (temperature, density, moisture content). For this reason a truly understanding of paper behavior to compression is needed in order to evaluate the consolidation mechanisms involved. A comprehensive analysis of the consolidation process during hot-pressing must examine the elastic, viscous as well as plastic behavior of the paper sheet in transverse compression, which is seen as highly nonlinear due to the cellular structure of the fiber mat.

#### **3.3.2 Background**

The success of modern continuum mechanics in modeling composite materials behavior is truly remarkable. For instance, the general theories of elasticity, plasticity, and viscoelasticity all rely on the continuum hypothesis. However, while continuum mechanics has provided a powerful means of studying the physics of deformation of composite materials, there are situations when the continuum hypothesis is simply inadequate. These problems are generally associated with inelastic behavior of composites and are mainly attributed to the necessity to homogenize two distinctly different materials into a single continuum.

High temperature environments profoundly amplify all the problems associated with a mechanical analysis of composite structures. This particular problem is due to severe internal stresses developed at the constituent level when a compos-

ite structure is heated. This stress state of the material is caused by mismatched thermal expansions of the constituents. A classic single continuum structural analysis is unable to detect these stresses as the thermal expansion coefficients of the composite are homogenized into a single value. Garnich and Hansen [50] developed an approach to structural analysis of composites, which consists of treating the material as a *multiphase continuum* (multicontinuum), thereby allowing one to retain information at the constituent level. Consistent with a single continuum theory, each component is assumed present at every point in the continuum. The fundamental difference is that the components retain their identity rather than being homogenized in some sense. However, this approach presents some restrictions because it is fundamental to develop a mathematical means of accounting for the interactions between the constituents. In their work, Garnich and Hansen developed a set of kinematic constraints relating the constituent deformation fields for thermal-elastic behavior. The basic form of the constraints is seen to be generally valid for inelastic behavior also. The development follows some fundamental relationships between the properties of the constituents and the properties of the composite which first appeared with Hill (see [50]). Implicit to the development are the concepts of a representative volume element (RVE), also discussed by Hill, and macroscopically uniform stresses and strains associated with the RVE of a statistically homogeneous medium.

Nevertheless, due to the simplicity and elegance of continuum mechanics, the homogenized single continuum approach remains the most prominent analysis technique for composite structures. This approach has led to significant advances in anisotropic plasticity, viscoelasticity, and viscoplasticity. However, a single continuum theory is unsuitable for modeling many of the deformation mechanisms associated with the inelastic behavior of composites. Particularly weak areas include damage mechanics and high temperature behavior. The chief difficulty in each case is the lack of ability to isolate the material response at the constituent level.

There are another approaches to composite structural analysis that bring constituent information into the solution process. Perhaps the most prominent are due to Aboudi [2], [3] with the method of cells. However, in contrast to the approach suggested by Garnich and Hansen [50], this model is coupled to the structural analysis in the solution process and therefore bring a high computational premium. The approach introduced by these authors does not directly

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couple the micromechanic model to the structural analysis. Rather, analytical expressions providing micromechanical information are obtained as a precursor to the general structure analysis.

#### **3.3.3 Development of the mechanical model for paper**

##### **Nonlinear transverse compression behavior of paper**

The following paragraphs aim to highlight some structural features of paper and its behavior under tensile or compression stresses. Understanding the structural changes that take place when paper is stressed, either in a compression or in a tension mode, is fundamental to the development of a mechanical model for paper based on a cellular solids approach.

**Characterizing paper as a cellular material** Paper is a stochastic network of fibers. Since fibers are much longer than the thickness of the paper sheet, the network is planar and almost two-dimensional. The two-dimensional structure governs many paper properties but also the three-dimensional porous structure is important.

In the papermaking process, fibers form flocs of some characteristic size. The hydrodynamics of the web forming process and the flocculation tendency of the fibers lead to correlations for the local grammage of paper.

Even though not completely random, the structure of paper is for many purposes nonuniform, disordered and irregular. The two-dimensional random fiber network gives a good representation of the structure of paper at short length scales, below fiber length. Kallmes *et al* (1961) (see [127]), showed that ordinary handsheets have the same in-plane mechanical properties as sheets made by couching many thin sheets. The two-dimensional network structure should therefore explain the in-plane properties of paper. Kallmes *et al* analyzed mathematically the statistical geometry of two-dimensional random fiber networks and found good agreement with direct microscopic measurements of thin paper sheets. The Corte-Kallmes theory describes what happens when fibers of constant dimensions are randomly and isotropically distributed on a plane. Real fibers do not have a constant length, width or thickness, but the average dimensions should be enough to specify the geometry in all cases of practical interest.

At low grammage, a paper sheet is essentially two-dimensional because a me-

chanical contact can form between two fibers whenever their in-plane projections cross. Some sheet area may also be completely empty with no fiber coverage.

Fibers must then be bent more and more to make contact with other fibers. At some point, sufficient bonding is no longer possible and empty space forms between fibers in the  $z$ -direction. The frequency of pores is higher when the local grammage is lower than the average. The porosity of the network depends on the rate at which pores form when grammage grows [128].

The sizes of three-dimensional pores in paper are difficult to determine because of the connected pathwork of irregular cavities. The situation is much more complex than in two dimensions where “pores” can be defined as the polygons bordered by fiber segments. One can visualize the three-dimensional porous structure as a collection of ellipsoidal pores with narrow “throats” connecting them [163].

The three-dimensional pore structure of paper controls the density and optical properties directly and the mechanical properties and dimensional stability indirectly through relative bonded area (RBA), which usually characterizes the bonding degree of paper.

The three-dimensional network is either layered or “felted” (see Figure 3.6). The mutual entanglement of fibers in the latter case is important for the  $z$ -directional properties of paper.

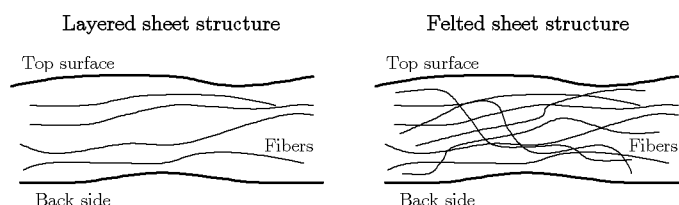


Figure 3.6: Comparison of layered and felted sheet cross section (adapted from [127]).

Papermaking fibers are 1-2 orders of magnitude longer than a typical paper sheet is thick. Most of the fiber length must be aligned in the plane of the paper sheet. A layered network forms if the fibers land on the wire one after another. In a felted structure, the fibers do not deposit in a clear sequence. A layered network forms in a handsheet mold using low pulp consistencies. A felted sheet structure results when paper forms at high consistency or under pulsating

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drainage. In the latter case the pressure pulses fibers back and forth so that they cannot land on the wire freely, independent of one another. At high consistency, three-dimensional fiber aggregates or flocs form in the suspension and are then squeezed in the planar sheet.

A felted sheet structure should give better out-of-plane or z-directional strength than layered structure because fibers are stronger than bonds. Indeed, high consistency forming promotes the out-of-plane strength of paper (see [127]).

In machine-made papers, there are more fibers aligned in the machine direction than perpendicular to it. Fiber orientation refers to this anisotropy in the structure of paper. The fiber orientation of paper directly affects the in-plane mechanical properties and dimensional stability of paper. The anisotropy of paper properties also depend on the drying shrinkage and wet straining of the web. In most cases, a low orientation index is best for paper performance since this makes paper properties similar in all in-plane directions. The variation of fiber orientation through the thickness of the sheet is also relevant for paper performance. Orientation difference between the sheet surface and middle layers affects bending stiffness, and the difference between the surfaces (two-sidedness) causes curl. A small fraction of the fiber axis also has a z-directional orientation. This is misleading, since only fiber segments can have any appreciable orientation in the z-direction. Thus, the z-directional “fiber orientation” is actually z-directional fiber segment orientation.

In addition, the network structure of paper depends on the *collapsibility*, *conformability*, and *flexibility* of wet fibers. These factors and the *swelling* of wet fibers determines the *densification of paper structure* in wet pressing and drying. Fiber conformability is not a directly measurable quantity but a general term that characterizes fiber behavior in the web consolidation process. Conformable fibers can bend and match the shape of each other to give a dense and well-bonded network. The conformability of fibers depends on their cross-sectional dimensions and internal fibrillation, and the chemical composition and morphology of the cell wall [127].

Fibers have a circular or rectangular cross section in wood, but they may flatten or collapse to a ribbon in the pulping and papermaking process or during wet pressing, drying or calendering. The perimeter does not change if a fiber collapses. Studies of pulps from softwoods grown in Finland have shown a linear dependence of fiber collapsibility on the cell wall thickness (see [127]). Collapsed

ribbon-like fibers are flexible and can have a higher bonded area than uncollapsed tubular fibers. Fiber collapse therefore improves the strength properties of paper. Wet fiber flexibility can assess fiber conformability. It decreases rapidly with increasing fiber thickness, and increases with decreasing yield and increasing beating. According to Kerekes *et al* (1985) (see [127]), mechanical pulp fibers usually have a lower wet fiber flexibility than chemical pulp fibers. Hattula *et al* (1988) suggested that the effects of beating and yield on fiber flexibility probably come from an increase in the porosity or delamination of the cell wall (see [127]). The swelling degree of pulp fibers depends on their chemical composition and internal fibrillation. Hemicelluloses promote fiber swelling and lignin inhibits it. For the latter reason, chemical pulps often swell more than mechanical pulps. The swelling of chemical pulp fibers increases with beating. Also with mechanical pulps, refining often increases the water retention value, but primarily because of increased fines content rather than because of increased fiber swelling.

The mechanical properties of single fibers have received considerable study in recent years. The load-elongation behavior of single fibers is qualitatively similar to that of paper when the fibril angle is small. As an example, the elastic modulus of the fiber in the axial direction is determined by the initial linear section of the load-elongation curve. After the linear section the rate of load increase per unit elongation decreases. Much nonlinearity in the load-elongation behavior of single fibers can arise from *curl* and various defects such as *crimps*, *kinks*, and *microcompressions* rectified by the elongation. In contrast, Jayne (1957) and Jentzen (1964) suggest that fibers with no defects are linearly elastic or nearly so (see [127]). Defects can arise during the chipping of wood, pulping and refining and through the pulp line to the paper machine. Strong beating can induce kinks and dislocations in the fibers, but gentle beating especially in laboratory beaters promotes fiber swelling with resultant straightening. In this case, fiber strength improves. Beating can also result in reduced cross-sectional area of dry fibers that is sufficient to increase rupture stress and elastic modulus of the fiber. Beating at medium or high consistency produces curly fibers that have high number of kinks and microcompressions causing deterioration of fiber strength.

The 1950s and 1960s saw intensive study of inter-fiber bonding and its relationship to the mechanical and optical properties of paper. Inter-fiber bonds in



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paper form gradually as solid content increases in the papermaking process. In a paper sheet, the deformation of any inter-fiber bond involves corresponding deformations in the fiber segments that the bond couples. The mechanical response of the bond cannot be separated from the response of the bonded fiber segments. Even the bonding layer between two fibers is sometimes difficult to identify and separate from the actual fiber wall. The stresses that act on fibers and between them during drying affect the mechanical properties of fibers and bonds in the dry paper. Stretching of the wet web on the paper machine causes additional effects. Deformations in the internal structure of fibers and bonds explain qualitatively the changes that drying causes in the microscopic and macroscopic properties of paper. Such deformations are seldom directly observable. Concepts such as *internal stresses*, *dried-in stresses*, or *dried-in strains* often find use in explaining the effects.

On the paper machine, macroscopic stresses develop in the paper web as it proceeds through the machine. The drying stresses levels in the web cross-direction (CD) are much lower than in machine direction (MD) since web edges are free to shrink. The internal stress state of a machine-made paper is thus anisotropic, different in MD and CD. Web straining in the wet end of the paper machine causes permanent deformations in the shape of the fibers.

**Wet straining of the paper web** On the paper machine, the highest MD strain increments of the web occur in the wet end. In fact, in the press section and in the beginning of the dryer section of the paper machine, the web is wet, and fibers are soft and easily deformable. Web cohesion comes primarily from surface tension forces, mechanical interlocking, and colloidal interactions [127]. Fibers can slide against one another when the wet web is stressed. In static conditions, any stress in the web would rapidly vanish. At low machine speeds or high stress levels, the permanent deformations in the web are therefore large. The paper machine may strain the paper web by as much as 5 % [127].

**Microscopic yield phenomena** In a typical load-elongation curve of paper, one may see that in MD the curve is relatively short and linear. In CD, it extends further to large strains and is markedly nonlinear. Qualitatively, the MD behavior is near that of a linearly elastic material, and the CD behavior is similar to that of an elastic, ideally plastic material. Ideal plasticity means that above a

yield threshold, load does not increase although elongation grows. The primary difference between MD and CD curves is in the effect of drying stress. Drying stress is the most important single factor that affects the shape of the curve. One could think that the nonlinearity in the load-elongation curve arises from decreasing elastic modulus. In that case, elongation would be entirely reversible. In reality, most nonlinearity arises from irreversible or plastic elongation. If a paper specimen is stretched beyond the yield point and then released, it becomes permanently longer than it was originally. A small part of the initial nonlinearity is reversible as demonstrated by the shape of the deloading-loading cycles. The elastic modulus of paper,  $E$ , usually changes relatively little during elongation. The reversible or elastic strain, can therefore be calculated approximately by dividing stress by the elastic modulus,  $\varepsilon^{el} = \frac{\sigma}{E}$ . The remainder,  $\varepsilon - \frac{\sigma}{E}$ , is equal to the plastic, irreversible strain component,  $\varepsilon^{pl}$  (see Figure 3.7).

*In summary, the elongation of paper is not merely a viscoelastic phenomenon but contains a truly plastic permanent component.*

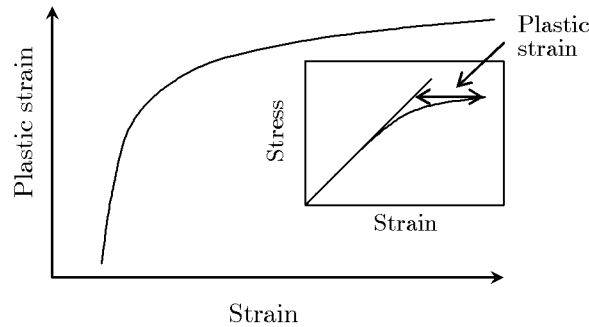


Figure 3.7: Onset of nonlinearity in the load-elongation curve of paper expressed by the plastic strain (on logarithmic scale) versus total strain. The inset shows the definition of plastic strain (adapted from [127]).

When a paper sheet stretches, two phenomena occur at the microscopic level: fiber segments elongate - in part irreversibly - and some bonds open gradually. These processes must consume energy because the area under the elongation curve represents work done on the system. Only part of that work is recoverable in elastic recoil upon release of the external stresses.

Despite the irreversible work when paper stretches in the plastic region, the number of load carrying elements in the fiber network does not change dramatically. Remember that elastic modulus is a measure of the elastic energy

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content. Ebeling [44], has measured the heat flow into and from paper during load-elongation tests at constant temperature. In the *elastic region*, heat flows into paper when strained (the Kelvin effect). The internal energy of the system increases as a sum of the external work and heat flow. If the external load is removed in the elastic region, paper releases the same amount of heat that it absorbed during elastic elongation, and the internal energy returns to its original value.

In the *plastic region*, paper releases heat with decreasing and increasing elongation. Plastic elongation is thermodynamically irreversible. Since the elastic modulus does not change correspondingly, the irreversible heat generation must come from changes in the microscopic or molecular configuration within fibers and bonds.

Seth and Page [160] have demonstrated that average behavior of fibers can qualitatively explain the nonlinear behavior of paper. For example, the influence of drying shrinkage on the load-elongation curve of paper comes from an increase in plastic elongation. Also, the shape of the curve changes little with drying shrinkage except for the location of the end point, *i.e.* the point of rupture.

In addition, changes in the bonding degree of the network showed to have no effect on the shape of the load-elongation curve [127], and neither can opening of bonds, which results from stretching the fibers, explain the shape of the curve. Page, Tydeman, and Htun [134], studied the opening of bonds under a light microscope and found that most bonds opened gradually and did not break completely even when paper was strained to failure. Complete bond failures were rare. In summary, the load-elongation behavior of paper seems to be controlled by the corresponding fiber behavior.

Figure 3.8 shows some characteristic curves of the load-elongation and load-compression of paperboard. The curves show some important features:

- elastic modulus is the same in tension and compression;
- nonlinear region is very short in compression;
- compressive strength is approximately one-third of the tensile strength in MD and one half in CD;
- compressive breaking strain is one-fourth of the tensile breaking strain in MD and one fifth in CD.

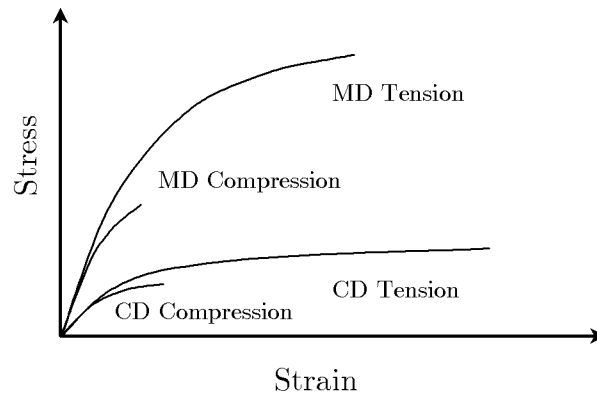


Figure 3.8: Stress-strain curve of a paperboard in tension and in compression (adapted from [127]).

The principal features of the curves are qualitatively the same in all ordinary paper and board grades. When the compression of paper or board increases, the ultimate failure is probably preceded by fiber *buckling* and bond delamination [49]. In buckling, axial compression changes abruptly into bending, and the load carrying capacity of the object can decrease considerably. In addition to localized bending, sheet delamination can also occur. If the fiber network has low density or low bonding degree, the compressive stress-strain curve has the interesting feature that even the nonlinear part of the compression curve is reversible. At high densities, the nonlinear region corresponds to irreversible plastic compression [49]. In tension, the nonlinear part of the stress-strain curve is almost exclusively irreversible.

#### *Out-of-plane strength*

Out-of-plane strength measures the ability of paper or board to withstand stress in the thickness direction. High out-of-plane strength is necessary in various converting and end-use operations, but it can sometimes be harmful. Printability is still the limiting factor because the correlation between creasability and out-of-plane strength is weak.

Figures 3.9 and 3.10 show the typical z-directional stress-strain curve in tension and compression, respectively. It indicates the following:

- elastic modulus is small;
- elastic region is short and plastic deformation starts almost immediately;

- breaking strength is small: less than 0.5 %.

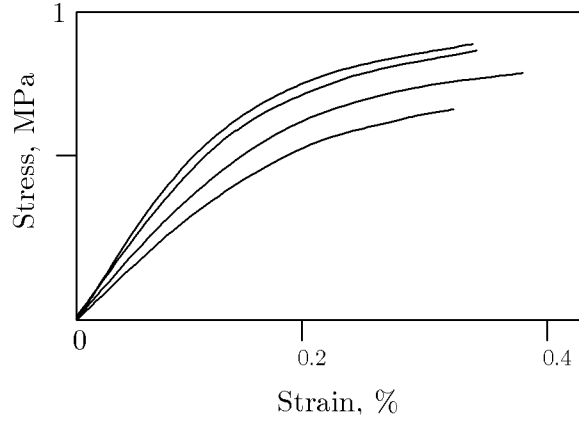


Figure 3.9: The out-of-plane stress-strain curve of a press-dried paper in *tension* (adapted from [127]).

In Figure 3.9, the elastic modulus in tension is 0.5 GPa. This is one-tenth of the typical in-plane moduli. Even this value is unusually high, and apparently it resulted from the press drying of paper. With conventional pressing and drying methods, the out-of-plane elastic modulus is about 0.05-0.1 GPa. For comparison, the transverse elastic modulus of fibers is much higher, in the order of 3-7 GPa depending on the cellulose content [113]. Plastic deformation starts in tension when fiber bonds begin to open. Apparently fibers show little elastic deformation before this.

The compressive behavior in Figure 3.10 is clearly different from the tensile behavior. The stress-strain curve is nonlinear from the very beginning. In contrast to the previous case, the tangent modulus increases with increasing compression. This comes from decreasing void volume. The compression of voids encounters much less resistance than the compression of the solid fiber wall material. This behavior must be very similar to that of any porous material, since the principal controlling factor seems to be the distribution of local pore volume [127].

Out-of-plane strength is sensitive to any nonuniformity or layering in the  $z$ -direction, since delamination will occur at the weakest plane. The location depends on the  $z$ -directional distribution of fines and fillers, density through bonding degree, and distribution of sizing agents if present. The material distributions

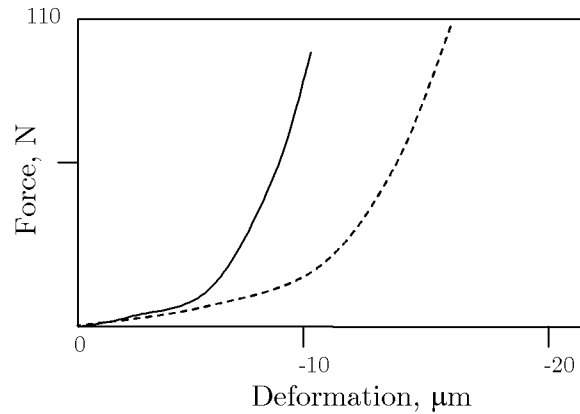


Figure 3.10: The out-of-plane stress-strain curve of a press-dried paper in compression (adapted from [156]).

depend on the configuration and operation of the forming and pressing sections of the paper machine.

The felted versus layered structure of the fiber network has strong influence on the out-of-plane strength. In the layered sheet, fibers lie on top one another in a well-defined sequence so sheet can delaminate without breaking any fibers. In a completely felted sheet, it is impossible to find simple delamination planes that would not involve fiber breaking or pull-out. In fast loading especially, fibers break rather than pull out because the minimum energy surface for delamination is too irregular. Since fibers are much stronger than bonds, even a small number of broken fibers can significantly increase the delamination energy. A felted structure obtained with high-consistency forming more than doubled the Scott-bond value [127]. Also, out-of-plane strength increases with density if density is increased by pressing or beating. The effect comes simply from the increase in bonded area. The relationship between density and out-of-plane strength can vary depending on pulp type and densification method (see [127]). Similar to the in-plane properties, beating increases out-of-plane strength more than conventional wet pressing. In wet pressing, flexible, beaten fibers conform better and form more bonds than stiff fibers. Press drying using the Condebelt method gives two or three times higher values of the delamination strength when compared with conventional drying. Presumably the structure of bonds changes.

Unlike some laminated fiber-reinforced composite materials, paper is a multi-

phase material composed of moisture, fibers, voids, and chemical additives. The fibrous raw materials which compose paper are typically organic with cellulose being the main component. Since cellulose fibers are self-binding, no matrix material is needed to form a sheet. Wood itself may be thought of as a natural composite consisting of cellulose fibers interconnected by a primarily lignin binder.

The three-dimensional physical structure of paper is basically an assembly of discrete fibers bonded together into a complex network. If the fibers were oriented randomly throughout the sheet, the material behavior would be isotropic. However, a single preferred orientation results from the hydrodynamic forces present in the papermaking machine, and confer some special properties to the material behavior. In the terminology of paper industry, this direction in the paper sheet with the highest stiffness ( $x$  direction) is called the machine direction. That with the lowest stiffness ( $y$  direction) is referred to as cross-machine direction. These orthogonal in-plane directions of material symmetry allow paper to be modeled as an orthotropic solid.

Being paper a laminar structure (*i.e.* the sheet is formed from a dilute suspension and the fibers are deposited flat on top of one another), the fibers in the sheet seldom lie more than a few fiber thickness out of horizontal plane. As a result of its laminar nature, paper is inherently susceptible to stresses which causes separation of this adjacent lamina. Paper is inherently weak in the interlaminar shear mode (about 1/20th of its strength and modulus in the tensile mode) [23]. The question now is to know the preferred mode of deformation experienced by paper and its structure, and how it can be modelled. For that a brief description of honeycombs and foams mechanics is presented in **Appendix C**.

#### *Application of cellular solids theory to paper*

As referred in **Appendix C**, the structure of cellular solids ranges from the near-perfect order of the bee's honeycombs to the disordered, three-dimensional networks of foams and sponges. Low-density solids, such as paper and felts, can be assembled as a random network of fibers, the contact points of which may be bonded together and, according to some authors mechanical and thermal properties of wood-based materials have much in common with those of cellular materials [51].

When subjected to low loads paper behaves as a linear elastic material. How-

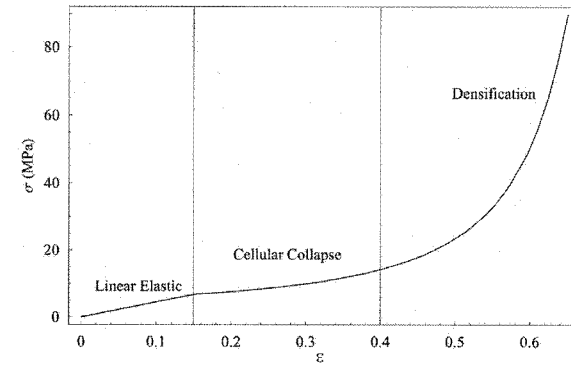


Figure 3.11: Characteristic stress-strain diagram for cellular materials (adapted from [204]).

ever, under very high loads its stress-strain curve shows a hysteresis. This phenomenon is due to a plastic strain of the web during compression. In order to obtain the nonlinear stress-strain curve, an approach to cellular materials theories was made. The aim of the present work is, therefore, to model the deformation of paper in terms of a cellular structure.

The mechanical properties of cellular materials in transverse compression are highly nonlinear resulting from the collapse of the cellular structure. The amount and type of the cellular collapse may be important in the resulting mechanical and physical properties of wood-based composites [204]. Figure 3.11 shows a typical nonlinear stress-strain curve of a cellular solid in transverse compression.

Three characteristic regions can be observed in both man-made and natural cellular materials: linear elastic, cellular collapse, and densification. The material at the beginning of compression deforms in a linear elastic manner. At the onset of cellular collapse, the cell wall material yields, and due to the cumulative collapse of the cell walls, the material continues to deform at a nearly constant stress level. Cellular collapse occurs either by elastic buckling, yielding or brittle crushing, depending on the type of the cell wall material. Different fracture mechanisms result in different stress-strain behavior. However, Wolcott [204] demonstrated that *elastic buckling* is a viable assumption as the form of collapse of the wall of wood cells. At the end of the collapse region, the cell wall structure starts to consolidate. At this point most of the cells are collapsed and opposing cell walls are in good contact. The characteristic of the densification region is the rapid stress increase as the compression continues. These regions are present in



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all types of cellular structures, but the initiation and the length of the regions are a function of the cell geometry which is characterized by the relative density.

Compressive stress-strain curves for loading of the cellular material can be represented by the modified Hooke's law, which takes into account the linear as well as the nonlinear mechanical response of the material by introducing an additional nonlinearizing term,  $\Phi(\varepsilon)$ :

$$\sigma = E\varepsilon\Phi(\varepsilon) \quad (3.10)$$

where  $\Phi(\varepsilon)$  is a nonlinear strain function.

The elasticity modulus of a *closed cellular solid* can, according to the classical beam theory, be written as [51]:

$$E = C_2 E_{cw} \rho_{rel}^\epsilon \quad (3.11)$$

where

$C_2 = \text{constant}$ ;

$\epsilon = \text{parameter which is a function of the material structure (1.5 - 3.0)}$ ;

$\rho_{rel} = \text{relative density, defined as the ratio of the apparent density of the cellular material, } \rho, \text{ to the real density of the solid of which it is made, } \rho_s$ ;

$E_{cw} = \text{Young's modulus of the cell wall material.}$

The Young's modulus of a closed cellular solid can be written as:

$$E = C_2 E_{cw} \rho_{rel}^3 \quad (3.12)$$

whereas for an *open-celled foam* the relation is:

$$E = C_2 E_{cw} \rho_{rel}^2 \quad (3.13)$$

Wolcott *et al* [204], applied to a closed cellular solid the theories developed by Gibson and Ashby [51], in order to model the stress-strain curve of wood under compressive stress in the z-direction. The resulting equation for elastic collapse of a closed cell foam was found to be [204]:

$$\sigma = C_3 E_{cw} \rho_{rel}^3 \left( \frac{1 - \rho_{rel}^{1/3}}{1 - \langle \rho_{rel}(\varepsilon) \rangle^{1/3}} \right)^3 \quad (3.14)$$

where  $C_3$  is a parameter of the model and  $\langle \rho_{rel}(\varepsilon) \rangle$  is the relative density function of the cellular material, which may be expressed as:

$$\langle \rho_{rel}(\varepsilon) \rangle = \rho_{rel} \left( 1 - \varepsilon^{pl} + \frac{2}{3} \ell \varepsilon^{pl} - \ell (\varepsilon^{pl})^2 \right)^{-1} \quad (3.15)$$

where  $\ell$  is the expansion ratio, *i.e.* the ratio of lateral expansion of the cellular material to the compression strain in the nonlinear stress-strain region.

Maiti *et al* [110], also proposed a similar approach using the equations for open cellular foams, but taking into account the elastic and plastic collapse. The resulting equations may be written as follows:

$$\sigma = C_3 E_{cw} \rho_{rel}^2 \left( \frac{1 - \rho_{rel}^{1/3}}{1 - \langle \rho_{rel}(\varepsilon) \rangle^{1/3}} \right)^2 \quad \text{for elastic collapse} \quad (3.16)$$

$$\sigma = \sigma_{ycw} E_{cw} \rho_{rel}^{3/2} \left( \frac{1 - \rho_{rel}^{1/3}}{1 - \langle \rho_{rel}(\varepsilon) \rangle^{1/3}} \right) \quad \text{for plastic collapse.} \quad (3.17)$$

where  $\sigma_{ycw}$  is the yield stress of the cell wall material.

These latter authors state that both rigid and elastomeric foams undergo no lateral expansion with compression strain in the nonlinear stress-strain region. They also state that the expansion rate for *wood*, defined for cellular materials as the ratio of lateral strain to compressive strain in the nonlinear region, will affect the plateau and densification strains by influencing how fast density increases with compression strain. Being so, in the previous equations, the relative density function will be expressed in terms of the relative density and plastic strain of the cellular material only. Therefore, the following expression adequately monitors the relative density function:

$$\langle \rho_{rel}(\varepsilon) \rangle = \rho_{rel} (1 - (\varepsilon - \varepsilon_y))^{-1} \quad (3.18)$$

where  $\varepsilon_y$  is yield strain of the cellular material.

Without doubt, the cell walls of wood fibers either fracture or plastically yield after or when they collapse because permanent deformations remain after the load is removed. However, the question arises whether the nonlinear mechanical properties can be adequately modeled assuming elastic buckling.

According to the experimental work of Ashby *et al* and Maiti *et al*, the  $\varepsilon_y$  for wood is relatively independent of density. One explanation for this phenomenon is that at low relative densities, the elastic buckling is reached prior to reaching the

### 3. Mathematical Model for High-Temperature Pressing of Paper 209

fully plastic moment. At higher relative densities, when plastic hinges develop, the  $\varepsilon_y$  changes slowly with density. To illustrate the argument presented here, the  $\varepsilon_y$  and stress of wood is plotted as a function of relative density for elastic and plastic collapse (see Figure 3.12).

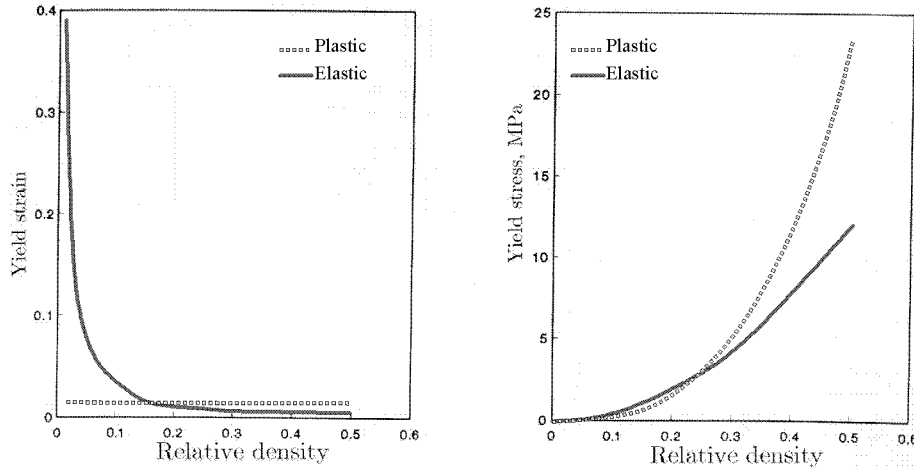


Figure 3.12:  $\varepsilon_y$  and  $\sigma_{ycw}$  as a function of relative density calculated assuming elastic and plastic collapse mechanisms (adapted from [204]).

For low relative densities, the difference between the predicted values of  $\sigma_{ycw}$  is small. However, large differences exist between the predicted values of  $\varepsilon_y$ . For higher relative densities when plastic collapse is likely, the error introduced by assuming elastic collapse is not serious for yield stress at relative densities less than 0.35. The yield strain predicted using both methods are similar for high relative densities. From their experimental studies, Gibson and Ashby found a value of  $\varepsilon_y$  for balsa of 0.015, which is equal to that of higher density species as yellow poplar and maple. Also, a value of 0.012 was calculated for several densities of balsa from data presented by Easterling *et al* [204]. Theories for the mechanical properties of cellular materials developed by Gibson and Ashby, and Maiti *et al* can then be used to accurately model wood in transverse compression. Whereas the assumption of elastic collapse may not be physically valid at high relative densities, it can be used to accurately model the nonlinear material behavior. *However, elastic buckling may actually be the preferred mode of cellular collapse for low relative densities.*

The nonlinear strain function  $\Phi(\varepsilon)$  is a nonlinear multiplier of the stress cal-

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culated assuming linear behavior. It depends on the strain and relative density. Therefore, it essentially monitors the cellular collapse in the material as a function of the cellular structure. In the present study, the approach developed by Maiti *et al* for open-celled foams will be used to characterize the solid network that constitutes paper. The solid matrix is therefore assumed to consist of open interconnected cells through which fluid flows as a consequence of material deformation. This assumption suggests no additional contributions to the elastic modulus of the solid material, such as that resulting from cell faces deformation. If one now compares Eqns. 3.10 and 3.16, the nonlinear function may be obtained as:

$$\Phi(\varepsilon) = \begin{cases} 1 & \varepsilon \leq \varepsilon_y \\ \frac{C_3/C_2}{\varepsilon} \left[ \frac{1 - \rho_{rel}^{1/3}}{1 - (\rho_{rel}(\varepsilon))^{1/3}} \right]^2 & \varepsilon > \varepsilon_y \end{cases} \quad (3.19)$$

This nonlinearizing function separates the linear elastic region from the collapse, and densification regions. Therefore, it is capable of describing the mechanical behavior during the full range of transverse compression of cellular materials. As shown above, the nonlinear strain function has a value of unity when the strain is below the yield strain of the cell wall. In this case, the modified Hooke's law returns to the ordinary Hooke's law describing the linear elastic behavior of the cell wall under low levels of strain. During the cellular collapse region the nonlinear strain function decreases until it reaches a minimum value at the onset of densification of the cell wall material. During the densification region, the nonlinear strain function increases and approaches infinity with increasing strain.

The linear elastic constant,  $C_2$ , is found to equal unity for man-made cellular materials [52] and wood [43]. This is correct in terms of a true material response. For  $C_2$  equal to unity,  $C_3$  is equal to the yield strain for the case of elastic collapse. However, for other values of  $C_2$ , it was shown that  $\varepsilon_y = \frac{C_3}{C_2}$  [204]. Wolcott *et al* suggested a value between 0.014 and 0.016 for the yield strain, *i.e.*  $C_3$  [204].

The applicability of the cellular material compression theories to describe the nonlinearity of the transverse compression of solid wood was demonstrated by several researchers [204], [43], [93], [94]. In addition, the consolidation of medium density fiberboard panels (MDF) has been described by Carvalho using this same approach [29]. A similar approach will be presented in this work for the transverse compression (the thickness direction) of both paper and felt.

### 3. Mathematical Model for High-Temperature Pressing of Paper 211

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#### **Elastoplastic moduli and viscous properties of paper** 1. *Elastoplastic properties of paper*

Instead of predicting the elasticity moduli of composites as the initial slope of the stress-strain curve, one can use some current approaches such as the well known “rule of mixtures”. In the elementary mechanics materials approach to micromechanical modeling fiber-packing geometry is not taken into account, and so, the representative volume element (RVE) may be a generic composite block consisting of fiber material bonded to matrix material. In this approach several assumptions have to be made [53]:

- the volume fractions in the RVE are assumed to be the same as those in the actual composite;
- fibers remain parallel and the dimensions do not change along the element;
- the area fractions must equal the volume fractions;
- perfect bonding at the interface is assumed and no slip occurs between fiber and matrix material;
- the fiber and the matrix are assumed to be linearly elastic and homogeneous; the matrix is assumed to be isotropic but the fiber can either be isotropic or orthotropic;
- the lamina (*i.e.* the RVE block) is assumed to be macroscopically homogeneous, linearly elastic and orthotropic.

When the RVE is subjected to a transversal normal stress, as shown in Figure 3.13, the response will be governed by the effective transverse modulus. If one assumes that the stresses in the composite, matrix and fibers are equal, then the *inverse rule of mixtures* can be expressed by the following equation:

$$\frac{1}{E} = \frac{\phi_f}{E_f} + \frac{\phi_m}{E_m} \quad (3.20)$$

where

$E_f$  = fiber modulus of elasticity;

$E_m$  = matrix modulus of elasticity;

$\phi_f$  = volume fraction of fibers;

$\phi_m$  = volume fraction of matrix.

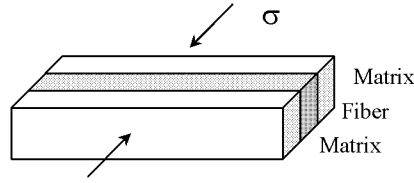


Figure 3.13: Transverse normal stress.

The volume fraction of fibers and matrix can be determined from the following expressions:

$$\phi_m = \frac{V_m}{V_f + V_m} = \frac{\rho_{composite}}{\rho_f (1 + y_{mf})} \quad (3.21)$$

$$\phi_f = 1 - \phi_m \quad (3.22)$$

where

$y_{mf}$  = mass ratio of matrix to fibers;

$V_f, V_m$  = fiber and matrix volumes;

$\rho_{composite}$  = density of the composite;

$\rho_f$  = density of the fiber material.

The assumption of equal stresses seems to be valid because equilibrium requires that forces must be equal for the series arrangement and both fibers and matrix blocks have equal areas normal to the direction of stress application.

On the other hand, if the RVE is subjected to a longitudinal normal stress (see Figure 3.14), the response is governed by the effective longitudinal modulus. Static equilibrium requires that the total resultant force on the element must equal the sum of the forces acting on the fiber and matrix. Under the assumptions that the matrix is isotropic, that the fibers are orthotropic, and that all the materials follow a one-dimensional Hooke's law, the *longitudinal rule of mixtures* becomes,

$$E = \phi_m E_m + \phi_f E_f \quad (3.23)$$

The assumption of a specific fiber-packing array is one possible refinement of the models. Although real composites have random-packing arrays, the assumption of a regular array is a logical simplification if one is to have any hope of developing simple design equations. Such an assumption allows the use of simple

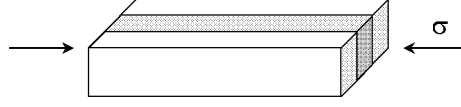


Figure 3.14: Longitudinal normal stress.

relations among fiber size, spacing, and volume fraction. Hopkins and Chamis [72] have developed a refined model for transverse properties based on a square fiber-packing array and a method of dividing the RVE into subregions.

Another general approach to estimating these properties involves the use of semiempirical equations which are adjusted to match experimental results by the use of curve-fitting parameters. The most widely used semiempirical equations were developed by Halpin and Tsai [61]. The Halpin-Tsai equation for the transverse modulus is:

$$\frac{E}{E_f} = \frac{1 + \vartheta \eta \phi_m}{1 - \eta \phi_m} \quad (3.24)$$

where

$$\eta = \frac{\frac{E_m}{E_f} - 1}{\frac{E_m}{E_f} + \vartheta} \quad (3.25)$$

and  $\vartheta$  is the curve-fitting parameter, which is also a measure of the reinforcement degree of the matrix by the fibers. However, Halpin and Tsai suggested a value of  $\vartheta = 2$  for a square array of circular fibers [53].

Salmén and de Ruvo [151] used the Halpin-Tsai equations to describe the mechanical properties of the cell wall of wood pulp fibers. In modeling the composite structure of the fiber or the fiber cell wall, the mechanical properties of the cell wall layers were related to the constituent polymer properties using these equations. In the model adopted by them, the cell wall was assumed to be constituted by cellulose microfibrils embedded in a matrix of hemicelluloses. The lignin present was considered to exist in isotropic separate lamellae located between the cell wall layers.

However, the effects of fiber discontinuity or fiber length in composite mechanics behavior is not taken into account in these analysis since it is assumed that fibers extend from one end of the lamina to the other end. Short fiber-reinforced composites are not as strong or as stiff as continuous fiber-reinforced composites,

although they show several attractive characteristics that make them worthy of consideration for other applications.

*Composites having randomly oriented short fiber reinforcement are nearly isotropic*, whereas unidirectional continuous fiber composites are highly anisotropic. If the fiber orientation in a composite is truly random in a three-dimensional sense, the composite exhibits three-dimensional isotropy. This situation is likely to exist when the fiber length is much less than the thickness of the lamina. However, in many composites the fiber length is greater than the thickness of the part and, thus in this case the fiber orientation in the thickness direction is not possible and the material exhibits two-dimensional isotropy or planar isotropy.

Cox [37] modeled paper as a planar material of continuous fibers without matrix material, introducing the concept of averaging the elastic constants over all possible orientations. Christensen and Waals [35] also used the averaging approach to find the isotropic elastic constants for continuous fiber composites with two-dimensional and three-dimensional random fiber orientation. They also used previously developed micromechanics equations by Hashin [63], [64] and Hill [68] to calculate the elastic constants for the three-dimensional case. The prediction from the Cox model for a glass/epoxy composite is well below that of the Christensen-Waals model, and the rule of mixtures prediction is much too high. The Christensen-Waals model is seen to give much better agreement with the measurements than the Cox model or the rule of mixtures, although none of the models take into account the fiber length.

Up to this point, only continuous fiber models for randomly oriented fiber composites have been presented. Weng and Sun [200] used the Christensen-Waals equations along with micromechanics equations which were modified to account for the effect of fiber length. This effect was modeled by using a “fictitious fiber”, which included the effect of matrix material at the ends of the fiber. The model equation for the effective modulus of the fictitious fiber is analogous to that of the modified Cox model.

A paper sheet is basically an assembly of discrete cellulose fibers bonded together into a complex network, thus it may be considered a composite material. Fibers tend to lie predominantly in the plane of the sheet. In addition, hydrodynamic forces present during sheet formation align the fibers primarily along the direction of web movement.

In time, paper has been modeled macroscopically using elastic, viscoelastic



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and inelastic formulations. In a macromechanics or continuous approach, the material is presumed homogeneous and the effects of its micro-scale constituents (see Figure 3.15) are detected only as averaged apparent properties. For paper materials, continuous theories are typically established for a paper sheet or laminate viewed as a three-dimensional orthotropic solid medium. The theory of linear orthotropic elasticity has often been used to model the macroscopic behavior of paper. Since the mechanical behavior of most papers is highly nonlinear even at low strains, linear elastic approach is unsuitable if high accuracy is desired. Therefore, the theories presented so far are not accurate enough, as all assume linear elastic behavior for the constituents of the representative volume element.

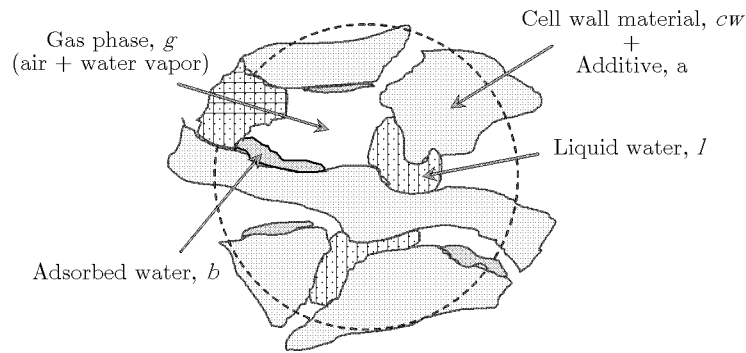


Figure 3.15: Micro-scale constituents of paper.

In order to estimate the “elastoplastic” modulus of a paper sheet, two micromechanical models were proposed (see Figure 3.16), in which the effects of its micro-scale constituents were taken into account: wood pulp fibers, adsorbed water on the fiber surface, gas (air and water vapor), liquid water, and chemical additives usually used in the papermaking industry. The term “fiber” is defined, hereafter, as the cell wall material and the adsorbed water in it. The following sections intend to define the micro-structure of paper adopted in the present work, and describe the micromechanical models to estimate the elastoplastic modulus of each representative volume element.

#### *Solid phase (“fiber” + additive)*

Model I suggests an arrangement in series for the “fiber” and the additive. If one assumes that the stresses applied on the set, and in each element, fiber and additive, are all equal, the inverse rule of mixtures for the transverse modulus of the solid phase,  $E_s$ , becomes

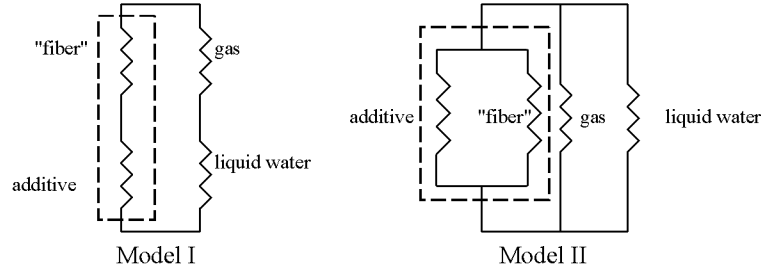


Figure 3.16: Micromechanical models for paper.

$$\frac{1}{E_s} = \frac{\phi_f}{E_f} + \frac{\phi_a}{E_a} \quad (3.26)$$

where  $\phi_f$  and  $\phi_a$  represent the volume fractions of “fiber” and additive, and  $E_f$  and  $E_a$  are the elastic moduli for “fiber” and additive, respectively.

Again, this equation does not take into consideration the fiber-packing arrangement and this fact leads to a lack of accuracy, as all fraction areas are assumed to be equal, which is not the case for the present material. This is, however, a reasonable assumption if one wants to avoid excessive complexity in the development of the micromechanical model. Another possibility is to use the semiempirical Halpin-Tsai equations, which for the solid phase is written as

$$\frac{E_s}{E_a} = \frac{1 + \vartheta\eta\phi_f}{1 - \eta\phi_f} \quad (3.27)$$

and

$$\eta = \frac{\frac{E_f}{E_a} - 1}{\frac{E_f}{E_a} + \vartheta}, \quad \vartheta = 2 \quad (3.28)$$

$$\phi_f = \frac{\rho_s}{\rho_f(1 + y_a^*)}, \quad \phi_a = 1 - \phi_f \quad (3.29)$$

$$\rho_s = \frac{1 + y_a^*}{\frac{1}{\rho_f} + \frac{y_a^*}{\rho_a}} \quad (3.30)$$

where  $\rho_f$  is the density of the “fiber”,  $\rho_a$  the density of the dry additive, and  $y_a^*$  is defined as the ratio of the solids weight of additive to the weight of “fiber” and is referred to as additive ratio.

If, on the other hand, a parallel assembly of fiber and additive is assumed (model II), the elasticity modulus for the solid phase will be given by:

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$$E_s = \phi_f E_f + (1 - \phi_f) E_a \quad (3.31)$$

as the static equilibrium requires that the total resultant force on the element must equal the sum of the forces acting on the fiber and additive. A new parameter  $\alpha_f$  is here defined as the ratio of the cross sectional area occupied by the fiber,  $A_f$ , to the cross sectional area of the solid,  $A_s$ , as illustrated in Figure 3.17. It is then obvious that in Model II the volume fractions of the constituents correspond, in fact, to their cross sectional area fractions.

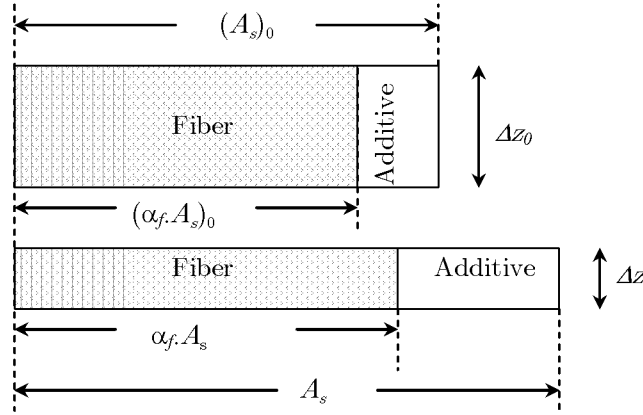


Figure 3.17: Schematic diagram of the solid phase dimensions.  $\Delta z$  is the thickness of the cell and  $\Delta z_0$  its initial value.

It is important to note that the term “fiber” comprises the cell wall material plus the adsorbed water on the fiber surface. Bearing this in mind, the contributions of air, water vapor and liquid water, inside and outside the fibers, are accounted for in the elasticity modulus of the representative volume element in the form of  $E_l$ , for the liquid phase, and  $E_g$  for the gas phase.

*“Fiber” (wood pulp fiber + adsorbed water)*

The properties of wood and wood fibers have been described in terms of various models of the structural organization of their components. The cell walls of the wood tracheids have a structural design, which among man-made materials would be classified as a fiber-reinforced composite. The basic reinforcing element is the cellulose microfibril and the surrounding matrix is represented by hemicellulose and lignin.

According to Muench [121] the fiber cell wall is composed of several sets of helical springs embedded in a matrix of non-crystalline material, in idealizing the helical winding of microfibrils in the cell wall. Other approaches suggested that single wood pulp fiber be formed by several layers, each of them with a specific role on its physical and mechanical properties. The primary cell wall consists of an unoriented cellulose microfibril network in a lignin-hemicellulose matrix. The secondary cell wall consists of three layers, which are mainly distinguished by a difference in the orientation of the cellulose fibrils. One of these layers –  $S_2$  – represents about 80 % of the secondary cell wall, which have its fibrils helically oriented around the fiber axis. Thus the mechanical properties of the fiber is governed by mechanical properties of the  $S_2$  layer [154].

The work of Schniewind [159] and Mark [111] is based on the concept of a laminated structure, thus recognizing the different layers in the tracheid cell wall. Each cell wall layer is assumed to consist of cellulose microfibrils embedded in a matrix of hemicelluloses. The lignin present is considered to exist in separate isotropic lamellae located in the middle of each cell wall layer.

Mark [112] has demonstrated that the parameters governing the elastic properties of the cell wall are the degree of crystallinity, the orientation of the microfibrils and the mechanical properties of the matrix polymers. In Mark's model the fiber is represented as a rectangular rod obtained, as it were, by opening the fiber longitudinally at the lumen, and the microfibrils are assumed to be continuous crystalline filaments. According to Salmén's model for the cell wall the fiber is represented as a rectangular rod, by pressing the hollow fiber in the cross direction and by interlocking the two adjacent planes of the lumen [154]. Thus, the fiber wall is built up as a laminate. In this last model the fibrils are assumed to be discontinuous. Both theories take into account the influence of the fibril angle on the elastic modulus in air and in water of a wood pulp fiber.

Kerr and Goring [81] proposed a structural arrangement for lignin, cellulose and hemicellulose in the  $S_2$  layer of the secondary cell wall. In their interrupted lamella model the microfibrils are dispersed in a lignin matrix. They concluded that the hemicellulose not only exists as a matrix around the microfibrils but must also be present in the lignin-containing entities. Later on, this cell wall model was modified to a "honeycomb" structure [155], where the lignin is located in discontinuous patches surrounded by the continuous fibrillar phase.

The structural rigidity of wood pulp fibers is dependent both on the stiffness

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of the main polymeric components: cellulose, hemicellulose and lignin, and on the structural organization of these components, as suggested by the models presented so far. The moisture content in particular has a considerable effect on the stiffness of the wood polymers and is thus an important parameter to be taken into consideration when describing fiber properties.

Salmén, Kolseth and de Ruvo [153] presented a model which enables the softening effect of water on wood pulp fibers. Two softening regions are suggested, one attributed to the glass transition of the water plasticized hemicellulose matrix and the other to the softening of disordered cellulose chains. It was demonstrated that the influence of water in the range of 25 to 90 % relative humidity can be described by the softening of the hemicellulose matrix. The fibril angle of the  $S_2$  layer and the chemical composition of the fiber were shown to have little influence on the relative change in modulus due to this hemicellulose softening. It was also shown that fiber softening occurring when fibers are immersed in water can be suitably modeled by treating the microfibrils as discontinuous reinforcing elements in the hemicellulose matrix of the fiber wall. Table 3.1 gives the measured values of relative rigidity (here defined as the ratio of the elastic modulus to its value at a reference state, usually 25 °C, 0 % RH) and the calculated values according to the micromechanical model by Salmén *et al* [153]. It should be recognized that the predicted values take account only of matrix softening occurring in the humidity region between 25-90 % RH. At higher humidities a gradual softening of the disordered regions in the microfibrils may reduce the relative rigidity appreciable, and then there will be poor agreement between the experimental values of the relative rigidity and the predicted values based only on matrix softening. The effect of this softening can only be accounted for in the model when the disordered regions soften fully on immersion in water.

Estimates of softening effects in wood and wood fibers based on a laminate concept have previously been made by Cave [30], who calculated the influence of humidity on the longitudinal modulus of wood, and by Mark [112], who estimated the influence of structural factors when the matrix is softened but only for a single fiber wall. In these estimates the reinforcing microfibrils have been considered as continuous and not influenced by the environment.

All structural models for the native fiber cell wall seem to agree that the hemicellulose is located on the surface of microfibrils but does not enter the microfibril structure [45]. This means that hemicellulose is coupled in parallel

Table 3.1: Relative rigidities due to different changes in the environment for a number of softwood tracheids (taken from Salmén, Kolseth and de Ruvo (1985)).

|                          | Cellulose | Hemicellulose | Lignin | Torsion (25-90 % RH) | Tension (50 % RH - wet) |
|--------------------------|-----------|---------------|--------|----------------------|-------------------------|
|                          |           |               |        | Meas. - Calc.        | Meas. - Calc.           |
| TMP                      | 44        | 30            | 26     | -                    | 0.4 - 0.25              |
| Chlorite delignified TMP | 45        | 30            | 25     | 0.52 - 0.52          | -                       |
|                          | 54        | 36            | 10     | 0.49 - 0.49          | 0.2 - 0.23              |
| Unbleached kraft         | 74        | 18            | 8      | 0.56 - 0.51          | -                       |
| Bleached kraft           | 78        | 22            | 0      | 0.47 - 0.50          | -                       |
|                          | 80        | 20            | 0      | 0.48 - 0.50          | 0.2 - 0.25              |
| Holocellulose            | 77        | 21            | 2      | 0.55 - 0.50          | 0.4 - 0.29              |
| High yield kraft         | 60        | 19            | 21     | 0.52 - 0.53          | -                       |
|                          | 72        | 20            | 8      | 0.55 - 0.52          | 0.3 - 0.25              |

with the cellulose in the fiber. As the wet rigidity of hemicellulose is negligible, the rigidity of the wet fiber must be due to the rigidity of the wet cellulose microfibrils only [45]. Thus the decrease in the modulus of pulp fibers on wetting must be due to the softening of the cellulose. As the modulus of the dry hemicellulose is much lower than that of cellulose [112], [36], the relative rigidities of wood pulp fibers should also be independent of the hemicellulose. *This means that the difference between the relative rigidities of different cellulosic fibers can generally be ascribed to differences in their cellulose components.*

There are two principal models for the coupling between ordered, crystalline cellulose and disordered, amorphous cellulose in the cellulose fibrils. The continuous microfibril model implies crystalline microfibrils parallel coupled to a matrix of amorphous cellulose. The discontinuous microfibril model implies crystalline cellulose coupled in series with amorphous cellulose in the microfibril. In the parallel coupled cellulose, the deformation would occur by shear of the crystalline microfibrils in the amorphous matrix. In the series coupled cellulose, deformation would occur through extension of the amorphous regions. [45]. Experimental data by Sakurada and coworkers [148], and Stöckmann [175] strongly support the series coupling in native (ramie) and regenerated (rayon) cellulose. For a series coupling the relative rigidity (the ratio of the modulus of the wet fiber to that of the dry fiber) of the wet fiber is approximated by the relative elastic modulus of the wet amorphous cellulose. Thus assuming series coupling of the amorphous and crystalline cellulose in the microfibril of the wood fibers, the relative rigidity of the fiber can be shown to be proportional to the extent of softening of the

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amorphous cellulose in the fiber.

Wolcott *et al* [204] used the cellular solids theory to calculate the fiber cell wall modulus of *Liriodendron tulipifera*, assuming that samples behave as elastomeric foams. As expected, the values for the elasticity modulus determined from 0.9 mm wood flakes were found to decrease with increasing temperature and moisture (see Figure 3.18). The only temperature and moisture ratio combination above the glass transition temperatures of lignin and hemicellulose is 225 °C for 0 % moisture. This condition also corresponds to the lowest cell wall modulus.

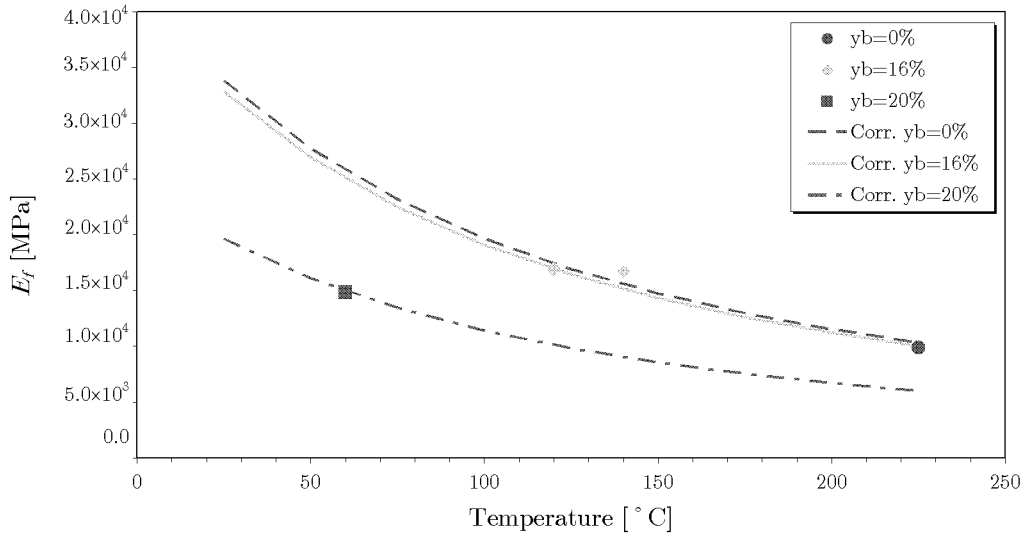


Figure 3.18: Curve fitting (lines) of Wolcott *et al* experimental data (filled symbols) for the fiber cell wall modulus of *Liriodendron tulipifera* (0.9 mm flakes) [204].

At the risk of some simplification, these experimental values were fitted to Eqn. 3.32, as to have an estimation of the  $E_f$  dependency on temperature and fiber moisture content:

$$E_f = E_{f_{fit}} \exp \left( -\frac{\beta_T}{T + T_{fit}} + \frac{\beta_{y_b}}{y_b - y_{b_{fit}}} \right) \quad (3.32)$$

where  $y_b$  is the mass fraction of adsorbed water on the fiber surface, expressed as kg H<sub>2</sub>O/kg ds (dry cell wall material). The parameters obtained are summarized on Table 3.2.

Table 3.2: Parameters of the fitting to determine Ef.

| $\beta_T$ | $\beta_{y_b}$ | $T_{fit}$ | $y_{b_{fit}}$               | $E_{f_{fit}}$ |
|-----------|---------------|-----------|-----------------------------|---------------|
| [°C]      |               | [°C]      | [kg H <sub>2</sub> O/kg ds] | [MPa]         |
| -2024     | 0.0016        | 468       | 0.2029                      | 562           |

### Additive

The contribution of each additive used in this work to the elasticity modulus of the composite was neglected, as the additive content of the paper samples was very low. In fact, experimental data obtained by thermal mechanical analysis for paper samples with different amounts of additives, usually used in the paper making industry, shown that these did not affect the elasticity modulus of paper, as the modulus for paper with additive did not differ significantly from that of a sample with no additive. Therefore, the transverse modulus of the solid phase becomes (see Eqn. 3.26):

$$E_s \simeq E_f \quad (3.33)$$

### Fluid (gas (air + water vapor) + liquid water)

The fluid contribution to the elasticity modulus of the composite,  $E_{fluid}$ , is given by either the transverse or the longitudinal rule of mixtures, depending on what model arrangement is considered (see Figure 3.16): gas and liquid water assembled in series or in parallel. It follows from the definition of the longitudinal and transverse rule of mixtures that,

$$\frac{1}{E_{fluid}} = \frac{\phi_g}{E_g} + \frac{\phi_l}{E_l} \quad (\text{Model I}) \quad (3.34)$$

$$E_{fluid} = \phi_g E_g + \phi_l E_l \quad (\text{Model II}) \quad (3.35)$$

where  $\phi_g$  and  $\phi_l$  are the volume fractions of gas (air and water vapor) and liquid water in the fluid phase, respectively.

The contribution of fluid flow to the elastic modulus was calculated from Boyle's law if the fluid is a gas like air. If the initial pressure of the gas is  $P_{g0}$  (usually atmospheric pressure) then the pressure,  $P_g$ , after a certain level of strain is given by

$$P_g V_g = P_{g0} V_{g0} \quad (3.36)$$



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where  $V_g$  and  $V_{g_0}$  define the volume occupied by the gas in the cellular structure at both states of compression. The pressure which must be overcome by the applied stress is

$$P'_g = P_g - P_{g_0} \quad (3.37)$$

and the contribution of the gas is given by [51]:

$$E_g = \frac{\partial P'_g}{\partial \varepsilon} = \frac{\left(1 - \frac{\rho}{\rho_s}\right) (1 - 2\nu) P_{g_0}}{\left(1 - \frac{\rho}{\rho_s} - \varepsilon (1 - 2\nu)\right)^2} \quad (3.38)$$

where  $\nu$  takes into account the lateral deformation of the cells. If lateral deformation is neglected, the contribution of the gas phase to the elasticity modulus of the cellular material may be expressed simply as:

$$E_g = \frac{P_g - P_{g_0}}{\varepsilon} \quad (3.39)$$

If the gas pressure at the initial temperature  $T_0$  is  $P_{g_0}$ , then the contribution of the gas at a temperature  $T$  is given by [51]:

$$E_g = E_{g_0} \left( \frac{T}{T_0} \right) \quad (3.40)$$

When  $P_{g_0}$  is atmospheric pressure, this contribution is small: it contributes to the modulus of closed-cell elastomeric foams but does not change that of other foams much. On the other hand, if  $P_{g_0}$  is much larger than atmospheric pressure or if the cell fluid is not air but is a liquid (when the almost-incompressible response of the fluid requires additional stretching of the cell faces) then the contribution of the cell fluid must not be neglected.

When the foam contains a liquid, the compression of the cells is accompanied by the compression of the fluid (if they are closed) or by the *flow from one cell to another (if they are open)*, and this introduces a new dependence on strain-rate. When the foam is compressed, the fluid that it contains is squeezed out; when extended, fluid is drawn in. The fluid has a viscosity, so work is done forcing it through the interconnected cells of the foam. The faster the foam is deformed the more work is done; the pore fluid flow introduces a strongly strain-rate dependent contribution to the strength.

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There are a number of ways to analyze this [69]. The simplest way is to consider the foam as a porous medium characterized by an absolute permeability,  $K$ ; then the fluid flow through the medium is described by Darcy's relation:

$$u_i = -\frac{K_i}{\mu_i} \frac{\partial P_h}{\partial L} \quad (3.41)$$

where  $u_i$  is the velocity of the fluid in the thickness direction of the medium,  $\mu_i$  is the dynamic viscosity of the fluid  $i$ ,  $K_i$  its permeability, and  $\frac{\partial P_h}{\partial L}$  is the hydraulic pressure gradient across the thickness  $L$  of the medium. This relation is valid when the inertial forces are negligible compared to the viscous forces.

The fluid flow through the cells requires a drop in pressure as its driving force. In this case, the pressure that must be overcome by the applied stress is the fluid pressure. Therefore, the contribution of the fluid to the Young's modulus of an open-celled foam may be derived as follows: if, on a first approach, one considers a *parallel assembly* of the three phases, solid, gas and liquid water (see Model II), it may be assume that the strain rate,  $\dot{\varepsilon}$ , is given by

$$\dot{\varepsilon} = \frac{\partial \varepsilon}{\partial t} = \frac{u_s}{L} = \frac{u_g}{L} = \frac{u_l}{L} \quad (3.42)$$

where  $u_s$ ,  $u_g$ ,  $u_l$ , are the solid, gas, and liquid water velocities, respectively. Also, the pressure gradient across the medium is proportional to

$$\frac{\partial P_h}{\partial L} \simeq -\frac{\sigma_i}{L} \quad (3.43)$$

where  $\sigma_i$  is the stress applied on each phase,  $s$ ,  $g$  or  $l$ . Substituting Eqns. 3.42 and 3.43 into Eqn. 3.41, gives the contribution of each phase, gas and liquid, to the strength of the open-celled foam:

$$\sigma_g = \frac{\mu_g L^2}{K_g} \frac{\partial \varepsilon}{\partial t} \quad (3.44)$$

$$\sigma_l = \frac{\mu_l L^2}{K_l} \frac{\partial \varepsilon}{\partial t} \quad (3.45)$$

*Paper (composite: solid phase + fluid)*

The elasticity modulus of the paper sample, from the composite point of view, is seen as the sum of the contributions of both solid and fluid phases. Consequently, the following relation based on the longitudinal rule of mixtures can then be written:

### 3. Mathematical Model for High-Temperature Pressing of Paper 225

$$E = E_s^* \phi_s + E_g \phi_g + E_l \phi_l \quad (3.46)$$

where  $\phi_s$ ,  $\phi_g$  and  $\phi_l$  are now the volume fractions of the solid, gas and liquid phases in the composite.

Eqn. 3.13 does not take into account the contribution of the gas and liquid phases. In fact, it only includes the cell wall material (it should be remembered that in Eqn. 3.13 the volume fraction of the solid phase is already included). Taking Eqns. 3.13 and 3.46, the elasticity modulus of the solid phase would then be given as

$$E = E_s^* \phi_s = C_2 E_s \rho_{rel}^2 = (C_2 E_s \rho_{rel}) \rho_{rel} \quad (3.47)$$

Again, substituting Eqn. 3.47 into Eqn. 3.46 to determine the elasticity modulus of the composite in compression, Eqn. 3.46 becomes

$$E = E_s^* \phi_s + E_g \phi_g + E_l \phi_l = \quad (3.48)$$

$$= C_2 E_s \rho_{rel}^2 \phi_s + E_g \phi_g + E_l \phi_l \quad (3.49)$$

Now, introducing the nonlinearizing function  $\Phi(\varepsilon)$  into Eqn. 3.49, the elasticity modulus of the composite may be expressed as:

$$E = C_2 E_s \rho_{rel}^2 \Phi(\varepsilon) \phi_s + E_g \phi_g + E_l \phi_l \quad (3.50)$$

The volume fractions of each phase in the composite may be determined assuming equal deformation of its constituents, *i.e.* the volume fractions equal the area fractions. The next step is to define  $\alpha$  as the ratio of the solid phase area to the total area of the RVE, and  $\beta$  as the ratio of the area occupied by the liquid phase to the area of the fluid, *i.e.* gas and liquid water (see Figure 3.19).

The volume fractions of the constituents in every RVE then become as follows:

$$\phi_s = \frac{V_s}{V} = \frac{A_s}{A} = \alpha \quad (3.51)$$

$$\phi_g = \frac{V_g}{V} = \frac{A_g}{A} = (1 - \alpha)(1 - \beta) \quad (3.52)$$

$$\phi_l = \frac{V_l}{V} = \frac{A_l}{A} = (1 - \alpha)\beta \quad (3.53)$$

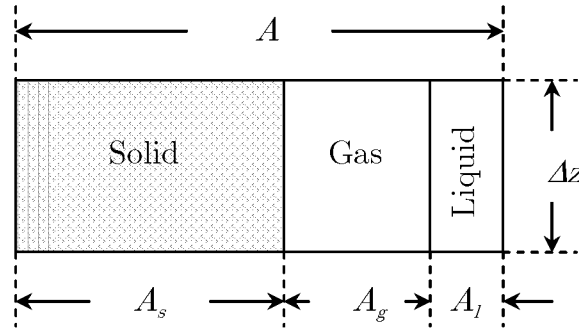


Figure 3.19: Schematic diagram of the representative volume element dimensions.

where  $V$ ,  $V_s$ ,  $V_g$  and  $V_l$  represent the volume of the RVE and that occupied by each phase, solid, gas and liquid.

Finally, the relative density is defined as the ratio of the apparent density of the porous material to the real density of the solid phase (cell wall material, additive and adsorbed water):

$$\rho_{rel} = \frac{\rho}{\rho_s} \quad (3.54)$$

where

$$\rho = \frac{m_{cw} + m_a + m_b}{V} \quad (3.55)$$

$$\rho_s = \frac{m_{cw} + m_a + m_b}{V_{cw} + V_a + V_b} = \frac{1 + y_a + y_b}{1/\rho_{cw} + y_a/\rho_a + y_b/\rho_b} \quad (3.56)$$

and

$m_{cw}$ ,  $m_a$ ,  $m_b$  = mass of the cell wall material, the additive and adsorbed water;

$V_{cw}$ ,  $V_a$ ,  $V_b$  = volume occupied by the cell wall material, the additive and the adsorbed water;

$y_a$  = mass of additive per kg of dry cell wall material;

$\rho_b$  = density of the adsorbed water.

Assuming there is no dry solid mass transfer from one cell to another, a mass balance may be written as

$$m_{cw} + m_a = (m_{cw} + m_a)_0 \quad (3.57)$$

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where the subscript “0” denotes the initial state of the RVE. From Eqns. 3.54 and 3.55 the relative density of each cell is expressed as

$$\rho_{rel} = \frac{\rho_0 \frac{\Delta z_0}{\Delta z} + \frac{mb}{A_z \cdot \Delta z}}{\rho_s} \quad (3.58)$$

where  $\Delta z$  is the thickness of the cell,  $\Delta z_0$  its initial value,  $A_z$  is the surface area of the cell open to fluid flow and  $\rho_0$  the initial apparent density of the dry cell defined as

$$\rho_0 = \frac{(m_{cw} + m_a) / N_{ijk}}{(A_T \cdot L_{z_0}) / N_{ijk}} = \frac{m_{cw} + m_a}{A_T \cdot L_{z_0}} \quad (3.59)$$

where  $N_{ijk}$  is the number of cells in the entire mat,  $A_T$  the surface area of the web and  $L_{z_0}$  its initial thickness. The subscript “z” is used hereafter to indicate the thickness direction. The in-plane directions will be denoted as “x” and “y”.

#### 2. Viscous properties of paper

*“Fiber”: Wood pulp fibers + adsorbed water*

The viscous behavior of paper arises, in part, from the fiber wall structure where crystalline and amorphous regions mix. Purely crystalline materials are usually elastic. They do not exhibit the complex rheology observed in amorphous materials. Amorphous materials have a glass transition temperature,  $T_g$ , below which they are glass-like, rigid, stiff and brittle. Above  $T_g$ , they soften and become increasingly fluid-like.

Paper consists mainly of lignin, hemicellulose and cellulose. The lignin and hemicellulose are amorphous polymers and essentially thermoplastic [54], while the cellulose is semicrystalline containing disordered (amorphous) and ordered regions (crystalline). For the polymeric wood components the dry glass transitions occur at rather high temperatures (see Figure 2.42, **Chapter 2**), at which decomposition rates are significant.

The creep, relaxation and plastic deformations of paper can be visualized as reorganization of the fibrils within the matrix, and it may be concluded that the rate-dependent dynamic response of paper should be sensitive to its content of lignin and hemicelluloses.

The glass transition temperatures of hemicellulose, native lignin and amorphous cellulose when dried are about 200 °C, 205 °C and 230 °C, respectively, as suggested by Salmén [154]. These values however, decrease significantly when

the material is in the wet state. The plasticizing effect of water lowering the glass transition temperatures of the individual wood polymers is exemplified in Figures 3.20a, 3.20b and 3.20c. The data presented has been estimated using the approach of Kaelble (see [153]) and is based on a free volume concept. Hemicellulose and amorphous cellulose have glass transition temperatures well below 100 °C in the presence of moisture [154], [149]. Lignin reaches at fairly low moisture content an equilibrium state, after which the glass transition is not affected by additional amounts of water. In fact, the glass transition temperature has been reported to be 115 °C for native lignin in a saturated state and for moist chemically modified lignin (*e.g.* kraft and sulphite lignin's) can be as low as 80 °C [154], [86].

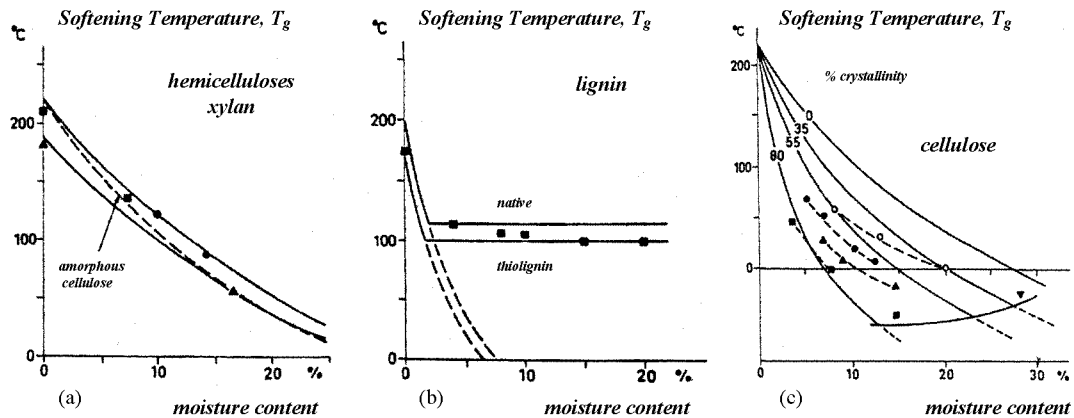


Figure 3.20: Influence of water on the glass transition temperature as calculated using the approach of Kaelbe of: (a) xylan, the squares and triangles refer to measurements by Goring and the rings to measurements by Häkkinen; (b) native lignin and thioglignin, the squares refer to measurements on thioglignin by Sakata and Senju, the dotted part of this calculation is not valid since the limit for water sorption is exceeded here; (c) the squares refer to experimental data on coton, the triangles and rings to measurements by Ogiwara *et al* on various treated dissolving pulps, and the turned over triangle to viscose. The lower border line crossing the  $T_g$  lines of different crystallinities indicates completely swollen cellulose. (adapted from [153])

For several decades the development of paper strength was of great interest. Various aspects of this problem have been investigated more or less thoroughly and the existing theories have been published in many monographs. Nevertheless, one aspect of this problem has hardly been dealt for a long time. This is

the problem of changes in the physical state of the wood fibers components in the course of paper manufacture. The effect of a transition of the polymeric constituents of paper from a glassy to a highly elastic state which dominates in the process of paper manufacture and converting is of paramount importance. For cellulose and materials based on it the transition: wet cellulose - dry cellulose is of particular importance. Wet cellulose is in a highly elastic state whereas dry cellulose is in a glassy state. Hence, a change in the physical state of cellulose may occur in the course of its drying.

The glass transition temperature will determine whether the wood constituent polymers are in the glassy or the rubbery phase. Although the highly crystalline cellulose includes amorphous regions, the contribution of these regions to the viscoelastic properties of wood is negligible [153]. Hemicelluloses are branched polymers and have low glass transition temperatures, below room temperature. It can be assumed that the hemicelluloses are in the rubbery state throughout the entire temperature and moisture range during hot-pressing [12]. It is believed that within the moisture and temperature ranges of impulse drying, lignin softening is the most dominant phenomenon because the other amorphous polymers being always above their glass transition temperatures [197]. Consequently, for well delignified pulps, such as bleached pulps, the dewatering effect is fairly independent of fibers thermal softening whereas for unbleached and mechanical pulps (*i.e.* lignin containing pulps) some additional softening can be verified. It should also be remembered that impulse drying is performed at high speeds, which means that the softening temperatures of the polymers involved may be shifted to higher temperatures due to the dynamic character of the process [199].

The viscoelastic flow of polymers can quite often be described in terms of thermal activation [199]. In such theories, the thermal dependence of the viscoelastic properties can be described using the time-temperature superposition principle, which is based on the fact that those properties show similar behavior at different temperatures for a given material [60]. The known Williams, Landel and Ferry [203] equation is an empirical description of the viscous property dependence of a given amorphous material in terms of its glass transition temperature. This equation predicts with rather accuracy the material behavior within the elastomeric region. Another empirical equation is the Arrhenius expression, which properly describes the response of the material below its glass transition temperature [41]. Therefore, the thermal softening of the polymeric components of paper may be

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described by the following expression, below the glass transition temperature:

$$\mu_f(T) = \mu^* e^{\frac{\Delta G}{RT}} \quad (3.60)$$

where  $\Delta G$  is the activation energy,  $\mu_f$  the fiber viscous parameter,  $R$  the universal gas constant and  $\mu^*$  a model parameter.

At low temperatures, Rättö and Rigdahl found an activation energy, describing the temperature-dependent deformation of paper, of about 6 kJ.mol<sup>-1</sup> [141], which may indicate that only small molecular movements are involved [141]. At higher temperatures, the glass transition of the wood polymers (mainly cellulose) is expected to be approached, which implies movements of larger molecular segments and also a higher activation energy. In other words, a second mechanism for the softening may be involved at higher temperatures. Rättö [141] then suggested a series coupling of different mechanisms, each having its own activation energy ( $\Delta G_1$  and  $\Delta G_2$ ), for the calculus of the effective modulus:

$$\frac{1}{\mu_f(T)} = \frac{1}{\mu_1^* e^{\frac{\Delta G_1}{RT}}} + \frac{1}{\mu_2^* e^{\frac{\Delta G_2}{RT}}} \quad (3.61)$$

The activation energy  $\Delta G_1$  can be considered to describe the thermal softening well below the major transition temperature. Rättö used the same approach introduced by Salmén [154] to evaluate the elastic tensile modulus of paper at high temperatures. By doing so, he assumed that the modulus  $\mu_f$  decreased around the main transition. Assuming a moisture content of 5 % corresponding to a main transition temperature of about 125 °C, the ratio of the logarithm of the modulus ( $\ln \mu_f$ ) to the logarithm of the modulus at 20 °C ( $\ln \mu^*$ ) was assumed to decrease to 0.5 at 125 °C and the material properties were adjusted accordingly (see Figure 3.21). This procedure gave an activation energy of 120 kJ.mol<sup>-1</sup> [141]. At temperatures above 145 °C, the modulus was assumed to be constant. Unfortunately, Rättö did not specify the magnitude of the parameters  $\mu_1^*$  and  $\mu_2^*$  in his work, and therefore those parameters were estimated here using the *Solver* function of Excel<sup>®</sup>. The following values were found: 2.33 and  $1.46 \times 10^{-15}$  Pa.s, respectively (assuming that  $\mu_f$ ,  $\mu_1^*$  and  $\mu_2^*$  are expressed in Pa.s).

Finally, plotting the modulus determined by Eqn. 3.61 (Model 2)), following the approach developed by Rättö, and data obtained by a simple Arrhenius expression used to describe a single softening mechanism (Eqn. 3.60, Model 1), it is clear that the curves follow the same trend, but the magnitude of the modulus



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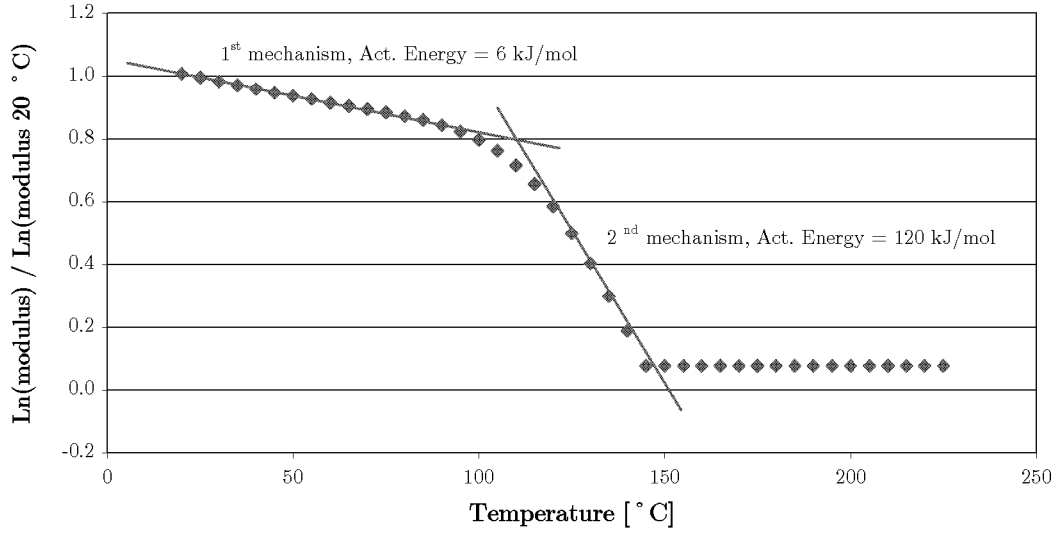


Figure 3.21: The ratio of the logarithm of the modulus  $\mu_f$  to the logarithm of the modulus at 20 °C, as a function of temperature using two softening mechanisms.

$\mu_f$  is quite different (see Figure 3.22).

The work performed by Rättö [141] shows that the softening behavior of paper can be described using an Arrhenius expression. Even though the series coupling model was based on polymer physics, it should be considered only as a suggestion. A better understanding of the mechanical-thermal transitions of wood polymers and their activation energy is certainly needed in this case. A drawback of the theoretical method is that the inclusion of moisture dependence of the viscous parameter is complex. For simplicity, however, a simple Arrhenius expression was used in the present work. The parameter  $\mu^*$  and the activation energy considered here were  $1 \times 10^8$  Pa.s and  $3241 \text{ J.mol}^{-1}$ , respectively, as already used by Carvalho to estimate the fiber viscous parameter in the case of MDF [29]. It is worth noting that these two approaches, performed by Rättö and Carvalho, give quite different results. In fact, those used by Carvalho are in the order of  $10^8$  Pa.s, far above the values presented in Figure 3.22.

#### Water

Water viscosity is strongly temperature dependent. At 20 °C, water viscosity is approximately 1.00 mPa.s whereas at 60 °C it is about 0.5 mPa.s, *i.e.* a drop of about 50 %. Then, increasing the temperature of the wet web, water viscosity

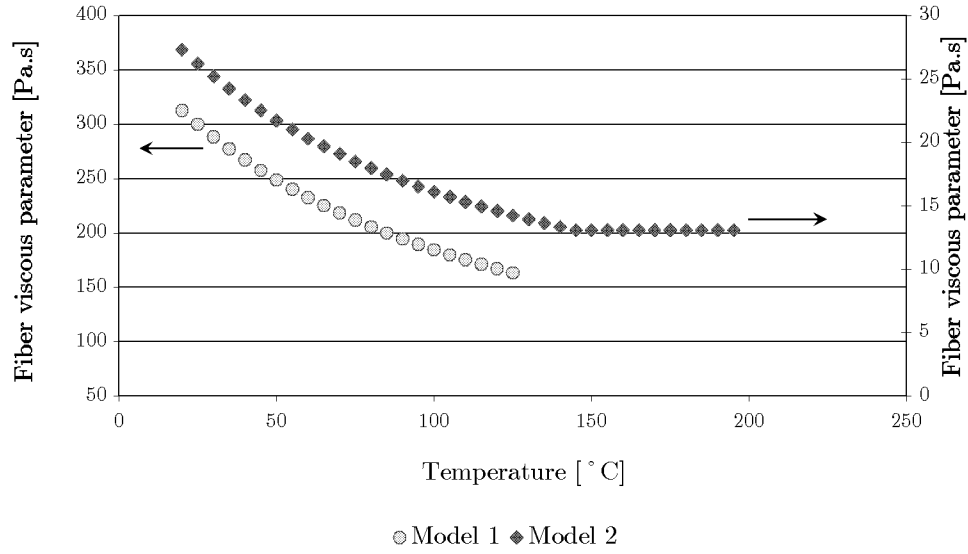


Figure 3.22: Comparison between a model with one softening mechanism (Model 1) and a model with two softening mechanisms (Model 2).

is reduced as it is the flow resistance into the sheet, as well as through the felt.

Water viscosity may be determined as a function of temperature using the following correlation, valid for temperatures above 20 °C:

$$\mu_l = 1.002 \times 10^{y'} \quad (3.62)$$

$$\text{with } y' = \frac{-1.37272(T - 20) - 0.001053(T - 20)^2}{T + 105} \quad (3.63)$$

where  $\mu_l$  is the liquid water viscosity expressed in mPa.s and  $T$  the temperature of the fluid in °C.

*Additives (Calcium carbonate, Alkyl ketene dimer, Cationic starch, Polyamide epichlorohydrin resin)*

The viscoelastic properties of paper are directly dependent on those of each additive. Despite its complexity, understanding the rheology of the additive is important for two reasons. First, the rheological behavior of the additive is a key factor influencing runnability and water retention. Understanding how to control the additive rheology is critical for achieving good runnability and optimum placement of the additive. Second, rheology is a powerful tool for characterizing the interactions between the different additives of a given formulation.

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Viscosity is the key rheological property for fluid materials such as paper additives. There are two general classes of flow behavior: Newtonian fluids, which have a constant viscosity, and non-Newtonian fluids, which have a viscosity that is dependent on the shear rate. On a log-log plot the curve of viscosity versus shear rate is often a straight line. This kind of rheological flow behavior is known as a “power law fluid” and is quite common for polymer fluids and colloidal systems [146].

There are two types of non-Newtonian flow behavior: pseudoplastic or shear-thinning behavior and dilatant or shear-thickening behavior. For a pseudoplastic material, the viscosity decreases with increasing shear rate, whereas for dilatant materials the viscosity increases along with shear rate. An additional type of flow behavior is known as Bingham plastic flow, which is an idealized type of flow having a combination of yield stress along with Newtonian flow above the yield stress. Most materials with yield stresses exhibit plastic flow behavior, which is really a combination of yield stress with pseudoplastic or shear-thinning flow.

These four basic rheological types of flow are the building blocks for more complex types of flow behavior. Generally, paper coatings exhibit yield stresses along with shear-thinning behavior followed by near-Newtonian flow at high shear [146].

In addition, rheological properties for fluid materials such as paper additives are time-dependent. There are two types of time-dependent rheological flow: thixotropy and rheopexy. As shearing occurs, the viscosity of a thixotropic system decreases with time while the viscosity of a rheoplectic system increases with time. Thixotropy is closely related to yield and shear-thinning behavior, which in turn is related to the shear-induced breakup of the internal structure of the fluid. Rheopexy is closely related to the same phenomenon that gives rise to dilatant or shear-thickening behavior. In a rheoplectic system, there is a shear-induced buildup of internal structure, resulting in an increase of viscosity with time.

Much of the non-Newtonian behavior of paper coatings (and paper additives in general) is due to the presence of particles in the coating formulation. The presence of particles causes an increase in viscosity; that is, it takes more force to achieve the same amount of flow as that of a fluid without any particles.

Einstein showed that the relative viscosity,  $\mu_{rel}$ , defined as the ratio of the viscosity of the suspension,  $\mu_{suspension}$ , to the viscosity of the suspending medium,

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$\mu_{medium}$ , is equal to:

$$\mu_{rel} = 1 + 2.5\phi_{solids} \quad (3.64)$$

where  $\phi_{solids}$  is the volume fraction of solids (see [146]). This equation holds true up to volume fractions of about 0.1. Above this value, inter-particle interactions causes a further increase in viscosity. As more and more particles are added, the suspension approaches a rigid state in which there is no longer room for the particles to move. This causes an exponential increase in viscosity as the volume fraction approaches the maximum packing volume fraction,  $(\phi_{solids})_m$ . The viscosity of concentrated suspensions is often described using the Mooney equation [120]:

$$\mu_{rel} = \exp [2.5\phi_{solids} / (1 - \phi_{solids} / (\phi_{solids})_m)] \quad (3.65)$$

or the Krieger-Dougherty equation [84]:

$$\mu_{rel} = (1 - \phi_{solids} / (\phi_{solids})_m)^{-2.5(\phi_{solids})_m} \quad (3.66)$$

It is also clear from many studies on paper coating formulations that paper coatings are viscoelastic materials. At small deformations below 1 % strain, the coatings behave more like a viscoelastic solid than a fluid [28]. However, at higher deformations (on the order of 1 % - 3 % strain), the coating structure begins to break down and the coatings behave more like viscoelastic fluids. One recent article discusses that the viscoelastic properties of paper coatings are primarily due to inter-particle association and flocculation [183].

Wet end additive formulations are complex mixtures of dispersed particles, water-soluble polymers and other additives. These components can interact and associate with each other, generating a wet structure that contributes to increase viscosity and viscoelastic behavior. In the present study four additives have been individually incorporated in the pulp suspension: calcium carbonate as a filler; alkyl ketene dimer acting as an internal sizing agent; cationic starch as a dry strength additive; and finally, the polyamide epichlorohydrin resin as a wet strength additive.

#### **Case 1** *Fillers - Calcium carbonate*

Precipitated calcium carbonate (PCC) is a fully synthetic product, and commercial PCC pigments typically have  $\text{CaCO}_3$  contents higher than 97 %: the

### 3. Mathematical Model for High-Temperature Pressing of Paper 235

remainder is  $\text{MgCO}_3$  and other residues. PCC coating pigment is produced in slurry form at solids contents of 71-75 %. This is not the case of the slurry used in the present case, which has a solids content of 30 %. In fact, the solids content of the pigment slurries are usually made as high as possible to keep the transportation costs as low as possible and to meet the requirements of the solids content of the coating color. The main limiting factor in reaching the highest possible solids content is viscosity of the slurry. The size, size distribution, specific surface area, and shape of the particles affect the viscosity of the pigment slurry. If the particle size is big, the size distribution is wide, and particle shape is roundish, it is possible to have low viscosity at relatively high solids content. But, if the situation is opposite, very high viscosity already at relatively low solids content may be found. The information on the properties of the PCC slurry used in the present work is very scarce and it was not possible to determine the viscosity of the slurry. Nevertheless, Eqns. 3.65 and 3.66 were used to estimate this parameter. The volume fraction of solids is given by:

$$\phi_{\text{solids}} = \frac{y_{\text{solids}}/\rho_{\text{solids}}}{y_{\text{solids}}/\rho_{\text{solids}} + 1/\rho_{\text{medium}}} \simeq 0.124 \quad (3.67)$$

If one assumes that the suspending medium is water, the density of calcium carbonate is  $2.83 \text{ g.cm}^{-3}$  [95] and the solids ratio, *i.e.* the ratio of solids to the total mass,  $y_{\text{solids}}$ , is 0.4. As  $\phi_{\text{solids}} > 0.1$ , Eqn. 3.64 is no longer valid and the viscosity of the slurry may be estimated as:

$$\mu_{\text{suspension}} = (\mu_l)_{20^\circ\text{C}} \exp [2.5 \times 0.124 / (1 - 0.124/0.64)] \simeq 1.47 \text{ mPa.s} \quad (3.68)$$

where  $\mu_l$  is the water viscosity at  $20^\circ\text{C}$ , *i.e.* approximately 1 mPa.s. As mentioned before, the viscosity of concentrated suspensions is dependent on the solids volume fraction and the maximum packing volume. Here the value  $(\phi_{\text{solids}})_m = 0.64$  was used, as suggested by Roper [146] for monodisperse spherical particles under low shear. Alternatively, Eqn. 3.66 gives a very similar result, as follows:

$$\mu_{\text{suspension}} = (\mu_l)_{20^\circ\text{C}} (1 - 0.124/0.64)^{-2.5 \times 0.64} \simeq 1.41 \text{ mPa.s} \quad (3.69)$$

The estimates for viscosity obtained here are lower than the reported in the literature. In fact, Imppola [75] suggested a value of 21.6 mPa.s for a PCC

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suspension at 62 % mass fraction of solids, which is not surprising since it contains a higher amount of solid particles. It is worth noting, however, that these values serve as estimates only and do not represent the real viscosity of the suspension used.

#### **Case 2** *Internal sizing agent - AKD (Alkyl ketene dimer)*

Alkyl ketene dimer is one of the most important neutral-alkaline sizing agents, and it has been known and used for more than thirty years. However, there is still some uncertainty in regard to its sizing mechanism: whether or not it really reacts with cellulosic components of the papermaking furnish.

The purpose of internal sizing is to modify the surface of paper to control water penetration, in order to either limit the pickup in a converting operation (at the size press or coater), or to impart water repellency to the end product.

Data from the manufacturers report a viscosity lower than 200 mPa.s for AKD suspensions [1].

#### **Case 3** *Dry strength additive - CS (Cationic starch)*

Starch is a natural polymer consisting of glucose monomers. The starch polymer is chemically much like cellulose, the difference lies in the construction which gives these materials different properties. According with their structure, cellulose forms fibers, which are partly crystalline; starch is totally amorphous and forms granules. The starches used in the paper industry come from many different sources. The most commonly used sources are corn, potato, wheat and tapioca, depending on the geographical area.

Starch, for use as a dry strength additive in the papermaking process, has to be modified to get the desirable properties before, during and after the pressing/drying process. Cooked native starch tend to be very viscous and forms gels at very low dry solids. Roughly the modification process of starch can be divided into two main groups: the degrading and the substituting.

To render the starch good functionality, it is necessary to make additional modifications. Important properties that are developed for starches are binding power, water retention, and rheological behavior during varying temperature. For example, with acetylation or hydroxypropylation, better viscosity-temperature stability is reached. This means that the variations in starch viscosity is minimized during the process.

### 3. Mathematical Model for High-Temperature Pressing of Paper 237

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The most important function of starch is, of course, to act as a binder. Other properties that starch brings to the paper are stiffness and posture, as the starch film is stiff [19]. Stiffness of paper is very important for runnability in the printing press and for readability of the paper. This property however limits the use of higher amounts of starch where surface elasticity is important.

Cationic starches are currently starch ethers produced at a raised pH and temperature by an etherification reaction, using an epoxy reagent containing a quaternary ammonium group. Cationic wet end starches can be manufactured from any native starch but, for reasons of solubility and molecular size, are mainly produced from potato starch. Normally, the dosages of cationic starch amount to 0.2 - 2.5 % of wet end solids [19]. Once adsorbed it also remains fixed on the wet end components, which boosts the number of bonds between fibers and therefore increases the dry-strength of paper [73].

As in polymer solutions in general, the viscosity of a starch solution depends on the average molecular size, temperature and solids content. In the present case 2 % of cationic starch was added to the pulp suspension, but information on rheological properties are scarce. Nevertheless, the viscosity of coating starch is reported in the literature in the range 200-500 mPa.s [19].

#### **Case 4** *Wet strength additive - PAE (Polyamide epichlorohydrin resin)*

The class of poly(amido-amine)-epichlorohydrin wet-strength agents has found wide acceptance among papermakers for a number of reasons including excellent effectiveness, wide versatility, low cost and ease of use.

The wet-strength resin is incorporated into the paper matrix by evenly distributing the polymer solution in the aqueous slurry of cellulose fibers, after what water is removed by drainage and drying. It is an important part of wet strengthening of paper, that during the drainage of water, the polymer adsorbs onto the cellulose fibers to a very high extent. The formation of a polymer network with the paper matrix and the formation of covalent chemical bonds between the polymer and the cellulose fibers are thought to be important criteria for wet-strength development. The efficiency of cationic PAE wet strength resins is good in the pH range of 6-9. Common PAE solutions have a viscosity around 130 mPa.s [1].

*Paper (Composite)*

At the risk of some simplification, the viscous parameter of the composite may be described by the longitudinal law of mixtures. This approach has been used to estimate the viscoelastic properties for copolymers and mixtures of polymers [31].

$$\mu = y_f \mu_f + y_a \mu_a \quad (3.70)$$

where

$y_f$  = mass fraction of “fiber”;

$\mu, \mu_f, \mu_a$  = viscous parameter of paper, “fiber” and additive, respectively.

Experiments have been conducted on laboratory-scale equipment to verify the degree of additive retention on the pulp suspension [118]. It was then concluded that the effect of the additive was almost negligible as the additive retention was quite low. In such circumstances, the viscous parameter of paper is given by the properties of the wet fibers themselves. The contribution of the additive to the behavior of the fibrous network is complex, and not clearly understood. Additionally, the most deformation occurs within the fibrous part of the composite material, and therefore, the fiber dominates the rheological behavior of the whole system. Consequently, the effect of the additive on the viscous properties of the composite is not addressed in this study, and the main focus was given to the description of the fiber material response during the consolidation process.

**Mechano-sorptive effects** Paper materials, like all natural polymers, are affected by changes in the environment, *i.e.* moisture and temperature. In fact, all natural polymers are more or less hydrogen bonded and their properties are thus intimately regulated by the relative humidity, *i.e.* the moisture content of the surrounding environment. The hygroscopicity of the wood polymers is an essential characteristic of wood fibers and paper products and governs many of the properties of these materials. It is therefore of fundamental interest to have a deeper understanding of the interaction between water and the wood fiber material. The sorption of water by paper follows the general behavior of a hydrophilic polymer exhibiting a sigmoid sorption curve [167], [179], as shown in Figure 3.23. The sorption properties of the wood fiber products may be described by the sorption properties of its constituents: the hemicelluloses, the lignin and the cellulose itself [179], where it is generally considered that the amorphous or



### 3. Mathematical Model for High-Temperature Pressing of Paper 239

disordered cellulose is sorbing water, the cellulose crystals having a negligible sorption capacity [190]. Sorption should occur on hydroxyl sites of the cellulose crystal surface but this is a question of distinguishing between amorphous and crystalline cellulose. The hemicelluloses, due to their higher hydroxyl content, have a higher sorption capacity than lignin [149].

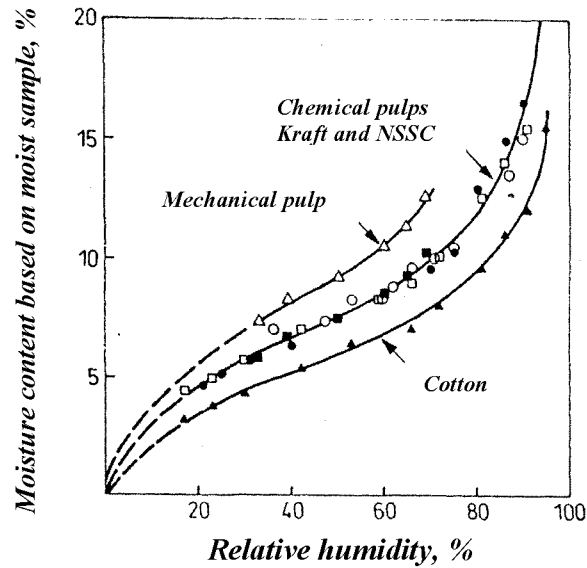


Figure 3.23: Sorption isotherms at 23 °C in absorption for papers made from mechanical pulp, from chemical pulps and from cotton linters (adapted from [149]).

The bound water content, defined as water which may not crystallize when sorbed, reaches at saturation a value of 0.35 g H<sub>2</sub>O / g amorphous cellulose [124] which may be calculated to be close to one water molecule per hydroxyl site on the cellulose. Such a relation may however be only partly true for the wood fiber material as it has been shown that the number of carboxylic acid groups present natively in the wood fiber material in the hemicelluloses has an influence on the amount of water sorbed by the material, particularly at high humidities [124].

When an excess of water is available, water uptake will depend both on the structural arrangement of the fiber network and on the hygroscopicity of the fibers themselves [18]. The pore sorption is of course dependent on the density of the paper product, so the stiffness of the fibers and the long fiber content are important for an open network with a high water uptake. In case of a sized paper,

no water will be taken up by pores in the structure but only by sorption into the fibers themselves [149].

The hygroexpansivity, which is associated with the moisture uptake, is probably mainly associated with the hemicelluloses, as water is dominantly sorbed by these [167], [179]. Due to the swelling of the wood polymer system, as water is sorbed, the stiffness of the material diminishes. As moisture acts as a plasticizer, the mechanical properties are particularly affected in the vicinity of the glass transition temperature of the wood components and depend on how this softening temperature is lowered with the addition of water [150]. From the structure of the fiber it is clear that the effects of moisture on the fiber elastic modulus are reflections of the parallel coupled system of the cellulose and the hemicelluloses, which minimizes the effect of the hemicellulose softening. On the other hand, the series coupling of disordered zones in the cellulose fibers makes the system very sensitive to moduli changes in these zones [149].

The fact that mechano-sorptive effects are most pronounced in compression [152] has led to hypotheses regarding the development of dislocations in the fiber structure which should lead to greater hygroexpansion and lower stiffness [71], [169]. In a material containing dried-in stresses, the molecules are extended in the direction of the applied drying stresses. When the moisture content is increased and the molecular mobility increases, these stretched molecules desire to contract. Under compressive forces the molecules experience low resistance towards contraction. Thus, due to the stress release, the elastic modulus of the material is lowered and the net hygroexpansion increases.

It has also been suggested that physical ageing-de-ageing should leave to mechano-sorptive effects [133]. The increase in moisture content moving the material close to or above its glass transition temperature causes de-ageing, *i.e.* increases the molecular mobility and the free volume of the polymer, a phenomenon similar to that of releasing dried-in stresses.

The greater the magnitude of change in relative humidity the larger is the mechano-sorptive creep [8]. With a larger humidity change, a higher moisture content is reached than if the sample is exposed to several smaller relative humidity steps [34]. The sorption of water also occurs relatively more rapidly if the change in moisture content is large [34]. It may be that, with more non-bonded water present with a larger moisture gradient, stresses may be released to a greater extent than if the moisture increase occurs in small intervals. With

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a constant moisture gradient through the sample, *i.e.* when there is a flow of water molecules through the sample, no mechano-sorptive effects are observable [7], [10]. In this case, water molecules associated with the hydroxyl groups of the wood polymers may be more stationary, only those having a lower bonding energy moving through the sample without interacting with the more bonded water. This could leave the wood polymers unaffected or at least not give them any greater freedom of movement, since no exchange of water molecules would occur.

*Therefore, in the present study it will be assumed that the effect of free water on the viscous parameter of the composite is somewhat negligible, although its contribution reveals to be important for the elasticity modulus. As for the adsorbed water, its effect is mainly attributed to the change in the glass transition temperature of paper components.*

#### Mechanical representation of visco/elastoplastic material behavior

Paper is a prime example of a nonlinear orthotropic material and its mechanical behavior is strongly influenced by the environmental conditions of temperature and relative humidity. In addition, most papers are capable of demonstrating every known rheological phenomenon. Current uses of paper and paperboard provide several challenging problems in engineering mechanics. Lack of accurate constitutive relations and reliable strength predictions under biaxial loading and variable environments hampers analysis of such problems. Therefore, it has been common practice in the paper industry to use trial and error, and empirical approaches for optimizing the designs of paper and paperboard products.

In a press-nip, as the fiber network becomes compacted, a hydraulic pressure builds up in the water held within the fiber walls (intra-fiber water) and some of the intra-fiber water is driven out [25], [192]. Thus, only a part of the structural stress is due to the underlying mechanical stiffness of the fiber network [178]. *The main resistance is due to the flow of the intra-fiber water within and out of the fiber walls, which is inherently a viscous phenomenon.* The rheology of the fiber network can therefore be expected to be rate-dependent, and a model of the fiber network rheology should capture the mechanical stiffness and the stress due to

the flow resistance inside the fibers. The success of modeling the water flow and web consolidation in a press nip depends strongly on the availability of reliable models both for the flow between the fibers and for the fiber network rheology.

Our first approach aims to present a rheological model which takes into account the flow resistance of intra- and extra-fiber water, the contribution of water vapor and air to the elastic modulus of the network, and the fiber network rheology itself. At the risk of some simplification, the proposed model may be represented by a mechanical analogue consisting of three elements coupled in series and in parallel (see Figure 3.24). One element is purely elastic (recoverable), the other is plastic (the unrecoverable strain is associated with the structure of the material), and the third element is viscous (time-dependent).

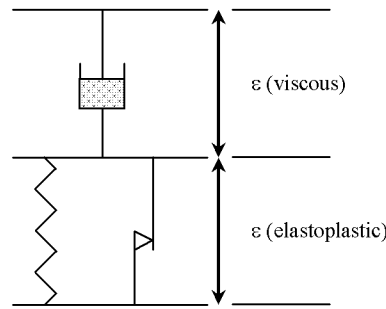


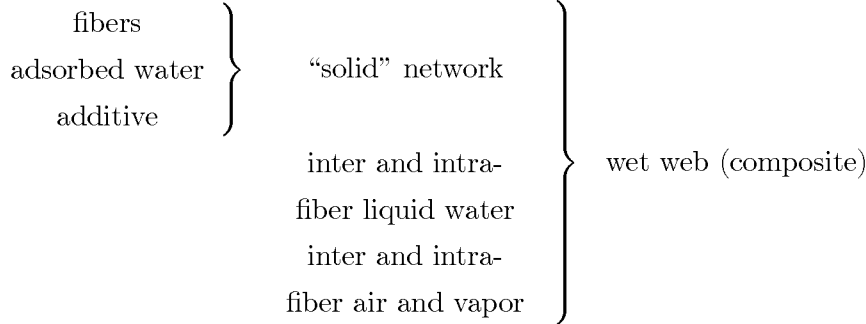
Figure 3.24: Mechanical analogue of the model proposed. The viscous strain consists of a dashpot, and the elastoplastic strain consists of a parallel arrangement of a spring and a so-called dry friction element, with a nonlinear yield strain.

As previously mentioned, the model components are comprised of viscous, elastic and plastic elements, with the *viscous elements characterizing the degree to which the medium components move or change position with time when subjected to a stress, the elastic and plastic elements characterizing the structural integrity of the medium*. When subjected to very low loads paper behaves almost as a linear elastic material. However, under very fast high loads its stress-strain curve shows a hysteresis. This phenomenon is due to a rapid plastic strain of the wet web under compression.

The extent of web compression has a significant influence on the result of the wet pressing process. A wet web which enters the press section comprises four materials: fibers, additives, water and air. Pulp fibers together with the additive and the adsorbed water - water that is located in the fiber wall surface - are the

### 3. Mathematical Model for High-Temperature Pressing of Paper 243

constituents of the “solid” network. The “solid” network forms together with water and air - both found between the fibers and inside them - the wet web.



In some publications, the word “web” denotes a “single paper sheet” rather than a “continuous sheet”; this denotation is also used in this thesis.

Dewatering behavior of the wet web has been examined through the years by several authors, and it appears analogous to the deformation of a viscoelastic material that can be simply modeled by a spring and a dashpot arranged in parallel (*i.e.* a Kelvin body). Kelvin was the first to suggest that the mechanical deformation of a wet sponge could be described in terms of elastic and viscous characteristics. A simple representation of such a viscoelastic medium is known as a Kelvin body, with viscous elements symbolized by a dashpot with viscosity  $\mu$ , and elastic elements symbolized by a spring with effective spring constant or Young’s modulus  $E$ . With the application of a stress, the strain on the two elements of the Kelvin body is the same, the stress being divided between the spring and the dashpot elements (see Figure 3.25(a)).

In addition, there is a strong dependence on temperature and time of the properties of polymers (such as cellulose) compared to those of other materials such as metals. This strong dependence on temperature and on how fast the material is deformed (time scale) is a result of the viscoelastic nature of polymers. Viscoelasticity implies a behavior similar to both viscous liquids in which the rate of deformation is proportional to the applied stress, and to pure elastic solids in which the strain is proportional to the stress. In viscous systems, all the work done on the system is dissipated in the form of heat, whereas, in elastic systems all the work is stored as potential energy as in a stretched (or compressed) spring.

According to Rodal [145] paper is deformed in three stages. At first, the volume is reduced. As higher pressures are applied, the fiber network starts to take up load and deformation is achieved through elastic-plastic buckling (as already discussed above). At some critical deformation of the fiber network, further

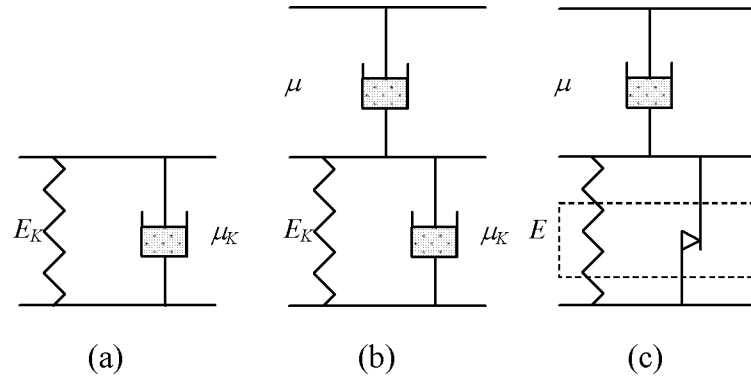


Figure 3.25: Mechanical analogue of a (a) Voigt-Kelvin unit, (b) a Voigt-Kelvin unit and a dashpot in a series arrangement, and (c) a so-called *modified Maxwell unit* (the proposed model in this thesis).

deformation can only be achieved by “crushing” of the fibers. The compression behavior of a paper sheet may then be modeled with theories developed to predict the nonlinear response of cellular materials in transverse compression.

Bearing this in mind the present work aims to accurately model the densification of paper in the pressing section of a paper machine, using simple arrangements of springs, dampers and “dry-friction” elements, taking into account the cellular structure of the material. The mechanical model developed here may then be referred to as *visco/elastoplastic*.

**Model derivation** The model proposed in this thesis consists of a parallel assembly of a perfectly plastic constituent with a yield stress, and a linear elastic element. It effectively expresses the fact that certain materials do not exhibit plastic flow below a defined strain level ( $\varepsilon \leq \varepsilon_y$ ). Additionally, a visco/elastoplastic model is obtained by the superposition of a viscous constituent. According to the Boltzmann superposition principle, the total strain of the material in the thickness direction is the sum of all the contributions which are therefore independent and additive, such that the rate of overall strain is given by:

$$\frac{\partial \varepsilon}{\partial t} = \frac{\partial \varepsilon_{ep}}{\partial t} + \frac{\partial \varepsilon_{vis}}{\partial t} \quad (3.71)$$

where

$\varepsilon$  = total strain of the web in the thickness direction;

$\varepsilon_{ep}$  = elastoplastic strain of the web in the thickness direction;

$\varepsilon_{vis}$  = strain in the thickness direction due to viscous flow.

The differential form of the mathematical representation of linear viscoelasticity is based on the governing differential equations of mechanical analogies, such as springs and dashpot elements. The analogies are phenomenological, therefore, they describe the observed phenomena adequately, but there is no physical insight into the problem. The governing differential equation for the Maxwell element (a spring and a dashpot in series) is:

$$\frac{\partial \sigma_T}{\partial t} = E \frac{\partial \varepsilon}{\partial t} - \frac{\sigma_T}{\tau^*} \quad (3.72)$$

where

$\sigma_T$  = total applied stress;

$\tau^*$  = retardation or relaxation time =  $\frac{\mu}{E}$ ;

$\mu$  = viscous parameter of the web.

In this first approach, a mechanical model was developed for the compression of paper subjected to a uniaxial load. The model proposed represents the behavior of the composite in the three main directions, although it will be assumed web deformation in the thickness direction only. At this stage, the heat and mass transfer model is not included, and therefore the temperature and moisture conditions are estimated assuming that all the constituents of the composite are at room temperature and that the moisture ratio (defined as the amount of water per kg of dry solid material) remains constant. This assumption may be considered if one assumes that water gradually occupies the void volume left by air leaving the porous material as the compression event takes place. Obviously, the model will not represent the true mechanical behavior of the composite, but serves as a basis to test the cellular materials approach to estimate the local mechanical properties.

The 3D model presented hereafter intends to represent the heat and mass transfer phenomena that may occur inside the paper web when submitted to the high-intensity conditions of impulse drying. In an attempt to simplify the model, it was assumed geometric symmetry, *i.e.* two planes of symmetry were considered, the vertical mid-planes, as illustrated in Figure 3.26. This simplification implies that the lateral edges of the sheet are exposed to the same ambient conditions;

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only the top and bottom surfaces of the sheet are submitted to different operating conditions. Consequently, only one fourth of the total web needs to be modelled.

The model validation will be performed using the results obtained during the compression tests described later in the present chapter. It is worth remembering that the paper samples were submitted to a roll-like press pulse with a maximum load in the range 5-6 MPa. The model therefore estimates the response of the material in terms of thickness evolution during the compression and decompression stages of the pressing event.

In the model construction the following assumptions were considered:

- the model is pseudo three-dimensional;
- the consolidation of the web occurs only in the thickness direction, and no lateral deformations are assumed;
- three phases are considered (solid, liquid and gaseous phases) and local thermodynamic equilibrium is assumed (see Figure 3.15);
- the gas mixture (air and water vapor) follows the ideal gas law;
- physical properties depend on temperature and moisture ratio of the material; transport properties that are dependent on changing physical properties can also vary with respect to time and space;
- paper is assumed to be isotropic in the in-plane direction of the sheet and to behave according to a visco/elastoplastic mechanical model;
- the viscous component in each position of the web depends on temperature and moisture;
- the elasticity modulus in each position of the web depends on temperature, moisture and density of the web.

To model the web it was assumed a representative volume element as represented in Figure 3.26, which consists of  $\frac{1}{4}$  of the total web. This fraction was divided into  $N_i \times N_j$  columns and  $N_k$  layers.



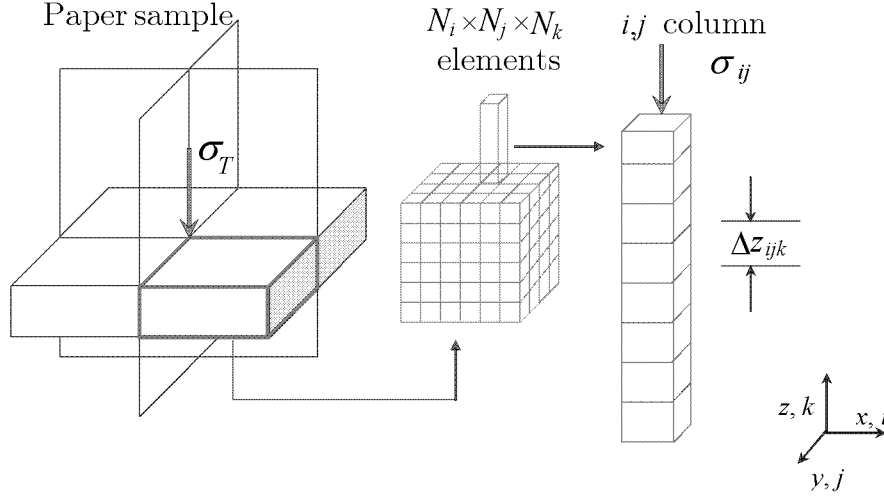


Figure 3.26: Schematic representation of the mechanical model in compression ( $N_i \times N_j \times N_k$  control volumes).

The fibrous network is compressed in the transverse direction, while the internal environment is continuously changing during the hot-pressing process. The fibers will not be positioned uniformly on the area of the sheet. When an external compressive stress is applied to the sheet, the stress will be transferred unevenly among the columns. Consequently, the stress is not transferred uniformly through the sheet. At thicker areas the stress will be higher. Additionally, two levels of cellularity can be identified within the columns. The first level of cellular structure is the consequence of the paper sheet formation process. At the beginning of the pressing process the space is gradually eliminated. As the fibers form continuous columns further compression starts to collapse the cellular structure of the sheet. As it was mentioned above, the cumulative thickness of the fibers at different horizontal positions in the sheet is different. Although the load is applied uniformly over the sheet surface, it becomes concentrated in only a small portion of the surface. Therefore, the consolidation of the continuous fiber columns start at different times during the pressing cycle. At the beginning of the pressing process the compressed area is small and the localized stress can be far higher than the applied load. As consolidation progresses, the compressed area rapidly increases and the stresses are continuously redistributed. Consequently, the external applied load is shared by more and more fiber columns within the sheet as

the density increases. The total load applied on the fibrous network is the summation of the loads applied for the compression of the individual fiber columns. On the other hand, the total strain of the web will be given by the addition of the individual strains of the  $N_k$  layers.

In order to produce a more realistic material response, modified Maxwell elements are combined in series, and then arranged in parallel, according to Figure 3.27.

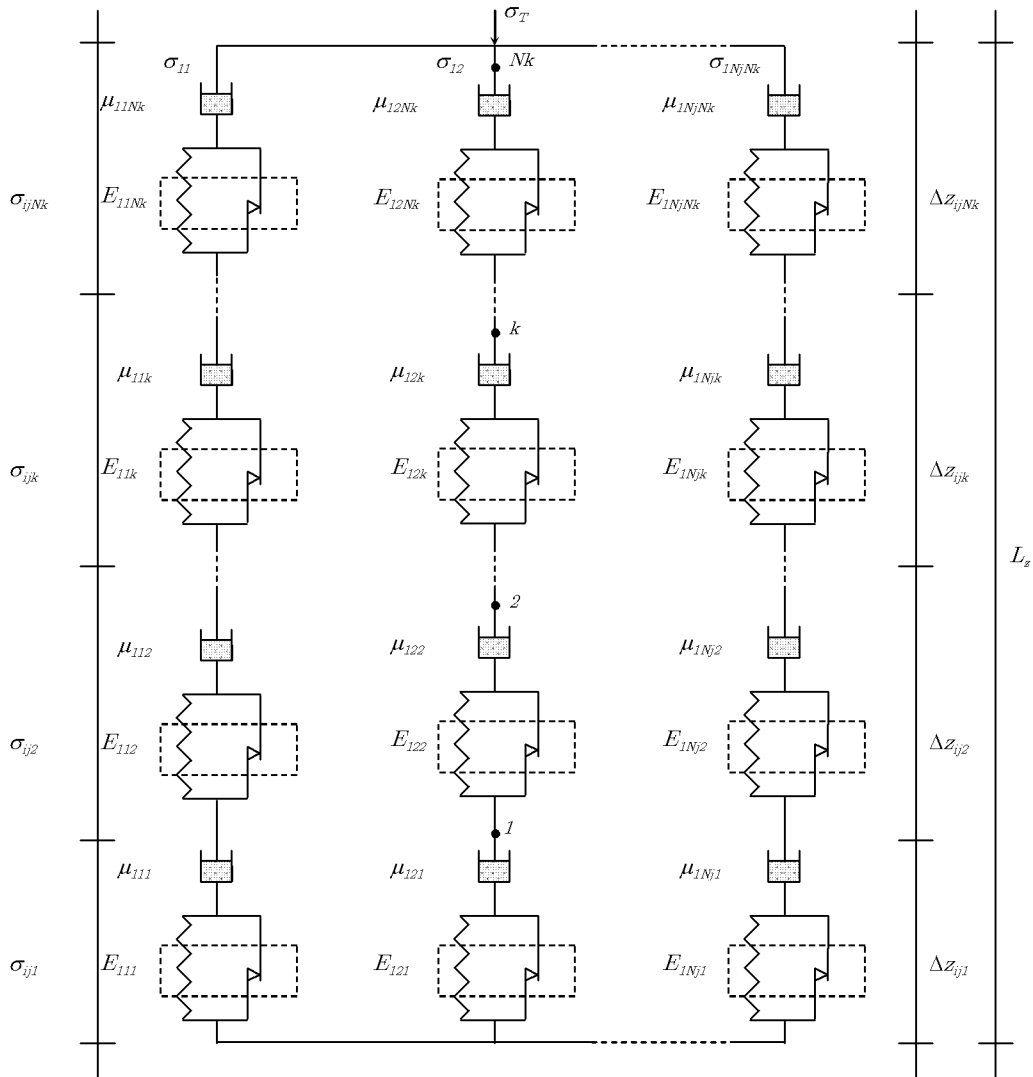


Figure 3.27: Representation of the compression of a column by a parallel assembly of modified Maxwell units arranged in series.

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As above mentioned, the applied stress is unevenly distributed among columns, but it is the same for each layer within the same column. Thus, it is assumed that there is no stress transfer resistance inside each  $ij$  column.

$$\begin{aligned}\sigma_{111} &= \sigma_{112} = \dots = \sigma_{11k} = \dots = \sigma_{11N_k} = \sigma_{11} \\ \sigma_{ij1} &= \sigma_{ij2} = \dots = \sigma_{ijk} = \dots = \sigma_{ijN_k} = \sigma_{ij}\end{aligned}\quad (3.73)$$

In addition, the total thickness of the individual columns,  $L_{ij}$ , is assumed to be the same and equal to the total thickness of the web,  $L_z$

$$L_{11} = L_{12} = \dots = L_{ij} = L_z \quad (3.74)$$

The strain of the  $ij$  column,  $\varepsilon_{ij}$ , and the local strain,  $\varepsilon_{ijk}$ , can be defined in several ways, but for engineering (and most theoretical) purposes, the strain is calculated as follows (according to Cauchy):

$$\varepsilon_{ij} = \frac{L_{ij}}{L_{ij0}} - 1 = \frac{L_z}{L_{z0}} - 1 \quad (3.75)$$

$$\varepsilon_{ijk} = \frac{\Delta z_{ijk}}{\Delta z_0} - 1 \quad (3.76)$$

in which the subscript “0” refers to the reference value of the variables.

It is known that the summation of the thickness of each element,  $\Delta z_{ijk}$ , is equal to the thickness of the press plate, and consequently equal to the thickness of each individual column  $ij$  (see Figure 3.28):

$$L_z = \sum_{k=1}^{N_k} \Delta z_{ijk} \quad (3.77)$$

The previous equation then becomes,

$$L_z = \Delta z_{ij1} + \Delta z_{ij2} + \dots + \Delta z_{ijk} + \dots + \Delta z_{ijN_k} \quad (3.78)$$

Assuming that the initial thickness of the  $N_k$  layers,  $\Delta z_0$ , are equal, then

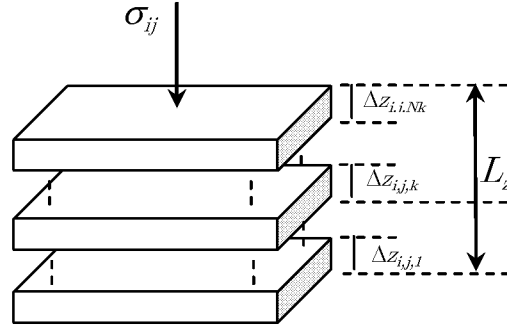


Figure 3.28: Schematic representation of an  $ij$  column with  $N_k$  layers. The stress development in each column is separately controlled by the nonlinear strain function from that position.

$$\begin{aligned}
 \varepsilon_{ij} + 1 &= \frac{\Delta z_0}{L_{z_0}} (\varepsilon_{ij1} + 1) + \frac{\Delta z_0}{L_{z_0}} (\varepsilon_{ij2} + 1) + \dots \\
 &\dots + \frac{\Delta z_0}{L_{z_0}} (\varepsilon_{ijk} + 1) + \dots + \frac{\Delta z_0}{L_{z_0}} (\varepsilon_{ijN_k} + 1) \\
 &= \frac{\Delta z_0}{L_{z_0}} \sum_{k=1}^{N_k} (\varepsilon_{ijk} + 1)
 \end{aligned} \tag{3.79}$$

where  $L_{z_0}$  is the initial thickness of the entire web.

Taking know the time derivative of the previous equation, it follows that

$$\frac{d\varepsilon_{ij}}{dt} = \frac{\Delta z_0}{L_{z_0}} \sum_{k=1}^{N_k} \frac{d\varepsilon_{ijk}}{dt} \tag{3.80}$$

According to the linear viscoelastic theory, the time-dependent response of a viscoelastic material, for an arbitrary loading history, can be expressed either in an integral or a differential form, if a single creep or relaxation for a prolonged time period is available.

The integral form of the mathematical representation of linear viscoelasticity is based on the superposition principle. It states that the effect of a complex loading history can be equated to the sum of independent load steps. Therefore, the time dependent response to the sum of independent load steps is expressed by a convolution integral, called the *Boltzmann Superposition Integral*. The

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Boltzmann Integral takes the following form to represent the time dependent strain  $\varepsilon(t)$  during the creep phenomenon

$$\varepsilon(t) = CCM(t) \sigma(0) + \int_0^t CCM(t - \xi^*) \frac{d\sigma}{d\xi^*}(\xi^*) d\xi^* \quad (3.81)$$

The time-dependent stress relaxation  $\sigma(t)$  can be described as

$$\sigma(t) = SRM(t) \varepsilon(0) + \int_0^t SRM(t - \xi^*) \frac{d\sigma}{d\xi^*}(\xi^*) d\xi^* \quad (3.82)$$

The use of the integral requires that either the creep compliance ( $CCM(t)$ ) or the stress relaxation modulus ( $SRM(t)$ ) be expressed analytically (*e.g.* a function fitted to measured data). Additionally, *the Boltzmann Integral is restricted to linear materials*. Direct derivation of the Boltzmann Integral for nonlinear materials is not presented. The extension of the Boltzmann Integral for nonlinear materials was proposed by Meinecke and Clark [116]. If the material is not strained initially, the time-dependent stress response of a nonlinear material is described by the following equation

$$\sigma(t) = \int_0^t SRM(t - \xi^*) \frac{d\sigma}{d\xi^*}(\xi^*) \Phi(\varepsilon(\xi^*)) d\xi^* \quad (3.83)$$

where  $\Phi(\varepsilon(\xi^*))$  is a nonlinear strain function.

The solution of this integral depends on the complexity of the  $\Phi(\varepsilon(\xi^*))$  term. It was pointed out by Meinecke and Clark [116] that the simplification of the integral still reaches sufficient accuracy:

$$\sigma(t) = \Phi(\varepsilon(\xi^*)) \int_0^t SRM(t - \xi^*) \frac{d\sigma}{d\xi^*}(\xi^*) d\xi^* \quad (3.84)$$

This equation indicates that once the solution of the integral of linear viscoelastic behavior is known, the result only has to be multiplied by the nonlinear strain function.

The time-dependent response of the visco/elastoplastic material for a complex loading history is provided either by the numerical evaluation of the Boltzmann Convolution Integral, or by the governing differential equations of a finite arrangement of modified Maxwell elements. Several problems arise during the numerical

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evaluation of the Boltzmann Integral: the solution time is long due to the small time step required for a stable solution, and the full stress and strain history have to be stored in order to reach a solution. Therefore, this solution technique was not considered.

An alternative method is the numerical solution of the governing differential equations of a finite arrangement of modified Maxwell elements. The following discussion will demonstrate the model development.

Considering that strain is only a function of two variables, *i.e.* time and stress, one may obtain the governing differential equation for the modified Maxwell element, which defines the material's behavior when subjected to a dynamic stress:

$$\varepsilon = f(\sigma, t) \quad (3.85)$$

or else,

$$\frac{d\varepsilon}{dt} = \underbrace{\left(\frac{\partial \varepsilon}{\partial \sigma}\right) \frac{d\sigma}{dt}}_{\text{elastoplasticity}} + \underbrace{\left(\frac{\partial \varepsilon}{\partial t}\right)_{\sigma}}_{\text{viscosity}} \quad (3.86)$$

which clearly states that the total deformation of the material may be separated into elastoplastic and viscous deformation.

It is also known that for cellular materials, the elasticity modulus depends both on strain and relative density of the solid. Therefore, part of the first term in Eqn. 3.86 may be estimated as described hereafter.

Taking the partial derivative of the applied stress and integrate, it follows that

$$\frac{\partial \sigma}{\partial \varepsilon} = E(\rho_{rel}, \varepsilon) \implies \sigma = \int E.d\varepsilon = E.\varepsilon \quad (3.87)$$

However, starting from Hooke's law and taking the derivative form of the equation, it follows that

$$\sigma = E.\varepsilon \implies \frac{\partial \sigma}{\partial \varepsilon} = E + \varepsilon \frac{\partial E}{\partial \varepsilon} \quad (3.88)$$

As for the viscous constituent of the Maxwell unit, it can be represented by Newton's law of viscosity,

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$$\left(\frac{\partial \varepsilon}{\partial t}\right)_{\sigma} = \frac{\sigma}{\mu} \quad (3.89)$$

Therefore, the governing differential equation for a modified Maxwell element may be expressed as

$$\frac{d\varepsilon}{dt} = \frac{1}{E + \varepsilon \frac{\partial E}{\partial \varepsilon}} \frac{d\sigma}{dt} + \frac{\sigma}{\mu} \quad (3.90)$$

Considering now the element  $ijk$  of an  $ij$  column, Eqn. 3.90 becomes

$$\frac{d\varepsilon_{ijk}}{dt} = \frac{1}{E_{ijk} + \varepsilon_{ijk} \frac{\partial E_{ijk}}{\partial \varepsilon_{ijk}}} \frac{d\sigma_{ijk}}{dt} + \frac{\sigma_{ijk}}{\mu_{ijk}} \quad (3.91)$$

The governing differential equation for a single column is obtained assuming linear viscoelastic behavior. In addition, the elasticity modulus of the column,  $E_{ij}$ , is only a function of the elasticity modulus of the  $N_k$  layers of the column. It may then be written, for a single column

$$\frac{d\varepsilon_{ij}}{dt} = \frac{1}{E_{ij}} \frac{d\sigma_{ij}}{dt} + \frac{\sigma_{ij}}{\mu_{ij}} \quad (3.92)$$

As for the entire mat, it will be assumed the same rheological behavior, *i.e.* the total compression of the fibrous network is described by the viscoelastic constitutive relation

$$\frac{d\varepsilon_T}{dt} = \frac{1}{E_T} \frac{d\sigma_T}{dt} + \frac{\sigma_T}{\mu_T} \quad (3.93)$$

where the subscript “ $T$ ” refers to the entire structure.

Since the Boltzmann Superposition principle states that the response to an input can be divided into independent and additive contributions to that same response, one may say that

$$\frac{1}{E_{ij}} \frac{d\sigma_{ij}}{dt} + \frac{\sigma_{ij}}{\mu_{ij}} = \frac{\Delta z_0}{L_{z_0}} \left( \sum_{k=1}^{N_k} \frac{1}{E_{ijk} + \varepsilon_{ijk} \frac{\partial E_{ijk}}{\partial \varepsilon_{ijk}}} \frac{d\sigma_{ijk}}{dt} + \frac{\sigma_{ijk}}{\mu_{ijk}} \right) \Rightarrow \quad (3.94)$$

$$\Rightarrow \left\{ \begin{array}{l} \frac{1}{E_{ij}} \frac{d\sigma_{ij}}{dt} = \frac{\Delta z_0}{L_{z_0}} \sum_{k=1}^{N_k} \frac{1}{E_{ijk} + \varepsilon_{ijk} \frac{\partial E_{ijk}}{\partial \varepsilon_{ijk}}} \frac{d\sigma_{ijk}}{dt} \\ \frac{\sigma_{ij}}{\mu_{ij}} = \frac{\Delta z_0}{L_{z_0}} \sum_{k=1}^{N_k} \frac{\sigma_{ijk}}{\mu_{ijk}} \end{array} \right. \quad (3.95)$$

The elastic and viscous parameters  $E_{ij}$  and  $\mu_{ij}$  will then be given by

$$E_{ij} = \frac{N_k}{\sum_{k=1}^{N_k} \frac{1}{E_{ijk} + \varepsilon_{ijk} \frac{\partial E_{ijk}}{\partial \varepsilon_{ijk}}}} \quad (3.96)$$

$$\mu_{ij} = \frac{N_k}{\sum_{k=1}^{N_k} \frac{1}{\mu_{ijk}}} \quad (3.97)$$

Again, from Eqns. 3.92 and 3.93, and assuming that the  $ij$  columns deform evenly, it is possible to obtain the global parameters,  $E_T$  and  $\mu_T$ ,

$$E_T = \frac{1}{N_i \cdot N_j} \sum_{ij} E_{ij} \quad (3.98)$$

$$\mu_T = \frac{1}{N_i \cdot N_j} \sum_{ij} \mu_{ij} \quad (3.99)$$

Prior to present the constitutive equations of the model it is important to define some variables and physical properties. The strain distribution along the web will be affected by compressibility, and thus it is necessary to derive the relationship between the strain in each element (layer) and the  $z$ -coordinate (see Figure 3.29). As the web thickness is continuously changing throughout the pressing event, the  $z$ -coordinate also changes in time. In order to set the space integration domain it was adopted the Landau transformation (see [29]), which has been used in several drying problems.



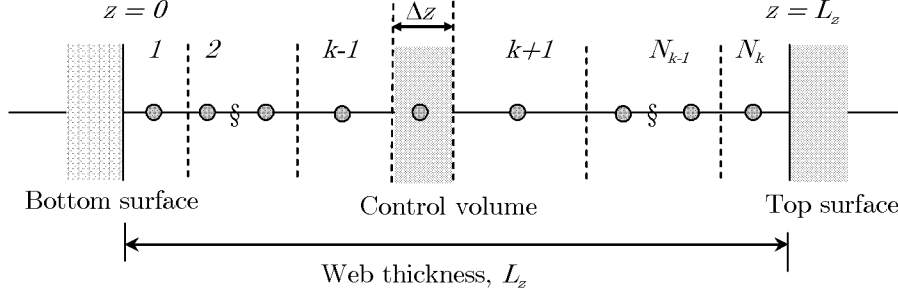


Figure 3.29: Discretization in the thickness direction of the web;  $N_k$  is the number of considered points.

$$\mathbf{Z}_{ijk} = \frac{z_{ijk}}{L_z} \quad (\text{Landau}) \quad (3.100)$$

For each layer, the thickness will be given by

$$\Delta z_{ijk} = 2 \left( z_{ijk} - \sum_{l=1}^{k-1} \Delta z_{ijl} \right) \quad (3.101)$$

Therefore, the strain of each layer may be calculated as follows:

$$\varepsilon_{ijk} = \frac{2z_{ijk}}{\Delta z_0} - 1 - 2 \sum_{l=1}^{k-1} (\varepsilon_{ijl} + 1) \quad (3.102)$$

The  $z$ -coordinate may then be determined as

$$z_{ijk} = \frac{\Delta z_0}{2} \left( \varepsilon_{ijk} + 2 \sum_{l=1}^{k-1} \varepsilon_{ijl} + 2k - 1 \right) \quad (3.103)$$

For simplicity, it is hereby defined the following normalized and dimensionless variables that will be used in the constitutive equations of the model: time is normalized by the dwell time of the pressing event,  $\tau$ ; the total thickness of the web is normalized by its initial value; the thickness of every  $ijk$  element is divided by the actual thickness of the web. In addition, the elastic parameters  $E_T$ ,  $E_{ij}$  and  $E_{ijk}$  are divided by a reference value  $E_0$ , and the viscous parameters  $\mu_T$ ,  $\mu_{ij}$ , and  $\mu_{ijk}$  divided by  $\mu_0$ . Finally, a dimensionless elastic parameter is defined as the inverse of the reference elastic strain,  $\mathbf{H}_0$ , and a viscoelastic parameter,  $\mathbf{V}_0$ , is also presented.

$$\mathbf{z}_{ijk} = \frac{z_{ijk}}{L_z(t)} \quad \mathbf{L}_z = \frac{L_z}{L_{z0}} \quad \Delta \mathbf{z}_{ijk} = \frac{\Delta z_{ijk}}{L_{z0} \mathbf{L}_z} \quad \Delta \mathbf{z}_0 = \frac{\Delta z_0}{L_{z0}} = \frac{1}{N_k}$$

$$\theta = \frac{t}{\tau} \quad \sigma_T = \frac{\sigma_T}{\sigma_0} \quad \sigma_{ij} = \frac{\sigma_{ij}}{\sigma_0} \quad \mathbf{H}_0 = \frac{E_0}{\sigma_0}$$

$$\mathbf{E}_T = \frac{E_T}{E_0} \quad \mathbf{E}_{ij} = \frac{E_{ij}}{E_0} \quad \mathbf{E}_{ijk} = \frac{E_{ijk}}{E_0} \quad \mathbf{V}_0 = \frac{\tau \cdot \sigma_0}{\mu_0}$$

$$\mu_T = \frac{\mu_T}{\mu_0} \quad \mu_{ij} = \frac{\mu_{ij}}{\mu_0} \quad \mu_{ijk} = \frac{\mu_{ijk}}{\mu_0}$$

### Model equations in dimensionless form and initial conditions

In this model the dependent variables are the vertical position,  $z_{ijk}$ , the compressive stress,  $\sigma_{ij}$ , and the total thickness of the web,  $L_z$ . Consequently, the three equations that describe the consolidation process are: one relating the vertical position to the local strain of each element; one to determine the stress applied on each column; and finally one that determines the thickness of the entire web as a function of the applied stress. Additionally, the model requires one equation to determine the global elastic parameter as a function of the elasticity modulus of each control volume (defined by Eqn. 3.50), and one to determine the global viscous parameter as a function of the viscous parameters of each control volume (defined by Eqn. 3.70).

Using the normalized, dimensionless variables, the equations of the model are written as follows:

$$\frac{\partial \mathbf{z}_{ijk}}{\partial \theta} = \frac{\Delta \mathbf{z}_0}{2 \mathbf{L}_z} \left( \frac{\partial \varepsilon_{ijk}}{\partial \theta} + 2 \sum_{l=1}^{k-1} \frac{\partial \varepsilon_{ijl}}{\partial \theta} \right) - \frac{\mathbf{z}_{ijk}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \quad (3.104)$$

$$\text{where } \frac{\partial \varepsilon_{ijk}}{\partial \theta} = \frac{1}{\mathbf{H}_0 \left( \mathbf{E}_{ijk} + \varepsilon_{ijk} \frac{\partial \mathbf{E}_{ijk}}{\partial \varepsilon_{ijk}} \right)} \frac{\partial \sigma_{ij}}{\partial \theta} + \frac{\mathbf{V}_0}{\mu_{ijk}} \sigma_{ij} \quad (3.105)$$

$$\text{Initial condition} : \quad \theta = 0; \quad \varepsilon_{ijk} = 0; \quad \mathbf{z}_{ijk} = \frac{k - 0.5}{N_k} \quad (3.106)$$

Then extending the analysis to the  $ij$  column one obtains,

$$\frac{\partial \sigma_{ij}}{\partial \theta} = \mathbf{H}_0 \mathbf{E}_{ij} \frac{\partial \mathbf{L}_z}{\partial \theta} - \mathbf{H}_0 \mathbf{V}_0 \frac{\mathbf{E}_{ij}}{\mu_{ij}} \sigma_{ij} \quad (3.107)$$

$$\textbf{Initial condition} \quad : \quad \theta = 0; \quad \sigma_{ij} = 0; \quad \mathbf{L}_z = 1 \quad (3.108)$$

The total response of the web can be represented by Eqn. 3.109:

$$\frac{\partial \mathbf{L}_z}{\partial \theta} = \frac{1}{\mathbf{H}_0 \mathbf{E}_T} \frac{\partial \sigma_T}{\partial \theta} + \frac{\mathbf{V}_0}{\mu_T} \sigma_T \quad (3.109)$$

$$\textbf{Initial condition} \quad : \quad \theta = 0; \quad \mathbf{L}_z = 1 \quad (3.110)$$

The constitutive equations and physical properties necessary to solve the model equations are provided above in this section and also in **Section 3.3.4** (see “Transport and physical properties of the composite”).

**Numerical solution** The model contains three dependent variables and three partial time derivative governing equations. After discretization, the resulting set of ODEs was integrated using the double precision version of the LSODES subroutine, developed by Radhakrishnan and Hindmarsh [10], which uses an integrator based on the Gear method.

The spatial discretization followed the approach of the control domains. For modeling purposes one fourth of the web was discretized in 1000 points, 10 in each direction, each grid point corresponding to a control domain. Figure 3.29 shows the discretization grid in the thickness direction of the web. Additionally, a C++-based subroutine was built and serves as a starting point for the solution of the integrated mechanical model. This subroutine aims to solve the set of heat and mass transfer differential equations that will be integrated in the global mechanical model. It is also worth noting that the uneven deformation of contiguous control domains leads to the problem of inconsistency of the boundary conditions in their interfaces. However, at this point, this is not a true problem since the heat and mass transfer will not be taken into account. Instead, the temperature and moisture ratio conditions will be assumed constant during the pressing event.

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In addition, the mat is treated as it was formed by a single column with  $N_k$  layers, which in their turn constitute the control domains. The parameters of the DLSODES subroutine were selected according to the instructions of the manual.

**Results and discussion** The viscoelastoplastic model was used to predict the evolution of thickness, elastic and viscous moduli and density, in time and at any given position in a high moisture ratio paper web. Several simulation runs were carried out and in each case the applied pressure pulse recorded in the experiment (see Figure 3.30) was used as an input to the model. The results presented hereafter correspond to a typical compression event performed at room temperature. Obviously, this is not representative of an impulse drying event in terms of temperature, but the main objective here was to test the applicability of the cellular solids approach to the estimation of the mechanical properties of paper. For that purpose, the effect of some physical properties and model parameters on the mechanical response of paper was evaluated.

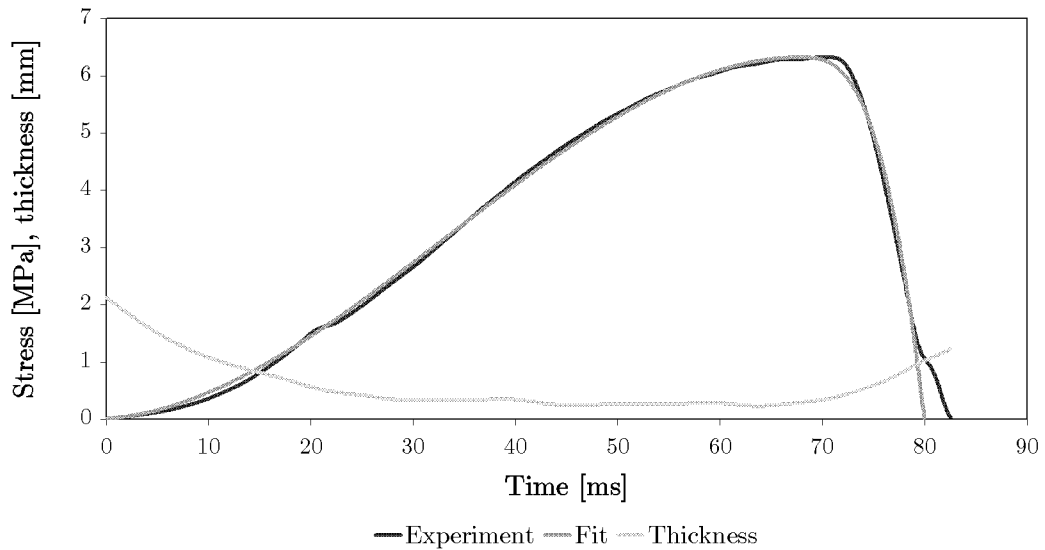


Figure 3.30: Stress pulse imposed to a high moisture ratio paper web formed by four  $60 \text{ g.m}^{-2}$  25 °SR hardwood paper sheets and the corresponding web thickness evolution. Temperature:  $\approx 25 \text{ }^\circ\text{C}$ ; pulse length: 83 ms; peak pressure: 6.3 MPa; moisture ratio: 2.33 kg  $\text{H}_2\text{O}$ /kg ds.

The experimental stress pulse was fitted to the following expression:

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$$\sigma_T = \begin{cases} \sigma_0 (\theta'^3 - fp_1 \theta'^2) / fp_3 & \theta' < \theta_m \\ \sigma_0 [1 + fp_2 (\theta' - \theta_m)^3] & \theta' \geq \theta_m \end{cases} \quad (3.111)$$

where  $\theta'$  is the dimensionless time defined by Eqn. 3.112. The fitting parameters are  $fp_1 = \sqrt{2}$ ,  $fp_2 = -216.349$ ,  $fp_3 = -\frac{4}{27} (fp_1)^3$  and  $\theta_m = \frac{2\sqrt{2}}{3} = \frac{2fp_1}{3}$ .

$$\theta' = fp_4 + \frac{(1 - fp_4)(t - fp_5)}{fp_6 - fp_5} \quad (3.112)$$

where  $fp_4$ ,  $fp_5$  and  $fp_6$  take the values 0.5, 35.2 ms and 71.9 ms, respectively. For simplicity, the results presented hereafter will be expressed in terms of dimensionless time defined as time divided by its corresponding value at the point of maximum applied stress, as already used in several graphs presented in this thesis.

The operating conditions and paper properties used in the simulation runs are summarized on Tables 3.3 and 3.4. The performance of the viscoelastoplastic model was evaluated in terms of thickness evolution of the paper samples subjected to a pressure pulse as that illustrated in Figure 3.30, as well as some other model variables such as densities, gas pressure, water volume fraction and elastic modulus. It is important to note that, at this stage of the model development, no property gradients in the thickness direction of the paper web are expected. This results from assuming no heat and mass transfer within the medium, *i.e.* both liquid and gas phases were being compressed and no fluid flow occurred at the boundaries of the web.

Table 3.3: Operating conditions used in the simulation runs

|                                  |                                    |
|----------------------------------|------------------------------------|
| Temperature of the pressing head | $T_p = 25 \text{ } ^\circ\text{C}$ |
| Pulse length                     | $\tau = 83 \text{ ms}$             |
| Peak pressure                    | $\sigma_0 = 6.3 \text{ MPa}$       |
| Pulse shape                      | Roll                               |

Prior to present the main results from the simulation runs, it should be referred that the elasticity modulus of the composite was estimated by means of the micromechanical model that considers a parallel assembly of the three elements

Table 3.4: Paper properties used in the simulation runs

|                                   |                                               |
|-----------------------------------|-----------------------------------------------|
| Initial thickness                 | $L_{z_0} = 2.129609 \text{ mm}$               |
| Initial moisture ratio            | $MR_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ |
| Grammage                          | $Gr = 257.1 \text{ g.m}^{-2}$                 |
| Refining level                    | 25 °SR                                        |
| Pulp type                         | Bleached hardwood                             |
| Density of the cell wall material | $\rho_{cw} = 1550 \text{ kg.m}^{-3}$          |
| Density of the additive           | $\rho_a = 1100 \text{ kg.m}^{-3}$             |
| Mass fraction of additive         | $y_a = 0.0015 \text{ kg additive/kg fibers}$  |

that constitute the medium: solid (“fiber” + additive), liquid water and gas (air + vapor). Additionally, the elasticity modulus for the solid phase was calculated using the same approach, *i.e.* “fiber” and additive assembled in parallel. A similar approach was performed by Carvalho [29] to estimate the elastic parameters of medium density fiberboard (MDF). The author tested the applicability of different micromechanical models, combined with the well known theory of cellular solids to take into account the change in the materials density, and advanced that this kind of approach could predict, in a very acceptable way, the density profiles and compression stresses typically observed in the industrial production of MDF. Given the similarity between MDF and paper in terms of its internal structure and chemical composition, the same micromechanical approach was adopted in the present study.

In order to understand the role of the different material properties and model parameters on the mechanical behavior of paper several simulation runs were carried out using the C<sup>++</sup>-based subroutine included in **Appendix F**. Given the extreme relevance of the viscous parameter on the materials response to dynamic compression, this property was the first to be studied. The effect of fiber elasticity modulus and the above defined elastic constant,  $C_2$ , was also taken into account. Finally, the contribution of the liquid phase to the elasticity modulus of the composite was not overseen. In fact, it plays a fundamental role in this respect, which is not surprising if one considers the amount of water in the paper samples under study. Opposing relevance is given to the contribution of the gas phase, at least during the compression stage of the pressing event, where steam generation is not expected to occur. However, when the medium tends to be saturated, the gas may actually be trapped in the pores, thus increasing the gas pressure and its contribution to the mechanical stiffness of the composite. At the risk of some

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simplification, the water elasticity modulus was taken equal to the reciprocal to the coefficient of compressibility of liquid water, *i.e.* the bulk modulus. For water at room temperature and atmospheric pressure, the bulk modulus takes the value of 2068 MPa [161]. Although it increases with pressure, this was not taken in consideration. The value referred in the literature was used as a starting point, and several values above and below it were tested.

The influence of the above mentioned parameters and material properties is presented hereafter.

- The effect of fiber viscous parameter

The influence of the viscous parameter on the performance of the viscoelasto-plastic model was studied by carrying out a set of simulation runs, in which all the physical properties and operating conditions were kept constant, except the fiber viscosity. One of the assumptions of the model is that the viscous parameter of the composite does not include the contribution of the liquid phase. Instead, water is envisaged as playing a fundamental role in the development of the elasticity modulus of paper. As the adsorbed water, as well as the additive, have very low viscosities when compared to the viscosity of the fiber material, only this last constituent is considered for the calculus of the viscous parameter by means of Eqn. 3.60 with  $\mu^* = 1 \times 10^8$  Pa.s and  $\Delta G = 3241$  J.mol<sup>-1</sup> [29]. Figures 3.31 to 3.36 illustrate the effect of fiber viscosity on the mechanical response of a saturated paper web subjected to a peak pressure of 6.3 MPa at room temperature. The results were obtained for three different values of  $\mu^*$ :  $1 \times 10^8$ ,  $1 \times 10^7$  and  $1 \times 10^6$  Pa.s. Additional properties such as water volume fraction, density and gas pressure, were evaluated over the entire press pulse. However, the time evolution of such variables must be regarded with caution as the mass transfer was not considered in this first approach. For that very reason, no property profile was assumed in the three main directions. Consequently, the results presented hereafter are representative of each volume element inside the paper web. The inclusion of the heat and mass transfer in the global model will, therefore, represent the material behavior in a more realistic way.

The main aspect to retain from the results of the simulation runs is that fiber viscosity plays an important role in the dewatering and consolidation process. In fact for the higher viscous parameter, a lower level of strain is attained, and there is no evidence of strain recovery in the decompression stage of the press pulse at

all. Additionally, no significant differences were observed in the material response when the viscous parameter  $\mu^*$  was reduced from  $1 \times 10^8$  to  $1 \times 10^7$  Pa.s (see Figure 3.31). However, a value of  $\mu^* = 1 \times 10^6$  Pa.s was found to produce a mechanical response closer to that observed during the compression tests performed in the laboratory press (see Figure 3.30), *i.e.* the web gradually deforms to a minimum thickness level and when load is released the material starts to expand, although a certain level of strain remains at the end of the press pulse (see Figures 3.31 and 3.32). This seems to indicate that the fiber viscous parameter is overestimated by the relation used by Carvalho [29] to estimate the viscous parameter of MDF fibers. In fact the parameters used by Carvalho were obtained for wood fibers with a quite different chemical composition from those used here, which may in part explain the discrepancies found. A proper estimation of the fiber viscous parameter for the present case would certainly produce more realistic results.

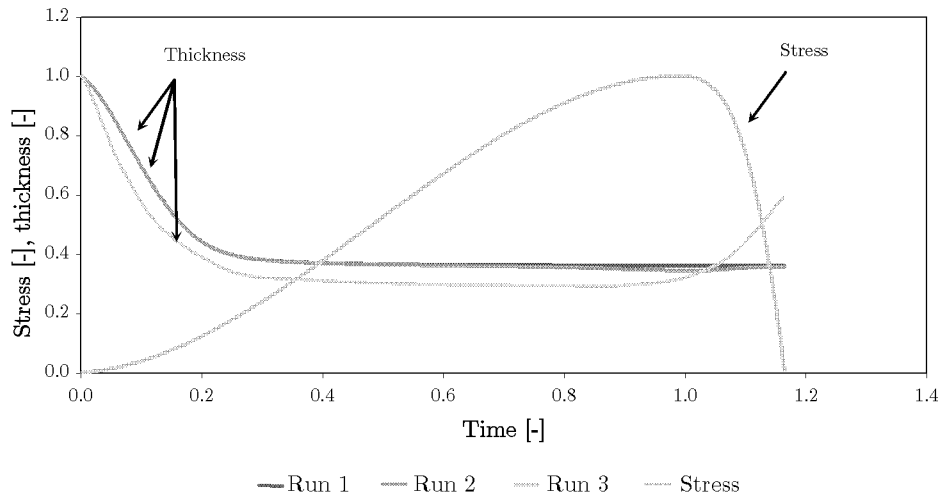


Figure 3.31: Applied stress and predicted thickness evolution for a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the viscous parameter  $\mu^*$ . Run 1:  $\mu^* = 1 \times 10^8$  Pa.s; Run 2:  $\mu^* = 1 \times 10^7$  Pa.s; Run 3:  $\mu^* = 1 \times 10^6$  Pa.s. Additional parameters:  $C_2 = 0.5$ ;  $E_l = 0.005 \times 206.8$  Pa;  $MR_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{f_{fu}} = 5.62 \times 10^{-2}$  MPa.

The lowest viscous parameter also produced the highest web density profile during the entire compression phase. Again, when load starts to reduce the web expands and density decreases. As a consequence of volume reduction, the water volume fraction increases to a maximum followed by a plateau. As the applied



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stress is further increased, the gas pressure builds up (as almost no web thickness reduction is observed). Beyond this point, there is no significant volume reduction of both liquid water and gas, which explains the fast increase of the gas pressure as well as its elasticity modulus. At this stage, the gas phase is envisaged as the main cause for the increase of the elastic parameter of the composite (see Figures 3.34 and 3.35).

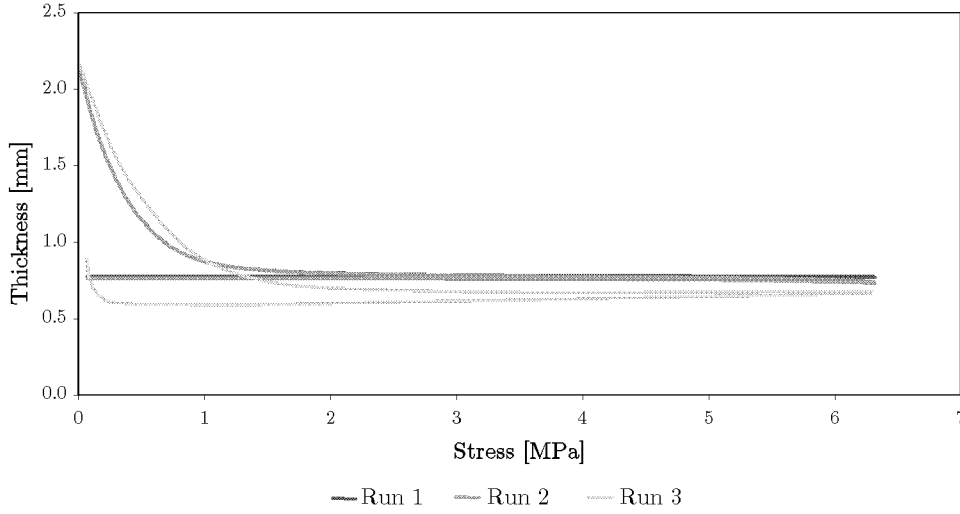


Figure 3.32: Predicted stress-strain behavior for a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the viscous parameter  $\mu^*$ . Run 1:  $\mu^* = 1 \times 10^8 \text{ Pa.s}$ ; Run 2:  $\mu^* = 1 \times 10^7 \text{ Pa.s}$ ; Run 3:  $\mu^* = 1 \times 10^6 \text{ Pa.s}$ . Additional parameters:  $C_2 = 0.5$ ;  $E_l = 0.005 \times 206.8 \text{ Pa}$ ;  $\text{MR}_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{ffit} = 5.62 \times 10^{-2} \text{ MPa}$ .

It should be mentioned that the elastic parameter  $E'_{sijk}$ , represented in Figure 3.34, corresponds to the contribution of the solid phase to the elastic modulus of the composite (first term in Eqn. 3.49). As it depends on the relative density of the material, some similarities may be found between the evolution of  $E'_{sijk}$  and  $\rho_{rel_{ijk}}$  throughout the pressing event (see Figures 3.34 and 3.36).

At the risk of some simplification, and as no additional data concerning the viscosity of fibers was found in the literature, the value of  $\mu^*$  used in the subsequent simulation runs was set to  $1 \times 10^6 \text{ Pa.s}$ . A proper definition of this parameter is therefore needed in a future work.

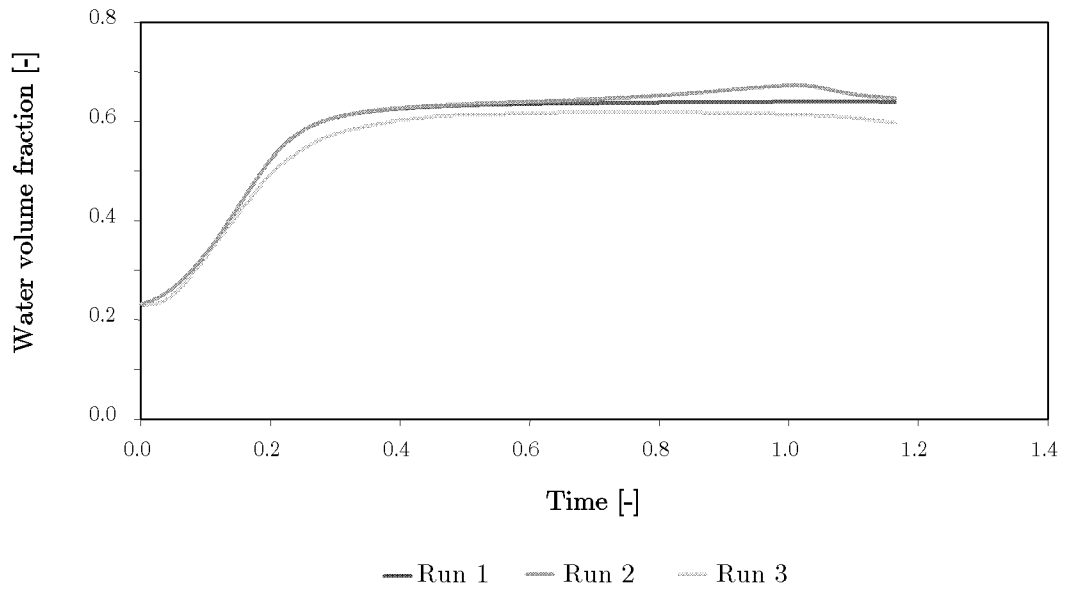


Figure 3.33: Predicted water volume fraction evolution for a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the viscous parameter  $\mu^*$ . Run 1:  $\mu^* = 1 \times 10^8 \text{ Pa.s}$ ; Run 2:  $\mu^* = 1 \times 10^7 \text{ Pa.s}$ ; Run 3:  $\mu^* = 1 \times 10^6 \text{ Pa.s}$ . Additional parameters:  $C_2 = 0.5$ ;  $E_l = 0.005 \times 206.8 \text{ Pa}$ ;  $\text{MR}_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{fit} = 5.62 \times 10^{-2} \text{ MPa}$ .

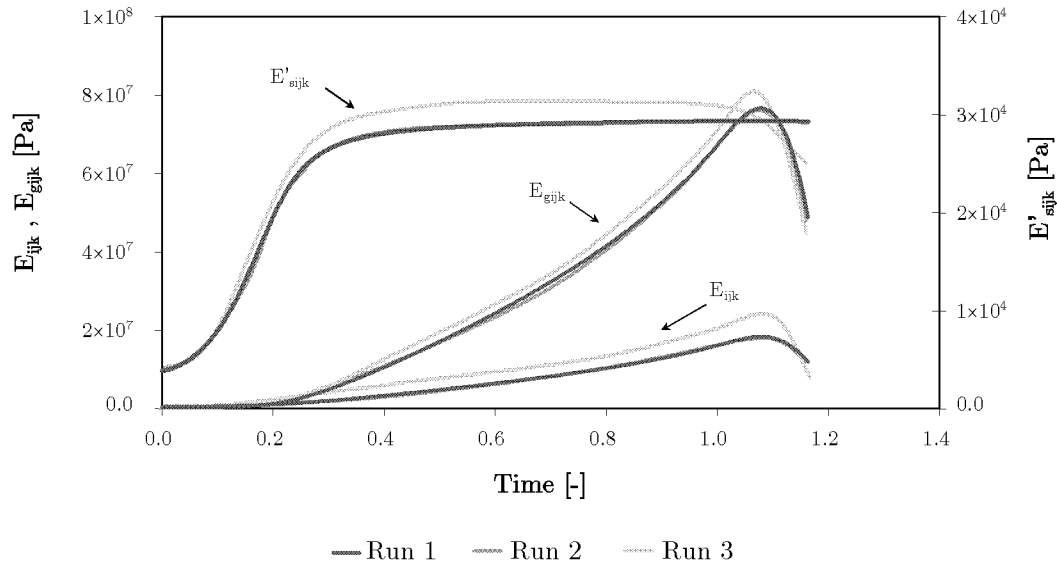


Figure 3.34: Predicted contribution of the gas and solid phases to the elastic parameter of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the viscous parameter  $\mu^*$ . Run 1:  $\mu^* = 1 \times 10^8$  Pa.s; Run 2:  $\mu^* = 1 \times 10^7$  Pa.s; Run 3:  $\mu^* = 1 \times 10^6$  Pa.s. Additional parameters:  $C_2 = 0.5$ ;  $E_l = 0.005 \times 206.8 \text{ Pa}$ ;  $MR_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{ffit} = 5.62 \times 10^{-2} \text{ MPa}$ .

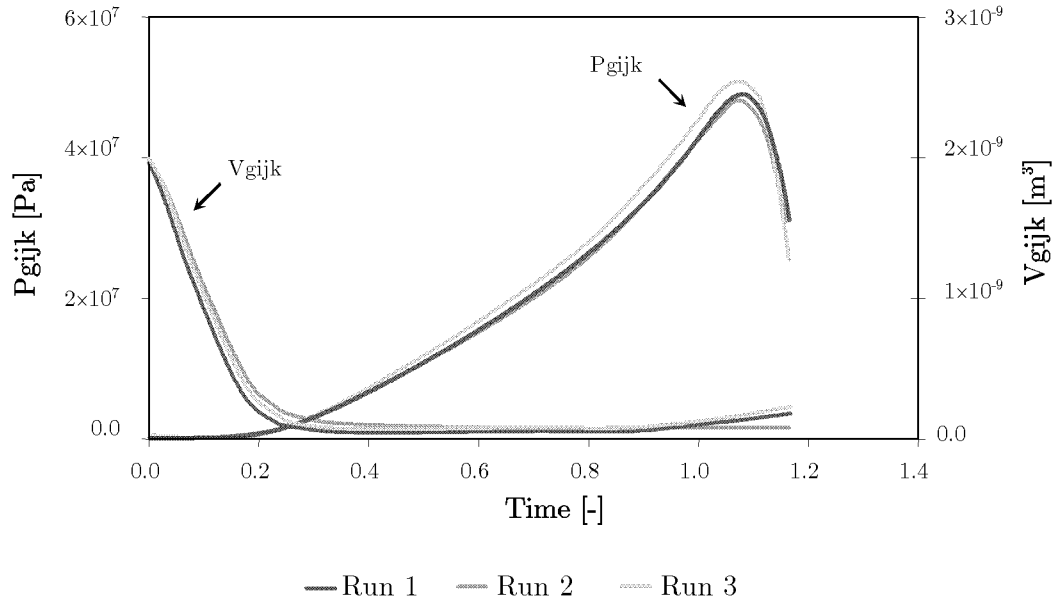


Figure 3.35: Predicted volume of the gas phase and its corresponding pressure inside a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web during a pressing event performed at 25 °C. The results were obtained for different values of the viscous parameter  $\mu^*$ . Run 1:  $\mu^* = 1 \times 10^8 \text{ Pa.s}$ ; Run 2:  $\mu^* = 1 \times 10^7 \text{ Pa.s}$ ; Run 3:  $\mu^* = 1 \times 10^6 \text{ Pa.s}$ . Additional parameters:  $C_2 = 0.5$ ;  $E_l = 0.005 \times 206.8 \text{ Pa}$ ;  $\text{MR}_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{fit} = 5.62 \times 10^{-2} \text{ MPa}$ .

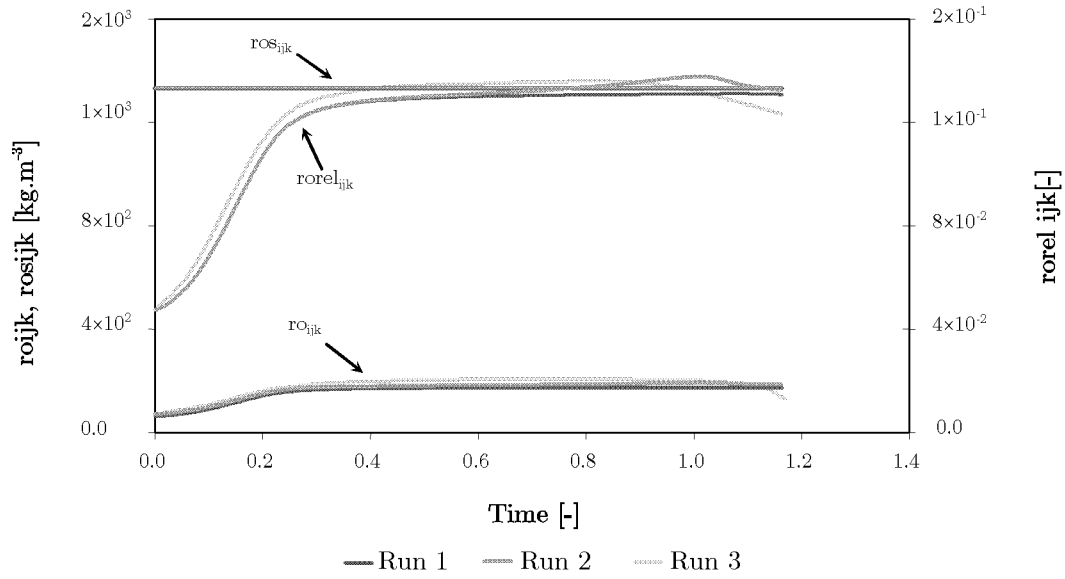


Figure 3.36: Prediction of apparent, relative and solid phase densities of a  $4 \times 60$  g.m<sup>-2</sup> 25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the viscous parameter  $\mu^*$ . Run 1:  $\mu^* = 1 \times 10^8$  Pa.s; Run 2:  $\mu^* = 1 \times 10^7$  Pa.s; Run 3:  $\mu^* = 1 \times 10^6$  Pa.s. Additional parameters:  $C_2 = 0.5$ ;  $E_l = 0.005 \times 206.8$  Pa;  $MR_{in} = 2.33$  kg H<sub>2</sub>O/kg ds;  $E_{ffit} = 5.62 \times 10^{-2}$  MPa.

- The effect of  $C_2$ , water elasticity modulus and ingoing moisture ratio

In order to evaluate the effect of the elastic constant  $C_2$  on the mechanical response of the material, all the other properties and parameters were maintained, including those studied in this subsection, *i.e.* water elasticity modulus and moisture ratio. The elastic constant directly affects the contribution of the solid network to the global elasticity of the composite (see Eqn. 3.49). It was therefore expected that an increase of  $C_2$  would result in a lower web deformation, as the contribution of the first term in Eqn. 3.49 would gain relevance. No clear evidence was found in this respect however. In fact, the increase of  $C_2$  from 0.5 to 1 did not produce any significant change in the output variables. It was then concluded that this parameter has no significant relevance in the process, at least in the actual operating conditions. These conclusions were based on the simulation results presented in Figures 3.38 to 3.43. In fact, the difference is actually hard to note. The picture is altogether different for the water elasticity modulus.

The results presented in Figure 3.37 were obtained for the same elasticity modulus but considering different ingoing moisture ratios, *i.e.*  $MR_{in} = 1.80$  and  $MR_{in} = 2.33$  kg H<sub>2</sub>O/kg ds. The results clearly state that for this level of moisture no significant changes are introduced in the system. Although moisture induces fiber conformability and flexibility, which facilitates the consolidation of the structure, the effect of such high amounts of water in the paper web is much more notorious in terms of its contribution to the global elasticity modulus of the composite, which takes into account the liquid water volume fraction. Obviously, Figures 3.40, 3.41 and 3.42 are somehow affected by the moisture ratio difference.

In order to evaluate the effect of water elasticity modulus, the mechanical behavior of the fiber mat was simulated setting  $E_l = 206.8$ ,  $0.5 \times 206.8$  and  $0.25 \times 206.8$  MPa. This parameter was found to have a significant influence on the mechanical response of the material, as illustrated hereafter (Figures 3.38 to 3.43). The results obtained with the highest value of the modulus ( $E_l = 206.8$  MPa) are not presented as almost no web consolidation was observed. In terms of thickness similar trends were observed, with the lowest value of  $E_l$  giving the highest strain levels. The influence of  $E_l$  is most notorious in terms of its contribution to the elasticity modulus of the composite. Figure 3.41 shows clear evidence of that. The elasticity modulus of the composite is significantly lower for the lowest value of  $E_l$ . At the final stage of decompression the modulus is also affected by the increase of the gas pressure.

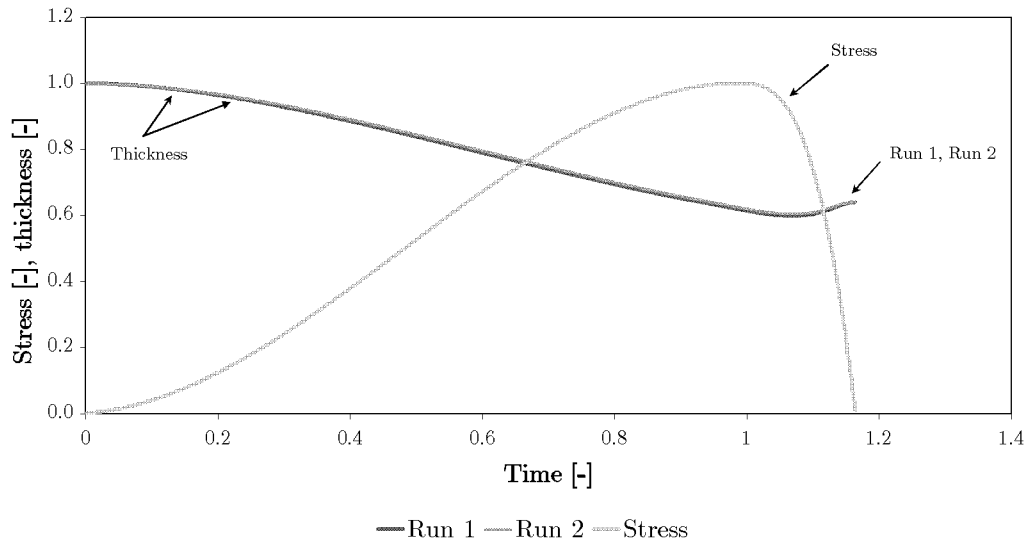


Figure 3.37: Applied stress and predicted thickness evolution for a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different web ingoing moisture ratios. Run 1:  $\text{MR}_{in} = 1.80 \text{ kg H}_2\text{O/kg ds}$ ; Run 2:  $\text{MR}_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ . Additional parameters:  $C_2 = 0.5$ ;  $E_l = 0.25 \times 206.8 \text{ Pa}$ ;  $\mu^* = 1 \times 10^6 \text{ Pa.s}$ ;  $E_{ffit} = 5.62 \times 10^{-2} \text{ MPa}$ .

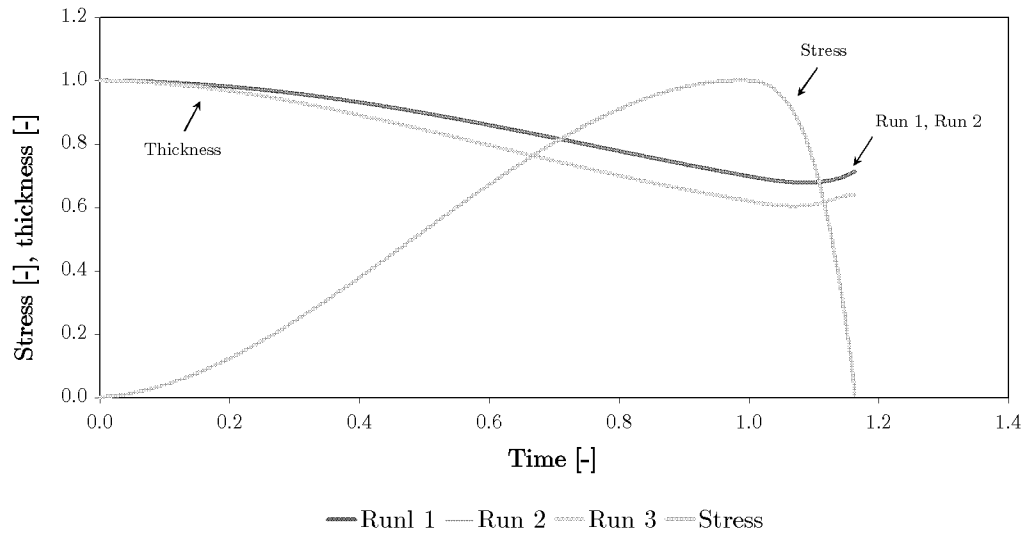


Figure 3.38: Applied stress and predicted thickness evolution for a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 1:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ); Run 2:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.1$ ); Run 3:  $E_l = 0.25 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ). Additional parameters:  $\text{MR}_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{fit} = 5.62 \times 10^{-2} \text{ MPa}$ .



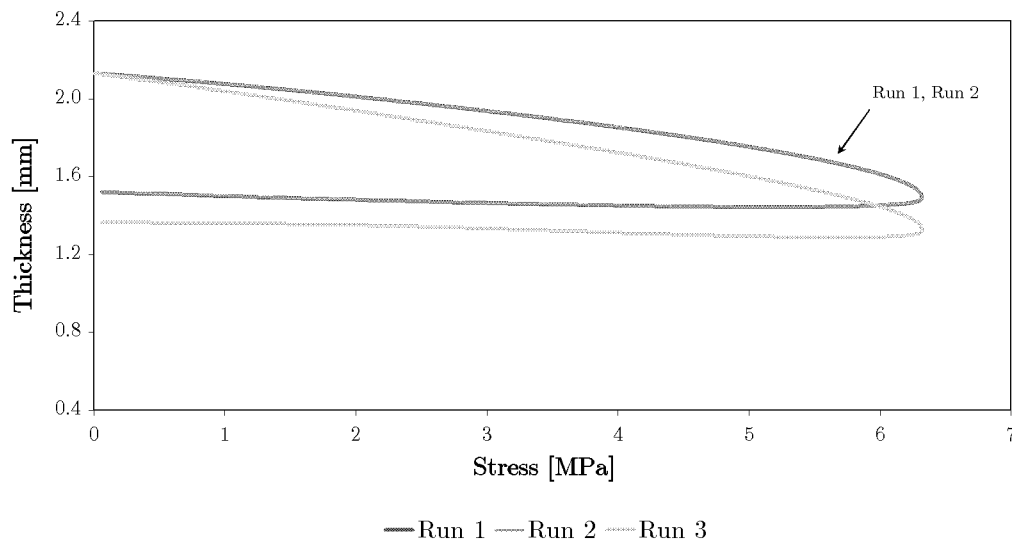


Figure 3.39: Predicted stress-strain behavior for a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 1:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ); Run 2:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.1$ ); Run 3:  $E_l = 0.25 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ). Additional parameters:  $\text{MR}_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{fit} = 5.62 \times 10^{-2} \text{ MPa}$ .

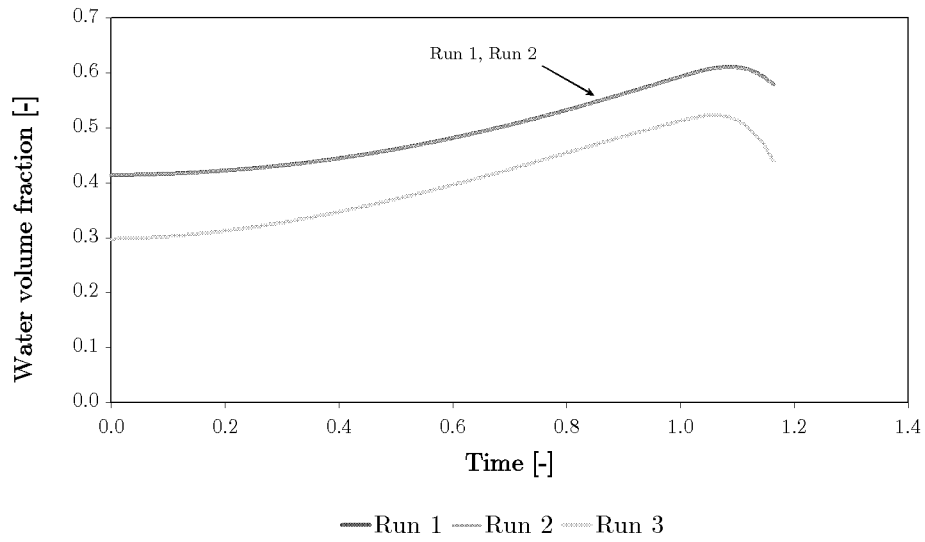


Figure 3.40: Predicted water volume fraction evolution for a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 1:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ); Run 2:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.1$ ); Run 3:  $E_l = 0.25 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ). Additional parameters:  $\text{MR}_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{fit} = 5.62 \times 10^{-2} \text{ MPa}$ .

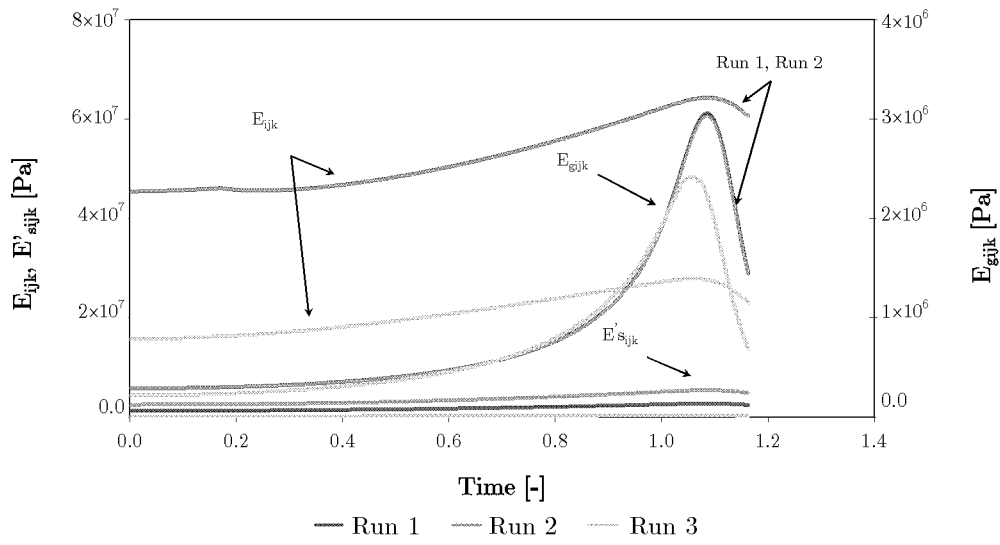


Figure 3.41: Predicted contribution of the gas and solid phases to the elastic parameter of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 1:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ); Run 2:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.1$ ); Run 3:  $E_l = 0.25 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ). Additional parameters:  $\text{MR}_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{fit} = 5.62 \times 10^{-2} \text{ MPa}$ .

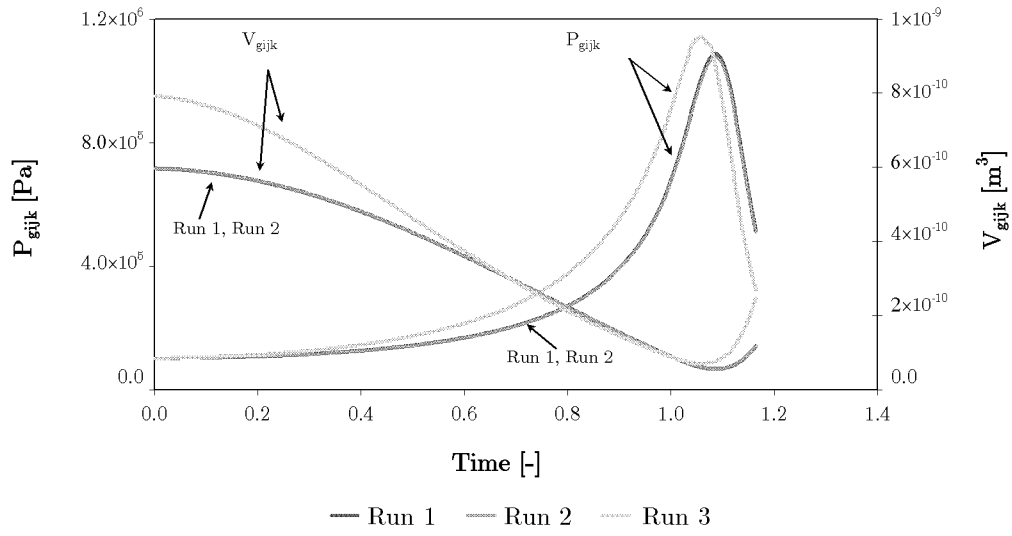


Figure 3.42: Predicted volume of the gas phase and its corresponding pressure inside a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web during a pressing event performed at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 1:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ); Run 2:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.1$ ); Run 3:  $E_l = 0.25 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ). Additional parameters:  $MR_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{fit} = 5.62 \times 10^{-2} \text{ MPa}$ .

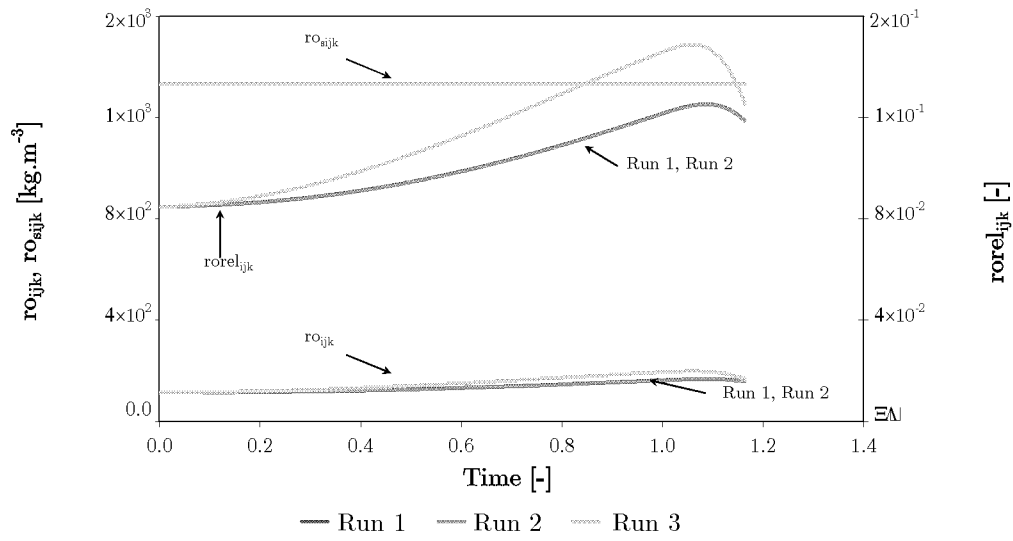


Figure 3.43: Prediction of apparent, relative and solid phase densities of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 1:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ); Run 2:  $E_l = 0.5 \times 206.8 \text{ MPa}$  ( $C_2 = 0.1$ ); Run 3:  $E_l = 0.25 \times 206.8 \text{ MPa}$  ( $C_2 = 0.5$ ). Additional parameters:  $\text{MR}_{in} = 2.33 \text{ kg H}_2\text{O/kg ds}$ ;  $E_{ffit} = 5.62 \times 10^{-2} \text{ MPa}$ .

- The effect of fiber elasticity modulus

The effect of fiber elasticity modulus on the material behavior was evaluated taking three different values of the  $E_{ffit}$  in Eqn. 3.32, *i.e.* 562, 5.62 and  $5.62 \times 10^{-2}$  MPa, and three values for  $E_l$  (Runs 4 and 5:  $0.5 \times 206.8$  MPa; Runs 1 and 2:  $0.025 \times 206.8$  MPa; Run 3:  $0.005 \times 206.8$  MPa). The highest value of  $E_{ffit}$  (Run 3; Figure 3.44), obtained by fitting the experimental data from Wolcott *et al* for the fiber cell wall modulus of *Liriodendrum tulipifera* (0.9 mm flakes), produced almost no mat consolidation even for the lowest value of  $E_l$ .

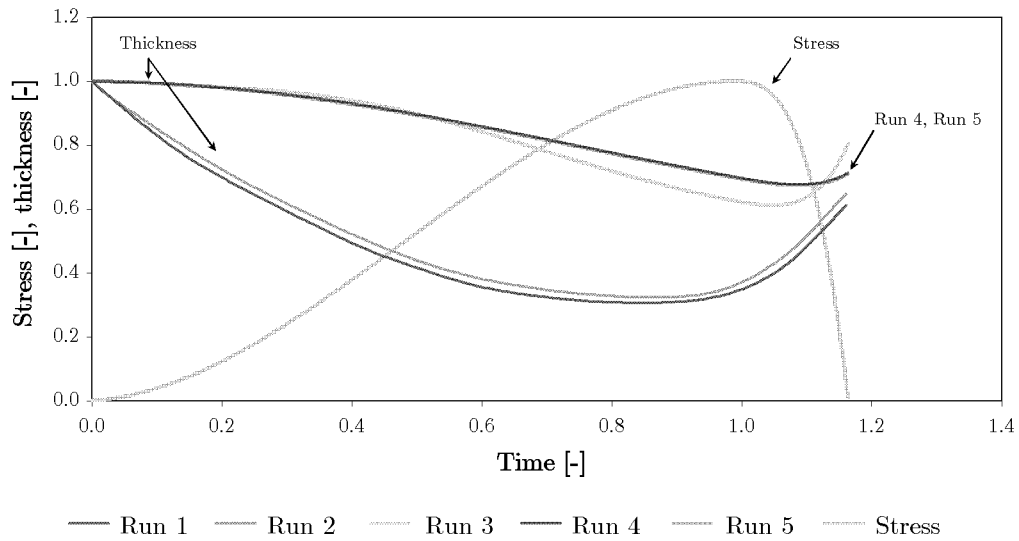


Figure 3.44: Applied stress and predicted thickness evolution for a  $4 \times 60$  g.m $^{-2}$  25 °SR hardwood paper web at 25 °C. The results were obtained for different fiber elastic parameter  $E_{ffit}$ . Run 1:  $E_{ffit} = 5.62 \times 10^{-2}$  MPa;  $E_l = 0.025 \times 206.8$  MPa; Run 2:  $E_{ffit} = 5.62$  MPa;  $E_l = 0.025 \times 206.8$  MPa; Run 3:  $E_{ffit} = 562$  MPa;  $E_l = 0.005 \times 206.8$  MPa; Run 4:  $E_{ffit} = 5.62 \times 10^{-2}$  MPa;  $E_l = 0.5 \times 206.8$  MPa; Run 5:  $E_{ffit} = 5.62$  MPa;  $E_l = 0.5 \times 206.8$  MPa. Additional parameters:  $MR_{in} = 2.33$  kg H $_2$ O/kg ds;  $C_2 = 0.5$ ;  $\mu^* = 1 \times 10^6$  Pa.s.

The picture is altogether different when comparing the results from Run 3 in Figures 3.31 and 3.44. In fact, for the same  $E_l$  ( $0.005 \times 206.8$  MPa) the lowest value of  $E_{ffit}$  ( $5.62 \times 10^{-2}$  MPa) produces a considerable mat deformation, which emphasizes the role of this parameter in the consolidation process of the material. However, the two lowest values of the fiber elasticity modulus produced no significant differences (Runs 1, 2 and 4, 5 in Figure 3.44). In this case, the

main factor affecting the behavior of the material seems to be the water elasticity modulus (Runs 1, 2:  $E_t = 0.025 \times 206.8$  MPa; Runs 4, 5:  $E_t = 0.5 \times 206.8$  MPa). This is ascribed to the major influence of the water elasticity modulus, which is even more notorious given the moisture ratio levels used in the present work. The contribution of the solid phase to the mechanical behavior of the composite is obviously important, but water also plays a fundamental role in this respect.

#### 3.3.4 Development of a simultaneous heat and mass transfer model for paper in impulse drying

In an effort to further understand the transport phenomena involved in impulse drying a heat and mass transfer model was developed, and the results from the simulation runs were compared to the experimental data collected during the impulse drying tests performed in the laboratory platen press. Although the knowledge concerning dewatering and consolidation of a paper web in a press machine has increased tremendously, there is still a need to increase the actual understanding, especially if high temperature conditions are involved as in the case of impulse drying.

The 3D model presented hereafter intends to represent the heat and mass transfer phenomena that may occur inside the paper web when submitted to the high-intensity conditions of impulse drying. In an attempt to simplify the model, it was assumed geometric symmetry, *i.e.* two planes of symmetry were considered, the vertical mid-planes, as illustrated in Figure 3.26. This simplification implies that the lateral edges of the sheet are exposed to the same ambient conditions; only the top and bottom surfaces of the sheet are submitted to different operating conditions. Consequently, only one fourth of the total web needs to be modelled.

In the model construction the following assumptions were considered:

- the model is three-dimensional, although the consolidation of the web occurs in the thickness direction only, and no lateral deformations are assumed;
- the medium is composed of three phases, solid, liquid and gas, and local thermodynamic equilibrium is assumed (see Figure 3.15); any heat and mass transfer resistance among the different phases is neglected;

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- the gas phase is formed by air and water vapor that may eventually be generated during the process, and it exists in the extra-fiber pore space; additionally, it behaves as an ideal gas;
- the liquid phase is composed of water; the convective flows of gas and liquid phases are assumed to follow the Darcy's relation;
- the solid phase is formed by cell wall material from the cellulose fibers, additive and water adsorbed on the fiber surface; the effect of fiber swelling due to water adsorption has been neglected;
- paper is assumed to be isotropic in the plane direction of the sheet;
- the consolidation of the sheet is induced by the applied mechanical pressure as the compression event is pressure controlled;
- the physical properties depend on temperature, moisture ratio and local steam pressure; transport properties that are dependent on changing physical properties can also vary with time and space; the mechanical properties (elastic and viscous parameters) also depend on the local temperature and moisture ratio of the material; inside each RVE no property change is assumed;
- although cellulosic fibers may plasticize within the layers near the hot plate, no additional heat transfer resistance is considered;
- the heat transferred to the paper sheet comes, exclusively, from the heated pressing head; no internal heat generation is assumed, which means that the energy transferred from the cure reaction of some additives added to the pulp suspension is neglected;
- moisture can exist in any of the three different phases: as vapor in the gas, as free liquid, or as adsorbed water within the porous solid matrix;
- if free liquid is present (*i.e.* above the fiber saturation point) the vapor and adsorbed phases remain saturated at the local temperature, and the free liquid water is in equilibrium with its saturated vapor; in the absence of liquid (*i.e.* below fiber saturation point), adsorbed water concentration and gas phase composition obey to a sorption isotherm at local temperature;



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- the main heat and mass transfer mechanisms are:
  1. ordinary heat conduction between the heated plate surface and the interior layers of the paper (the time of exposure to the heat source is neglected);
  2. convective heat and mass transfer: the driving forces of the water removal mechanism in impulse drying are the pressure and the temperature gradients. The applied pressure results in an hydraulic pressure gradient in the thickness direction of paper causing a compression and a water flow, which in turn is enhanced by increasing the temperature of the web. Also, the higher temperature of the heated plate compared to that of the paper web causes a heat flux into the sheet. This heats up the water and the fiber network, and when the temperature is equal to the saturation temperature at the corresponding hydraulic pressure, vapor is formed. The pressure gradient between the surface and the core of the web results in a flow of heat and vapor to the inner layers of the web, thus increasing their temperature. As a positive pressure differential is established from the interior of the web to the lateral edges, a mixture of air and water will flow out through the edges of the web;
  3. phase change of water either from the adsorbed or liquid state into vapor; the diffusion mechanism of adsorbed water was not considered in the model;
- the capillary pressure is determined according to the equivalent pore theory developed by Silvy and Butel [162]; relative permeabilities are introduced for both fluids as a function of water effective saturation.

#### Model equations

The development of a mathematical model for any system involves the formulation of equations describing the physics of the process based on the fundamental laws of conservation of matter and energy. For high temperature pressing five coupled equations have to be solved to calculate the heat and mass transfer in the wet fiber web: the continuity equations for free liquid water, water vapor, gas

phase and energy, and one equilibrium equation (moisture sorption isotherm or one describing the liquid/vapor saturation).

**The energy conservation equation**

$$\frac{\partial (\rho_p C_p T)}{\partial t} + \dot{M} (\Delta H_{vap} + Q_l) = - \left( \frac{\partial \varphi_{tx}}{\partial x} + \frac{\partial \varphi_{ty}}{\partial y} + \frac{\partial \varphi_{tz}}{\partial z} \right) \quad (3.113)$$

where  $T$  is the temperature,  $\rho_p$  and  $C_p$  are the density and the specific heat capacity of paper,  $\dot{M}$  the amount of vaporized water per unit time and volume,  $\Delta H_{vap}$  the latent heat of vaporization of water,  $Q_l$  the differential heat of sorption for the wood-water system, and  $\varphi_{tx}$ ,  $\varphi_{ty}$  and  $\varphi_{tz}$  are the total heat fluxes in the three main directions  $x$ ,  $y$  and  $z$  defined as,

$$\varphi_{tx} = -\lambda_{px} \frac{\partial T}{\partial x} + (\rho_g v_{gx} C_{pg} + \rho_l v_{lx} C_{pl}) T \quad (3.114)$$

$$\varphi_{ty} = -\lambda_{py} \frac{\partial T}{\partial y} + (\rho_g v_{gy} C_{pg} + \rho_l v_{ly} C_{pl}) T \quad (3.115)$$

$$\varphi_{tz} = -\lambda_{pz} \frac{\partial T}{\partial z} + (\rho_g v_{gz} C_{pg} + \rho_l v_{lz} C_{pl}) T \quad (3.116)$$

where  $\lambda_{pi}$  is the thermal conductivity of paper in a given  $i$  direction,  $\rho_g$ ,  $\rho_l$ ,  $C_{pg}$ , and  $C_{pl}$  the specific densities and heat capacities of both gas and liquid phases, and finally  $v_{gi}$  and  $v_{li}$  represent the superficial velocity of gas and liquid in the three main directions.

The first term in Eqn. 3.113 refers to the accumulation of heat in the system, and may be rewritten as follows:

$$\frac{\partial (\rho_p C_p T)}{\partial t} = \rho_p \left( T \frac{\partial C_p}{\partial t} + C_p \frac{\partial T}{\partial t} \right) + C_p T \frac{\partial \rho_p}{\partial t} \quad (3.117)$$

Although the specific heat capacity depends on the temperature and moisture ratio of the material, the findings of Carvalho [29] suggest that even at the extreme temperature and moisture operating conditions, it is acceptable to assume that

$$T \frac{\partial C_p}{\partial t} \ll C_p \frac{\partial T}{\partial t} \quad (3.118)$$

Assuming that the specific density of the dry solid remains constant, Eqn. 3.117 may now be written in a simpler form

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$$\frac{\partial (\rho_p C_p T)}{\partial t} = \rho_p C_p \frac{\partial T}{\partial t} + C_p T \frac{\partial \rho_p}{\partial t} \quad (3.119)$$

#### The conservation equation for water vapor

To establish the mass balance for water vapor, two possible scenarios may be drawn: (i) *below the fiber saturation point*: at this stage, there is no free liquid water within the web, which means that the vapor formed comes entirely from the vaporization of the adsorbed water on the cellulose fibers; (ii) *above the fiber saturation point*: as adsorbed water is assumed to be retained on the surface of the cellulose fibers, the liquid water is considered to be in equilibrium with its saturated vapor. The water vapor mass balance may then be expressed as:

$$\left( \dot{M}_b + \dot{M}_l \right) = \frac{\partial (\phi_g \rho_v)}{\partial t} + \left( \frac{\partial \varphi_{vx}}{\partial x} + \frac{\partial \varphi_{vy}}{\partial y} + \frac{\partial \varphi_{vz}}{\partial z} \right) \quad (3.120)$$

where  $\dot{M}_b$  and  $\dot{M}_l$  are the amount of adsorbed or liquid water vaporized per unit time and volume.  $\phi_g$  is the volume fraction of gas in the entire mat,  $\rho_v$  the specific density of vapor and,  $\varphi_{vx}$ ,  $\varphi_{vy}$  and  $\varphi_{vz}$  are the total water vapor fluxes defined as

$$\varphi_{vx} = \rho_v v_{gx} - \phi_g D_x^{eff} \frac{\partial \rho_v}{\partial x} \quad (3.121a)$$

$$\varphi_{vy} = \rho_v v_{gy} - \phi_g D_y^{eff} \frac{\partial \rho_v}{\partial y} \quad (3.121b)$$

$$\varphi_{vz} = \rho_v v_{gz} - \phi_g D_z^{eff} \frac{\partial \rho_v}{\partial z} \quad (3.121c)$$

where  $D_i^{eff}$  is the effective diffusivity of water vapor in the pores of the mat for a given  $i$  direction.

Finally, Eqns. 3.121a to 3.121c may be expressed in terms of the dependent variables  $T$  and  $P_v$  (vapor partial pressure),

$$\varphi_{vx} = \frac{MM_v}{R} \left[ \frac{P_v}{T} v_{gx} - \phi_g D_x^{eff} \frac{\partial}{\partial x} \left( \frac{P_v}{T} \right) \right] \quad (3.122a)$$

$$\varphi_{vy} = \frac{MM_v}{R} \left[ \frac{P_v}{T} v_{gy} - \phi_g D_y^{eff} \frac{\partial}{\partial y} \left( \frac{P_v}{T} \right) \right] \quad (3.122b)$$

$$\varphi_{vz} = \frac{MM_v}{R} \left[ \frac{P_v}{T} v_{gz} - \phi_g D_z^{eff} \frac{\partial}{\partial z} \left( \frac{P_v}{T} \right) \right] \quad (3.122c)$$

where  $MM_v$  is the molar mass of water and  $R$  the universal gas constant.

It is worth noting at this point that, the term representing the accumulation of vapor in the porous structure (see Eqn. 3.120) is a matter of some controversy because it directly relates to the postulations of the different dewatering mechanisms proposed in the literature for the impulse drying process. As already discussed in this text, the theory of a vapor–liquid displacing front suggests that the two phases coexist since the early stages of the pressing event, and that vapor plays a fundamental role in the dewatering process [6]. Accordingly, the steam generated cannot be neglected. Other authors, however, support the idea of a pressing/flashing mechanism, according to which a vapor phase would form at nip opening, and never before [109]. This theory suggests that the hydraulic pressure developed inside the paper web during the pressing event is high enough to prevent steam generation. Once the nip is opened a sudden pressure drop occurs and liquid water flashes into vapor. As a consequence, one may say that the amount of generated steam is relevant only in the final stage of the process.

Recent findings suggest that displacement dewatering could be a result of flashing at nip decompression [105]. In fact, Lucisano [105] advances that for short pulses, in the order of 25 ms, the hydraulic pressure in most of the sheet is high enough to prevent steam generation and water is present in the liquid phase until the pressure is released. An increase in nip residence time to 250 ms revealed a significant in-nip steam generation but only in the decompression stage of the event. The impulse drying experiments were performed using 60 g.m<sup>-2</sup> paper sheets submitted to a maximum applied pressure of 8 MPa and the temperature was about 220 °C. In summary, impulse pressing trials on samples of total web grammage < 120 g.m<sup>-2</sup> showed phase change only after decompression, and no vapor fronts could be seen before the point of maximum applied pressure. When similar pressure pulses and temperatures were applied to webs of higher grammage, a temperature peak, falling down to about 100 °C, was observed just before the end of the pressure pulse. This behavior was observed even for pulse lengths as high as 500 ms. In addition, the author found clear evidence of steam generation in the sheet layers near the hot plate, but no phase transition was seen in the region closer to the felt, where the temperature remained under 100 °C. The experimental investigation described above is in agreement to that performed in the present study (see **Subsection** “Transport and physical properties of the composite”). In fact, no clear evidence of steam generation was recorded in impulse drying experiments using either 60 or 80 g.m<sup>-2</sup> wet paper

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sheets pressed at temperatures as high as 350 °C and peak pressures around 6 MPa (see Figure 2.27 in **Chapter 2**). However, for longer press pulses, ranging from 75 to 200 ms, some discreet temperature peaks were recorded at the final stage of decompression, which may in fact indicate some steam generation (see Figures 3.86 to 3.88). When high moisture ratio paper webs with grammage of about 240 and 320 g.m<sup>-2</sup> were submitted to peak pressures around 6 MPa and temperatures ranging from 25 to 350 °C over 75, 120 and 2000 ms, no temperature peaks were observed (see Figures 3.71 to 3.85). Unfortunately, the most promising operating conditions were not covered, *i.e.* a pulse length of 120 ms and temperatures above 150 °C. In fact, up to 150 °C the internal temperature of the paper web at the vertical position corresponding to 60 or 80 g.m<sup>-2</sup> remains under 100 °C, suggesting that no in-nip steam generation takes place under such operating conditions.

In conclusion, for modeling purposes steam generation will only be considered for the case of high moisture ratio paper webs with grammages of 240 and 320 g.m<sup>-2</sup> pressed above 150 °C, and 60 and 80 g.m<sup>-2</sup> wet paper sheets submitted to extended press nips of 75, 120 and 200 ms. Consequently, the term representing the accumulation of vapor is most relevant in the final stage of decompression, when steam generation is expected to occur. As for the case of short press pulses in which 60 and 80 g.m<sup>-2</sup> wet paper sheets were pressed from room temperature up to 350 °C, it was assumed steam generation just prior to nip opening at temperatures above 200 °C.

Expressing the accumulation term as a function of the dependent variables  $T$  and  $P_v$ , the mass balance may be written as:

$$\begin{aligned} \dot{M}_v = & \frac{\phi_g M M_v}{R.T} \left( \frac{\partial P_v}{\partial t} \right) - \frac{\phi_g M M_v P_v}{R.T^2} \left( \frac{\partial T}{\partial t} \right) + \frac{M M_v}{R} \left( \frac{P_v}{T} \right) \frac{\partial \phi_g}{\partial t} + \dots \\ & \dots + \left( \frac{\partial \varphi_{vx}}{\partial x} + \frac{\partial \varphi_{vy}}{\partial y} + \frac{\partial \varphi_{vz}}{\partial z} \right) \end{aligned} \quad (3.123)$$

where  $\dot{M}_v$  represents the amount of water being vaporized per unit time and volume ( $\dot{M}_v = \dot{M}_b + \dot{M}_l$ ).

Even assuming steam generation in the final stage of decompression, there are still two different scenarios that have to be taken into account:

*Above fiber saturation point*

The vapor generated comes from the vaporization of the free liquid water. Therefore,

$$\dot{M}_v = \dot{M}_l \quad (3.124)$$

$$\dot{M}_b = 0 \quad (3.125)$$

The liquid water being vaporized is assumed to be in equilibrium with its saturated vapor. Considering as valid the assumptions of ideal-gas and ideal-solution, the criterion of vapor/liquid equilibrium produces a simple and useful equation known as Raoult's law expressed as

$$y_{m,i} P_v = x_{m,i} P_i^{sat} \quad (3.126)$$

where  $y_{m,i}$  and  $x_{m,i}$  are the mole fractions of the constituent  $i$  in the gas and liquid phases, respectively,  $P_v$  the total pressure of the vapor phase, and  $P_i^{sat}$  is the saturation or vapor pressure of pure species  $i$  at temperature  $T$ . According to the previous equation, the left-hand side is the partial pressure of pure species  $i$  in the vapor phase and equals the product of the liquid phase mole fraction of species  $i$  and its vapor pressure at temperature  $T$ .

Considering now the liquid-vapor equilibrium of water, Eqn. 3.126 becomes,

$$P_v = P^{sat} = f(T) \quad (3.127)$$

Taking the derivative form of Eqn. 3.127, it follows that

$$\frac{\partial P_v}{\partial t} = \frac{\partial P^{sat}}{\partial t} = \left( \frac{\partial P^{sat}}{\partial T} \right) \left( \frac{\partial T}{\partial t} \right) \quad (3.128)$$

*Below fiber saturation point*

At this stage there is no liquid water in the porous medium. The vapor results exclusively from the vaporization of the adsorbed water. For modeling purposes the diffusion of the adsorbed water is neglected, and only the phase transition from the adsorbed state into vapor is considered.

Under the present assumptions, one may say that,

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$$\dot{M}_v = \dot{M}_b \quad (3.129a)$$

$$\dot{M}_l = 0 \quad (3.129b)$$

The adsorbed water is now in equilibrium with the vapor in the pores. Therefore, the water/vapor equilibrium may be described by a sorption isotherm as that derived by Nadler *et al* [123] (see Eqn. 3.212). The relative humidity,  $RH$ , and the moisture ratio at the equilibrium (here defined as  $MR_{eq}$ ) are related by the following equation:

$$MR_{eq} = f(RH) \quad (3.130a)$$

$$\text{and } RH = \frac{P_v}{P_{sat}} \quad (3.130b)$$

Taking here the moisture ratio as the amount of adsorbed water per kg of dry solids ( $m_{dry}$ , cell wall material + additive), one may assume that the amount of water being vaporized per unit time and volume is given by the variation of the moisture ratio of the web,

$$\dot{M}_b = -\frac{\partial}{\partial t} \left( \frac{m_{dry} \cdot MR_{eq}}{V} \right) = -\frac{\partial}{\partial t} (\rho_{dry} \cdot MR_{eq}) \quad (3.131a)$$

$$\text{and } MR_{eq} = \frac{m_b}{m_{dry}} \quad (3.131b)$$

where  $\rho_{dry}$  is the apparent density of the dry solid.

Eqn. 3.131a may be rewritten as:

$$-\dot{M}_b = MR_{eq} \frac{\partial \rho_{dry}}{\partial t} + \rho_{dry} \frac{\partial MR_{eq}}{\partial t} \quad (3.132)$$

And

$$\frac{\partial MR_{eq}}{\partial t} = \frac{\partial RH}{\partial t} \left( \frac{\partial MR_{eq}}{\partial RH} \right)_T = \frac{1}{P_{sat}} \left( \frac{\partial P_v}{\partial t} \right) \left( \frac{\partial MR_{eq}}{\partial RH} \right)_T \Rightarrow (3.133)$$

$$\Rightarrow \frac{\partial P_v}{\partial t} = \frac{P_{sat} \left( \frac{\partial MR_{eq}}{\partial t} \right)}{\left( \frac{\partial MR_{eq}}{\partial RH} \right)_T} = -\frac{\frac{P_{sat}}{\rho_{dry}} \left( \dot{M}_b + MR_{eq} \frac{\partial \rho_{dry}}{\partial t} \right)}{\left( \frac{\partial MR_{eq}}{\partial RH} \right)_T} \quad (3.134)$$

where  $\left(\frac{\partial MR}{\partial RH}\right)_T$  is the derivative form of the sorption isotherm.

### The conservation equation for the gas phase

Following the same approach used for the vapor mass balance, the conservation equation for the gas phase may be written as:

$$\left(\dot{M}_b + \dot{M}_l\right) = \frac{\partial(\phi_g \rho_g)}{\partial t} + \left(\frac{\partial \varphi_{gx}}{\partial x} + \frac{\partial \varphi_{gy}}{\partial y} + \frac{\partial \varphi_{gz}}{\partial z}\right) \quad (3.135)$$

where  $\rho_g$  is the specific density of the gas phase, and  $\varphi_{gx}$ ,  $\varphi_{gy}$  and  $\varphi_{gz}$  are the gas fluxes in the three main directions of flow, given as:

$$\varphi_{gx} = \rho_g v_{gx} = \rho_g \left( -\frac{K_{gx}}{\mu_g} \frac{\partial P_g}{\partial x} \right) \quad (3.136a)$$

$$\varphi_{gy} = \rho_g v_{gy} = \rho_g \left( -\frac{K_{gy}}{\mu_g} \frac{\partial P_g}{\partial y} \right) \quad (3.136b)$$

$$\varphi_{gz} = \rho_g v_{gz} = \rho_g \left( -\frac{K_{gz}}{\mu_g} \frac{\partial P_g}{\partial z} \right) \quad (3.136c)$$

where  $K_{gx}$ ,  $K_{gy}$  and  $K_{gz}$  are the permeabilities of the gas phase in the porous medium in each  $i$  direction.

Developing the gas accumulation term, one gets

$$\begin{aligned} \frac{\partial(\phi_g \rho_g)}{\partial t} &= \phi_g \frac{\partial(\rho_g)}{\partial t} + \rho_g \frac{\partial(\phi_g)}{\partial t} = \dots \\ \dots &= \frac{\phi_g M M_v}{R} \frac{\partial}{\partial t} \left( \frac{P_g}{T} \right) + \frac{M M_v P_g}{R.T} \frac{\partial \phi_g}{\partial t} \end{aligned} \quad (3.137)$$

Substituting Eqn. 3.137 into Eqn. 3.135, the gas mass balance takes the final form,

$$\frac{\phi_g M M_v}{R} \frac{\partial}{\partial t} \left( \frac{P_g}{T} \right) + \frac{M M_v P_g}{R.T} \frac{\partial \phi_g}{\partial t} = - \left( \frac{\partial \varphi_{gx}}{\partial x} + \frac{\partial \varphi_{gy}}{\partial y} + \frac{\partial \varphi_{gz}}{\partial z} \right) + \dot{M}_v \quad (3.138)$$

where  $\dot{M}_b$  and  $\dot{M}_l$  are the amount of adsorbed or liquid water vaporized per unit time and volume.  $\phi_g$  is the volume fraction of gas in the entire mat.



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#### The conservation equation for the liquid phase

When the material is above the fiber saturation point, the amount of vapor generated comes from the liquid phase in equilibrium with its saturated vapor. Therefore, the amount of vaporized liquid is defined by the liquid/vapor equilibrium relation (see Eqn. 3.128).

The mass balance is given as:

$$\frac{\partial(\phi_l \rho_l)}{\partial t} = - \left( \frac{\partial \varphi_{lx}}{\partial x} + \frac{\partial \varphi_{ly}}{\partial y} + \frac{\partial \varphi_{lz}}{\partial z} \right) - \dot{M}_l \quad (3.139)$$

where  $\rho_l$  is the specific density of the liquid phase, and  $\varphi_{lx}$ ,  $\varphi_{ly}$  and  $\varphi_{lz}$  are the liquid fluxes in the three main directions of flow, given as:

$$\varphi_{lx} = \rho_l v_{lx} = - \frac{\rho_l K_{lx}}{\mu_l} \left( \frac{\partial P_g}{\partial x} - \frac{\partial P_c}{\partial x} \right) \quad (3.140a)$$

$$\varphi_{ly} = \rho_l v_{ly} = - \frac{\rho_l K_{ly}}{\mu_l} \left( \frac{\partial P_g}{\partial y} - \frac{\partial P_c}{\partial y} \right) \quad (3.140b)$$

$$\varphi_{lz} = \rho_l v_{lz} = - \frac{\rho_l K_{lz}}{\mu_l} \left( \frac{\partial P_g}{\partial z} - \frac{\partial P_c}{\partial z} \right) \quad (3.140c)$$

where  $K_{lx}$ ,  $K_{ly}$  and  $K_{lz}$  are the permeabilities of the liquid phase in the porous medium in each  $i$  direction, and  $P_c$  the capillary pressure.

Again, developing the accumulation term of the liquid phase, the resulting global balance for the liquid water is given by

$$\phi_l \frac{\partial \rho_l}{\partial t} + \rho_l \frac{\partial \phi_l}{\partial t} = - \left( \frac{\partial \varphi_{lx}}{\partial x} + \frac{\partial \varphi_{ly}}{\partial y} + \frac{\partial \varphi_{lz}}{\partial z} \right) - \dot{M}_l \quad (3.141)$$

**Initial and boundary conditions** The continuity and energy equations developed above describe the dynamics of the drying process inside the web. The resulting set of partial differential equations are solved with the boundary conditions describing the heat and mass transport at the surfaces of the web. These conditions can be different for different types of drying processes or for different dryer designs.

For the case of impulse drying one side of the web is in contact with a hot surface, and the other side is open to ambient atmosphere conditions, as well as the lateral edges of the sheet. The hot surface boundary is assumed to be at

constant temperature and impermeable to liquid, vapor and air (therefore, the flows are set to zero; from Darcy's relation this also means that the gradients for both liquid and gas vanish).

The open surface boundary condition depends on the saturation degree of the paper web and its supporting material, *i.e.* the felt or the sintered metal plate. In the present study, two sets of paper samples were submitted to impulse pressing: (i) "saturated sheets" (it is, however, assumed that a certain amount of air exists inside the web); (ii) unsaturated sheets. For modeling purposes it was considered, in both cases, that the layer of the paper sheet near the interface paper/supporting medium tends to be saturated during the entire press cycle. In fact, even at extreme temperature conditions, the temperature recorded at the open surface of saturated paper samples remained under 100 °C, which indicates that no steam was generated at the boundary. As for the unsaturated sheets, it was assumed that due to compression, the layer near the interface becomes saturated with water, and also that the liquid water leaving the paper sheet fills the superficial pores of the supporting material up to complete saturation, which may actually be the case as for low grammage paper sheets no steam generation was observed (it is advanced that water is flashed into vapor only after the press pulse has ended). At the expansion phase two situations may occur: (i) the liquid water remains at the paper/supporting material interface, thus ensuring fluid continuity; (ii) water is reabsorbed by the paper sheet, thus decreasing the saturation of the supporting material. For simplicity, saturation at this boundary was considered to take place over the entire pressing event.

If the paper is saturated in the region near the interface there is no fluid discontinuity. If, on the other hand, the backing material is not saturated, it is suggested that permeability reduces to zero as a consequence of fluid discontinuity (this is also equivalent to a zero saturation gradient at that boundary) [15]. Accordingly, at this same interface the gas pressure is assumed to be atmospheric. However, if one considers that both gas and liquid are at atmospheric pressure, it would result in a zero capillary pressure corresponding to a fully saturated medium, which is not the case.

A suitable boundary condition would consider the well-known "capillary end effect", according to which the liquid will cross the exit face of the porous medium (the interface with the liquid continuum) only if it is completely saturated. This means that at the boundary one of two situations may occur:

$$S_{l,eff} = 1 \implies S_l = 1 \quad (3.142a)$$

$$\text{or} \quad v_{l_z} = 0 \quad \text{if} \quad S_{l,eff} < 1 \quad (3.142b)$$

In summary, if the interface is completely saturated (effective water saturation,  $S_{l,eff} = 1$ ) the velocity of the gas phase is set to zero, resulting in a zero gas saturation gradient. This means that the gas phase is being compressed instead.

If, on the other hand,  $S_{l,eff} < 1$  it is assumed fluid discontinuity, which is equivalent to a zero water saturation gradient at that boundary. The pressure of the vapor phase at this boundary is assumed the same as in the ambient air.

At the considered symmetry planes the heat and mass flows vanish, which means that the heat and mass gradients are all set to zero.

Apart from these boundary conditions, the partial differential equations developed are associated with initial conditions representing the values of the dependent variables at the beginning of the process.

#### Initial conditions

- Energy

At the beginning of the pressing event the temperature at any given RVE is equal to ambient atmospheric temperature,  $T_{amb}$ , except the paper surface contacting the heated plate, which is at  $T_p$ :

$$T(x, y, z \neq L_z, 0) = T_{amb} \quad (3.143)$$

$$T(x, y, L_z, 0) = T_p \quad (3.144)$$

- Vapor

Above fiber saturation point:

$$P_v(x, y, z, 0) = P^{sat}(T = T_{amb}) \quad (3.145)$$

Below fiber saturation point

$$P_v(x, y, z, 0) = P_v(MR = MR_{in}; T = T_{amb}) \quad (3.146)$$

- Gas

$$P_g(x, y, z, 0) = P_{amb} \quad (3.147)$$

- Liquid water

Above fiber saturation point:

$$\phi_l(x, y, z, 0) = \phi_{l_0} \quad (3.148)$$

where  $\phi_{l_0}$  is the liquid fraction at the beginning of the pressing event.

Below fiber saturation point:

$$\phi_l(x, y, z, 0) = 0 \quad (3.149)$$

### Boundary conditions

- Energy

$$\frac{\partial T}{\partial x}(0, y, z, t) = 0 \quad (3.150a)$$

$$\frac{\partial T}{\partial y}(x, 0, z, t) = 0 \quad (3.150b)$$

$$T(x, y, 0, t) = T_{amb} \quad (3.150c)$$

$$T(L_x, y, z, t) = T_{amb} \quad (3.150d)$$

$$T(x, L_y, z, t) = T_{amb} \quad (3.150e)$$

$$T(x, y, L_z, t) = T_p \quad (3.150f)$$

where  $T_p$  is the temperature of the heated plate.

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- Vapor

$$\frac{\partial P_v}{\partial x}(0, y, z, t) = 0 \quad (3.151a)$$

$$\frac{\partial P_v}{\partial y}(x, 0, z, t) = 0 \quad (3.151b)$$

$$\frac{\partial P_v}{\partial z}(x, y, L_z, t) = 0 \quad (3.151c)$$

Above fiber saturation point:

Unsaturated medium

$$P_v(L_x, y, z, t) = P^{sat}(T = T_{amb}) \quad (3.152)$$

$$P_v(x, L_y, z, t) = P^{sat}(T = T_{amb}) \quad (3.153)$$

$$\bullet S_{l,eff} = 1 \quad \frac{\partial P_v}{\partial z}(x, y, 0, t) = 0 \text{ (saturated interface)} \quad (3.154)$$

$$\bullet S_{l,eff} < 1 \quad P_v(x, y, 0, t) = P^{sat}(T = T_{amb}) \quad (3.155)$$

If the medium is saturated during the entire press cycle, only liquid water is assumed to cross the open surfaces, and vapor is compressed.

Saturated medium

$$\frac{\partial P_v}{\partial x}(L_x, y, z, t) = 0 \quad (3.156)$$

$$\frac{\partial P_v}{\partial y}(x, L_y, z, t) = 0 \quad (3.157)$$

$$\frac{\partial P_v}{\partial z}(x, y, 0, t) = 0 \quad (3.158)$$

Below fiber saturation point

$$P_v(L_x, y, z, t) = P_v(MR = MR_{in}; T = T_{amb}) \quad (3.159)$$

$$P_v(x, L_y, z, t) = P_v(MR = MR_{in}; T = T_{amb}) \quad (3.160)$$

$$P_v(x, y, 0, t) = P_v(MR = MR_{in}; T = T_{amb}) \quad (3.161)$$

- Gas

$$\frac{\partial P_g}{\partial x}(0, y, z, t) = 0 \quad (3.162a)$$

$$\frac{\partial P_g}{\partial y}(x, 0, z, t) = 0 \quad (3.162b)$$

$$\frac{\partial P_g}{\partial z}(x, y, L_z, t) = 0 \quad (3.162c)$$

Above fiber saturation point:

Unsaturated medium

$$P_g(L_x, y, z, t) = P_{amb} \quad (3.163)$$

$$P_g(x, L_y, z, t) = P_{amb} \quad (3.164)$$

$$\bullet S_{l,eff} = 1 \quad \frac{\partial P_g}{\partial z}(x, y, 0, t) = 0 \text{ (saturated interface)} \quad (3.165)$$

$$\bullet S_{l,eff} < 1 \quad P_g(x, y, 0, t) = P_{amb} \quad (3.166)$$

If the medium is saturated during the entire press cycle, only liquid water is assumed to cross the open surfaces, and the gas phase is compressed.

Saturated medium

$$\frac{\partial P_g}{\partial x}(L_x, y, z, t) = 0 \quad (3.167)$$

$$\frac{\partial P_g}{\partial y}(x, L_y, z, t) = 0 \quad (3.168)$$

$$\frac{\partial P_g}{\partial z}(x, y, 0, t) = 0 \quad (3.169)$$

Below fiber saturation point:

$$P_g(L_x, y, z, t) = P_{amb} \quad (3.170)$$

$$P_g(x, L_y, z, t) = P_{amb} \quad (3.171)$$

$$P_g(x, y, 0, t) = P_{amb} \quad (3.172)$$

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- Liquid water

Above fiber saturation point:

$$\frac{\partial \phi_l}{\partial x}(0, y, z, t) = 0 \quad (3.173)$$

$$\frac{\partial \phi_l}{\partial y}(x, 0, z, t) = 0 \quad (3.174)$$

$$\frac{\partial \phi_l}{\partial z}(x, y, L_z, t) = 0 \text{ (impermeable surface, } K_{l_z} = 0) \quad (3.175)$$

Unsaturated medium

$$\frac{\partial \phi_l}{\partial x}(L_x, y, z, t) = 0 \text{ (fluid discontinuity, } v_{l_x} = 0) \quad (3.176)$$

$$\frac{\partial \phi_l}{\partial y}(x, L_y, z, t) = 0 \text{ (fluid discontinuity, } v_{l_y} = 0) \quad (3.177)$$

$$\begin{aligned} \phi_l(x, y, 0, t) &= S_l \cdot \phi_{eff}(x, y, 0, t) = \phi_{eff}(x, y, 0, t) \\ &\text{(saturated interface)} \end{aligned} \quad (3.178)$$

Saturated medium

$$\phi_l(L_x, y, z, t) = S_l \cdot \phi_{eff}(L_x, y, z, t) = \phi_{eff}(L_x, y, z, t) \quad (3.179)$$

$$\phi_l(x, L_y, z, t) = S_l \cdot \phi_{eff}(x, L_y, z, t) = \phi_{eff}(x, L_y, z, t) \quad (3.180)$$

$$\phi_l(x, y, 0, t) = S_l \cdot \phi_{eff}(x, y, 0, t) = \phi_{eff}(x, y, 0, t) \quad (3.181)$$

Below fiber saturation point:

$$\phi_l(x, y, z, t) = 0 \quad (3.182)$$

The heat and mass transfer model equations developed above will be solved together with the constitutive equations representing the mechanical behavior of the material. The resulting set of PDE's in dimensionless variables is presented in **Section 3.3.5** "A proposed global model for the consolidation of water saturated paper webs in high-intensity processes".

### Transport and physical properties of the composite

**Specific densities** Data from steam tables for the density of liquid water were correlated with temperature by Stanish *et al* [174] using:

$$\rho_l (kg.m^{-3}) = 1157.8 - 0.5361 T (K). \quad (3.183)$$

As the gaseous phase is regarded as an ideal mixture of vapor and dry air,  $\rho_v$  and  $\rho_{air}$ , the densities of air and water vapor, are given as:

$$\rho_v = \frac{P_v \cdot MM_v}{RT} \quad (3.184)$$

$$\rho_{air} = \frac{P_{air} \cdot MM_{air}}{RT} \quad (3.185)$$

where  $MM$  is the molar mass ( $kg.mol^{-1}$ ),  $T$  the local temperature (K),  $P$  the partial pressure (Pa),  $R$  the universal gas constant ( $8.314 J.mol^{-1}.K^{-1}$ ) and the subscripts “ $v$ ” and “ $air$ ” refer to water vapor and dry air.

Additionally, the density of the gas,  $\rho_g$ , is expressed by the following relation (assuming ideal gas behavior):

$$\rho_g = \frac{P_g \cdot MM_g}{RT} = \rho_v + \rho_{air} \quad (3.186)$$

where the molar mass of the gaseous phase,  $MM_g$ , is simply given as a function of the molar mass of its constituents:

$$MM_g = MM_{air} + (MM_v - MM_{air}) \cdot \frac{P_v}{P_g} \quad (3.187)$$

As for the density of the constituents of the “solid” phase, *i.e.* cell wall material (mainly cellulose), additive and adsorbed water, the following data are referred in the literature. The specific density of cellulose varies according to the wood species and therefore it depends on the pulp type. Carlsson (see [192]) suggested the value of  $1550 kg.m^{-3}$  for softwood bleached kraft pulp fibers and  $1460 kg.m^{-3}$  for thermomechanical pulp fibers. Also, Kajanto *et al* [77] suggests the value of  $1500 kg.m^{-3}$  for cellulosic fibers and advances that the wall density of papermaking fibers is lower than this value because of submicroscopic to molecular porosity in the fiber wall. This porosity depends on the chemical composition of the wood fiber and the pulping method. Accounting for these effects the author suggested that fiber density reduces to  $1000-1100 kg.m^{-3}$ .



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On the other hand, data concerning the chemical additives used in the present study are scarce. However, Krogerus [85] indicates a value of about  $2700 \text{ kg.m}^{-3}$  for the density of precipitated calcium carbonate. As for the remaining additives a value of  $1100 \text{ kg.m}^{-3}$  was used. Finally, at the risk of some simplification the density of adsorbed water was assumed to be equal to the density of the free liquid water within the web.

**Viscosity** The viscosity of liquid water, fiber and additives were already described in Section 3.3.3. The question here is how to determine the viscosity of the gaseous phase. According to the kinetic theory of gases, the viscosity at moderate pressures is independent of pressure and varies to the square of absolute temperature [14]. The viscosity of water saturated vapor deviates from this behavior at pressures below  $10^3$  and above  $10^6$  Pa. It is known that the local pressure inside the press nip may reach or even go beyond the upper limit since the applied pressure is in that order of magnitude. Bearing this in mind, the relation referred by Stanish *et al* [174] for an air-water vapor mixture was used in the present work. It was obtained as a linear combination of the component viscosities, weighted by their mole fractions in the mixture:

$$\mu_g = \frac{(4.06 \times 10^{-8} T + 6.36 \times 10^{-6}) P_{air} + (3.20 \times 10^{-8} T - 1.57 \times 10^{-6}) P_v}{P_g} \quad (3.188)$$

where  $\mu_g$  is expressed in Pa.s.

**Water vapor diffusivity** The bulk diffusivity of air-water vapor mixtures may be given by a semi-empirical relation [174]:

$$D_{AB} = 2.20 \times 10^{-5} \left( \frac{101325}{P_g} \right) \cdot \left( \frac{T}{273.15} \right)^{1.75} \quad (3.189)$$

where  $D_{AB}$  is expressed in  $\text{m}^2.\text{s}^{-1}$ .

In general, the effective diffusivity may be expressed as a random-pore gas diffusivity for porous solids as

$$D^{eff} = (\epsilon)^2 . D_{AB} \quad (3.190)$$

where  $\epsilon$  accounts for both the volume occupied by the solid and the tortuosity of the void space. In wood, an additional attenuation factor,  $\delta_f$ , is used to account

for closed pores resulting from the cellular nature of the solid. The effective diffusivity for wood is then:

$$D^{eff} = \delta_f \cdot (\epsilon l)^2 \cdot D_{AB} \quad (3.191)$$

For simplicity, the approach suggested by Hata *et al* [65] for the water vapor diffusivity in the void volume of a wood particleboard will be used. The authors estimated the diffusivity in the thickness direction as

$$D_z^{eff} = 0.1 D_{AB} \quad (3.192)$$

whilst in the in-plane direction they considered it equal to the diffusivity in air,

$$D_x^{eff} = D_y^{eff} = D_{AB} \quad (3.193)$$

This is a simplification of the model, as the water vapor diffusivity inside a porous medium depends on the density of the medium itself. In fact, as the medium is being compressed, the void volume between the fibers is reduced which may decrease the water vapor effective diffusivity.

**Thermal conductivity** The thermal conductivities of all gases increase with pressure, although the effect is relatively small at low and moderate pressures. In fact, in the region from  $10^{-3}$  to 10 bar the conductivity increases about 1 percent or less per bar [142]. Such increases are often ignored in the literature. This is indeed the case for the present study. Although it was not practical to measure the gas pressure inside the paper sheet, the simulation runs performed during the execution of this work showed no evidence of elevated gas pressures. Bearing this in mind, the effect of pressure on the thermal conductivity of the gaseous phase was not considered.

The thermal conductivity of a gas mixture is not usually a linear function of mole fraction. Generally, if the constituent molecules differ greatly in polarity, the mixture thermal conductivity is larger than would be predicted from a mole fraction average. For nonpolar molecules, the opposite trend is noted and is more pronounced the greater the difference in molecular weights or sizes of the constituents. At the risk of some simplification, one may estimate the thermal conductivity of a mixture of water vapor and dry air simply as:

$$\lambda_g = y_{m,air} \cdot \lambda_{air} + y_{m,v} \cdot \lambda_v \quad (3.194)$$

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where

$\lambda_g$  = thermal conductivity of the gaseous phase;

$\lambda_{air}, \lambda_v$  = thermal conductivity of dry air and water vapor;

$y_{m,air}, y_{m,v}$  = mole fractions of air and water vapor in the gas phase, respectively.

The thermal conductivity of water vapor was estimated from an empirical relation suggested by Miller *et al* (see [14]) for water vapor at 1 bar and temperature between 273 and 1070 K:

$$\lambda_v = 7.341 \times 10^{-3} - 1.013 \times 10^{-5} T + 1.801 \times 10^{-7} T^2 - 9.100 \times 10^{-11} T^3 \quad (3.195)$$

where  $\lambda_v$  is expressed in  $\text{W.m}^{-1}.\text{K}^{-1}$ .

As for the other component of the gaseous phase, dry air, data is scarce. Therefore a constant value of  $0.026 \text{ W.m}^{-1}.\text{K}^{-1}$  was used [15].

At moderate pressures, up to 50 or 60 bar, the effect of pressure on the thermal conductivity of liquids is usually neglected, except near the critical point, where the liquid behaves more like a dense gas than a liquid [14]. For liquid water Miller *et al* (see [14]) suggested the following empirical relation valid in the temperature range of 273-623 K:

$$\lambda_l = -3.838 \times 10^{-1} + 5.254 \times 10^{-3} T - 6.369 \times 10^{-6} T^2 \quad (3.196)$$

where the thermal conductivity of liquid water,  $\lambda_l$ , is expressed in  $\text{W.m}^{-1}.\text{K}^{-1}$ .

Also, the thermal conductivity of the dry solid, *i.e.* the cell wall material,  $\lambda_{dry}$ , has been reported by several authors, as summarized on Table 3.5.

Table 3.5: Thermal conductivity of the dry fiber.

| Thermal conductivity of the dry fiber<br>[ $\text{W.m}^{-1}.\text{K}^{-1}$ ] | Reference                           |
|------------------------------------------------------------------------------|-------------------------------------|
| 0.08                                                                         | Wilhelmsson (see [89])              |
| 0.157                                                                        | Kartovaara <i>et al</i> (see [141]) |
| 0.335                                                                        | Hartley <i>et al</i> ([62])         |

Finally, the thermal conductivity of paper was estimated by some authors using somewhat similar approaches. Kartovaara *et al* (see [141]) suggested a

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simple arrangement of plates parallel to each other with air in the spaces between them, to model the fiber material in the  $z$ -direction. Kaviany (see [141]) then advanced the following relation to determine the thermal conductivity of dry paper,  $\lambda_p$ :

$$\frac{\lambda_p}{\lambda_{air}} = \frac{\lambda_{dry}/\lambda_{air}}{\phi \cdot \lambda_{dry}/\lambda_{air} + 1 - \phi} \quad (3.197)$$

where  $\phi$  is the total porosity of the medium.

Although the paper geometry is much more complicated than a simple arrangement of parallel plates and fibers, and do not consist only of cellulose, the model serves the purpose of describing the thermal conductivity as a function of porosity or the degree of compaction. However, water is not taken into account in this model.

Larsson *et al* [89] used the relation suggested by Wilhelmsson, and firstly derived by Depoy [38], to determine the thermal conductivity for a moist paper web, as follows:

$$\lambda_p = \frac{\lambda_{dry} + \text{MR} \cdot \lambda_l}{1 + \text{MR}} \quad (3.198)$$

where MR is the moisture ratio of the web expressed in kg H<sub>2</sub>O/kg ds.

Recent investigations, performed by Lucisano [105], highlighted the influence of temperature and density on the thermal conductivity of moist paper webs. The author measured the thermal conductivity of water-saturated blotter paper preconditioned to temperatures between 23 and 83 °C and pressed to dryness levels between 30 and 55 %. Increasing the temperature of the samples, the author found no evidence of a significant response of the thermal conductivity, which is in agreement with the general behavior of most common materials for the same temperature interval. The effect of solids content on the thermal conductivity was more evident; it increased with solids, which seems to be in contrast with the results obtained by the normal practice to calculate the thermal properties of wet paper by linear combination of the thermal properties of water and dry cellulose. In fact, the thermal conductivity of water is higher than that of dry cellulose, which suggests a decreasing trend with increasing solids. Lucisano suggested the fact that the thermal conductivity of fibers wetted by unpressable water might be significantly different from that of dry cellulose, which could in part explain the discrepancies observed. In addition, if air is present the thermal conductivity

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will be significantly lower than that of a completely air-free sample. It should be noted that for the above mentioned samples the author found values between 0.5 and  $1.6 \text{ W.m}^{-1}.\text{K}^{-1}$ , which is far above the thermal conductivity of dry cellulose and even liquid water. Bearing this in mind, a proper description of the thermal conductivity for water saturated paper would be an appropriate combination of the properties of water and wetted air-free fibers [105]. Following this idea, the thermal conductivity of moist fibers,  $\lambda_f$ , was estimated by combining the properties of dry cellulose and water adsorbed on the fiber surface, as in Eqn. 3.198:

$$\lambda_f = \frac{\lambda_{dry} + y_b \cdot \lambda_l}{1 + y_b} \quad (3.199)$$

If one now considers a water-saturated paper web in which pores are filled with liquid water, the thermal conductivity might be defined as:

$$\frac{\lambda_p}{\lambda_l} = \frac{\lambda_f / \lambda_l}{\phi_{eff} \cdot \lambda_f / \lambda_l + 1 - \phi_{eff}} \quad (3.200)$$

where  $\phi_{eff}$  is the effective porosity of the medium, *i.e.* the volume fraction open to fluid flow.

If on the other hand, air and water vapor are present in the medium, the thermal conductivity of the fluid formed by air, vapor and liquid water must be estimated, and then substitute  $\lambda_l$  in Eqn. 3.200 by  $\lambda_{fluid}$ .

Assuming a parallel assembly of air and water vapor, the thermal conductivity of the fluid may be estimated as:

$$\frac{\lambda_{fluid}}{\lambda_g} = \frac{\lambda_l / \lambda_g}{\phi'_g \cdot \lambda_l / \lambda_g + 1 - \phi'_g} \quad (3.201)$$

where  $\phi'_g$  is defined as the pore volume occupied by air and water vapor, *i.e.* the gas saturation,  $S_g$ .

As the majority of the experimental work in this field has been devoted to the measurement of thermal conductivity in the thickness direction of paper, it is extremely difficult to estimate this property in the plane of the sheet. It was decided, therefore, to follow the approach introduced by Humphrey [74], which consists of multiplying the thermal conductivity in the thickness direction of paper by a factor of 1.5. This is an empirical approach based on the experimental work of Ward and Skaar for a urea-formaldehyde particleboard (see [29]).

**Specific heat capacity** The specific heat capacity of paper is the contribution of the specific heat capacity of its constituents: air, water vapor, liquid and adsorbed water, additive and cell wall material. In a first analysis, the heat capacity of paper,  $C_p$ , could be expressed as:

$$C_p = y_{air} \cdot C_{p_{air}} + y_v \cdot C_{p_v} + y_l \cdot C_{p_l} + y_b \cdot C_{p_b} + y_{dry} \cdot C_{p_{dry}} \quad (3.202)$$

where  $y_i$  are the mass fractions and  $C_{p_i}$  the specific heat capacities of the  $i$  constituent.

For rough calculations, Lehtinen (see [89]) suggests that the thermal properties of wet and compressed webs can be assumed to be similar to those of water. A reasonable approach is that presented by Wilhelmsson (see [89]) following the commonly accepted practice of calculating the specific heat of paper as a linear combination of the (constant) specific heat of dry fibers and the (temperature-dependent) specific heat of water, as indicated hereafter:

$$C_p = \frac{C_{p_{dry}} + MR \cdot C_{p_l}}{1 + MR} \quad (3.203)$$

It is clear, from Eqn. 3.203, that the specific heat capacity of paper decreases with increasing solids content, *i.e.* as the moisture ratio decreases this property tends to the specific heat capacity of dry fibers. In fact, in Wilhelmsson's work the specific heat capacity of the dry fiber was  $1.3 \text{ kJ.kg}^{-1}.\text{K}^{-1}$  (see [89]), which is lower than the specific heat capacity of water, considered constant and equal to  $4.2 \text{ kJ.kg}^{-1}.\text{K}^{-1}$ . In this analysis, the total amount of water is taken into account, both in vapor and liquid form, as the moisture ratio value is used in Eqn. 3.203. This is valid if one assumes no significant difference between the specific heat capacity for liquid water and its vapor. Also, the presence of air and additive was neglected.

**Latent heat of vaporization** The latent heat of vaporization of water may be given by the following equation adapted from the Clausius-Clapeyron equation (see [74]):

$$\Delta H_{vap} = 2.511 \times 10^6 - 2.48 \times 10^3 (T - 273.15) \quad (3.204)$$

where  $\Delta H_{vap}$  is expressed in  $\text{J.kg}^{-1}$ .

Alternatively, the heat of vaporization data from steam tables were correlated with temperature by Stanish *et al* [174] using the following polynomial:

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$$\Delta H_{vap} = 2.792 \times 10^6 - 160 T - 3.43 T^2 \quad (3.205)$$

where  $\Delta H_{vap}$  is expressed in J.kg<sup>-1</sup>. This last approach was used in the present work.

**Differential heat of sorption** The differential heat of sorption for the wood-water system depends on the amount of water present in the specimen, according to the equation of Bramhall, Eqn. 3.206. This relation was used by Humphrey for wood particleboard [74], and later by Carvalho for MDF (medium density fiberboard) [29].

$$Q_l = 1.176 \times 10^6 \exp(-0.15y_b) \quad (3.206)$$

where  $Q_l$  is expressed in J.kg<sup>-1</sup> and  $y_b$  in kg adsorbed water/kg ds.

**Water vapor pressure** The vapor pressure may be determined by the following relation obtained from the data of Keenan and Keyes (see [29]):

$$\log P^{sat} = 10.745 - \frac{2141.0}{T} \quad (3.207)$$

where  $P^{sat}$  is the vapor pressure expressed in Pa.

**Adsorption isotherm** The moisture sorption equilibria and its influence on the performance characteristics of cellulosic products is an important phenomenon which has attracted much interest and has resulted in substantial volume of research work. A brief review of the literature reveals some important features of moisture isotherms of paper, paperboards and other cellulosic materials. The first is that the isotherms are sigmoid in shape due to the affinity of cellulose for water molecules [173] (see [32]). The second important feature is the hysteresis effect which exists between the adsorption and desorption isotherms.

A number of qualitative mechanisms have been postulated by several authors for the cause of sorption hysteresis in cellulosic materials. Urquhart [189] (see [32]) attributed hysteresis to differences in availability of hydroxyl groups in cellulose for attachment of water molecules during the adsorption and desorption parts of the equilibrium cycle. On the other hand, Barkas [13] (see [32]) suggested a connection between sorption and mechanical hysteresis. Chatterjee *et al*

[32], applied the theory of the independent “domains” developed by Everett [47] (see [32]) to represent the complex sorption equilibrium of bleached kraft paperboard. The basis of this theory is that hysteresis is caused by an irreversibility of microscopic independent domains within the absorbent structure. Each of these domains can exist in metastable equilibrium in either of two states, one containing more water than the other. Additionally, their distribution among these two states is assumed to be described by a domain-distribution function which acts like a memory of the system and keeps track of all the moisture contents corresponding to the humidity changes undergone during the sorption equilibrium cycle. The applicability of this theory was confirmed by the good agreement with the experimental data obtained by Chatterjee *et al* [32], which suggests that the hysteresis observed in the adsorption-desorption curves might be due to the existence of micro domains inside the cellulosic fibers that deform in a plastic and irreversible way retaining part of the moisture.

It is well known that the mechanical properties of paper depend greatly on the moisture content, and is thus imperative the knowledge of the adsorption isotherms for this material. As already mentioned, Chatterjee *et al* [32] studied the isotherms but only for the case of bleached kraft paperboard at room temperature (24 °C). Nevertheless, their data will be used as a basis of comparison with some theoretical models to estimate the adsorption isotherm.

There are few adsorption models for paper, and the experimental work is performed at room temperature, as in the previous research by Chatterjee *et al* (at least to the author’s knowledge). As for the wood-water system the scenario is somewhat different. There are several examples of sorption isotherms obtained experimentally for different wood species. Keylwerth [82] presented the adsorption isotherms for picea of Stika at temperatures up to 130 °C. As higher temperatures are involved in wood drying, Kauman [79] presented a method to extrapolate experimentally determined data to higher temperatures. The method is valid in the temperature range of 26-204 °C. Additionally, Simpson [164] tried to apply the Hailwood-Horobin [59] equation to the adsorption data from the Wood Handbook (USDA Forest Products Laboratory) for temperatures from 20 to 100 °C and atmospheric pressure. However, Simpson obtained a better agreement between the relative humidity and the moisture ratio at equilibrium using the model suggested earlier by Bradley [17] (see [29]):



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$$HR = \exp \left[ - \left( a_2 a_1^{MR_{eq}} + a_3 \right) \right] \quad (3.208)$$

where  $HR$  is the relative humidity,  $MR_{eq}$  is the moisture ratio at the equilibrium expressed in %, and  $a_1$ ,  $a_2$  and  $a_3$  are parameters determined as a function of temperature as:

$$a_1 = 0.839 + 2.02 \times 10^{-5} T + 1.56 \times 10^{-6} T^2 \quad (3.209)$$

$$a_2 = 3.56 + 3.92 \times 10^{-3} T + 4.45 \times 10^{-5} T^2 \quad (3.210)$$

$$a_3 = 0.219 + 1.64 \times 10^{-5} T \quad (3.211)$$

The previous equation was also used, in its inverted form, by Lartigue and Puigalli [91] to fit the experimental data of adsorption isotherms for pine wood in the temperature range of 20-60 °C.

Among several other models, that presented by Nadler *et al* [123] (see [29]) was selected to estimate the sorption isotherms for paper. This approach was made based on the fact that the model can predict with reasonable accuracy the trend observed in the experimental results obtained by Chatterjee *et al* for paperboard [32]. The correlation presented by Nadler *et al* was obtained from data of the Wood Handbook (USDA Forest Products Laboratory) and may be written as:

$$\begin{aligned} MR_{eq} &= Cst_1 + Cst_2.HR + Cst_3.HR^2 + Cst_4.HR^3 + \quad (3.212) \\ &\quad + Cst_5.T + Cst_6.T.HR + \frac{Cst_7}{T} \\ Cst_1 &= 1.2969; \quad Cst_2 = 36.6069; \quad Cst_3 = -53.5160 \\ Cst_4 &= 45.9798; \quad Cst_5 = -1.2245 \times 10^{-2}; \\ Cst_6 &= -3.5224 \times 10^{-2}; \quad Cst_7 = -53.7984 \end{aligned}$$

where  $Cst_i$  ( $i = 1, \dots, 7$ ) are constants of the model and  $T$  is expressed in °C. It is worth noting that the results obtained from Eqn. 3.212 are average values for adsorption and desorption. From Figure 3.45 it may be observed a reasonable agreement between the experimental results obtained by Chatterjee *et al* [32] and the sorption isotherm predicted according to Nadler's model at the corresponding temperature (24 °C). Another important feature of the isotherm is the intersection

on the ordinate axis at 100 % relative humidity, which gives the well-known fiber saturation point (*FSP*). In fact, the *FSP* occurs at RH in the range 99.9-99.99 % [80], and corresponds to the point at which fibers are saturated, but no free water is present in the capillary structure whatsoever. The fiber saturation point is 1 to 2 % higher for hardwood pulp fibers than for softwood pulp fibers, probably due to the higher amount of hemicelluloses of the former, which results in a higher capacity to adsorb water. According to Kollman and Côté [83], cellulose (the main component of wood) is responsible for 47 % of water uptake, 37 % are attributed to hemicelluloses and, finally, 16 % of water is retained by lignin.

Following Peralta [136], who used the Hailwood-Horobin equation in the extrapolation of the boundary isotherms (1<sup>st</sup> adsorption/desorption curves), Chatterjee *et al* artificially closed the hysteresis loop at the upper end by taking the average of the extrapolated limiting adsorption and desorption equilibrium moisture contents at an RH of 100 % which gave a value of 29.51 % [32] (see Figure 3.45). Additionally, Stone and Scallan [176] investigated the RH range between 90 and 99.99 % using two independent techniques to determine the *FSP* (the description of those techniques is not within the scope of the present work) and they advanced that the value of 0.3 g/g (or 30 % equilibrium moisture content), commonly reported in the literature for wood and pulp fiber, was too low and found the actual *FSP* of air-dried and reswollen black sprucewood to vary from 0.4 to 1.2 g/g as the wood was pulped by the kraft process. This means that the averaging procedure using by Chatterjee *et al* underpredicted the true equilibrium moisture content in the range of 90-100 %. Bearing this in mind, the model suggested by Nadler *et al* was extrapolated to higher equilibrium moisture contents, leading to a value of the *FSP* within the range reported by Stone and Scallan. To do so, a simple multiplying factor was introduced in Eqn. 3.212. Although it is a rough approximation it serves as a starting point. It should be emphasized that sorption equilibria data for paper is scarce if not inexistent for the operating conditions of the impulse drying process. The effect of the multiplying factor is illustrated in Figure 3.45. A factor of 1.5 was selected as it gives an average sorption isotherm that leads to a fiber saturation point of 42.34 % at 24 °C, which is considerably higher than that estimated by Chatterjee *et al*, and lies within the range suggested by Stone and Scallan.

Moreover, the sorption isotherm given by Nadler's model was extrapolated to higher temperatures, as those used in impulse drying (see Figure 3.46). Unfortu-

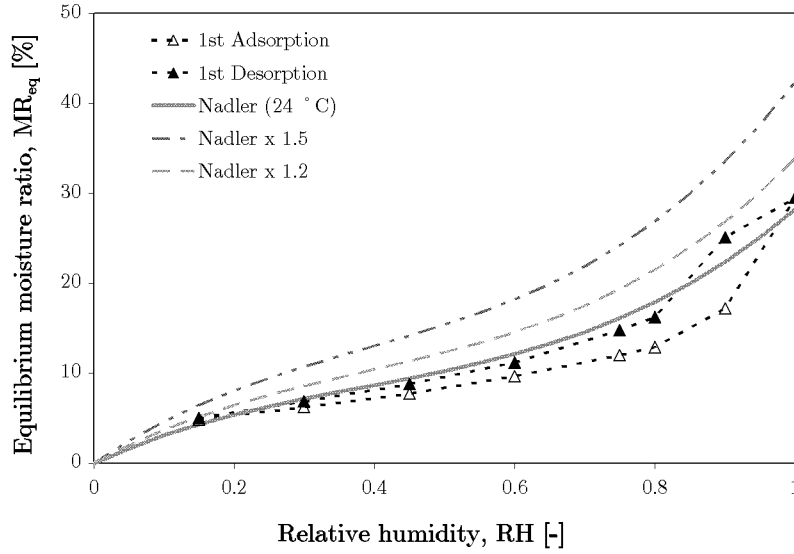


Figure 3.45: Moisture sorption equilibria: experimental curves obtained by Chatterjee *et al* [32], and predicted values from the model suggested by Nadler *et al* [123].

nately, it was not possible to compare the estimated isotherms with experimental data for the same operating conditions. Consequently, the presented model was used for its simplicity and apparently good performance, at the risk of some simplification.

It was also noted, from Nadler's estimated isotherms, that the fiber saturation point decreases linearly with increasing temperature, as illustrated in Figure 3.47.

Therefore, the fiber saturation point was estimated as a function of temperature of the porous medium fitting, by the method of least squares, the average values of equilibria moisture content given by the model presented by Nadler *et al*. The following relation corresponds to a multiplying factor of 1.5 as explained above:

$$FSP = 43.60605 - 0.05284 T \quad (3.213)$$

where  $T$  is expressed in °C and  $FSP$  in %.

**Permeabilities and capillary pressure** Many problems in scientific and industrial fields as diverse as agricultural, biomedical, chemical and petroleum engineering, food and soil mechanics, involve multiphase flow and displacement

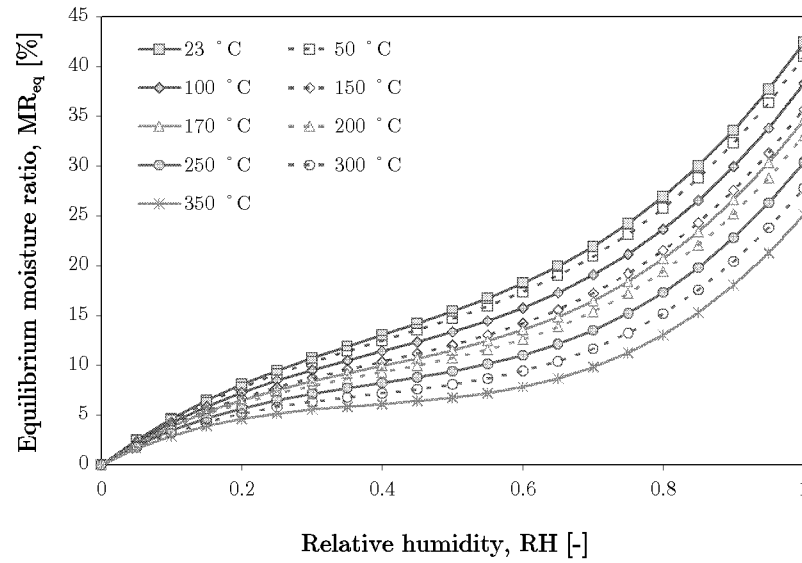


Figure 3.46: Sorption isotherms estimated by the model presented by Nadler *et al* [123] using a multiplying factor of 1.5, for different temperature levels.

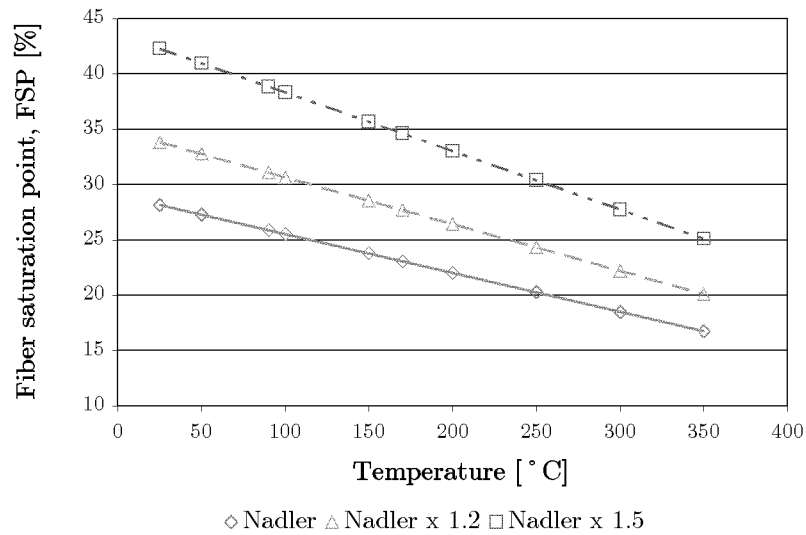


Figure 3.47: Fiber saturation point as a function of temperature.

### 3. Mathematical Model for High-Temperature Pressing of Paper 307

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processes in a heterogeneous porous medium. These processes constitute a complex set of phenomena that are controlled by several factors, such as the pore space morphology, the interplay between the viscous and capillary forces, the contact angles of the fluids with the surface of the pores among several other complex phenomena. Computer simulation of multiphase flow through porous media continues to be challenging mainly due to the difficulty in estimating the capillary pressure and the relative fluid permeabilities. The problem is even more complex if the medium is deformable, as in the case of paper.

The wet pressing of paper may be envisaged as the simultaneous flow of two fluids, water and a mixture of air and water vapor, in a deformable porous medium. Due to the presence of the two phases, the capillary pressure is an important aspect that has to be taken into account in a two phase modeling.

The capillary pressure,  $P_c$ , defined as the difference between the pressure of the liquid phase and that of the gas in the porous medium, may also be defined as a function of the hydraulic diameter,  $D_h$ , and its evaluation is induced by the well-known Laplace equation (see [4]):

$$P_c = \frac{4\gamma \cos \theta_c}{D_h} \quad (3.214)$$

where  $\gamma$  is the surface tension of water and  $\theta_c$  is the contact angle between the solid surface and the wetting fluid. The hydraulic diameter is defined as the ratio of the wetting fluid volume to the wetted surface, thus it is a function of the saturation level of the medium. The capillary pressure is also a strong function of the temperature by means of the interfacial tension and the contact angle, which in their turn depend on temperature.

For the temperature range of 0-100 °C, the surface tension of liquid water may be represented by the following relation obtained from the data of Vargaftik [191]:

$$\gamma = 76.059 - 0.1676 (T - 273.15) \quad (3.215)$$

where  $\gamma$  is expressed in mN.m<sup>-1</sup> and  $T$  in K.

The contact angle, *i.e.* the angle formed at the junction point of the solid, liquid and gas phases when a drop of water is placed onto the surface of paper, is strongly influenced by the composition unevenness of the non-homogeneous solid material, which is manifested by different local values of the contact angle. On the

interface between porous materials, including wood and paper, wetting is accompanied also by penetration. This fact results in the permanent change of contact angle with time and this change implies problems of equilibrium determination. A common practice is to determine the contact angle at the first moments of the wetting process or another constant moment, and using mathematical-statistical methods it is possible to determine the arithmetic mean values of the evaluated statistical set. Liptáková and Kúdela [100] studied the time-dependence of the contact angle formed between water and wood surface. Their results confirm that the values of the contact angle on the phase boundary are permanently decreasing with increasing time. They then divided the wood wetting process into three stages: the first stage is characterized by the intensive decrease of the contact angle (the diameter of the drop increases up to a constant value, and simultaneously the height of the drop is considerably decreasing); the contact angle decreases gradually (the diameter of the drop is constant and the height is further decreasing; they advanced that all roughness in the surface layer of wood was filled with water; during the third stage, the liquid recedes from the previously wetted wood surface and gradually penetrates into the substrate. From their findings, a contact angle of  $55.39^\circ$  was defined at the beginning of the wetting, and an equilibrium value, corresponding to the end of the second stage of the process, of  $18.82^\circ$ . The authors also emphasized that at the end of the wetting process, *i.e.* after 32 s, the contact angle was zero. A quite similar behavior was observed by Trejo-O'Reilly *et al* for tracing paper. The authors tested different liquids, namely water, formamide, ethylene glycol and diiodomethane. The time-dependence of the contact angle was similar to that reported by Liptáková and Kúdela [100] although the time scale was shorter. In fact, after some milliseconds from the beginning of the wetting process, Trejo-O'Reilly *et al* [182] observed a contact angle of less than  $20^\circ$ . These experimental studies thus suggest that a very small contact angle may be assumed for the case studied in the present work. In fact, the paper samples were prepared several hours prior to the impulse drying trials, which means that water has already penetrated the porous structure. Therefore, for non-sized paper it is reasonable to assume that the contact angle is practically zero. In the presence of a strong sizing agent, the level of penetration decreases and the drop of water forms a contact angle higher than  $90^\circ$ , which suggests that no penetration occurs, as advanced by Hagemeyer and Manson [58].

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Estimation of the hydraulic diameter as a function of liquid saturation has been one of the most complex issues in the field of two phase modeling in porous media. In fact, once the hydraulic diameter is known one can estimate the capillary pressure and also the relative permeabilities. Thus, let's first remember some definitions regarding the relative permeabilities.

The tensor  $K_i$  represents the permeability tensor relative to the fluid “ $i$ ”, and may be expressed as:

$$K_i = k_{ri}(S_l) \cdot K \quad (3.216)$$

where the relative permeability  $k_{ri}$  is a function of liquid saturation,  $S_l$ , and  $K$  is the absolute permeability defined for saturated conditions. It is worth, at this point to define the liquid saturation as the ratio of the volume of liquid to the pore volume (defined as the void volume excluding the volume occupied by the adsorbed water):

$$S_l = \frac{V_l}{V_p} \quad (3.217)$$

Michaels (see [202]) defined the relative permeabilities as a function of saturation according to the following relations:

$$k_{rl} = \frac{\int_0^{S_l} \frac{D_h^2(u)}{\xi_l^2(u)} du}{\int_0^1 \frac{D_h^2(u)}{\xi_l^2(u)} du} \quad (3.218)$$

$$k_{rg} = \frac{\int_{S_l}^1 \frac{D_h^2(u)}{\xi_g^2(u)} du}{\int_0^1 \frac{D_h^2(u)}{\xi_g^2(u)} du} \quad (3.219)$$

where  $\xi_l$  and  $\xi_g$  are the tortuosities for the liquid and the gas phases. Assuming a simple relation to determine the hydraulic diameter as  $D_h = S_l^2$ , Michaels deduced the relative permeabilities from Eqns. 3.218 and 3.219 as:

$$k_{rl} = S_l^4 \quad (3.220)$$

$$k_{rg} = (1 + 3S_l) \cdot (1 - S_l)^3 \quad (3.221)$$

Alternatively, Jewett [76] suggested a similar relation for the relative permeability of the liquid as:

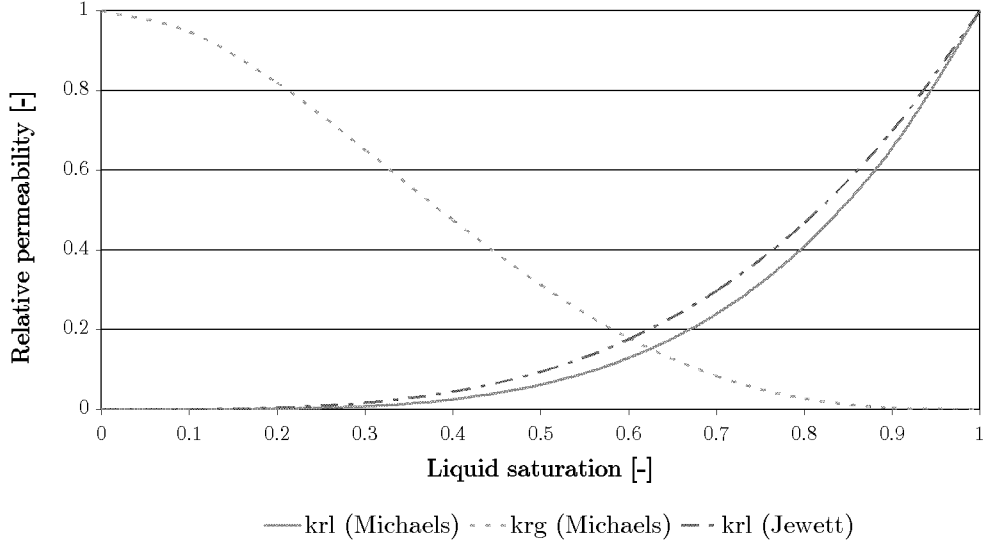


Figure 3.48: Relative permeabilities, estimated according to the models of Jewett and Michaels, for the liquid phase (blue and green lines) and gas (red line) as a function of liquid saturation of the porous medium.

$$k_{rl} = S_l^{3.4} \quad (3.222)$$

This simplistic form of calculating the hydraulic diameter seems to be valid only for low saturation levels [15], which is not the case in the present work. Nevertheless, the estimation of Michaels for the relative permeabilities has been used here. The results obtained from Eqns. 3.220, 3.221 and 3.222 are illustrated in Figure 3.48. Although the results lack of experimental validation, they present a similar trend as those published in the literature.

It seems clear that the most important and difficult point is to obtain a relation between the hydraulic diameter and the saturation level. To obtain such an expression, the Adam (see [157]) equation is introduced:

$$(1 - S_l) = \int_{D_c}^{\infty} f(u) du \quad (3.223)$$

where  $f$  is the hydraulic diameter density function and  $D_c$  is the critical hydraulic diameter. It is then assumed that all the pores with a diameter less than  $D_c$  are filled with liquid.

As described in detail in **Chapter 4**, Silvy [162] has developed a theory ca-



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pable of predicting the hydraulic diameter, the relative permeabilities and consequently, the capillary pressure. According to the theory of the “equivalent pore” the porous medium is modeled by an equivalent surface established by using a conformal transformation of the oriented pore-particle interfaces. The resulting equivalent pore is usually an ellipsoid that can be characterized by three parameters,  $a$ ,  $b$  and  $c$ , that show the pore anisotropy through the ellipticities  $a/b$  and  $c/b$  (see Figures 3.49 and 3.50).

Silvy and Butel [162] used the concept of the equivalent pore to solve analytically the definition of the pore saturation and the repartition of the saturated pore volume versus the pore size dimension in an anisotropic porous structure progressively wetted by a fluid. For fluid transfer in a porous medium fully or partially saturated, the hydraulic diameter is the relevant parameter to characterize the pore size. The wetting fluid volume and the wetted surface are evaluated considering the progressive invasion of the non-wetting fluid in the porous structure in order to get the highest hydraulic diameter, which corresponds to a minimum energy consumption. It is then necessary to evaluate the partition of the pore volume as a function of the optimum wetted surface in respect of the highest value of the hydraulic diameter. Once the ellipsoid surface is known, the hydraulic diameter is calculated for each level of saturation. In addition, the hydraulic diameter density function depends on the ellipticities and the mean hydraulic diameter. The calculation of Eqn. 3.223 on a general triaxial ellipsoid is rather complex and Silvy and Butel [162] illustrated this computing for the case of spheroids either oblate or prolate that can be obtained by dilatations of a general ellipsoid (see Figures 3.49 and 3.50, respectively), and taking  $c/b = 1$ .

The authors then defined a dimensionless hydraulic diameter as:

$$D_h^o = \frac{D_h}{\langle D_{h_{\text{Silvy}}} \rangle} \quad (3.224)$$

where  $\langle D_{h_{\text{Silvy}}} \rangle$  is the mean hydraulic diameter. Solving analytically Eqn. 3.223 they obtained the following relation for the case of oblate spheroids:

$$D_h^o = \frac{3}{2} u^2 \frac{b}{a} \frac{\left\{ 1 + \left( \frac{a}{b} \right)^2 \cdot \ln \left[ \frac{b}{a} (e + 1) \right] \right\}}{\sqrt{1 + \left[ \left( \frac{b}{a} \right)^2 - 1 \right] \cdot u^2}} \quad (3.225)$$

where  $u$  and  $e$  are defined as:

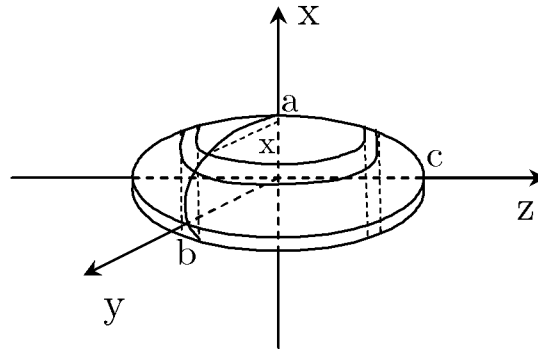


Figure 3.49: Schematic drawing of the oblate equivalent triaxial ellipsoid (adapted from [162]).

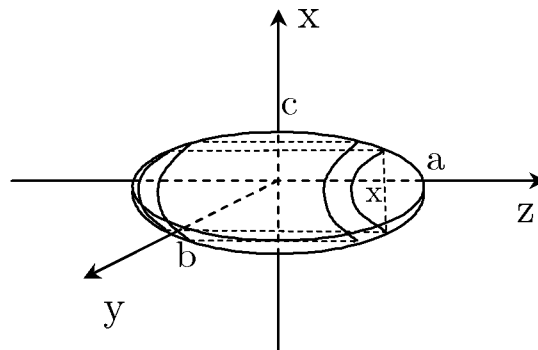


Figure 3.50: Schematic drawing of the prolate equivalent triaxial ellipsoid (adapted from [162]).

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$$u = S_l^{\frac{1}{3}} \quad (3.226)$$

$$e = \sqrt{1 - \left(\frac{a}{b}\right)^2} \quad (3.227)$$

$$\text{and } \frac{a}{b} \leq 1.0 \quad (3.228)$$

Accordingly, for the case of prolate spheroids they derived a similar relation:

$$D_h^o = \frac{3}{2} u^2 \frac{a}{b} \frac{\left\{ \left(\frac{b}{a}\right)^2 + \frac{b}{a \cdot e} \cdot \arcsin e \right\}}{\sqrt{1 + \left[ \left(\frac{b}{a}\right)^2 - 1 \right] \cdot u^2}} \quad (3.229)$$

where  $u$  and  $e$  are defined as:

$$u = S_l^{\frac{1}{3}} \quad (3.230)$$

$$e = \sqrt{1 - \left(\frac{b}{a}\right)^2} \quad (3.231)$$

$$\text{and } \frac{a}{b} \geq 1.0 \quad (3.232)$$

For the present case, the ratio  $a/b$  tends to be  $\leq 1$ , as the paper sheets tested are isotropic in the in-plane direction.

As it will be mentioned in **Chapter 4**, the mean value of the hydraulic diameter is strictly equal to the mean secant of the conducting pores section by an isotropic sampling of the porous medium, giving [162]:

$$\langle D_{h_{\text{silvy}}} \rangle = 4 \frac{\phi_{eff}}{S_{l_v}} \quad (3.233)$$

where  $\phi_{eff}$  is the effective porosity, equal to the volume fraction of pores, and  $S_{l_v}$  is the volume specific surface of the porous medium expressed in  $\text{m}^{-1}$ . This last property is defined as the area of friction accessible to the fluid during its transfer through the sheet, reported to the volume of the porous media. As the degree of compaction increases the fibers are brought closer to each other, which decreases the accessible area of friction. Silvy and Butel [162] reported that in the case of unbeaten and moderate beaten (33 °SR) Eucalyptus pulp, a maximum for the development of  $S_{l_v}$  was observed, as it depended on the advance of the beating

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of the pulp. In the case of softwood and groundwood pulp the authors noticed a continuous decrease of  $St_v$  with the compaction (density) as a consequence of the lower relative extra-fiber or effective porosity of these pulps in the wet state.

From the experimental work performed by Silvy and Butel [162] a linear relation between the volume specific surface and the apparent density of the porous medium was obtained. However, this relation lacks of some accuracy and serves only as a rough approximation. In addition, the same expression was used for softwood and hardwood pulps, as the data published in the literature is scarce, at least to the authors knowledge. The specific surface may then be estimated using:

$$St_v = (3564.6 - 2809\rho) \cdot 100 \quad (3.234)$$

where  $\rho$  is expressed in  $\text{g.cm}^{-3}$ , and  $St_v$  is expressed in  $\text{m}^{-1}$ .

This means that, according to the model developed by Silvy, the hydraulic diameter may be determined as follows:

$$D_h = 4 \frac{\phi_{eff}}{St_v} \cdot \frac{3}{2} u^2 \frac{b}{a} \frac{\left\{ 1 + \left(\frac{a}{b}\right)^2 \cdot \ln \left[ \frac{b}{a} (e + 1) \right] \right\}}{\sqrt{1 + \left[ \left(\frac{b}{a}\right)^2 - 1 \right] \cdot u^2}} \quad (3.235)$$

if one considers the medium to be formed by oblate spheroid pores.

Then, from this description the capillary pressure is deduced from Eqn. 3.214. It is also worth mention that, in order to validate the model, Silvy and Butel [162] compared the calculated hydraulic diameter to those measured on paper samples using mercury porosimetry. From their results they could observe a good agreement between the model and the experiments. They also advanced that the method is valid not only for paper but also for other porous structures.

In order to illustrate this approach for the present case, some numerical examples are presented here, emphasizing the evolution of the hydraulic diameter and the capillary pressure with pore saturation. Figures 3.51 to 3.54 were obtained for different effective or extra-fiber porosities of the sheet, trying to illustrate the effect of the compaction level. The first two figures, *i.e.* 3.51 and 3.52 were obtained assuming  $a/b = 1$  and  $b/c = 1$ . This suggests that the pores are perfect spheres according to the diagrams presented above (Figures 3.49 and 3.50). On the hand, taking  $a/b = 0.8$  one obtains a porous medium formed by oblate

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spheroid pores, as suggested by the theory of the equivalent pore. Both situations imply that the medium is assumed to be isotropic in the sheet plane, which is the case of the paper samples under study.

Tables 3.6 and 3.7 summarize some parameters of the model, namely the ellipticities, the mean hydraulic diameter and the maximum diameter obtained at total saturation.

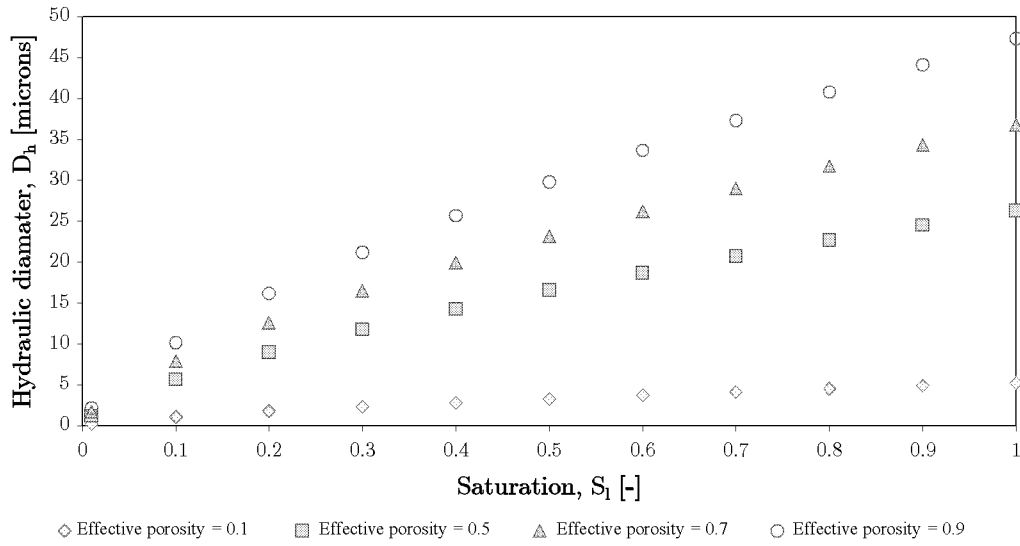


Figure 3.51: Hydraulic diameter versus saturation for  $c/b = 1$  and  $a/b = 1$  for different values of porosity.

Table 3.6: Parameters of the Silvy's model ( $a/b = 1$ ) and hydraulic diameters.

| Effective porosity | Mean hydraulic diameter | Parameter $a/b$ | Parameter $b/c$ | Maximum hydraulic diameter |
|--------------------|-------------------------|-----------------|-----------------|----------------------------|
| [-]                | [ $\mu m$ ]             | [-]             | [-]             | [ $\mu m$ ]                |
| 0.1                | 3.50                    | 1               | 1               | 5.26                       |
| 0.5                | 17.52                   | 1               | 1               | 26.28                      |
| 0.7                | 24.53                   | 1               | 1               | 36.80                      |
| 0.9                | 31.54                   | 1               | 1               | 47.31                      |

The effect of temperature is introduced with the temperature dependence of the surface tension of the liquid water. As an example, the capillary pressure was estimated at the operating conditions of the impulse drying trials performed in the present study. For the purpose, spheric pores and an effective porosity of 0.1

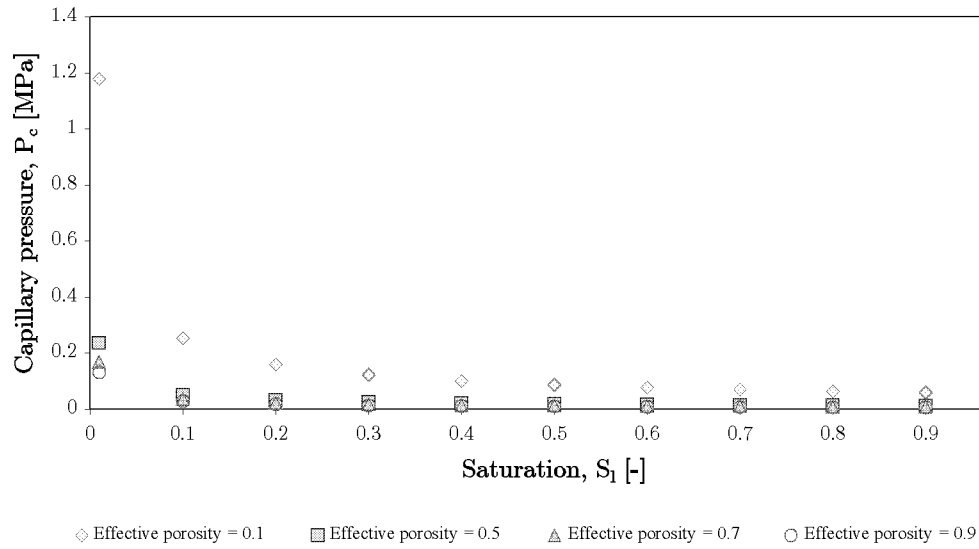


Figure 3.52: Capillary pressure versus saturation for  $c/b = 1$  and  $a/b = 1$  for different values of porosity.

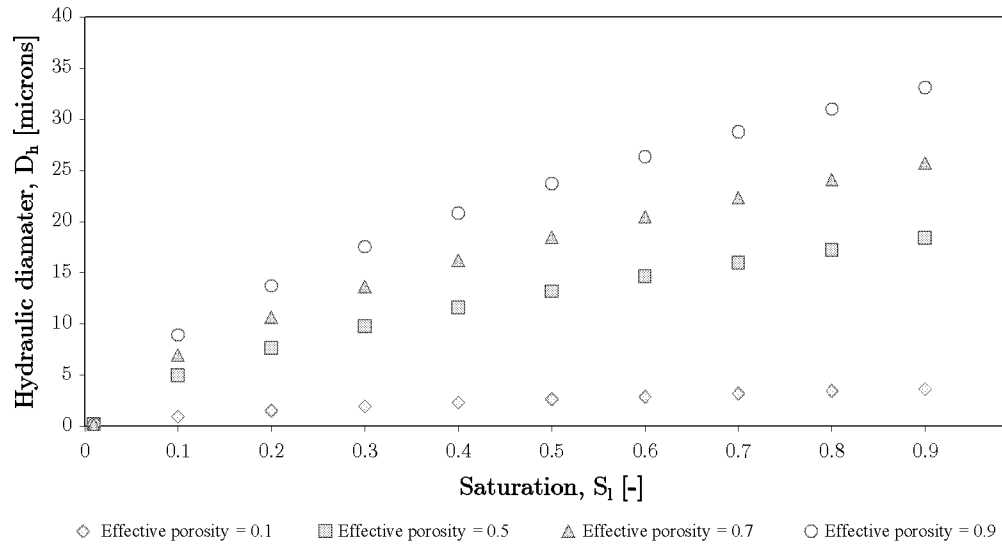


Figure 3.53: Hydraulic diameter versus saturation for  $c/b = 1$  and  $a/b = 0.8$  for different values of porosity.

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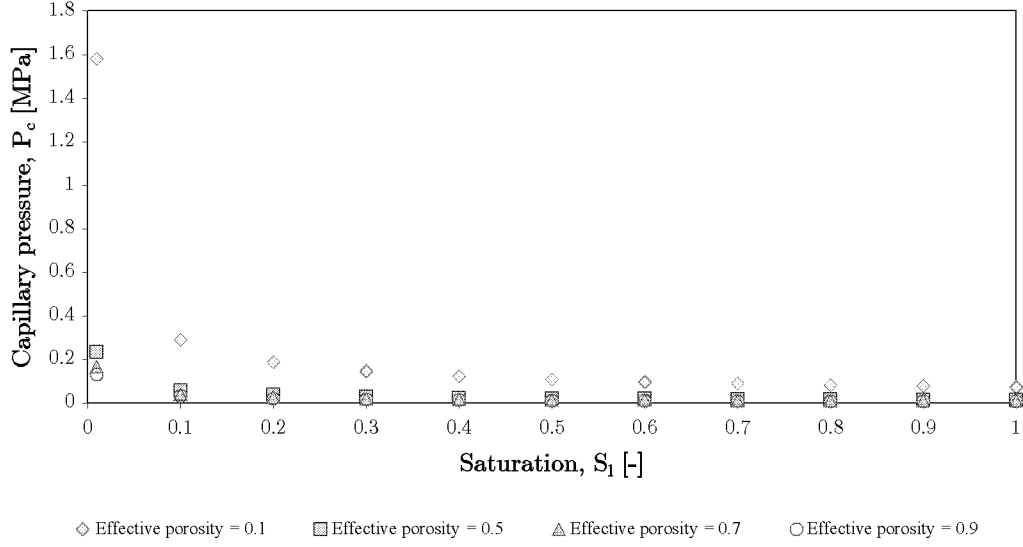


Figure 3.54: Capillary pressure versus saturation for  $c/b = 1$  and  $a/b = 0.8$  for different values of porosity.

Table 3.7: Parameters of the Silvy's model ( $a/b = 0.8$ ) and hydraulic diameters.

| Effective porosity | Mean hydraulic diameter | Parameter $a/b$ | Parameter $b/c$ | Maximum hydraulic diameter |
|--------------------|-------------------------|-----------------|-----------------|----------------------------|
| [-]                | [ $\mu\text{m}$ ]       | [-]             | [-]             | [ $\mu\text{m}$ ]          |
| 0.1                | 3.50                    | 0.8             | 1               | 3.90                       |
| 0.5                | 17.52                   | 0.8             | 1               | 19.48                      |
| 0.7                | 24.53                   | 0.8             | 1               | 27.27                      |
| 0.9                | 31.54                   | 0.8             | 1               | 35.06                      |

were assumed. As expected, Figure 3.55 clearly shows a decrease of the capillary pressure with temperature.

The estimates presented above are in agreement with that reported in the literature. In fact, Silvy and Butel [162] and Bloch [15] presented an extensive description of the equivalent pore theory and its application to the estimation of the capillary pressure for different pore geometries. The values of capillary pressure calculated here are within the range of capillary pressures obtained by the previous authors for bleached hardwood paper samples. Therefore, the model was integrated in the heat and mass transfer model developed in the present study.

In the previous analysis a non-zero value of the capillary pressure at  $S_l = 1$  means that a certain capillary pressure must be built up at the interface of the

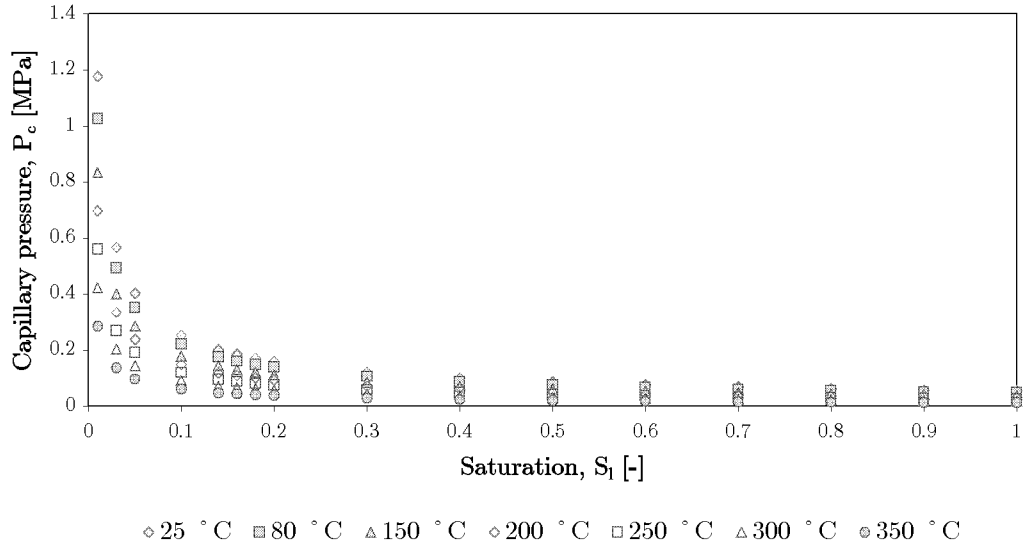


Figure 3.55: Capillary pressure versus saturation calculated at different operating temperatures (model parameters:  $a/b = 1$  and  $c/b = 1$ ;  $\phi_{eff} = 0.1$ ).

two fluids before the drainage of the wetting fluid starts. The minimum pressure required to start the displacement of the wetting fluid with a non-wetting one is called the threshold pressure. On the other hand, even at a high capillary pressure, a certain amount of water remains bounded to the fiber surface, thus defining an irreducible water saturation,  $S_{l_0}$ . This means that below this saturation level, the velocity of the liquid water may be considered null. It is therefore convenient to defined the effective water saturation,  $S_{l,eff}$ :

$$S_{l,eff} = \frac{S_l - S_{l_0}}{1 - S_{l_0}} \quad (3.236)$$

Another particular parameter is the critical saturation defined by Benet as the saturation level above which the Darcy coefficient for the gas phase is zero (see [15]). Another definition is that introduced by Baluais (see [15]) who states there is a saturation level beyond which exists fluid discontinuity. According to Bloch [15], the critical saturation may be obtained from the inflexion point of the curve capillary pressure versus saturation. If this point does not exist, then the critical saturation may be taken equal to 1. An interesting conclusion is that beyond this saturation level one may assume that the gas phase is no longer being expelled from the porous material but, instead, is being compressed. The associated gas



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saturation,  $S_{g0}$ , is also referred to as residual gas saturation. As data related to these saturation levels are difficult to find in the literature, it was assumed that  $S_{l0} = S_{g0} = 0.01$  (see Figure 3.56).

Consequently, the capillary pressure and the relative permeabilities will be expressed in terms of effective liquid saturation in order to take into account these saturation limits.

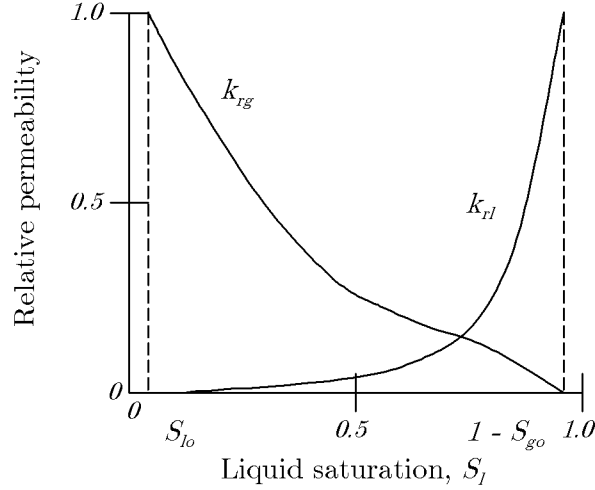


Figure 3.56: Illustration of the relative permeabilities dependance with liquid saturation.  $S_{l0}$  and  $S_{g0}$  represent the critical liquid saturation and residual gas saturation of a porous medium, respectively.

In order to complete the analysis of the permeability one needs to estimate the absolute, or total, permeability of the porous medium. This is done under saturated conditions.

From Eqn. 3.216 the permeability tensor for the fluid phase “ $i$ ” may be expressed simply as:

$$\underline{\underline{K_i}} = k_{ri}(S_{l,eff}) \cdot \underline{\underline{K}} = \begin{bmatrix} k_{ri} \cdot K_x & 0 & 0 \\ 0 & k_{ri} \cdot K_y & 0 \\ 0 & 0 & k_{ri} \cdot K_z \end{bmatrix} \quad (3.237)$$

where  $K_x$ ,  $K_y$  and  $K_z$  correspond to the absolute permeability in the three main directions,  $x$ ,  $y$  and  $z$ .

There is a large body of literature concerning the absolute permeability of paper. Both transversal and in-plane absolute permeability of paper samples

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have been measured and some empirical laws have been established to describe the porosity dependence of permeability. For instance, Mulder [122] defined the following empirical relation to describe the transversal permeability of paper,  $K_z$ :

$$K_z = a_M \cdot \phi^{b_M} \quad (3.238)$$

where  $a_M$  and  $b_M$  are parameters of the model that take the values presented on Table 3.8 (from [122]). These values were obtained for an absolute porosity in the range 0.45-0.85 approximately.

Table 3.8: Parameters of the relation for the calculus of  $K_z$  (Mulder).

| Paper grade                                                                            | $a_M$<br>[m <sup>2</sup> ] | $b_M$<br>[-] |
|----------------------------------------------------------------------------------------|----------------------------|--------------|
| 100 % bleached sulphate Swedish softwood, 23 °SR                                       | $1.06 \times 10^{-14}$     | 8.30         |
| 100 % bleached sulphate eucalyptus, 45 °SR                                             | $4.80 \times 10^{-15}$     | 8.62         |
| 100 % unbleached sulphate Swedish softwood, 23 °SR                                     | $1.86 \times 10^{-13}$     | 12.33        |
| 85 % bleached sulphate Swedish softwood + 15 % English<br>China clay grade "C", 23 °SR | $3.06 \times 10^{-14}$     | 10.31        |

Similar parameters were obtained by Silvy and Butel [162] for hardwood and softwood pulps using the same relation used by Mulder. The results, valid for absolute porosities in the range 0.53-0.80 (approximately), are summarized on Table 3.9.

Table 3.9: Parameters of the relation for the calculus of  $K_z$  (Silvy and Butel).

| Paper grade | $a_M$<br>[m <sup>2</sup> ] | $b_M$<br>[-] |
|-------------|----------------------------|--------------|
| Softwood    | $1.214 \times 10^{-13}$    | 1.248        |
| Hardwood    | $2.09 \times 10^{-12}$     | 2.22         |

As for the in-plane permeability  $K_{xy}$ , Vomhoff [192] established the following empirical relation:

$$K_{xy} = a_v \cdot b_v^\phi \quad (3.239)$$

where  $a_v$  and  $b_v$  are parameters of the model determined by the method of least squares.

More recently Reverdy-Bruas [143] determined experimentally both the transversal and the in-plane permeability of paper samples made from softwood and

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hardwood pulps. From her findings she concluded that: (i) the transversal permeability is significantly higher for the unbeaten pulp, and also higher for hardwood pulps, as they present a more open fibrous structure; (ii) the same trend is observed for the in-plane permeability, *i.e.* the unbeaten pulp is much more permeable; (iii) the permeability tensor for unbeaten pulps, either of hardwood or softwood pulps, is anisotropic with higher values for the transversal permeability. In general the ratio of the transversal permeability to the in-plane permeability tends to decrease as the porosity increases. Also, the permeability tensor measured for hardwood and softwood pulps beaten to 36 °SR tend to be isotropic. The author then tried to fit the experimental results to exponential and power laws, commonly accepted in the literature for the permeability of paper and felt (a more detailed description of these models will be given in **Chapter 4**).

For the transversal permeability:

$$K_z = a_z \cdot \phi^{b_z} \quad (\text{power law}) \quad (3.240)$$

$$K_z = c_z \cdot \exp(d_z \cdot \phi) \quad (\text{exponential law}) \quad (3.241)$$

and the in-plane permeability:

$$K_{xy} = a_{xy} \cdot \phi^{b_{xy}} \quad (\text{power law}) \quad (3.242)$$

$$K_{xy} = c_{xy} \cdot \exp(d_{xy} \cdot \phi) \quad (\text{exponential law}) \quad (3.243)$$

where  $a_z$ ,  $a_{xy}$ ,  $c_z$ ,  $c_{xy}$ ,  $b_z$ ,  $b_{xy}$ ,  $d_z$  and  $d_{xy}$  are model parameters as summarized on Tables 3.10 and 3.11.

Table 3.10: Parameters of the relation for the calculus of  $K_z$  (Reverdy-Bruas).

| Paper grade                                | $a_z$<br>[m <sup>2</sup> ] | $b_z$<br>[-] | $c_z$<br>[m <sup>2</sup> ] | $d_z$<br>[-] |
|--------------------------------------------|----------------------------|--------------|----------------------------|--------------|
| Softwood, 36 °SR, 3 × 60 g.m <sup>-2</sup> | $7.61 \times 10^{-15}$     | 14.03        | $3.69 \times 10^{-24}$     | 23.62        |
| Hardwood, 36 °SR, 3 × 60 g.m <sup>-2</sup> | $3.32 \times 10^{-14}$     | 13.57        | $1.12 \times 10^{-23}$     | 24.49        |

The results presented by Reverdy-Bruas [143] were obtained in the porosity range 0.5-0.75, approximately.

Table 3.11: Parameters of the relation for the calculus of Kxy (Reverdy-Bruas).

| Paper grade                                 | $a_{xy}$<br>[m <sup>2</sup> ] | $b_{xy}$<br>[-] | $c_{xy}$<br>[m <sup>2</sup> ] | $d_{xy}$<br>[-] |
|---------------------------------------------|-------------------------------|-----------------|-------------------------------|-----------------|
| Softwood, 36 °SR, 12 × 60 g.m <sup>-2</sup> | $2.57 \times 10^{-14}$        | 16.35           | $2.78 \times 10^{-24}$        | 24.40           |
| Hardwood, 36 °SR, 12 × 60 g.m <sup>-2</sup> | $5.30 \times 10^{-14}$        | 15.26           | $1.28 \times 10^{-23}$        | 23.86           |

### 3.3.5 A proposed global model for the consolidation of water saturated paper webs in high-intensity processes

After the identification of the several heat and mass transfer mechanisms involved in the consolidation process of paper at high-intensity operating conditions, it was then necessary to understand their interaction with the rheological behavior of the fibrous network. The global model must be able to simulate changes in the moisture content and structural properties of the paper web as it passes through a press nip. Once it has been calibrated, the model is expected to predict, in an acceptable way, the effects of changes in operating conditions, such as hot platen temperature, peak pressure, pulse shape and nip dwell time, and the state of the web, *i.e.* the ingoing moisture ratio, grammage, permeability or rheology.

The global model presented here was developed under the same assumptions as those enumerated for the mechanical and heat and mass transfer models described in the previous sections of this chapter. Therefore, the resulting set of PDE's will be presented here as a function of dimensionless variables.

#### Model equations

It is then convenient to present the several variables of the model, as well as the transport and physical properties in their dimensionless form.

The spatial variables  $x$  and  $y$ , corresponding to the coordinates in the in-plane direction of the paper web, are normalized by the initial values of its half length,  $L_{x0}$ , and half width,  $L_{y0}$ , respectively. The  $z$ -coordinate is normalized by the actual thickness of the web,  $L_z(t)$ , according to the transformation of Landau:

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$$\mathbf{X} = \frac{x}{L_{x_0}} \quad (3.244a)$$

$$\mathbf{Y} = \frac{y}{L_{y_0}} \quad (3.244b)$$

$$\Rightarrow \mathbf{Z} = \frac{z}{L_z(t)} \quad (3.244c)$$

Additionally, time is normalized by the length of the press pulse and the physical and transport properties for the three main directions are divided by their corresponding initial values.

$$\mathbf{L}_z = \frac{L_z}{L_{z_0}} \quad \Delta \mathbf{z}_{ijk} = \frac{\Delta z_{ijk}}{L_{z_0} \mathbf{L}_z} \quad \Delta \mathbf{z}_0 = \frac{\Delta z_0}{L_{z_0}} = \frac{1}{N_k}$$

$$\theta = \frac{t}{\tau} \quad \sigma_T = \frac{\sigma_T}{\sigma_0} \quad \sigma_{ij} = \frac{\sigma_{ij}}{\sigma_0}$$

$$\mathbf{E}_T = \frac{E_T}{E_0} \quad \mathbf{E}_{ij} = \frac{E_{ij}}{E_0} \quad \mathbf{E}_{ijk} = \frac{E_{ijk}}{E_0}$$

$$\mu_T = \frac{\mu_T}{\mu_0} \quad \mu_{ij} = \frac{\mu_{ij}}{\mu_0} \quad \mu_{ijk} = \frac{\mu_{ijk}}{\mu_0}$$

$$\mathbf{T} = \frac{T - T_{amb}}{T_p - T_{amb}} \quad \mathbf{T}_0 = \frac{T_{amb}}{T_p - T_{amb}}$$

$$\rho_g = \frac{\rho_g}{\rho_{g_0}} \quad \rho_l = \frac{\rho_l}{\rho_{l_0}} \quad \rho_v = \frac{\rho_v}{\rho_{g_0}} \quad \rho_p = \frac{\rho_p}{\rho_{p_0}}$$

$$\mathbf{C}_p = \frac{C_p}{C_{p_0}} \quad \mathbf{C}_{pg} = \frac{C_{pg}}{C_{pg_0}} \quad \mathbf{C}_{pl} = \frac{C_{pl}}{C_{pl_0}} \quad \rho_{dry} = \frac{\rho_{dry}}{\rho_0}$$

$$\lambda_{px} = \frac{\lambda_{px}}{\lambda_{pz_0}} \quad \lambda_{py} = \frac{\lambda_{py}}{\lambda_{pz_0}} \quad \lambda_{pz} = \frac{\lambda_{pz}}{\lambda_{pz_0}}$$

$$\mathbf{v}_{gx} = \frac{v_{gx}}{v_{gz_0}} \quad \mathbf{v}_{gy} = \frac{v_{gy}}{v_{gz_0}} \quad \mathbf{v}_{gz} = \frac{v_{gz}}{v_{gz_0}} \quad v_{gz_0} = \frac{L_{z_0}}{\tau}$$

$$\mathbf{v}_{lx} = \frac{v_{lx}}{v_{lz_0}} \quad \mathbf{v}_{ly} = \frac{v_{ly}}{v_{lz_0}} \quad \mathbf{v}_{lz} = \frac{v_{lz}}{v_{lz_0}}$$

$$\phi_g = \frac{\phi_g}{\phi_{g_0}} \quad \phi_l = \frac{\phi_l}{\phi_{l_0}}$$

$$\mathbf{D}_x^{eff} = \frac{D_x^{eff}}{D_{0z}^{eff}} \quad \mathbf{D}_y^{eff} = \frac{D_y^{eff}}{D_{0z}^{eff}} \quad \mathbf{D}_z^{eff} = \frac{D_z^{eff}}{D_{0z}^{eff}}$$

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$$\begin{aligned}
 \mathbf{P}_v &= \frac{P_v}{P_0} & \mathbf{P}_g &= \frac{P_g}{P_0} & \mathbf{P}^{sat} &= \frac{P^{sat}}{P_0} \\
 \mathbf{K}_{gx} &= \frac{K_{gx}}{K_{gz_0}} & \mathbf{K}_{gy} &= \frac{K_{gy}}{K_{gz_0}} & \mathbf{K}_{gz} &= \frac{K_{gz}}{K_{gz_0}} \\
 \mathbf{K}_{lx} &= \frac{K_{lx}}{K_{lz_0}} & \mathbf{K}_{ly} &= \frac{K_{ly}}{K_{lz_0}} & \mathbf{K}_{lz} &= \frac{K_{lz}}{K_{lz_0}} \\
 \mu_g &= \frac{\mu_g}{\mu_{g0}} & \mu_l &= \frac{\mu_l}{\mu_{l0}} & \mathbf{R}_x &= \frac{L_{z0}}{L_{x0}} & \mathbf{R}_y &= \frac{L_{z0}}{L_{y0}}
 \end{aligned}$$

The following dimensionless numbers were also defined as:

$$\begin{aligned}
 \mathbf{H}_0 &= \frac{E_0}{\sigma_0} & \mathbf{V}_0 &= \frac{\tau \cdot \sigma_0}{\mu_0} \\
 \mathbf{Fo}_z &= \frac{\lambda_{pz_0} \tau}{\rho_{p0} C_{p0} L_{z0}^2} & \mathbf{Fo}_x &= \mathbf{R}_x^2 \mathbf{Fo}_z & \mathbf{Fo}_y &= \mathbf{R}_y^2 \mathbf{Fo}_z \\
 \mathbf{Pe}_{gz} &= \frac{\rho_{g0} C_{pg0} v_{gz_0} L_{z0}}{\lambda_{pz_0}} & \mathbf{Pe}_{lz} &= \frac{\rho_{l0} C_{pl0} v_{lz_0} L_{z0}}{\lambda_{pz_0}} \\
 \mathbf{Pe}_{mgz} &= \frac{v_{gz_0} L_{z0}}{\phi_{g0} D_{0z}^{eff}} & \mathbf{Pe}_{mgx} &= \frac{\mathbf{Pe}_{mgz}}{\mathbf{R}_x} & \mathbf{Pe}_{mgy} &= \frac{\mathbf{Pe}_{mgz}}{\mathbf{R}_y} \\
 \mathbf{Fo}_{mz} &= \frac{\phi_{g0} D_{0z}^{eff} \tau}{L_{z0}^2} & \mathbf{Fo}_{mx} &= \mathbf{R}_x^2 \mathbf{Fo}_{mz} & \mathbf{Fo}_{my} &= \mathbf{R}_y^2 \mathbf{Fo}_{mz} \\
 \mathbf{Np}_{gz} &= \frac{P_0 K_{gz_0} \tau}{\mu_{g0} L_{z0}^2} & \mathbf{Np}_{gx} &= \mathbf{R}_x^2 \mathbf{Np}_{gz} & \mathbf{Np}_{gy} &= \mathbf{R}_y^2 \mathbf{Np}_{gz} \\
 \mathbf{Np}_{lz} &= \frac{P_0 K_{lz_0} \tau}{\mu_{l0} L_{z0}^2} & \mathbf{Np}_{lx} &= \mathbf{R}_x^2 \mathbf{Np}_{lz} & \mathbf{Np}_{ly} &= \mathbf{R}_y^2 \mathbf{Np}_{lz} \\
 \dot{\mathbf{M}} &= \frac{\tau \dot{M}}{\rho_{p0}} & \dot{\mathbf{M}}_v &= \frac{\tau \dot{M}}{\rho_{v0}} & \dot{\mathbf{M}}_l &= \frac{\tau \dot{M}_l}{\rho_{l0}} \\
 \dot{\mathbf{M}}_b &= \frac{\tau \dot{M}_b}{\rho_0} & \rho_{v0} &= \frac{MM_v P_0}{R(T_p - T_{amb})}
 \end{aligned}$$

Finally it is important to note that due to the transformation of Landau in the z-coordinate, the time derivative of any given property  $\beta$  may be expressed as follows:

$$\left(\frac{\partial \beta}{\partial t}\right)_z = \frac{1}{\tau} \left(\frac{\partial \beta}{\partial \theta}\right)_z - \frac{\mathbf{Z}}{\tau \mathbf{L}_z} \left(\frac{\partial \mathbf{L}_z}{\partial \theta}\right)_z \left(\frac{\partial \beta}{\partial \mathbf{Z}}\right)_t \quad (3.245)$$

$$\text{or else} \quad \left(\frac{\partial \beta}{\partial \theta}\right)_z = \left(\frac{\partial \beta}{\partial \theta}\right)_z + \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left(\frac{\partial \beta}{\partial \mathbf{Z}}\right)_t \quad (3.246)$$

The constitutive equations of the global model and the corresponding initial and boundary conditions, set for the case of high moisture ratio paper samples submitted to impulse drying, may be rewritten as follows, in terms of dimensionless variables.

Considering the operating conditions in terms of temperature and applied pressure, as well as the higher moisture content of the paper samples tested, it was assumed, for simulation purposes, that the web remains above the fiber saturation point even at the highest temperature of pressing. This means that all the vapor formed comes from the liquid water and no adsorbed water is vaporized.

In summary, the global model considers the following dependent variables:

- heat and mass transfer: five dependent variables (temperature, water vapor pressure, gas pressure, volume fraction of liquid water and moisture ratio);
- mechanical behavior: three dependent variables (the vertical position, the stress level in each representative column of the mat, and the total thickness of the web).

The corresponding model equations are:

- heat and mass transfer: one energy balance, three mass balances (vapor, gas and liquid) and one equation describing vapor-liquid saturation;
- mechanical behavior: one equation that relates the vertical position and local deformation, one to determine the stress developed in each representative column of the mat, and finally one equation for the total thickness of the web.

### The energy conservation equation

$$\begin{aligned} \frac{\partial T}{\partial \theta} = & -\frac{\mathbf{F} \mathbf{o}_z}{\rho_p C_p} \left( \mathbf{R}_x^2 \frac{\partial \varphi_{tx}}{\partial \mathbf{X}} + \mathbf{R}_y^2 \frac{\partial \varphi_{ty}}{\partial \mathbf{Y}} + \frac{1}{\mathbf{L}_z} \frac{\partial \varphi_{tz}}{\partial \mathbf{Z}} \right) - \frac{\dot{\mathbf{M}} (\Delta H_{vap} + Q_l)}{\rho_p C_{p0} C_p (T_p - T_{amb})} - \dots \\ & \dots - \frac{\mathbf{T} + T_0}{\rho_p} \frac{\partial \rho_p}{\partial \theta} + \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left( \frac{\partial T}{\partial \mathbf{Z}} + \frac{\mathbf{T} + T_0}{\rho_p} \frac{\partial \rho_p}{\partial \mathbf{Z}} \right) \end{aligned} \quad (3.247)$$

Heat fluxes

$$\varphi_{tx} = -\lambda_{px} \frac{\partial T}{\partial \mathbf{X}} + \left( \frac{\mathbf{P} \mathbf{e}_{gz}}{\mathbf{R}_x} \rho_g \mathbf{v}_{gx} C_{pg} + \frac{\mathbf{P} \mathbf{e}_{lz}}{\mathbf{R}_x} \rho_l \mathbf{v}_{lx} C_{pl} \right) (\mathbf{T} + T_0) \quad (3.248a)$$

$$\varphi_{ty} = -\lambda_{py} \frac{\partial T}{\partial \mathbf{Y}} + \left( \frac{\mathbf{P} \mathbf{e}_{gz}}{\mathbf{R}_y} \rho_g \mathbf{v}_{gy} C_{pg} + \frac{\mathbf{P} \mathbf{e}_{lz}}{\mathbf{R}_y} \rho_l \mathbf{v}_{ly} C_{pl} \right) (\mathbf{T} + T_0) \quad (3.248b)$$

$$\varphi_{tz} = -\frac{\lambda_{pz}}{\mathbf{L}_z} \frac{\partial T}{\partial \mathbf{Z}} + (\mathbf{P} \mathbf{e}_{gz} \rho_g \mathbf{v}_{gz} C_{pg} + \mathbf{P} \mathbf{e}_{lz} \rho_l \mathbf{v}_{lz} C_{pl}) (\mathbf{T} + T_0) \quad (3.248c)$$

Initial condition

$$\mathbf{T}(\mathbf{X}, \mathbf{Y}, \mathbf{Z} \neq 1, 0) = 0 \quad (3.249a)$$

$$\mathbf{T}(\mathbf{X}, \mathbf{Y}, \mathbf{Z} = 1, 0) = 1 \quad (3.249b)$$

Boundary conditions

$$\frac{\partial T}{\partial \mathbf{X}}(0, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (3.250a)$$

$$\frac{\partial T}{\partial \mathbf{Y}}(\mathbf{X}, 0, \mathbf{Z}, \theta) = 0 \quad (3.250b)$$

$$\mathbf{T}(\mathbf{X}, \mathbf{Y}, 0, \theta) = 0 \quad (3.250c)$$

$$\mathbf{T}(1, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (3.250d)$$

$$\mathbf{T}(\mathbf{X}, 1, \mathbf{Z}, \theta) = 0 \quad (3.250e)$$

$$\mathbf{T}(\mathbf{X}, \mathbf{Y}, 1, \theta) = 1 \quad (3.250f)$$



The conservation equation for water vapor

$$\begin{aligned}
 \dot{\mathbf{M}}_v &= \mathbf{Fo}_{\mathbf{m}_z} \left( \mathbf{R}_x^2 \frac{\partial \varphi_{vx}}{\partial \mathbf{X}} + \mathbf{R}_y^2 \frac{\partial \varphi_{vy}}{\partial \mathbf{Y}} + \frac{1}{\mathbf{L}_z} \frac{\partial \varphi_{vz}}{\partial \mathbf{Z}} \right) + \dots \\
 &\dots + \frac{\phi_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_v}{\partial \theta} - \frac{\phi_g \mathbf{P}_v}{(\mathbf{T} + T_0)^2} \frac{\partial \mathbf{T}}{\partial \theta} + \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \phi_g}{\partial \theta} - \dots \\
 &\dots - \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left( \frac{\phi_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}} - \frac{\phi_g \mathbf{P}_v}{(\mathbf{T} + T_0)^2} \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} + \dots \right. \\
 &\left. \dots + \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \phi_g}{\partial \mathbf{Z}} \right) \quad (3.251)
 \end{aligned}$$

Vapor fluxes

$$\varphi_{vx} = -\frac{\mathbf{D}_x^{eff} \phi_g}{\mathbf{T} + T_0} \left( \frac{\partial \mathbf{P}_v}{\partial \mathbf{X}} - \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \mathbf{X}} \right) + \frac{\mathbf{Pe}_{mgz}}{\mathbf{R}_x} \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \mathbf{v}_{gx} \quad (3.252a)$$

$$\varphi_{vy} = -\frac{\mathbf{D}_y^{eff} \phi_g}{\mathbf{T} + T_0} \left( \frac{\partial \mathbf{P}_v}{\partial \mathbf{Y}} - \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \mathbf{Y}} \right) + \frac{\mathbf{Pe}_{mgz}}{\mathbf{R}_y} \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \mathbf{v}_{gy} \quad (3.252b)$$

$$\varphi_{vz} = -\frac{\mathbf{D}_z^{eff} \phi_g}{\mathbf{L}_z (\mathbf{T} + T_0)} \left( \frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}} - \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} \right) + \mathbf{Pe}_{mgz} \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \mathbf{v}_{gz} \quad (3.252c)$$

Initial conditions

Above fiber saturation point:

$$\mathbf{P}_v(\mathbf{X}, \mathbf{Y}, \mathbf{Z}, 0) = \mathbf{P}^{sat}(\mathbf{T} = 0) \quad (3.253)$$

Boundary conditions

$$\frac{\partial \mathbf{P}_v}{\partial \mathbf{X}}(0, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (3.254a)$$

$$\frac{\partial \mathbf{P}_v}{\partial \mathbf{Y}}(\mathbf{X}, 0, \mathbf{Z}, \theta) = 0 \quad (3.254b)$$

$$\frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, 1, \theta) = 0 \quad (3.254c)$$

Above fiber saturation point:

Unsaturated medium

$$\mathbf{P}_v(1, \mathbf{Y}, \mathbf{Z}, \theta) = \mathbf{P}^{sat}(\mathbf{T} = 0) \quad (3.255a)$$

$$\mathbf{P}_v(\mathbf{X}, 1, \mathbf{Z}, \theta) = \mathbf{P}^{sat}(\mathbf{T} = 0) \quad (3.255b)$$

$$\bullet S_{l,eff} = 1 \quad \frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, 0, \theta) = 0 \text{ (saturated interface)} \quad (3.255c)$$

$$\bullet S_{l,eff} < 1 \quad \mathbf{P}_v(\mathbf{X}, \mathbf{Y}, 0, \theta) = \mathbf{P}^{sat}(\mathbf{T} = 0) \quad (3.255d)$$

The conservation equation for the gas phase

$$\begin{aligned} \frac{\partial \mathbf{P}_g}{\partial \theta} = & -\frac{\mathbf{N}\mathbf{P}_{gz}}{\phi_g} \left( \mathbf{R}_x^2 \frac{\partial \varphi_{gx}}{\partial \mathbf{X}} + \mathbf{R}_y^2 \frac{\partial \varphi_{gy}}{\partial \mathbf{Y}} + \frac{1}{\mathbf{L}_z} \frac{\partial \varphi_{gz}}{\partial \mathbf{Z}} \right) (\mathbf{T} + T_0) + \dots \\ & \dots + \frac{\mathbf{M}_v(\mathbf{T} + T_0)}{\phi_g} + \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \theta} - \frac{\mathbf{P}_g}{\phi_g} \frac{\partial \phi_g}{\partial \theta} + \dots \\ & \dots + \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left( \frac{\partial \mathbf{P}_g}{\partial \mathbf{Z}} - \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} + \frac{\mathbf{P}_g}{\phi_g} \frac{\partial \phi_g}{\partial \mathbf{Z}} \right) \end{aligned} \quad (3.256)$$

Gas fluxes

$$\varphi_{gx} = -\frac{\mathbf{K}_{gx}}{\mu_g} \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_g}{\partial \mathbf{X}} \quad (3.257a)$$

$$\varphi_{gy} = -\frac{\mathbf{K}_{gy}}{\mu_g} \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_g}{\partial \mathbf{Y}} \quad (3.257b)$$

$$\varphi_{gz} = -\frac{\mathbf{K}_{gz}}{\mu_g} \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_g}{\partial \mathbf{Z}} \quad (3.257c)$$

Initial conditions

$$\mathbf{P}_g(\mathbf{X}, \mathbf{Y}, \mathbf{Z}, 0) = \frac{P_{amb}}{P_0} \quad (3.258)$$

*Boundary conditions*

$$\frac{\partial \mathbf{P}_g}{\partial \mathbf{X}}(0, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (3.259a)$$

$$\frac{\partial \mathbf{P}_g}{\partial \mathbf{Y}}(\mathbf{X}, 0, \mathbf{Z}, \theta) = 0 \quad (3.259b)$$

$$\frac{\partial \mathbf{P}_g}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, 1, \theta) = 0 \quad (3.259c)$$

Above fiber saturation point:

$$\begin{array}{l} \text{Unsaturated medium} \\ \mathbf{P}_g(1, \mathbf{Y}, \mathbf{Z}, \theta) = \frac{P_{amb}}{P_0} \end{array} \quad (3.260a)$$

$$\mathbf{P}_g(\mathbf{X}, 1, \mathbf{Z}, \theta) = \frac{P_{amb}}{P_0} \quad (3.260b)$$

$$\bullet S_{l,eff} = 1 \quad \frac{\partial \mathbf{P}_g}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, 0, \theta) = 0 \text{ (saturated interface)} \quad (3.260c)$$

$$\bullet S_{l,eff} < 1 \quad \mathbf{P}_g(\mathbf{X}, \mathbf{Y}, 0, \theta) = \frac{P_{amb}}{P_0} \quad (3.260d)$$

**The conservation equation for the liquid phase**

$$\begin{aligned} \frac{\partial \phi_l}{\partial \theta} = & -\frac{\mathbf{Np}_{lz}}{\rho_l} \left( \mathbf{R}_x^2 \frac{\partial \varphi_{lx}}{\partial \mathbf{X}} + \mathbf{R}_y^2 \frac{\partial \varphi_{ly}}{\partial \mathbf{Y}} + \frac{1}{\mathbf{L}_z} \frac{\partial \varphi_{lz}}{\partial \mathbf{Z}} \right) - \frac{\dot{\mathbf{M}}_l}{\rho_l} - \dots \\ & \dots - \frac{\phi_l}{\rho_l} \frac{\partial \rho_l}{\partial \theta} + \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left( \frac{\partial \phi_l}{\partial \mathbf{Z}} + \frac{\phi_l}{\rho_l} \frac{\partial \rho_l}{\partial \mathbf{Z}} \right) \end{aligned} \quad (3.261)$$

*Water fluxes*

$$\varphi_{lx} = -\frac{\rho_l \mathbf{K}_{lx}}{\mu_l} \left( \frac{\partial \mathbf{P}_g}{\partial \mathbf{X}} - \frac{\partial \mathbf{P}_c}{\partial \mathbf{X}} \right) \quad (3.262a)$$

$$\varphi_{ly} = -\frac{\rho_l \mathbf{K}_{ly}}{\mu_l} \left( \frac{\partial \mathbf{P}_g}{\partial \mathbf{Y}} - \frac{\partial \mathbf{P}_c}{\partial \mathbf{Y}} \right) \quad (3.262b)$$

$$\varphi_{lz} = -\frac{\rho_l \mathbf{K}_{lz}}{\mu_l} \frac{1}{\mathbf{L}_z} \left( \frac{\partial \mathbf{P}_g}{\partial \mathbf{Z}} - \frac{\partial \mathbf{P}_c}{\partial \mathbf{Z}} \right) \quad (3.262c)$$

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*Initial conditions*

Above fiber saturation point:

$$\phi_l(\mathbf{X}, \mathbf{Y}, \mathbf{Z}, 0) = 1 \quad (3.263)$$

*Boundary conditions*

Above fiber saturation point:

$$\frac{\partial \phi_l}{\partial \mathbf{X}}(0, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (3.264a)$$

$$\frac{\partial \phi_l}{\partial \mathbf{Y}}(\mathbf{X}, 0, \mathbf{Z}, \theta) = 0 \quad (3.264b)$$

$$\frac{\partial \phi_l}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, 1, \theta) = 0 \text{ (impermeable surface, } K_{l_z} = 0) \quad (3.264c)$$

Unsaturated medium

$$\frac{\partial \phi_l}{\partial \mathbf{X}}(1, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \text{ (fluid discontinuity, } v_{l_x} = 0) \quad (3.265a)$$

$$\frac{\partial \phi_l}{\partial \mathbf{Y}}(\mathbf{X}, 1, \mathbf{Z}, \theta) = 0 \text{ (fluid discontinuity, } v_{l_y} = 0) \quad (3.265b)$$

$$\begin{aligned} \phi_l(\mathbf{X}, \mathbf{Y}, 0, \theta) &= S_l \cdot \phi_{eff}(\mathbf{X}, \mathbf{Y}, 0, \theta) = \\ &= \phi_{eff}(\mathbf{X}, \mathbf{Y}, 0, \theta) \text{ (saturated interface)} \end{aligned} \quad (3.265c)$$

#### Equilibrium equations

As the liquid water is assumed to be in equilibrium with the saturated vapor within the porous medium, the following equation may be written:

$$\frac{\partial \mathbf{P}_v}{\partial \theta} = \frac{\partial \mathbf{P}^{sat}}{\partial \theta} = \left( \frac{\partial \mathbf{P}^{sat}}{\partial \mathbf{T}} \right) \left( \frac{\partial \mathbf{T}}{\partial \theta} \right) + \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left[ \frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}} - \left( \frac{\partial \mathbf{P}^{sat}}{\partial \mathbf{T}} \right) \left( \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} \right) \right] \quad (3.266)$$

Additionally, the amount of adsorbed water, in equilibrium with the water vapor in the pores, may then be determined by the sorption isotherm for a given local temperature inside the paper web, according to the equation of Nadler *et al* [123] (see Eqn. 3.212 or alternatively Eqn. 3.213).

$$MR_{eq}(\mathbf{X}, \mathbf{Y}, \mathbf{Z}, \theta) = MR_{eq}(HR = 1; \mathbf{T}) \quad (3.267)$$

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#### Mechanical constitutive equations

The vertical position for each  $ijk$  representative volume element:

$$\frac{\partial \mathbf{Z}_{ijk}}{\partial \theta} = \frac{\Delta \mathbf{z}_0}{2\mathbf{L}_z} \left( \frac{\partial \varepsilon_{ijk}}{\partial \theta} + 2 \sum_{l=1}^{k-1} \frac{\partial \varepsilon_{ijl}}{\partial \theta} \right) - \frac{\mathbf{Z}_{ijk}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \quad (3.268a)$$

$$\text{where } \frac{\partial \varepsilon_{ijk}}{\partial \theta} = \frac{1}{\mathbf{H}_0 \left( \mathbf{E}_{ijk} + \varepsilon_{ijk} \frac{\partial \mathbf{E}_{ijk}}{\partial \varepsilon_{ijk}} \right)} \frac{\partial \boldsymbol{\sigma}_{ij}}{\partial \theta} + \frac{\mathbf{V}_0}{\boldsymbol{\mu}_{ijk}} \boldsymbol{\sigma}_{ij} \quad (3.268b)$$

$$\text{Initial condition} \quad : \quad \theta = 0; \quad \varepsilon_{ijk} = 0; \quad \mathbf{Z}_{ijk} = \frac{k - 0.5}{N_k} \quad (3.268c)$$

The applied stress in every  $ij$  column:

$$\frac{\partial \boldsymbol{\sigma}_{ij}}{\partial \theta} = \mathbf{H}_0 \mathbf{E}_{ij} \frac{\partial \mathbf{L}_z}{\partial \theta} - \mathbf{H}_0 \mathbf{V}_0 \frac{\mathbf{E}_{ij}}{\boldsymbol{\mu}_{ij}} \boldsymbol{\sigma}_{ij} \quad (3.269a)$$

$$\text{Initial condition} \quad : \quad \theta = 0; \quad \boldsymbol{\sigma}_{ij} = 0; \quad \mathbf{L}_z = 1 \quad (3.269b)$$

The total thickness of the web:

$$\frac{\partial \mathbf{L}_z}{\partial \theta} = \frac{1}{\mathbf{H}_0 \mathbf{E}_T} \frac{\partial \boldsymbol{\sigma}_T}{\partial \theta} + \frac{\mathbf{V}_0}{\boldsymbol{\mu}_T} \boldsymbol{\sigma}_T \quad (3.270a)$$

$$\text{Initial condition} \quad : \quad \theta = 0; \quad \mathbf{L}_z = 1 \quad (3.270b)$$

#### Numerical solution

In order to solve the model constitutive equations a finite-differences approach was used, and the resulting set of ODEs was numerically integrated using a specialized solver for stiff equations based on the Gear method developed by Hindmarsh [70]. The DLSODES subroutine developed by Hindmarsh uses a knowledge of the sparsity structure of the Jacobian matrix to avoid redundant computation of zero-valued Jacobian entries.

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Using the finite-differences approach, the eight coupled equations used for the simulation of high temperature pressing of paper yield a system of ordinary differential equations. The four PDEs describing the mass and heat conservation are parabolic as the highest time derivative is of first order and the spatial derivatives are of second order. Following the procedure described by Patankar [135] to discretize the right-hand side of the constitutive equations, a scheme of first order central differences was used for the conduction/diffusion terms, and the upwind difference technique was employed for the discretization of the convective terms, which in this case means that variables are attributed the upstream values in relation to the direction of the flux. A backward difference scheme was used for the vertical temperature gradient term in the energy balance, as some numerical problems came up when high platen temperatures were used. This was attributed to the sudden temperature increase at the beginning of the pressing event. Using this discretization method the problem of boundaries inconsistency is solved, as the time derivatives are evaluated at the grid points, whereas the heat and mass fluxes are determined at the boundaries of the RVE (as a result of the central differences scheme).

In the finite difference solution method, the web was divided into 1000 uniform RVE (10 grid points in each direction, determined according to a sensitivity analysis to this parameter). The choice of the time increment and the grid spacing determine the stability and accuracy of the solution procedure and also dictates the amount of computation required in solving the problem. In the present case the Gear method uses a system of predictor/corrector equations to generate a variable integration step, according to a given grid dimension, type and order of the finite-differences scheme and error.

The DLSODES subroutine was integrated in a C<sup>++</sup>-based program containing the constitutive equations of the heat and mass transfer model together with the differential equations describing the mechanical behavior of the material and all the relations required to determine the transport and physical properties at any point in the paper web.

## Results and discussion

Testing of the model's computational performance and validation of its predictions were performed for high-intensity pressing of high moisture ratio paper webs. The results from the impulse drying experiments described in **Chapter**

### 3. Mathematical Model for High-Temperature Pressing of Paper 333

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2 were compared with model simulations both to verify the model predictions and to derive appropriate parameter values. The results of these activities are summarized here.

For those model parameters that could not be estimated by independent means, or were determined under different operating conditions, appropriate values were obtained by comparing the simulation runs performed with the mechanical model to a base set of experimental drying data. This was done for the viscous parameter of the cellulose fiber ( $1 \times 10^6$  Pa.s), the elastic constant  $C_2$  (0.5), the elasticity modulus of liquid water ( $0.025 \times 10^8$  Pa) and fiber elastic parameter  $E_{ffit}$  ( $5.62 \times 10^{-2}$  MPa). One aspect of model verification was to compare drying data from experiments run under different conditions with model simulations using the parameter values obtained from the base data. The model predictions presented hereafter were, therefore, obtained for those parameter values evaluated from the mechanical simulation results.

The global model was used to predict the evolution of the dependent variables of the heat and mass transfer model (temperature, gas pressure, vapor pressure, water volume fraction and moisture ratio), as well as those related to the mechanical model (web thickness and, stress and density profiles) throughout a typical impulse drying event. The model performance was evaluated for the high-intensity pressing conditions summarized on Table 3.12, imposing the same press pulse as that illustrated in Figure 3.30 to high moisture ratio (“saturated”) paper webs. The description of the web main properties is presented on Table 3.4 and the stress pulse fitting parameters are also on Table 3.12.

Figure 3.57 illustrates the experimental stress pulse at 25 °C and the corresponding fit used as an input to the model.

It is convenient at this point to remember the discretization drawing presented in Figure 3.26. In the finite difference solution method, the web was divided into 10 uniform layers. Layer 1 denotes the open surface layer while layer 10 denotes that close to the hot surface. For better understanding the coordinate system Figure 3.58 is presented. It is worth noting that the vertical positions given by the variable  $Z_{ijk}$  correspond to the center point of each control volume.

Taking the initial dimensions of the web as  $L_{x_0} = L_{y_0} = 37.5$  mm and  $L_{z_0} = 2.129609$  mm ( $L_{z_0}$  is obtained from the LVDT recordings) it is possible to establish the relation between each coordinate and the physical distance of the grid points to the middle planes represented in Figure 3.58, as presented in Table 3.13

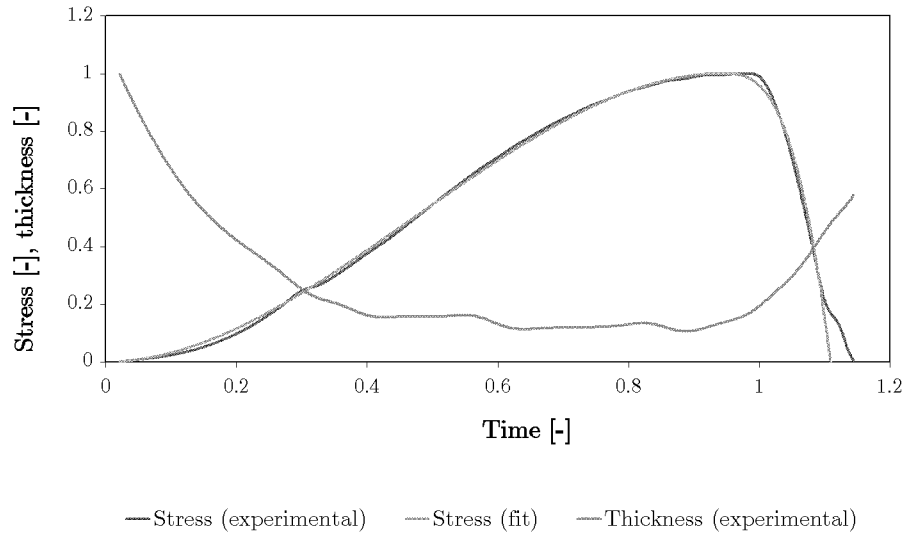


Figure 3.57: Normalized stress pulse imposed at 25 °C to a paper web formed by four 60 g.m<sup>-2</sup> 25 °SR hardwood paper sheets, and the corresponding web thickness evolution. The stress fitting is also presented.

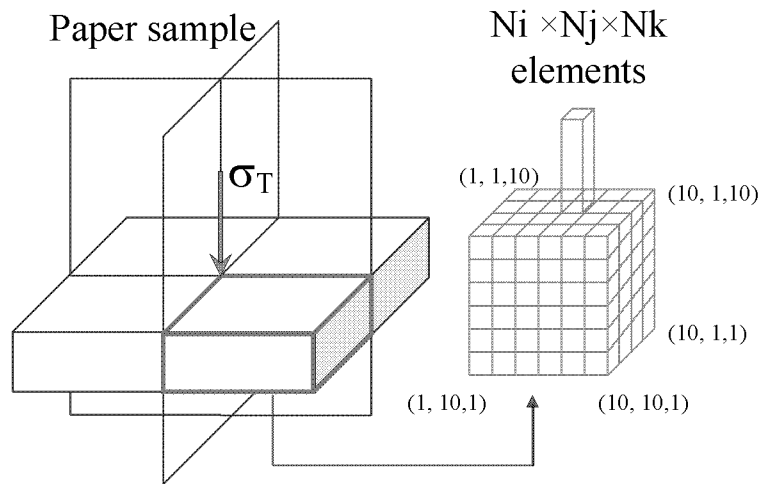


Figure 3.58: Schematic representation of the RVEs and the coordinate system.



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Table 3.12: Operating conditions used in the simulation runs and stress fitting parameters

|                                  |                                  |            |            |
|----------------------------------|----------------------------------|------------|------------|
| Temperature of the pressing head | $T_p = 25\text{ }^\circ\text{C}$ | 80         | 150        |
| Pulse length                     | $\tau = 83\text{ ms}$            | 76         | 76         |
| Peak pressure                    | $\sigma_0 = 6.3\text{ MPa}$      | 6.1        | 6.0        |
| Pulse shape                      | Roll                             | Roll       | Roll       |
| Fitting parameters               |                                  |            |            |
| $fp_1$                           | $\sqrt{2}$                       | $\sqrt{2}$ | $\sqrt{2}$ |
| $fp_2$                           | -216.349                         | -199.742   | -210.41    |
| $fp_3$                           | -0.419                           | -0.419     | -0.419     |
| $fp_4$                           | 0.5                              | 0.5        | 0.5        |
| $fp_5$                           | 35.2 ms                          | 29.3       | 28.8       |
| $fp_6$                           | 71.9 ms                          | 65.9       | 65.5       |
| $\theta_m$                       | 0.943                            | 0.943      | 0.943      |

Table 3.13: Main grid points and their corresponding position inside the paper web

| Coordinates | Vertical      | Coordinates | MD position | Coordinates | CD position |
|-------------|---------------|-------------|-------------|-------------|-------------|
|             | position [mm] |             | [mm]        |             | [mm]        |
| (1,1,1)     | 0.106         | (1,1,1)     | 1.875       | (1,1,1)     | 1.875       |
| (1,1,3)     | 0.532         | (3,1,1)     | 9.375       | (1,3,1)     | 9.375       |
| (1,1,5)     | 0.958         | (5,1,1)     | 16.875      | (1,5,1)     | 16.875      |
| (1,1,7)     | 1.384         | (7,1,1)     | 24.375      | (1,7,1)     | 24.375      |
| (1,1,9)     | 1.810         | (9,1,1)     | 31.875      | (1,9,1)     | 31.875      |
| (1,1,10)    | 2.023         | (10,1,1)    | 35.625      | (1,10,1)    | 35.625      |

The predictions under high-intensity conditions are summarized in the following figures. Figure 3.59 and 3.60 illustrate the results obtained for the variables related to the mechanical model, *i.e.* the total thickness of the sheet,  $\mathbf{L}_z$ , the applied stress  $\sigma_{ij}$ , and the local density,  $\rho_{ijk}$ .

As the medium was assumed to be almost saturated at the beginning of the pressing event, the consolidation of the mat is somehow prevented by the action of the liquid water. Additionally, the high stress rate applied to the web induces the development of the hydraulic pressure in the extra-fiber space during the compression phase. It should be noted that, in this case, no steam generation was assumed, as the temperature recordings showed no clear evidence of phase change. Then, when load is suddenly released, the web expands, although at a different rate.

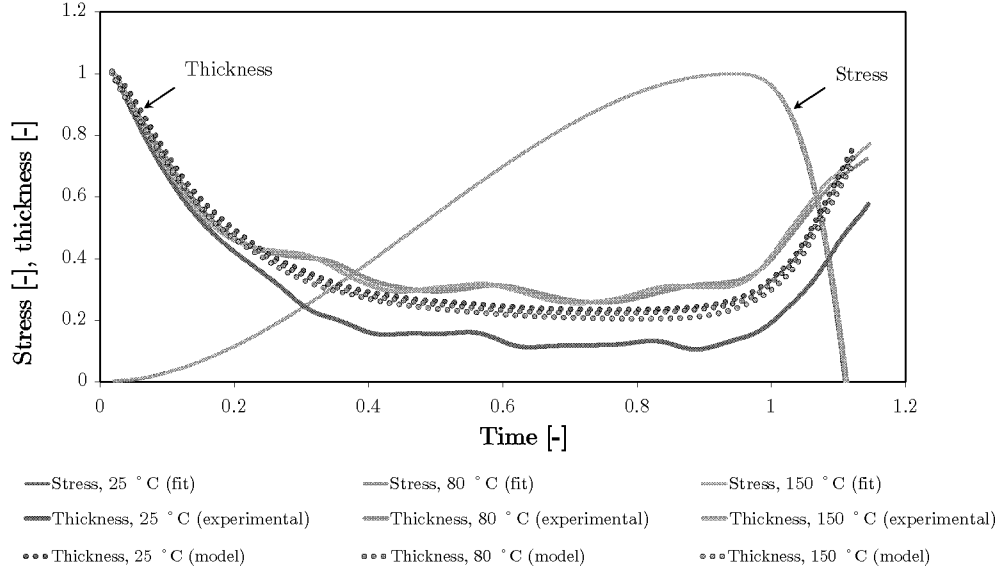


Figure 3.59: Comparison between the experimental data and the mathematical predictions for the total web thickness. The peak pressure was 6.3 , 6.1 and 6.0 MPa, the pulse length 83, 76 and 76 ms and the pressing temperature 25, 80 and 150 °C, respectively. The corresponding stress pulses are also presented.

Under the assumption of even deformation of the  $ij$  columns for the evaluation of the mean global elasticity modulus of the composite,  $E_T$ , Eqn. 3.269a gives the same stress values for each column, which are also equal to the total applied stress,  $\sigma_T$ . As for the local density,  $\rho_{ijk}$ , it may be evaluated as a function of the thickness of each layer according to:

$$\begin{aligned} \rho_{ijk} &= \left( \frac{m_{cw} + m_a + m_b}{V} \right)_{ijk} = \\ &= \frac{\rho_0 \Delta z_0 + \left( \frac{mb}{A_z} \right)_{ijk}}{\Delta z_{ijk}} \end{aligned} \quad (3.271)$$

where  $\Delta z_{ijk}$  is given by

$$\Delta z_{ijk} = 2 \left( z_{ijk} - \sum_{l=1}^{k-1} \Delta z_{ijl} \right) \quad (3.272)$$

Additionally, the effective porosity of each layer will be given as

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$$\phi_{eff,ijk} = 1 - \frac{\rho_{ijk}}{\rho_{s,ijk}} = 1 - \rho_{rel,ijk} \quad (3.273)$$

Figure 3.60 illustrates the evolution of the relative density of the composite as a function of time and at different vertical positions within the paper web, highlighting the stratification phenomena often reported in the literature.

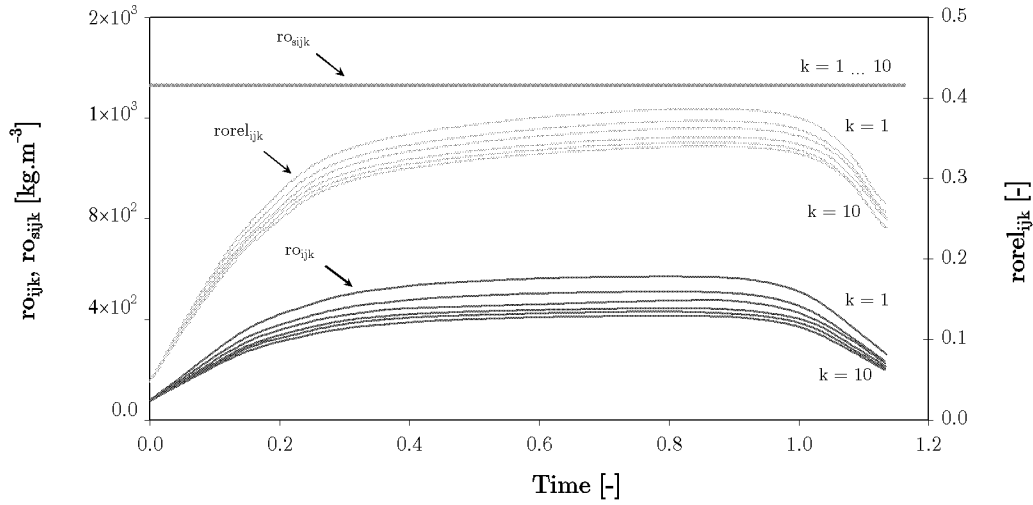


Figure 3.60: Model predictions for the apparent, relative and solid phase densities of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web at 150 °C. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Densities are plotted for different vertical positions within the paper web:  $k = 1$  denotes the layer near the permeable backing material, and  $k = 10$  the layer near the heated platen press.

Observing Figures 3.59 and 3.60 it may be concluded that the heat and mass transfer model together with the mathematical description of the mechanical behavior of paper, describe with some accuracy the consolidation process. In fact, the maximum deformation level attained here is not very dissimilar from that calculated using the mechanical model only. However, more representative thickness and density profiles were now obtained. At the initial stage of the pressing event the web deforms to a great extent at a relatively low stress. Then, as a result of fiber stiffness and water resistance to compression, the strain rate decreases and the thickness remains almost constant as the stress is further increased. Not

surprisingly, this is in agreement with the mechanical behavior of the cellular solids (see Figure 3.11), *i.e.* the initial deformation stage corresponding to the linear elastic and cellular collapse phases, followed by a consolidation mechanism in which a higher level of stress is required to further deform the web. When the applied stress is suddenly released the web expands rapidly but not to its initial state. Therefore, the model appears to be in good agreement with the experimental results, at least for the actual operating conditions. Additionally, the assumption of elastic collapse as the preferred mode of deformation is here validated, as the relative density values determined by the model are in the density range for which the differences between elastic and plastic collapse modes of deformation are not significant. An advantage of considering elastic collapse is that the yield strain,  $\varepsilon_y$  or  $C_3$  is considered to be independent of relative density.

In terms of the heat and mass transfer, the dependent variables are the temperature, gas pressure, vapor pressure, liquid volume fraction and finally, moisture ratio. Figure 3.61 shows a comparison between the simulated temperature profiles and the experimental profiles. From the simulation study it was found that the mat consolidation plays an important role on the heat and mass transfer process. In the very beginning of the press pulse it is observed a steep temperature increase in the superficial layers of the sheet close to the hot platen. This is ascribed to the temperature gradient established between the two surfaces, which induces an extremely high heat flux to the wet paper web. Peak heat fluxes reported in the literature lie in the range of  $2\text{--}8 \text{ MW.m}^{-2}$  and results in extraordinary high dewatering rates in impulse drying [87]. As for the inner layers of the sheet the increase in temperature is more gradual and starts a few milliseconds after nip closing as heat has to be transported in the thickness direction. At this initial stage heat is transferred from the outer surface to the interior of the sheet mainly by conduction. Besides the energy transport through conduction, transport by convection is also important. In fact, the water in the layers near the hot platen will move in the direction of the felt or backing material during the pressing operation, thus exchanging its heat with the fibers while passing through the porous structure. The more a sheet is compressed the more water will be transported from the hot platen side to the cold felt side. As the inner layers of the sheet are continuously heated, the temperature gradient in the thickness direction decreases as well as the heat flux from the top surface of the sheet. As a consequence the temperature increase is now more gradual.

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It is also advanced that the increased temperature used in hot pressing operations enhance dewatering by decreasing water viscosity and improving fiber flexibility and conformability. It is then generally agreed that impulse drying provides additional densification and may, according to some authors [21], [172], be responsible for the unique density profile in the thickness direction of the web as a result of what is known as stratification. Additionally, the extreme temperature conditions imposed to the paper web are envisaged as the main cause of delamination. In fact, during the compression of the web an hydraulic pressure builds up inside the porous structure, thus shifting the water boiling temperature and preventing steam generation. However, if the hot platen temperature is higher than the saturation temperature at the corresponding hydraulic pressure, steam is generated. This is most likely to occur in the layers close to the hot surface where the temperature is highest. The saturation temperature profile given in Figure 3.61 was obtained assuming that the hydraulic pressure is close to the applied pressure. Obviously this is not true and the resulting saturation temperature is given here in excess. In fact, the hydraulic pressure developed within the porous medium is not so high, corresponding to a lower saturation temperature. It is therefore expected that the temperature at the outer surface of the paper web never exceeds  $T_{sat}$ , preventing boiling, at least for the actual temperature and pressure operating conditions.

If vapor is formed near the outer surface of the web an additional resistance to heat transfer appears. The porosity of the medium is also seen as an important factor in the development of steam in the pore space as it directly affects the permeability of the medium. As the web is being compressed, its void space decreases, as well as its permeability. If water is trapped inside the porous medium, an increase in temperature may therefore generate steam.

As the mat is being compressed the internal gas pressure builds up as a consequence of web thickness reduction (see Figure 3.62). As no additional vapor is assumed to be generated during the pressing event, for the actual temperature, its contribution to the increase of the gas pressure is not considered. In fact, the partial vapor pressure is significantly lower and its increase results once more from the decreased porosity of the medium. It is also advanced that the extremely high values of the gas pressure are due to the fact that gas is forced to leave the porous medium through the lateral edges. As the permeability of the medium is lower in the in-plan direction, the gas flux is reduced, thus increasing

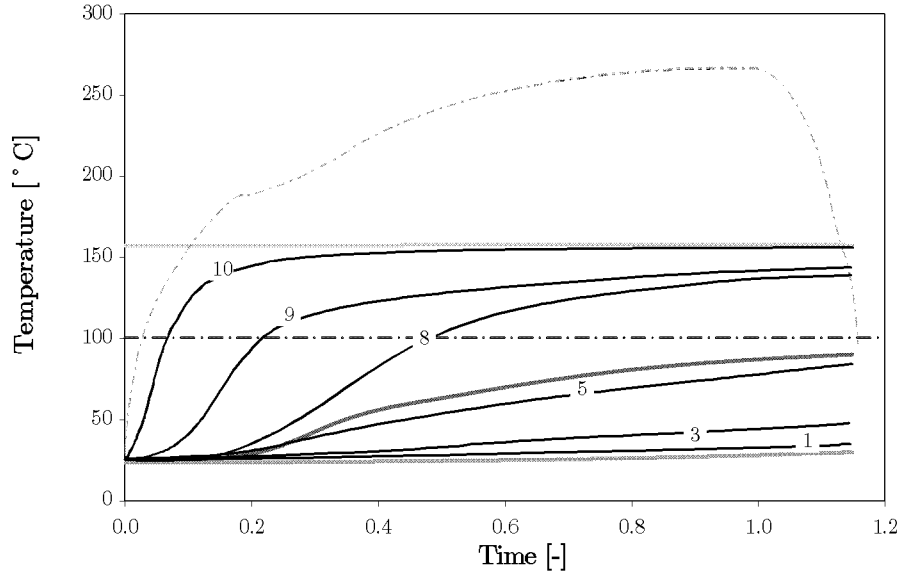


Figure 3.61: Experimental temperature profiles obtained for a 25 °SR 4×60 g.m<sup>-2</sup> hardwood paper web subjected to a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C ( $T_p$ : green;  $T_1$ : blue;  $T_2$ : red (as defined in Figure 2.22)). The results of a simulation run for the same operating conditions and paper properties are also presented (solid black lines). The predicted values were obtained for the vertical middle plane of the sheet at different vertical positions: (1) denotes the layer near the permeable backing material, and (10) the layer near the heated platen press. The red dash-dotted line represents the saturation temperature for an hydraulic pressure equal to the applied stress.

its pressure (see also Figure 3.66). As a conclusion, it may be said that the heat transfer occurs predominantly in the thickness direction of the web, as illustrated in Figures 3.63 and 3.64 (the horizontal profiles are almost constant), whereas the mass transfer of the gas phase takes place in the in-plane direction mainly (the vertical profiles are constant, as presented in Figure 3.67).

As no steam generation is assumed at the present conditions, the horizontal vapor profiles are almost constant (see Figure 3.65). A pressure increase with time is however observed as a consequence of volume reduction of the mat.

As for the moisture distribution within the paper web, two main conclusions may be drawn from Figures 3.68 and 3.69: (i) it is a consequence of liquid water flow in the thickness direction of the web (only water is able to flow across the outlet face contacting the backing material); (ii) due to the stratification of the

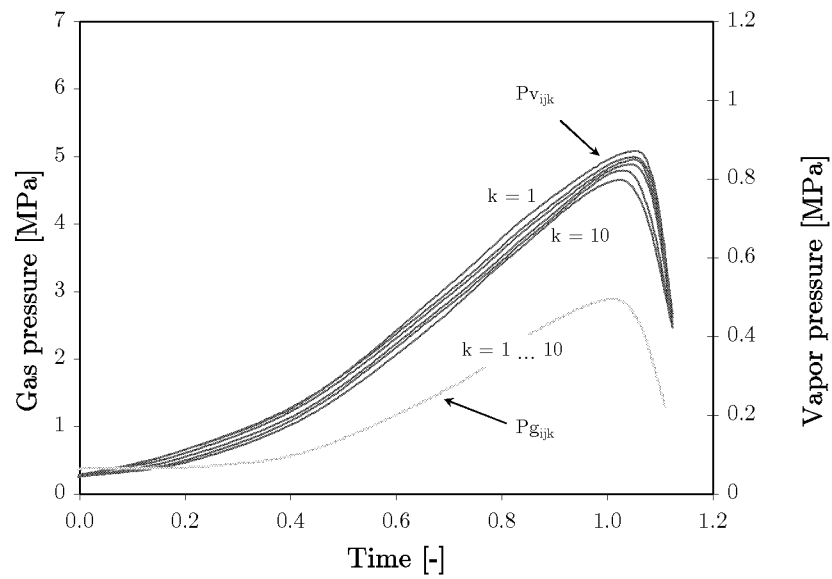


Figure 3.62: Predicted gas and vapor pressure values inside a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Pressure is plotted for the vertical middle plane of the sheet at different vertical positions:  $k = 1$  denotes the layer near the permeable backing material, and  $k = 10$  the layer near the heated platen press.

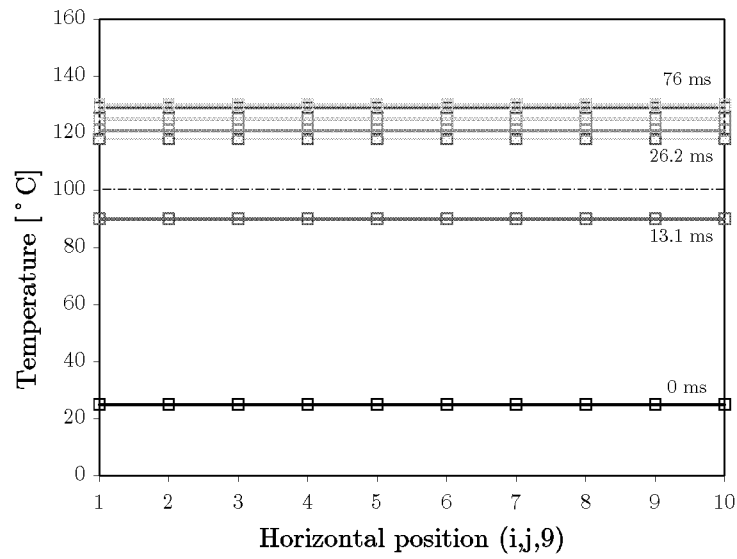


Figure 3.63: Horizontal temperature profiles predicted by the model for a  $4 \times 60$  g.m<sup>-2</sup> 25 °SR hardwood paper web. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Temperature is plotted for the layer denoted by  $k = 9$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sheet and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper web. Results are also presented for different stages of the pressing event.



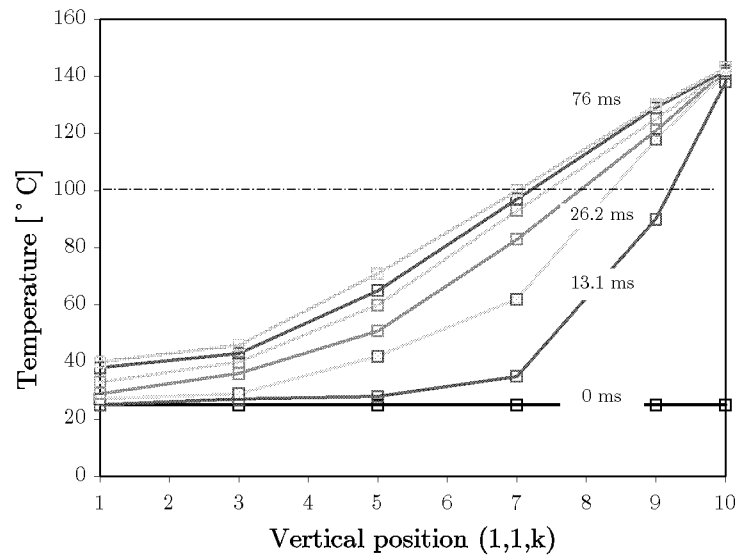


Figure 3.64: Vertical temperature profiles predicted by the model for a  $4 \times 60$  g.m<sup>-2</sup> 25 °SR hardwood paper web. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Temperature is plotted for the vertical middle plane of the sheet at different vertical positions:  $k = 1$  denotes the layer near the permeable backing material, and  $k = 10$  the layer near the heated platen press. Results are also presented for different stages of the pressing event.

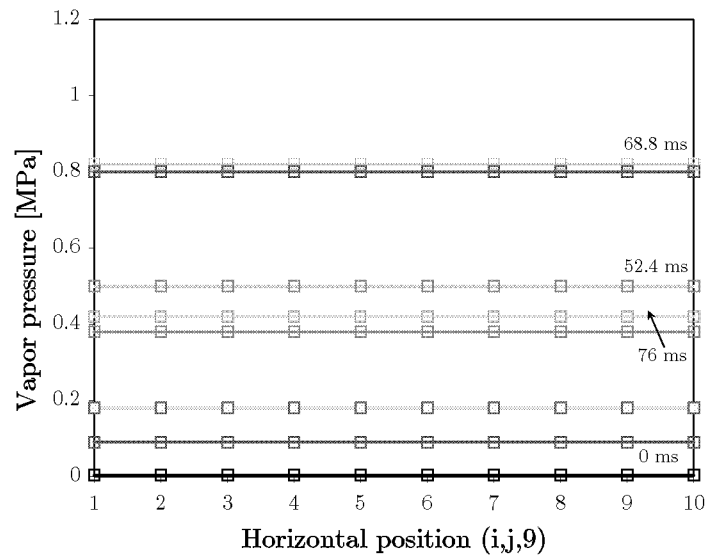


Figure 3.65: Horizontal vapor pressure profiles predicted by the model for a  $4 \times 60$   $\text{g.m}^{-2}$  25 °SR hardwood paper web. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Vapor pressure is plotted for the layer denoted by  $k = 9$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sheet and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper web. Results are also presented for different stages of the pressing event.

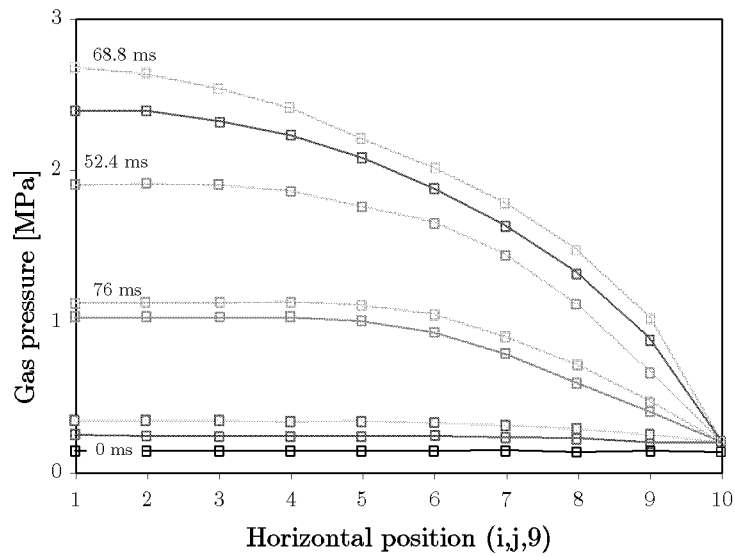


Figure 3.66: Horizontal gas pressure profiles predicted by the model for a  $4 \times 60$   $\text{g.m}^{-2}$  25 °SR hardwood paper web. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Pressure is plotted for the layer denoted by  $k = 9$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sheet and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper web. Results are also presented for different stages of the pressing event.

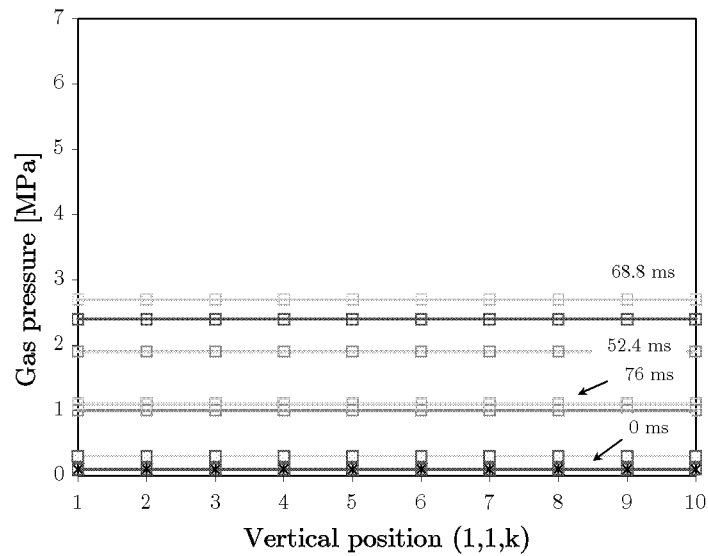


Figure 3.67: Vertical gas pressure profiles predicted by the model for a  $4 \times 60$   $\text{g.m}^{-2}$  25 °SR hardwood paper web. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Pressure is plotted for the vertical middle plane of the sheet at different vertical positions:  $k = 1$  denotes the layer near the permeable backing material, and  $k = 10$  the layer near the heated platen press. Results are also presented for different stages of the pressing event.

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web, the bottom layers have a lower amount of liquid water per kg of dry mass (and the layers contacting the heated platen present a somehow modest moisture ratio variation). In addition, in the expansion phase the applied mechanical pressure is decreased and the web will expand as the fluid fills up the created void volume (rewetting). This is observed in the moisture ratio profile at the layer close to the backing material (layer denoted as  $k = 1$  in Figure 3.68).

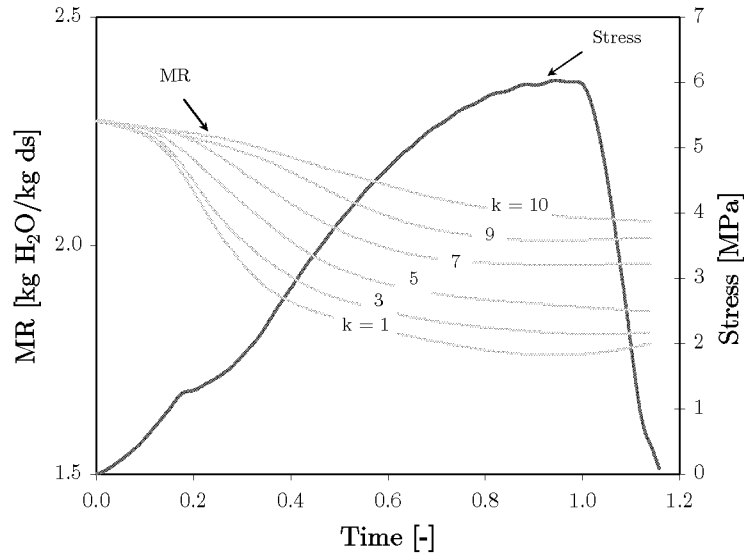


Figure 3.68: Predicted moisture ratio evolution with time at different vertical positions inside a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Moisture ratio is plotted for the vertical middle plane of the sheet at different vertical positions:  $k = 1$  denotes the layer near the permeable backing material, and  $k = 10$  the layer near the heated platen press. The pressure pulse applied on the paper web is also presented.

Finally, the evolution of liquid water volume fraction is given in Figure 3.70, which shows no clear evidence of a volume fraction gradient in the thickness direction of the sheet. This is ascribed to the fact that the volume reduction of the mat is comparable to the amount of expelled liquid water and to the compression of the gas and vapor phases. As the web is compressed the ratio of liquid water volume to the total volume of the layer is maintained almost constant in the thickness direction and through the entire pressing event. It is believed that the reduction of the effective porosity in the thickness direction is

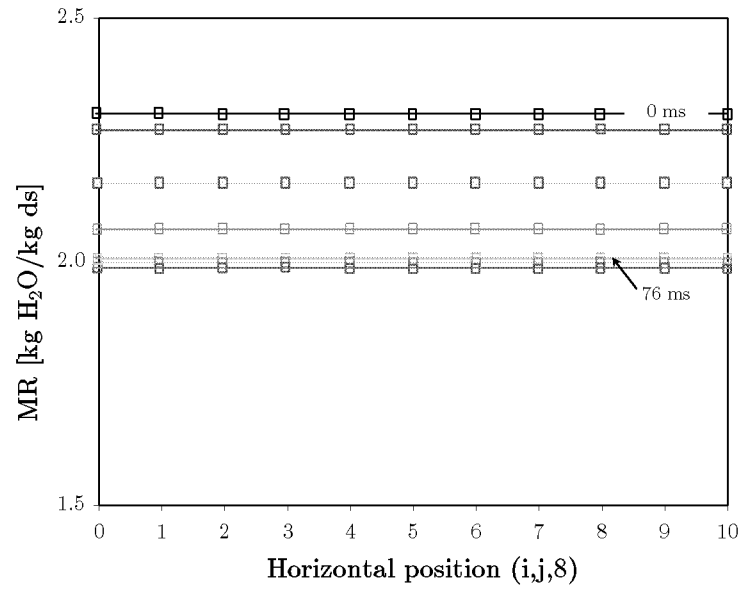


Figure 3.69: Horizontal moisture ratio profiles predicted by the model for a  $4 \times 60$  g.m<sup>-2</sup> 25 °SR hardwood paper web. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Moisture ratio is plotted for the layer denoted by  $k = 8$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sheet and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper web. Results are also presented for different stages of the pressing event.

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counteracted by the fact that liquid water tends to fill up the void volume created by the forced compression of vapor and air.

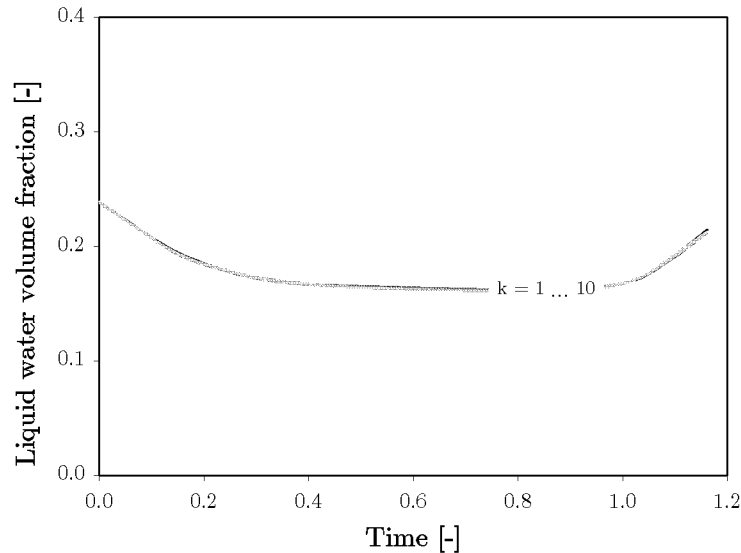


Figure 3.70: Evolution of liquid water volume fraction predicted by the model at different vertical positions inside a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood paper web. The results were obtained for a press pulse of 76 ms with a peak pressure of 6.0 MPa at 150 °C. Water volume fraction is plotted for the vertical middle plane of the sheet at different vertical positions:  $k = 1$  denotes the layer near the permeable backing material, and  $k = 10$  the layer near the heated platen press.

#### Concluding remarks

A mathematical model of the stress-strain behavior of high moisture ratio paper webs, including the heat and mass transfer mechanisms at moderate pressing temperatures, was presented here. The model predictions were in good agreement with the experimentally observed fiber network rheological behavior during a typical pressing event. In terms of temperature profiles predictions the model overestimates the temperature at the layers close to the heated platen. This was partially attributed to the existence of a heat transfer resistance at that interface, which was not considered in the theoretical model. Another source of error comes from the estimation of some model parameters, namely the liquid water elasticity modulus and fiber viscous parameter.

### 3.4 Experimental investigation of internal web temperature

In this section the transient temperature profiles of high moisture ratio and wet paper samples undergoing compression in a heated platen press were analyzed. The material properties and operating conditions were already described in detail in **Chapter 2**. The temperature recordings were obtained at the vertical positions illustrated in Figures 2.21 and 2.22.

The purpose of this investigation was to infer about the possibility of steam generation inside the paper web while this is still in the press nip. In fact, it has been advanced by several authors that steam formation is predominantly a post-nip phenomenon, and is seen as the major cause of delamination taking place at nip opening [105]. The observation of a vapor phase development inside the paper web has, therefore, important implications in the modeling process. From the present findings it was possible to define some model assumptions, as well as to specify some of the boundary conditions required to solve the constitutive equations of the heat and mass transfer model.

The temperature profile inside a paper sheet during a very long, low pressure pulse is well known and presents clear indications of the phase transition from liquid water to steam [106]. In this case, the onset of dry-out inside a paper web can be identified by the local temperature increasing above 100 °C. However, at very fast high loading conditions the behavior of liquid water in the porous matrix is altogether different. It apparently depends on the temperature and pulse length and also on the paper grammage [105].

Figures 3.71 to 3.79 show the results of measurements performed with embedded thermocouples in 240 and 320 g.m<sup>-2</sup> paper webs pressed from room temperature up to about 350 °C under similar press pulses. For these long pulses, and at platen temperatures equal and above 150 °C, almost all the thermocouples crossed the 100 °C barrier, which may indicate that steam was formed. However, the phenomenon greatly depends on the hydraulic pressure generated during compression.

Different conclusions may be drawn from the results obtained for the same paper webs pressed over a shorter period of time. Here, platen temperatures of 150 °C or below did not induce steam generation, as the temperature inside the webs remained under 100 °C (see Figures 3.80 to 3.85).



### 3. Mathematical Model for High-Temperature Pressing of Paper 351

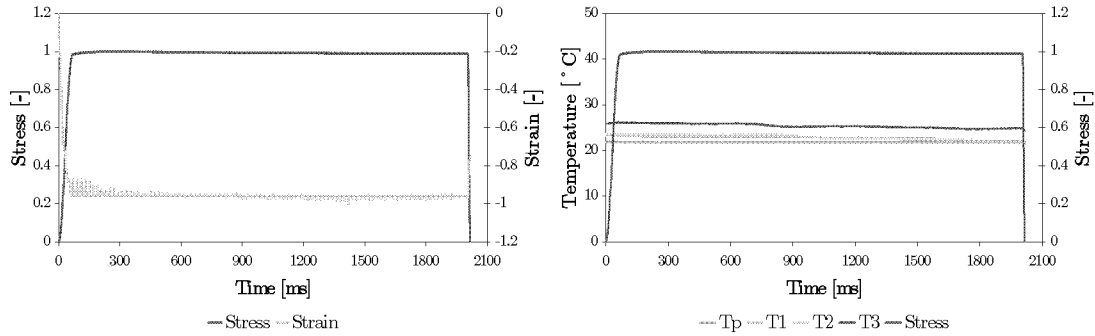


Figure 3.71: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 2017 ms with a peak pressure of 6.4 MPa. The plate temperature was set to room temperature. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22, and  $T_3$  the temperature at the paper/platen interface.

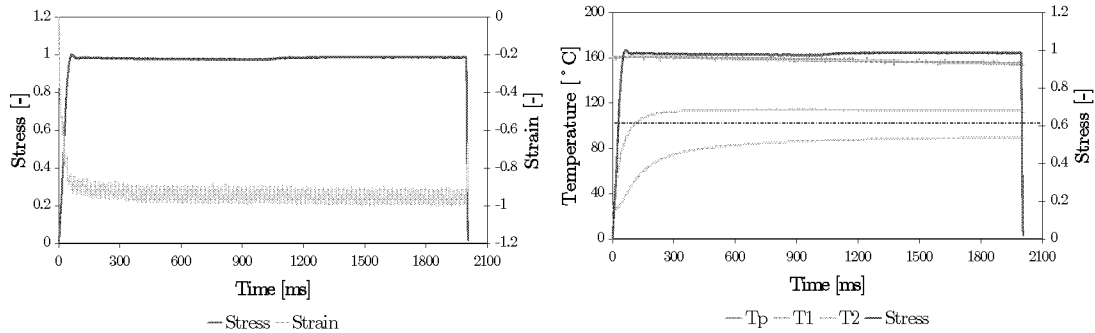


Figure 3.72: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 2008 ms with a peak pressure of 6.1 MPa. The plate temperature was set to 150 °C. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22.

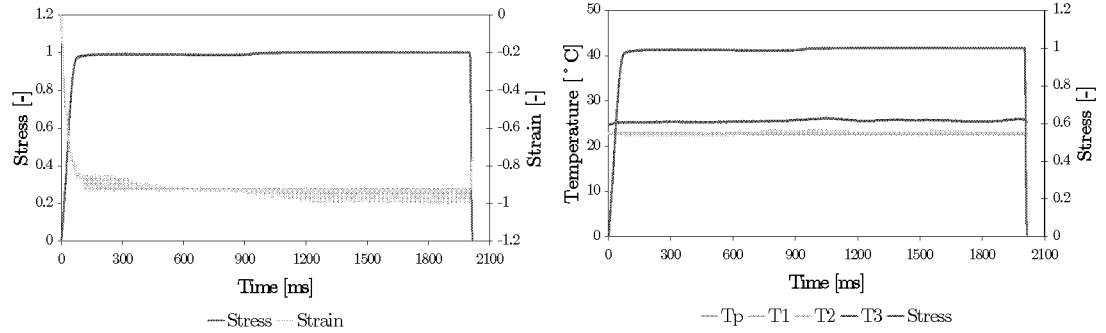


Figure 3.73: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 2017 ms with a peak pressure of 6.5 MPa. The plate temperature was set to room temperature. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 80 \text{ g.m}^{-2}$  40 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22, and  $T_3$  the temperature at the paper/platen interface.

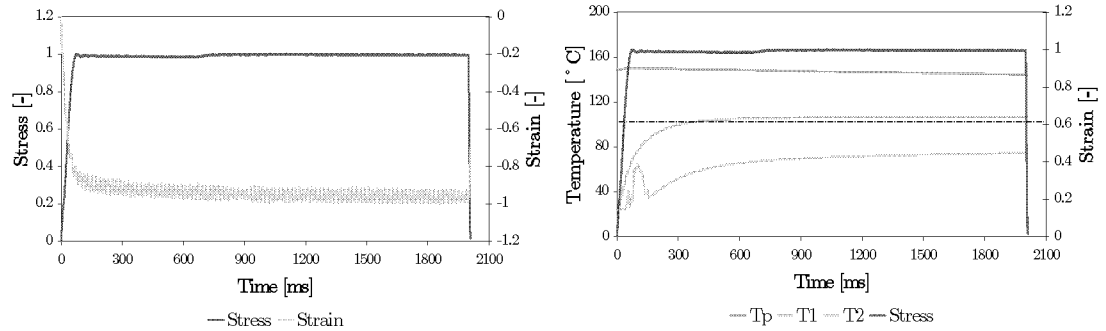


Figure 3.74: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 2011 ms with a peak pressure of 6.0 MPa. The plate temperature was set to 150 °C. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 80 \text{ g.m}^{-2}$  40 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22.

### 3. Mathematical Model for High-Temperature Pressing of Paper 353

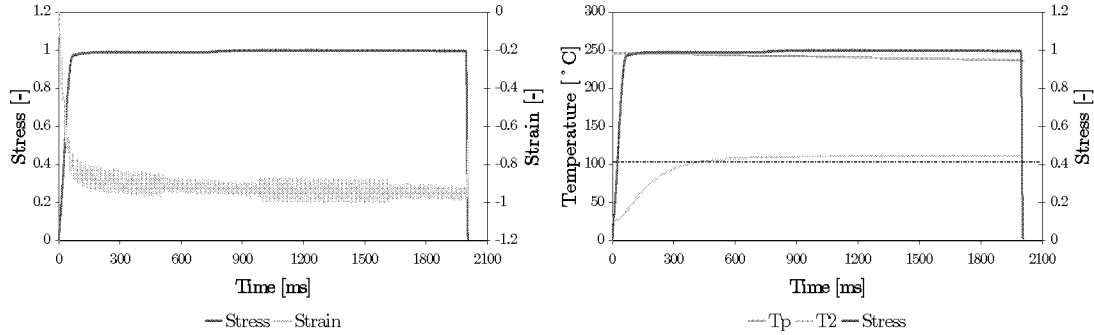


Figure 3.75: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 2008 ms with a peak pressure of 5.8 MPa. The plate temperature was set to 250 C. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 80 \text{ g.m}^{-2}$  40 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature and  $T_2$  the temperature at the vertical position defined in Figure 2.22.

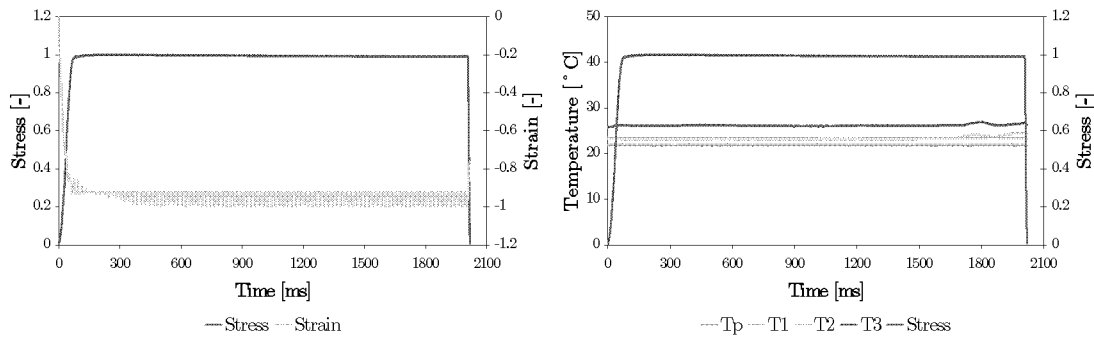


Figure 3.76: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 2020 ms with a peak pressure of 6.4 MPa. The plate temperature was set to room temperature. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 80 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22, and  $T_3$  the temperature at the paper/platen interface.

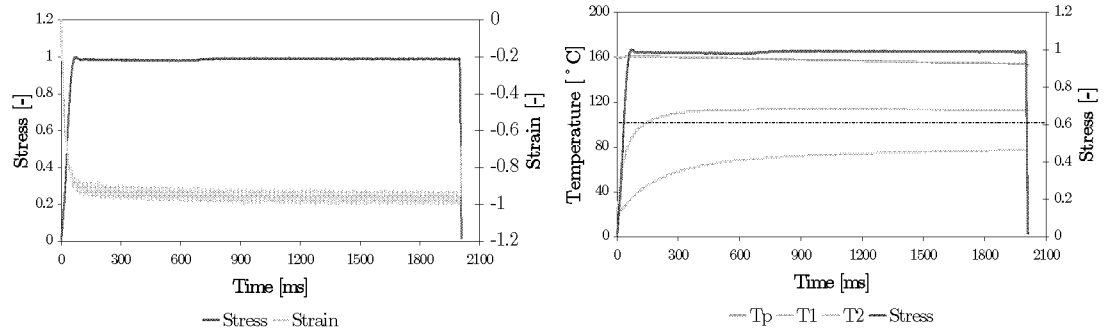


Figure 3.77: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 2013 ms with a peak pressure of 6.1 MPa. The plate temperature was set to 150 °C. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 80 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature, and  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22.

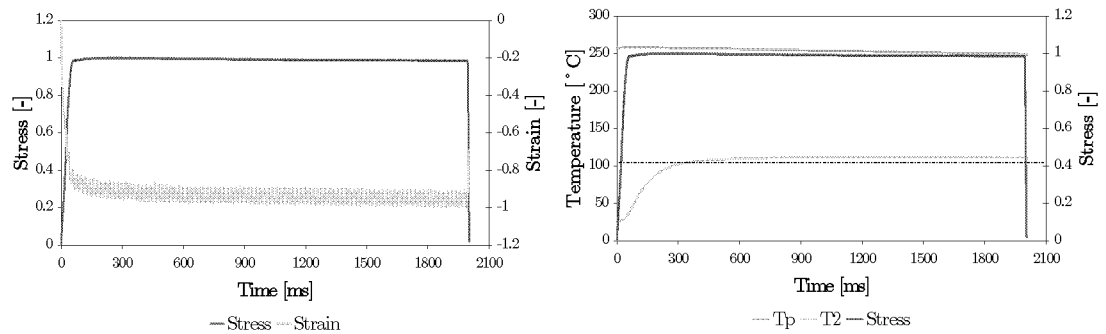


Figure 3.78: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 2006 ms with a peak pressure of 5.8 MPa. The plate temperature was set to 250°C. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 80 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature and  $T_2$  the temperature at the vertical position defined in Figure 2.22.

### 3. Mathematical Model for High-Temperature Pressing of Paper 355

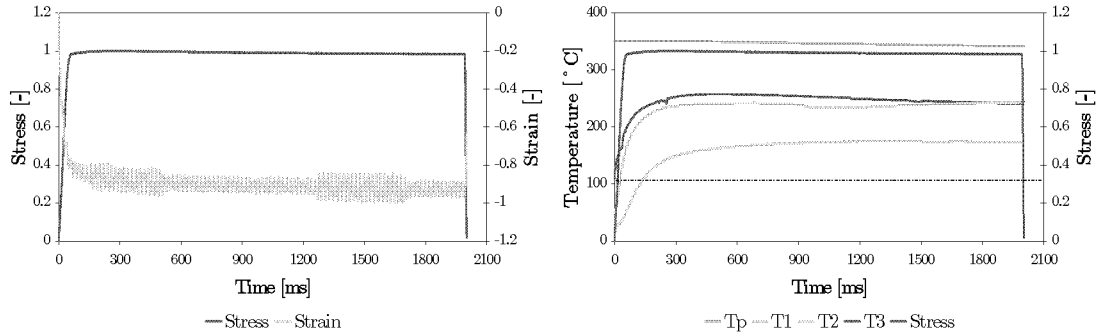


Figure 3.79: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 2004 ms with a peak pressure of 5.9 MPa. The plate temperature was set to 350 °C. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 80 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22, and  $T_3$  the temperature at the paper/platen interface.

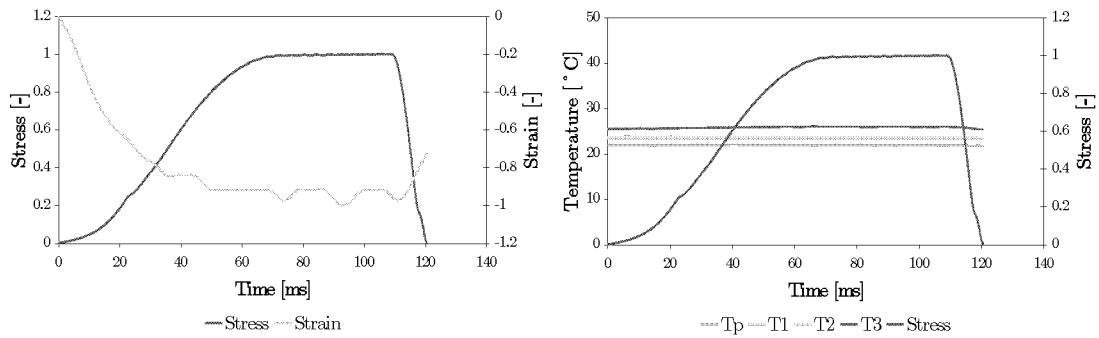


Figure 3.80: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 120 ms with a peak pressure of 6.4 MPa. The plate temperature was set to room temperature. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22, and  $T_3$  the temperature at the paper/platen interface.

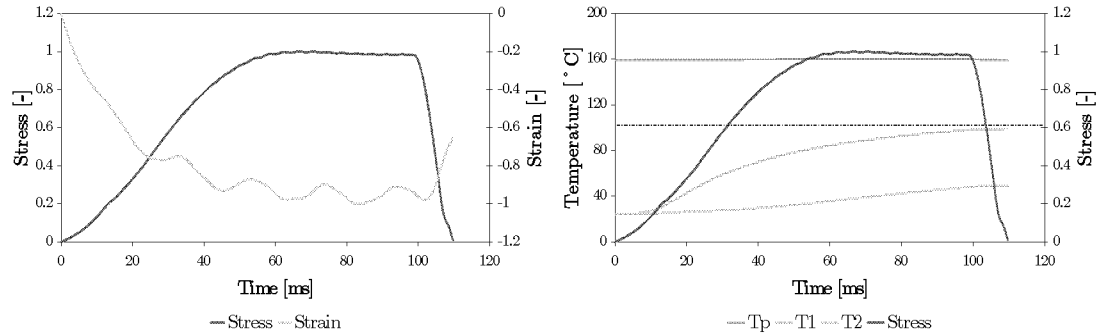


Figure 3.81: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 110 ms with a peak pressure of 6.0 MPa. The plate temperature was set to 150 °C. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22.

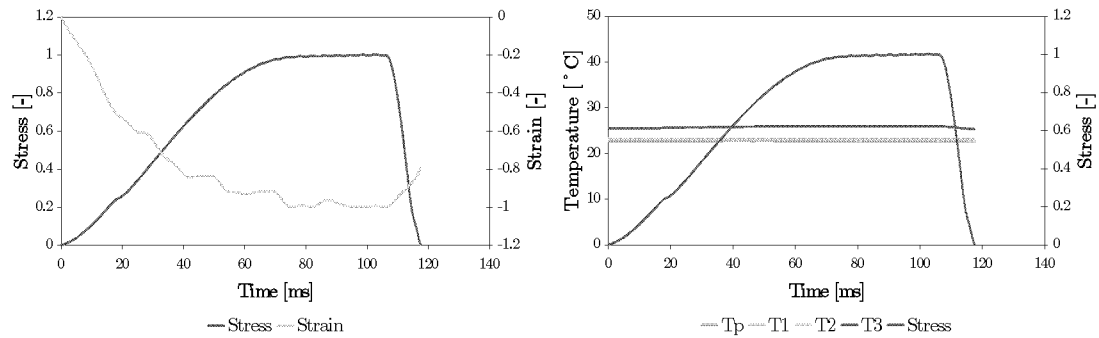


Figure 3.82: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 103 ms with a peak pressure of 6.4 MPa. The plate temperature was set to room temperature. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 80 \text{ g.m}^{-2}$  40 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22, and  $T_3$  the temperature at the paper/platen interface.

### 3. Mathematical Model for High-Temperature Pressing of Paper 357

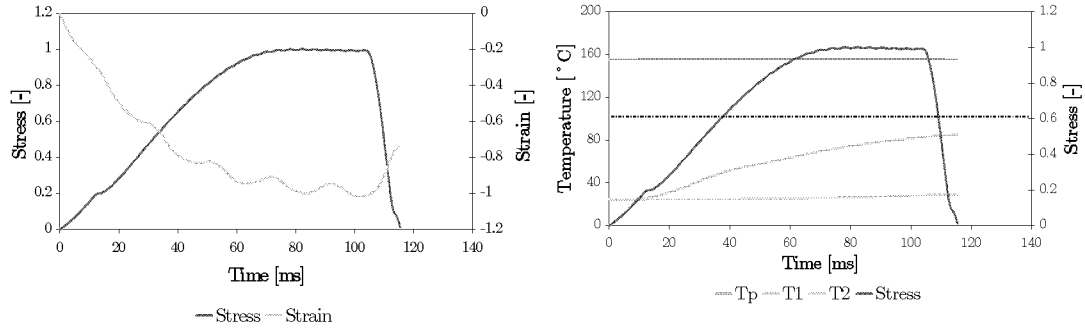


Figure 3.83: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 116 ms with a peak pressure of 6.0 MPa. The plate temperature was set to 150 °C. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 80 \text{ g.m}^{-2}$  40 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22.

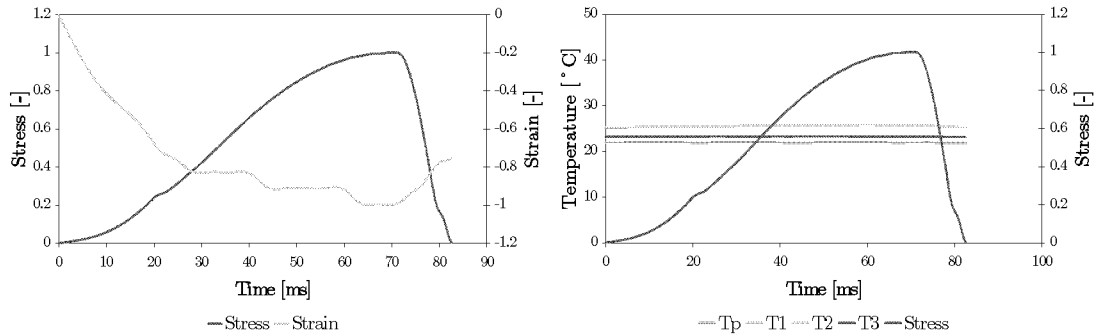


Figure 3.84: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 83 ms with a peak pressure of 6.3 MPa. The plate temperature was set to room temperature. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22, and  $T_3$  the temperature at the paper/platen interface.

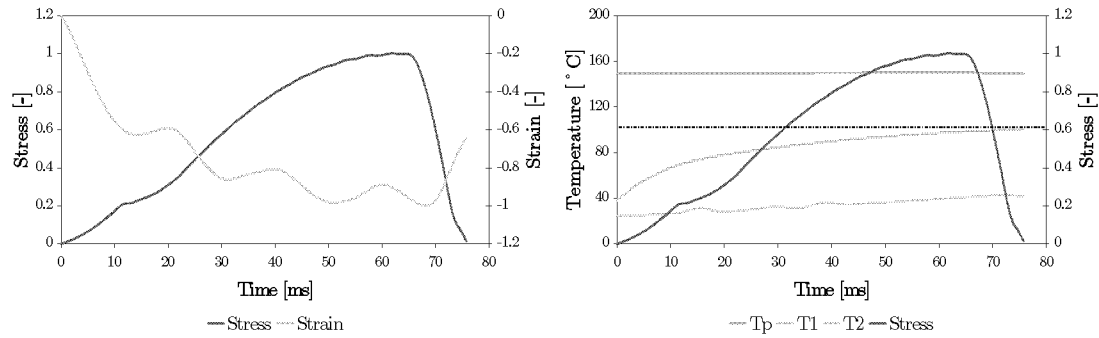


Figure 3.85: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 76 ms with a peak pressure of 6.0 MPa. The plate temperature was set to 150 °C. **Right:** The corresponding internal web temperatures during the press drying of a  $4 \times 60 \text{ g.m}^{-2}$  25 °SR hardwood saturated paper web.  $T_p$  represents the platen temperature,  $T_1$  and  $T_2$  the temperature at the vertical positions defined in Figure 2.22.

Similar pulses on lower grammage sheets, *i.e.*  $60 \text{ g.m}^{-2}$ , showed some interesting features: at temperatures higher than 200 °C a sudden increase of temperature was recorded when the mechanical load was released from the paper sample (see Figures 3.86 to 3.88). This suggests that thin sheets tend to exhibit phase change at the end of the press pulse. The flashing of water as pressure is relieved at the end of the nip is seen as a rapid temperature decrease down to 100 °C.

When even shorter press pulses (30 ms) were applied to  $60 \text{ g.m}^{-2}$  sheets (see Figure 2.27) no clear evidence of such temperature increase was found (except maybe for temperatures of 250 °C or above). It is speculated that this occurred as the increasing compression rate would cause an increase in the hydraulic pressure, which tends to shift the boiling point of water and prevent steam generation. This suggests that for short pulses the hydraulic pressure in most of the sheet is high enough to prevent evaporation and water is present in the liquid phase until the pressure is totally released, which would imply almost no steam generation in the press nip!



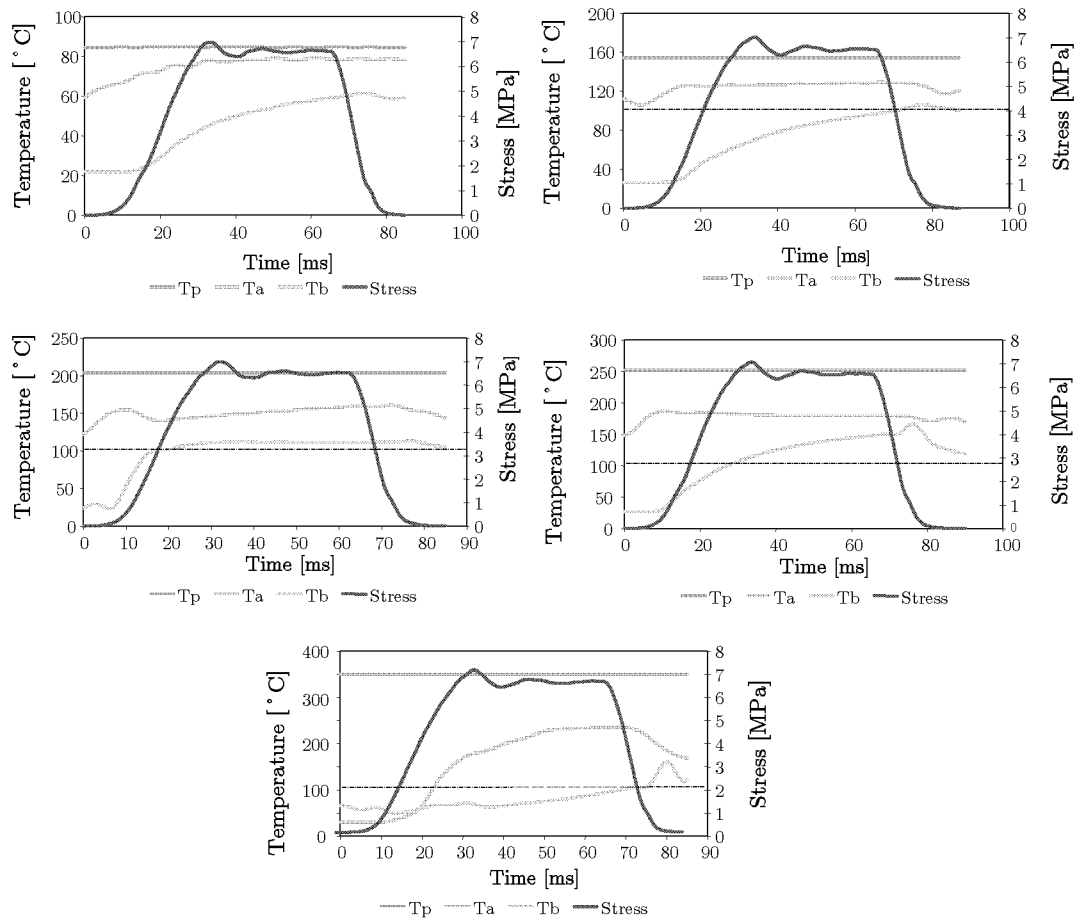


Figure 3.86: Internal web temperatures during press drying of hardwood unsaturated paper samples. The duration of the press pulse was set to 75 ms approximately. The hot plate temperature was set to 80, 150, 200, 250 and 350 °C. The grammage of the samples was 60 g.m<sup>-2</sup> and the refining level 25 °SR.  $T_p$  represents the platen temperature and,  $T_a$  and  $T_b$  refer to the temperature at the platen/paper and paper/felt interfaces.

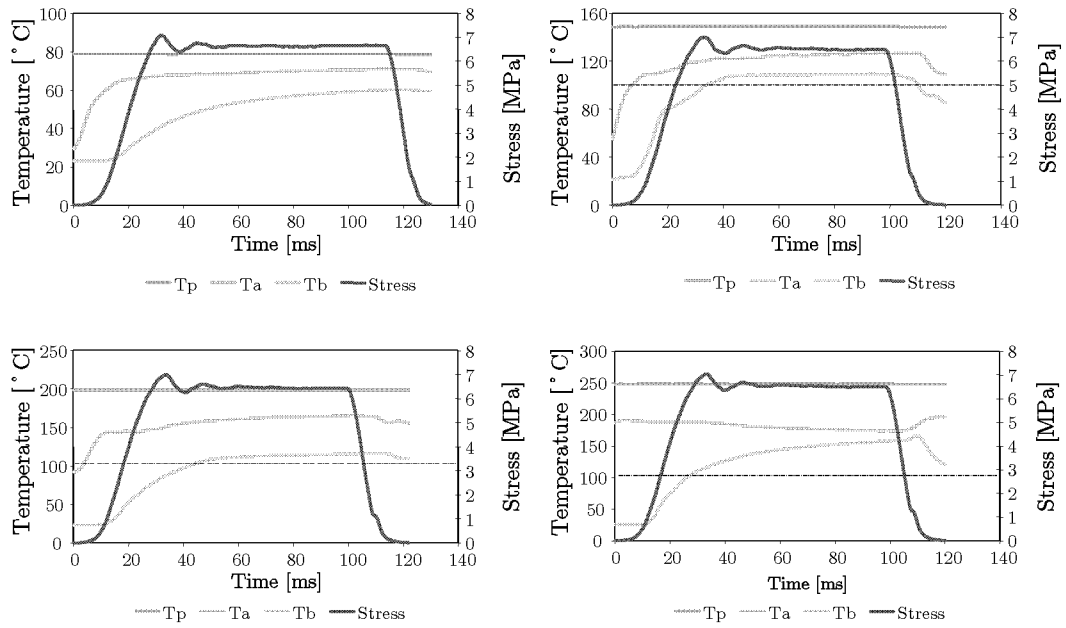


Figure 3.87: Internal web temperatures during press drying of hardwood unsaturated paper samples. The duration of the press pulse was set to 120 ms. The hot plate temperature was set to 80, 150, 200 and 250 °C. The grammage of the samples was  $60 \text{ g.m}^{-2}$  and the refining level 25 °SR.  $T_p$  represents the platen temperature and,  $T_a$  and  $T_b$  refer to the temperature at the platen/paper and paper/felt interfaces.

### 3. Mathematical Model for High-Temperature Pressing of Paper 361

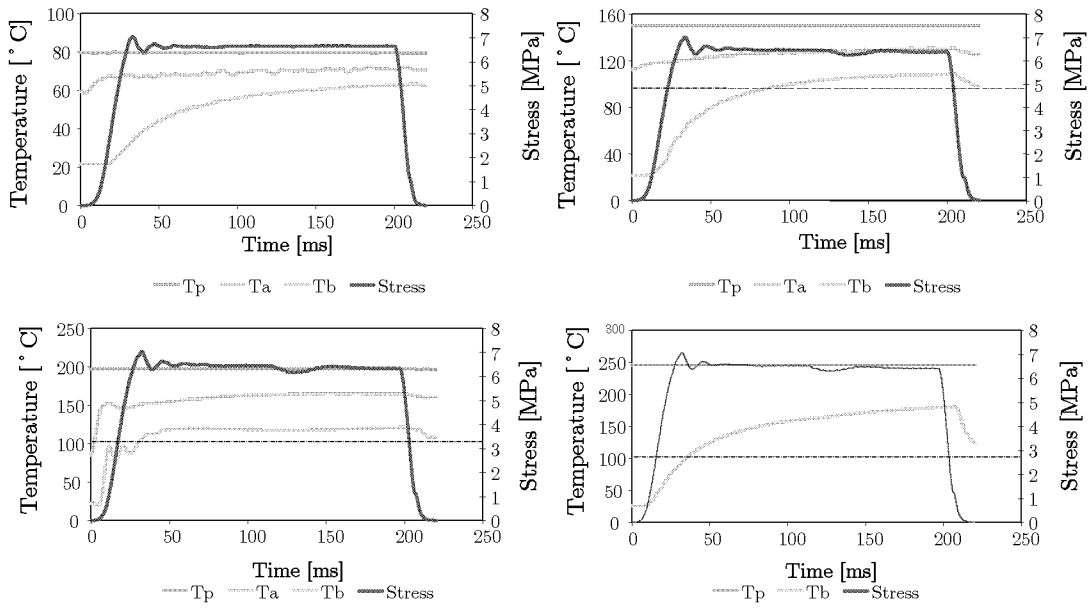


Figure 3.88: Internal web temperatures during press drying of hardwood unsaturated paper samples. The duration of the press pulse was set to 200 ms. The hot plate temperature was set to 80, 150, 200 and 250 °C. The grammage of the samples was 60 g.m<sup>-2</sup> and the refining level 25 °SR.  $T_p$  represents the platen temperature and,  $T_a$  and  $T_b$  refer to the temperature at the platen/paper and paper/felt interfaces.

### 3.5 Conclusions

In the beginning of this chapter a bibliographic review of the different dewatering models for paper under wet pressing conditions was elaborated. From the findings of those theoretical models and experimental studies performed by several authors working both on the field of wet pressing and high-intensity drying processes such as impulse drying, it was possible to develop a mathematical model capable of describing the mechanical behavior of wet paper under the typical high-intensity operating conditions of impulse drying, as a first approach to the development of a 3D global model integrating the heat and mass transfer mechanisms taking place during the pressing event. The presented model assumes paper as viscoelastoplastic material, and describes its behavior to compression under the approach to the cellular solids theory. It is based on the idea that the wet paper web may be conceived as a layered network with an internal structure close to that of foams or honeycombs. However, it gave predictions that did not agree, in an acceptable way, with the experimental results of uniaxial compression carried out in a laboratory platen press. The integration of the heat and mass transfer was therefore of utmost importance. This second approach was based on the fundamental laws of thermodynamics and fluid flow in compressible porous media. The performance of the global model was analyzed for the typical operating conditions of impulse drying in terms of pressure application, but not using the high temperature conditions used in the process. This was due to the lack of experimental data at temperatures above 150 °C. Such extreme operating conditions will be studied later in **Chapter 5**, where a global model for both paper and felt is presented.

Despite some limitations in terms of validation, the present model was used to simulate the evolution of web thickness, densities, internal web temperature, moisture content, gas pressure as well as vapor pressure inside the paper web when submitted to impulse drying operating conditions. The results from the simulation runs allowed to get some insight into the dewatering and consolidation mechanisms occurring inside the fiber network. Further, the heat and mass transfer showed to play an important role in the consolidation of the mat, since in the first model (mechanical representation) no fluid flow was considered. This means that both gas and liquid phases would be compressed instead, which would result in a higher resistance to compression. Obviously, the vertical profiles of the main variables of the model would be most affected. In terms of tempera-

### **3. Mathematical Model for High-Temperature Pressing of Paper 363**

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ture predictions the model overestimates the temperature in the web layers near the hot platen. This is ascribed to a substantial heat transfer resistance at that boundary, that was not taken into consideration. Instead, the top surface of the paper web was considered to be that of the heated platen.

In summary, the global model qualitatively predicts the heat and mass transfer in the porous medium, but it would most benefit from more refined boundary conditions, such as that at the paper/heated platen interface. On the other hand the viscoelastoplastic mechanical model seems to represent in an acceptable way the material's behavior to compression, provided that model parameters are estimated from data with small experimental error.



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# Chapter 4

## Felt

### 4.1 Introduction

Advances in press felts have been a necessary prerequisite for implementing many of the new pressing concepts. The working environment in today's presses is very hard on felts as the combined effect of high nip loads, elevated temperatures, often long nip lengths and various chemical compounds present in paper webs place high demands on felt materials. Over the years, papermakers have used the developments in wet felt design to improve water removal. In fact, the felt can have a significant effect on the solids content achieved in pressing. From the point of view of the final web solids content, the most important felt properties are the resistance to water flow, the uniformity of pressure application and the capacity to prevent water transport from felt pores to the paper web. None of these properties should be neglected when designing a felt. An improvement in one property can have an adverse effect on other properties. A higher permeability, for example, can easily yield a reduction in the capacity to prevent rewetting and an increase in pressure non-uniformity. In order to obtain the highest possible solids content in the paper web an optimum must be found among the different felt properties.

Considerations in designing a wet felt for the press section include the press configuration, the paper grade and furnish, the machine speed, the auxiliary vacuum and cleaning systems, the nip pressure, the temperature, and the paper qualities. The history of felt runnability and repeatability is also important [23].

A felt must have the capacity to handle the water load and, ideally, work as well as at the beginning of its running life. To attain this ideal, the felt must be

engineered to *resist compaction and filling*. Wool felts used before 1950 would usually fill up, wear and compact, making felt performance the main reason for felt removal. The felts made up of spun synthetic yarns exhibited better performance but still experienced filling and compaction, though to a lesser extent. The introduction of nylon in batt on mesh designs occurred around 1950 and increased felt life and improved felt quality. In the 1970s, development efforts in felt technology were geared to produce felts that were durable, to maintain papermaking qualities over longer periods. This translates to consistent machine speeds, efficiencies and paper production.

The *furnish and grade of paper* are also factors because of the difference between flow and pressure-controlled sheets. On flow-limited high impulse presses the felt must be able to maintain adequate void capacity for a hydraulic pressure gradient to exist. The magnitude of this gradient determines the rate of flow from the paper sheet. Grades like linerboard have their flow restricted by the pore structure and thickness of the sheet and because sheet crushing can occur, the felt must have sufficient void volume to remove the water. In the other extreme, pressure-controlled grades like newsprint and tissue, water flow is not restricted by the weight and caliper of the sheet. The most important characteristic of a felt for these paper grades is its ability to not rewet the sheet when pressure is removed. Maintaining a smooth, dense batt structure on the surface of the felt is the primary key to drying performance on a lightweight paper grade.

*Press section geometry, loading, roll covers, and mechanical condition* can all affect the runnability of the felt. A great pickup felt may be quite different from a felt designed to run on a last-press position. The pickup felt must have excellent void volume retention and water handling capacity while allowing smooth sheet transfer from nip-to-nip. The aim of the last press is to get the water out of the sheet. Therefore the felt must withstand high loads while not causing vibration or sheet marking [26].

The ability to provide optimum dewatering has been affected in recent years by the increase of *chemicals, fillers and recycled fiber*, and subsequent filling problems that this change brings and the ever-increasing demand to run the machinery at higher and higher speeds [26]. These types of developments continue to force felt suppliers to rethink their design applications.

The evolution in press felt construction from wool conventional woven products to synthetic batt on mesh designs was merely a prelude to the sophisticated

multiple-base fabric construction of today. Initially, multi-layer batt on mesh constructions, successfully run on roll presses, were used rather unsuccessfully on the shoe type impulse press. These batt on mesh constructions were made heavier, to prevent sheet marking, by increasing batt percentage. These constructions tend to compact rapidly, and the consequential sheet marking resulted in their premature removal. The sheet marking manifested itself as yarn marks from the base fabric, groove marks from the vented top roll, and water marks as a result of inadequate drainage within the nip [14].

As the application of impulse pressing expands to more critical grade structures, further demands were placed upon press felts. A great effort to develop press fabrics for the impulse drying process has been ongoing for many years. Felts for impulse drying must meet the same mechanical and chemical resistance requirements as press felts for conventional press sections but must survive the extreme temperature conditions. The surface of the fabric must provide a temperature resistant barrier that can withstand direct contact with the heated roll for extended periods of time. In addition, the felt surface must promote easy sheet release for good runnability and allow water to penetrate as the sheet is being dewatered. Finally, the body of the fabric must provide sufficient void volume to *readily* accept and hold the water removed from the sheet.

Fabric structure, together with roll temperature and nip residence time, are then the most important parameters controlling sheet runnability, sheet dryness, sheet quality, and paper properties. Also important are press load, ingoing moisture content and furnish composition. The performance of the press fabric is controlled by the fiber type, fiber diameter, and fabric structure. Extensive research in this field has resulted in press fabric structures that exhibit the appropriate temperature resistance, sheet release for runnability, dewatering capacity, and rewet resistance required for commercializing impulse drying.

Felts used in the papermaking industry, namely those applied in the press section, influence dewatering and paper properties as well. The water pressed out from the fiber bed must be collected and transported through the felt. This porous material usually consists of a couple of layers, one with high porosity which has a high capacity to hold water and one in contact with the fiber web, where finer material is used to minimize the marking on the paper.

Due to flow resistance, an hydraulic pressure builds up within the felt, which reduces the effective pressure compressing the paper web. The flow resistance in

the felts should therefore be low. During the last few decades the reduction of flow resistance have been one of the major objectives of felt development. If the felt is very rough in comparison to the paper web, there will be an uneven distribution of the applied pressure between the felt and the wet web. It has been suggested [42] that this non-uniformity leads to areas with much higher permeabilities. This same conclusion has already been drawn from the experimental work carried out by Smart [37] and Fekete [10]. These authors have systematically studied the effect of different components of the felt on water removal. They showed that the thickness of batt fibers on the paper side has the greatest effect on water removal. The type, coarseness and compression of the base are only of marginal importance in this respect. They also pointed out that the differences in the micro-scale pressure non-uniformity created by the felts are the main source of the differences in water removal. Another possible reason for the good performance of felts made of thin fibers in the batt is that they have higher flow resistance and higher capillary suction in the vicinity of the paper [40].

Prior to the description of the present work, a brief review on fluid flow in porous media is presented. Fluid flow has been a matter of extensive research since Reynolds and Poiseuille first studies. Until the turn of the 20th century the study of fluids was undertaken essentially by two groups: hydraulicians and mathematicians. The former group worked along empirical lines based on a vast experimentation, whereas mathematicians concentrated on analytical lines sometimes lacking the necessary complexity to describe the real nature of the process. It soon became clear that the study of fluids must be a blend of theory and experimentation.

#### **4.1.1 Foundations of flow analysis in compressible porous media**

The aspects of flow in porous media have been discussed in several articles over the years. Comprehensive reviews of this subject have been published by Ergun [9], Happel [13], Scheidegger [33], and Jönsson and Jönsson [18], [19], among others. Most articles describe fluid flow in rigid materials, or materials that are regarded as being rigid. The significant properties of these materials are porosity and permeability. The former is a measure of the pore space, and hence of the fluid capacity of the medium; the latter is a measure of the ease with which fluid

flows through the medium under the influence of an applied pressure.

Fluid flow in a compressible porous medium is influenced by another property: the compressibility of the medium. The compressibility is a measure of the mechanical strength of the material. The reduction in porosity of a compressible material subjected to drag forces of a fluid or to a mechanical pressure is due to deformation of the solid matter, bending and slipping of individual particles and disintegration of solid particles. The theory of laminar flow through homogeneous porous media is based on a classical experiment originally performed by Darcy. In Darcy's empirical law it is stated that the volumetric flow rate,  $Q$ , through a bed of cross-sectional area  $A$  is correlated to the hydraulic pressure drop  $\Delta P$  across the bed:

$$Q = \frac{K.A.\Delta P}{\mu.L} \quad (4.1)$$

where  $K$  is the specific permeability of the porous medium,  $\mu$  is the fluid dynamic viscosity and  $L$  the thickness of the medium. The permeability is characterized by the specific properties of the porous medium; properties such as *porosity*, the *shape and orientation* of the solid particles, the *surface area* exposed to the fluid, and the *pore-size distribution*, *i.e.*, it depends on the structure of the material.

Fluid flow through porous media has been described by the proportionality between the hydraulic pressure drop across the medium and the corresponding fluid superficial velocity, as presented by Darcy. This is only accepted, however, for low fluid velocities, as several studies found a pressure drop dependence on the square of fluid velocity. In fact, Reynolds was the first to suggest that the pressure drop due to friction, observed across the porous medium, was the sum of two terms, one proportional to the fluid velocity and the other being the product of the specific volume to the square of fluid velocity:

$$\frac{\Delta P}{L} = a^*.v + b^*.\rho_{fluid}.v^2 \quad (4.2)$$

where  $\rho_{fluid}$  is the fluid density,  $v$  the superficial or apparent fluid velocity and  $a^*$  and  $b^*$  are coefficients of proportionality.

Almost at the same time, Poiseuille investigated the laminar, incompressible flow through long cylindric pipes and tubes. He came to the following expression to relate the volume rate of flow to the frictional pressure drop:

$$Q = \frac{r^2 \cdot A \cdot \Delta P}{8\mu \cdot L_{pipe}} \quad (4.3)$$

where  $r$  is the radius of the pipe,  $A$  the cross-sectional area of flow,  $\Delta P$  the pressure drop across the pipe of length  $L_{pipe}$ . Eqn. 4.3 is also valid for fluid flow in a network of cylindrical parallel capillaries. For a nonuniform porous media it is possible to use the concept of mean hydraulic radius defined as:

$$r_h = \frac{\text{Pore cross-sectional area}}{\text{Wetted perimeter}} \quad (4.4)$$

Bearing in mind the similarities between Eqns. 4.1 and 4.3, it is not surprising that Kozeny related the permeability coefficient to the size and shape of the pores and the structure of the porous network. Kozeny and Carman then derived the commonly accepted relation shown in Eqn. 4.5 between the permeability coefficient and the void volume of the porous material, *i.e.* its porosity  $\phi$ .

$$K = \frac{\phi^3}{k_k \cdot S_v'^2} = \frac{\phi^3}{k_k \cdot S_o'^2 \cdot (1 - \phi)^2} \quad (4.5)$$

The new parameters in Eqn. 4.5,  $k_k$ ,  $S_v'$  and  $S_o'$  correspond to the well-known Kozeny factor, and the volume specific surface of both porous medium and its constituent particles, respectively.  $S_o'$  is simply defined as the external surface of the particles of the medium divided by its solid volume. As for the Kozeny factor, as denoted in the present work, may be defined as shown in Eqn. 4.6

$$k_k = k_0 \cdot \xi'^2 \quad (4.6)$$

where  $k_0$  is a shape factor, function only of the cross-sectional shape of the pipe or tube, and  $\xi'$  is the tortuosity factor of the porous medium. In addition, several studies performed by Sullivan [38] (see [2]) have shown that  $k_k$  follows a power law of porosity for high values of porosity. Moreover, Grace [12] emphasized that the relation derived by Kozeny-Carman as

$$\frac{Q}{A} = \frac{\phi^3}{k_k \cdot S_v'^2} \cdot \frac{\Delta P}{\mu \cdot L} \quad (4.7)$$

could not be employed, in its usual form, to the study of fluid flow in compressible porous media. In fact, several studies performed by Brown [3] shown that the shape factor,  $k_0$  remained constant throughout his experiments and was only dependent on the cross-sectional shape of the pores, whereas the Kozeny factor



increased significantly with porosity. Davies [6] suggested a power law correlation to express the Kozeny factor as a function of porosity, as shown in Eqn. 4.8.

$$k_k = w_1 \cdot \frac{\phi^3}{(1 - \phi)^{\frac{1}{2}}} \cdot [1 + w_2 \cdot (1 - \phi)^3] \quad (4.8)$$

$w_1, w_2$  : constants, 4.0 and 56, respectively.

Ingmanson *et al* [16] also found a similar relationship for cylindrical fibers, either of nylon or glass, randomly oriented in the plan perpendicular to the flow. Assuming a point-like contact among fibers, they came to values of  $w_1$  and  $w_2$  of 3.5 and 57, respectively. For porosities in the range of 0.70 to 0.80, the Kozeny factor takes the mean value 5.5 [16], which seems to be in accordance with the results obtained by Fowler and Hertel [11] (see [31]) from their air permeability experiments. However, Bliesner [2] advanced the argument that the Kozeny factor should take into account the degree of fiber deformation, when he verified that correlations of  $k_k$  obtained for cylindrical fibers could not be applied to collapsed wood fibers. In fact, collapsed fibers see their almost cylindrical cross-section being deformed into a more flat, elliptical appearance. As a consequence, the fiber surface area corrected by the corresponding bonded area produce a higher Kozeny factor, and this is even more pronounced for low porosities [2]. Labrecque [21] also investigated the influence of the fiber cross section shape on the resistance to flow in webs made from wood fibers. From his findings he concluded that for highly deformable fibers, for which the shape factor is important, the Kozeny factor determined for cylindrical particles can not be used. Instead, a corrected version of  $k_k$  may be obtained using the following relation:

$$\begin{aligned} k_k = & -12.29 + 42.9 \cdot \phi - 24.5 \cdot \phi^2 + (1.90 - 10.9 \cdot \phi + 9.6 \cdot \phi^2) \cdot f_s \quad (4.9) \\ & - (0.18 - 1.61 \cdot \phi + 1.45 \cdot \phi^2) \cdot f_s^2 \end{aligned}$$

where  $f_s$  is defined as the ratio of the maximum to the minimum dimension of the fiber cross section. Labrecque [21] has, however, emphasized that Eqn. 4.9 is valid for cellulosic fibrous mats with porosity between 60 and 80 % and shape factor up to 4.69.

One of the main difficulties of using the Kozeny-Carman equation is the knowledge of such dimensional properties as the porosity of the medium is changing

throughout the compression event. The model of Kozeny-Carman is based on the generalized Poiseuille's law for fluid flow through parallel capillaries of whatever cross-sectional area or hydraulic diameter,  $D_h$ . However, the mean velocity of the fluid is given here as a function of tortuosity of the medium. Figure 4.1 represents the differences between the two concepts introduced by the previous authors.

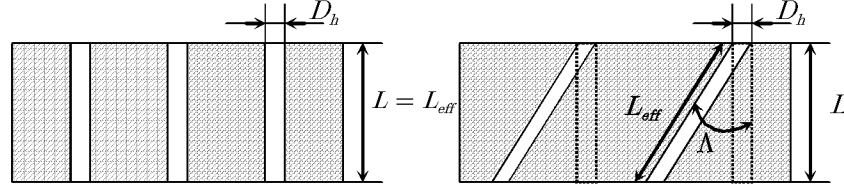


Figure 4.1: Fluid flow through a capillary, according to Poiseuille (left) and to Kozeny-Carman (right).

Thus, taking into account the effective path of fluid flow, with dimension  $L_{eff}$ , the superficial fluid velocity across the porous medium will be given as:

$$v = \frac{Q}{A} = f \left( \frac{\Delta P}{L_{eff}} \right) = f \left( \frac{\Delta P}{L / \cos \Lambda} \right) = f \left( \frac{\Delta P \cdot \cos \Lambda}{L} \right) \quad (4.10)$$

By definition, the tortuosity factor is given as a function of the angle formed by the two mean directions of fluid flow,  $\Lambda$ , as illustrated in Figure 4.1:

$$\xi' = \frac{L_{eff}}{L} = \frac{1}{\cos \Lambda} \quad (4.11)$$

Therefore, substituting Eqn. 4.11 into Eqn 4.10, the fluid velocity and the corresponding coefficient of permeability will be as follows:

$$\frac{Q}{A} = \frac{\phi^3}{k_0 \cdot S_v'^2} \frac{\Delta P}{\mu \cdot L} \cdot \cos^2 \Lambda \quad (4.12)$$

where,

$$K = \frac{\phi^3}{k_0 \cdot \xi'^2 \cdot S_v'^2} \quad (4.13)$$

$$\xi'^2 = \frac{1}{\cos^2 \Lambda} \quad (4.14)$$

Silvy [34], has demonstrated that the structure of a porous medium with a texture appearing to be disordered and random at microscopic level can be modelled by a conformal representation of its pore or particulate phase interface (see

Figure 4.2) based on an equivalent ellipsoid pore. The surface of the “equivalent pore” is taken to be equal to the surface areas of the pore and particle interfaces in the structure.

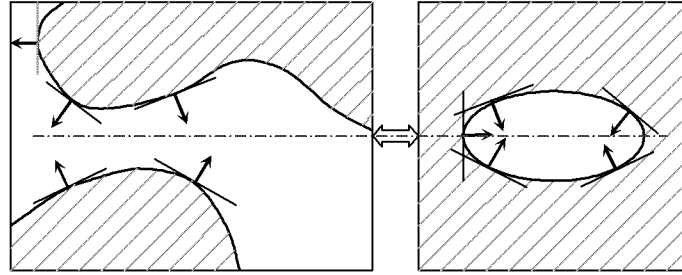


Figure 4.2: Schematics of the relation between a porous medium and its equivalent pore (adapted from [34]).

In order to investigate the flow of the fluid in the pores under the effect of a pressure gradient ( $\frac{\Delta P}{L}$ ) applied in a given direction of the structure (see Figure 4.3), it is necessary to find the directions of penetration in the porous medium such that the head loss in the course of flow is minimum. This condition is achieved for a maximum value of the hydraulic diameter,  $D_{h_{Silvy}}$ , of the sections penetrated by the fluid along its tortuous path.

As the value of the hydraulic diameter is proportional to the ratio of the conducting area to the wetted perimeter (Eqn. 4.4), the previous condition is reached when the shape of the sections is circular. It is possible then to optimize the fluid penetration into the structure, finding the directions of the planes for which the intersections with the interface of the equivalent pore are circular at any given instant. Flow of the water pressed out of the paper sheet or felt will be aided to a greater or lesser extent as it passes through the nip in the press depending on the orientation of the hydraulic pressure gradient, which causes flow in relation to these directions of penetration within the structure. The effective path of the water in relation to its apparent path can be calculated theoretically for a given direction of the hydraulic pressure gradient in the structure.

Silvy [35], defined the mean direction of flow (with dimension  $(L_{eff})_{Silvy}$ ) and the direction of fluid penetration (with dimension  $L_p$ ) as illustrated in Figure 4.3.

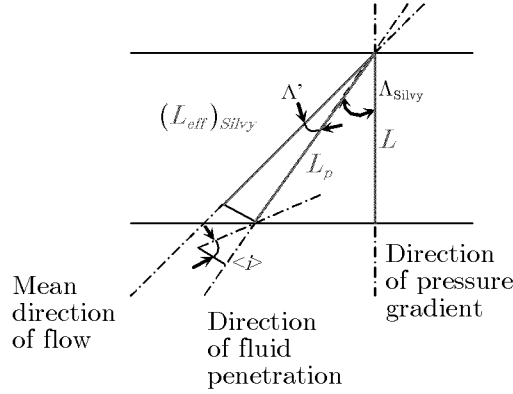


Figure 4.3: Schematic definition of the mean directions of flow, fluid penetration and pressure gradient, and the corresponding angles according to the model of Silvy (adapted from [35]).

The mean superficial velocity of the fluid in the porous medium is then expressed as a function of the angle of the direction of penetration,  $\Lambda_{Silvy}$ , and the angle between the mean direction of flow and the direction of fluid penetration,  $\Lambda'$ :

$$\begin{aligned} \langle v \rangle &= \left\langle \frac{Q}{A} \right\rangle = f \left( \frac{\Delta P}{(L_{eff})_{Silvy}} \right) = f \left( \frac{\Delta P}{L \left( \frac{L_p}{L} \right) \left( \frac{(L_{eff})_{Silvy}}{L_p} \right)} \right) = \quad (4.15) \\ &= f \left( \frac{\Delta P}{L} \cdot \cos \Lambda_{Silvy} \cdot \cos \Lambda' \right) \end{aligned}$$

This relation takes into account the orthoaxial shear of the fluid along its penetration in the porous structure, given by the term  $\cos \Lambda'$ , whereas  $\cos \Lambda_{Silvy}$  characterizes the projection of the mean fluid velocity, at the exit of the porous medium, onto the direction of the applied hydraulic pressure gradient. The movement of the fluid along the direction of penetration generates a rotational movement around the axis of penetration itself. This suggests a mean inclination angle for the fluid trajectory in relation to its direction of penetration, defined as  $\langle i \rangle$ . The mean fluid velocity is then evaluated according to the following relation:

$$\langle v \rangle = f \left( \frac{\Delta P}{L} \cdot \cos \Lambda_{Silvy} \cdot \cos \Lambda' \cdot \sin \langle i \rangle \right) \quad (4.16)$$

which means that the projection of the mean superficial velocity of the fluid onto the direction of the hydraulic pressure gradient is given by the value of  $\cos \Lambda_{\text{Silvy}} \cdot \sin \langle i \rangle$ .

The permeability factor for a pressure gradient in a given direction may then be expressed in terms of the principal permeabilities  $K_x$ ,  $K_y$ ,  $K_z$  defined according to Silvy as:

$$K_{x,y,z} = \frac{\phi \cdot (D_{\text{hSilvy}}/4)^2}{k_0 \cdot \xi_{x,y,z}'^2} \quad (4.17)$$

where the tortuosity factor in the three main directions is given by:

$$\xi_z'^2 = \frac{1}{\sin^2 \Lambda_{\text{Silvy}} \cdot \cos \Lambda' \cdot \sin \langle i \rangle} \quad (4.18)$$

$$\xi_y'^2 = \frac{1}{\cos^2 \Lambda_{\text{Silvy}} \cdot \cos \Lambda' \cdot \sin \langle i \rangle} \quad (4.19)$$

$$\xi_x'^2 = \frac{\pi}{2} \cdot \frac{1}{\cos \langle i \rangle} \quad (4.20)$$

As previously mentioned, for fluid transfer in a porous medium fully or partially saturated, the hydraulic diameter is the relevant parameter to characterize the pore size. This remark is to recall that in the case of fluid flow the relevant characteristic pore size is obtained from the ratio of a volume to an area, a quantity that would be difficult to identify by directly observing the unidimensional features of the structure. In fact, a tridimensional perception of the structure is required in order to evaluate this parameter from point to point in the medium. Nevertheless, the mean value of the hydraulic diameter is strictly equal to the mean secant of the conducting pores section by an isotropic sampling of the porous medium, giving:

$$\langle D_{\text{hSilvy}} \rangle = 4 \frac{\phi_{eff}}{S_v'} \quad (4.21)$$

where  $\phi_{eff}$  is the effective porosity, equal to the volume fraction of pores.

Therefore, the mean superficial velocity of the fluid evaluated in the direction of the applied hydraulic pressure gradient is given by:

$$\langle v \rangle = \frac{\phi_{eff}^3}{k_0 \cdot S_v'^2} \frac{\Delta P}{\mu \cdot L} \cdot \cos^2 \Lambda_{\text{Silvy}} \cdot \cos \Lambda' \cdot \sin \langle i \rangle \quad (4.22)$$

where,

$$K = \frac{\phi_{eff}^3}{k_0 \cdot S_v'^2 \cdot \xi_{Silvy}'^2} \quad (4.23)$$

$$\xi_{Silvy}'^2 = \frac{1}{\cos^2 \Lambda_{Silvy} \cdot \cos \Lambda' \cdot \sin \langle i \rangle} \quad (4.24)$$

The term  $\cos^2 \Lambda_{Silvy}$  is a function of the porous structure and of the direction of pressure application, whereas the terms  $\cos \Lambda'$  and  $\sin \langle i \rangle$  depend of the structure of the porous medium and, according to Silvy, these two last terms have a significant influence on the resistance to the fluid flow.

In the sequence of this theoretical work, Silvy and Butel [36] performed an experimental investigation in order to characterize the evolution of the porous structure with sheet compaction. Their objective was to validate the theoretical model based on the “equivalent pore” theory. The model allowed the authors to calculate the anisotropic permeability, *i.e.*, the permeability factor both in the plan and in the thickness direction of the fibrous mat. The structural parameters needed for the model were obtained by image analysis of thin slices of paper impregnated to saturation with a polymerized thermal hardening resin. The values of the permeability factor were then calculated from the image analysis measurements, *i.e.* lengths and areas of the pores. The authors expressed the permeability coefficient as a power law function of the effective (also called extra-fiber) porosity,  $\phi_{eff}$ , for the different pulps studied multiplied by a constant value, according to the following empirical relation:

$$K = K_f \cdot (\phi_{eff})^{\kappa^*} \quad (4.25)$$

with  $\kappa^*$  characterizing the degree of compaction, and  $K_f$  representing the fiber wall permeability. Therefore, they emphasize that water is expelled both through the extra-fiber pores of the structure and through the fiber walls. The previous relation allowed the authors to obtain the permeability factor both in the transversal and in the longitudinal directions and, for the range of sheet densities used, the ratio  $\frac{K_z}{K_x}$  increased from 1.0 to 1.3 as the sheet density increases with compression. The authors then suggested that transversal permeability is in fact favoured in respect to the longitudinal permeability when the sheet is compacted at its maximum in the press nip.

Apart from this study, Silvy and Butel [36] also measured the compressibility of wet felts and their permeability factors in the three main directions, *i.e.* for transversal flow along the felt thickness ( $z$ -direction), longitudinal flow in the machine direction ( $x$ -direction) and lateral flow in the cross direction ( $y$ -direction). Five felts with different design of their fabrics and batt fiber diameter, were investigated. They found the compaction of felts under study to obey to a decreasing exponential law:

$$L = L_0 \cdot \exp(-N^* \cdot P_t) \quad (4.26)$$

where  $L$  is the felt thickness,  $L_0$  its initial value, and  $N^*$  a factor characterizing the compressibility of the felt. In addition, they suggested a decreasing exponential law for the permeability coefficient in terms of pressure of compaction (or reversely, an increasing exponential law in terms of felt porosity) according to the following relation:

$$K_{x,y,z} = Cst' \cdot \exp(-Cst'' \cdot P_t) \quad (4.27)$$

where  $K_{x,y,z}$  are the permeability coefficients in the  $x$ ,  $y$  and  $z$  directions and  $Cst'$  and  $Cst''$  are constants.

Comprehensive reviews of various permeability relationships have been given by, for example, Scheidegger [33], Jackson and James [17] and Dullien [7]. According to several authors, the analysis of fluid flow through compressible porous media must take into account the compressibility of the medium and, consequently, the structural changes operated in the medium throughout the compression event.

When a compressible medium is subjected to hydraulic and/or mechanical pressure the total volume of the medium is decreased while at the same time fluid flows through the medium. The total pressure may be divided into two separate components: the mechanical stress exerted on the solid material, and the hydraulic pressure which gives rise to the fluid flow. Both these pressure components vary with position in the medium.

The volume reduction of a porous medium subjected to a pressure is due to the previously mentioned factors, among which bending, slipping and disintegration of the solid material are essentially irreversible processes (see **Chapter 3**). Hence, media in which these deformation mechanisms are of importance are subjected to nonrecoverable volume reductions. The amount of nonrecoverable

deformation is especially pronounced during the first compression, and then decreases as deformation is repeated [45].

Some empirical relations between volume reduction and applied pressure are available in the literature. The basic compressibility concept shows that it is a measure of the volume change of a system subjected to a compressive stress. The compressibility coefficient of the felt,  $N$ , may also be defined as the rate of variation of its thickness as a function of pressure variation, according to several studies performed with paper samples [32]:

$$N = -\frac{1}{L} \cdot \left( \frac{\partial L}{\partial P_t} \right)_T \quad (4.28)$$

where the subscript “ $T$ ” indicates that the compression takes place at constant temperature.

For a wide variety of materials it has been found that the correlation of the physical compressibility to applied pressure, during the first compression of the material, follows the relation [12]:

$$N = \varrho_1 \cdot P_t^{-\varrho_2} \quad (4.29)$$

where  $\varrho_1$  and  $\varrho_2$  are material-specific parameters. The value of  $\varrho_1$  varies widely for different materials, whereas  $\varrho_2 = \pm 1$  for most materials. When  $\varrho_2 = 1$  is assumed, the following relation is obtained:

$$[C_{fiber}] = \varrho_3 \cdot P_t^{\varrho_1} \quad (4.30)$$

The previous equation was first suggested by Qviller (1938) (see [31]) and later by Campbell [4], and has been used extensively to correlate fiber concentration  $[C_{fiber}]$  and pressure for fibrous materials.  $\varrho_3$  is a constant of the model and  $\varrho_1$  is a parameter that characterizes the mechanical strength of the material;  $\varrho_1$  is equal to zero for a rigid material and in this case the influence of pressure on fluid flow follows Darcy’s relationship. As the value of  $\varrho_1$  increases, *i.e.*, as the ability of the medium to sustain the compressive stress decreases, the fluid flow diminishes. This happens because the permeability decreases; the lower permeability of a more compressible medium is due to the steeper porosity gradient in such a medium. The lower fluid flow through a more compressible medium is mainly due to the lower porosity in the bottom layer of the medium, which in turn is due to blocking of the flow paths by fine particles or fibers.



The strain imposed to the felt, together with the paper web in the press nip, has been the subject of several studies. In order to model felt compression it is relevant to know the rheological behavior of the material, *i.e.* the relation between the applied stress and the resulting strain. In 1958, Linderot (see [31]) performed the first studies concerning the static compression of wool felts and analyzed their mechanical response, emphasizing that felt properties changed significantly throughout the paper machine operation. Some years later, Victory (1964) (see [31]) studied the compressibility of felts under dynamic conditions but at low pressures.

As mentioned above, Silvy found a decreasing exponential law to relate the thickness of the felt to the applied pressure. His experiments were performed in a quasi-static regime so that the hydraulic pressure inside the felt sample was negligible, *i.e.* the applied pressure was in fact standed by the structure of the material.

A more complex model was developed by Osterberg [29] who studied the rheology of non-saturated press felts. Like Silvy, Osterberg assumed that no hydraulic pressure would result from the fluid flow across the medium. Moreover, he stated that the classic theories of elasticity were no longer applicable if one takes into account the large deformation experienced by the felt in a press nip. Osterberg then suggested an empirical compressibility model defined as follows:

$$P_t = \varrho_4 \cdot \left( \frac{L_0 - L}{L - L_i} \right)^{\varrho_5} \quad (4.31)$$

where  $\varrho_4$ ,  $\varrho_5$  and  $L_i$  are characteristic of the felt and  $L_0$  is the initial thickness measured at atmospheric pressure.  $L_i$  is defined as the felt thickness at zero porosity (also named incompressible thickness), *i.e.* the ratio of the grammage to the specific density of the material that constitutes the felt. This model must, however, verify the following criteria: (i)  $P_t = 0$  at  $L = L_0$ ; (ii)  $\frac{dP_t}{dL} = 0$  at  $L = L_0$ ; and (iii)  $P_t \rightarrow \infty$  at  $L = L_i$ . The author suggested the introduction of other variables such as temperature and moisture content, among others, using the following relation:

$$\frac{L_0 - L}{L - L_i} = \wp \cdot Var_1^{\wp_1} \cdot Var_2^{\wp_2} \cdot \dots \cdot Var_n^{\wp_n} \quad (4.32)$$

$Var_i$  : variable,  $\wp, \wp_i$  : coefficients.

Swain [39] was also interested on the compressibility of press felts, and sug-

gested an empirical model to describe the relation between the pressure and the compression ratio,  $CR$ , defined as

$$CR = \frac{\varepsilon}{\varepsilon_{\max} - \varepsilon} = \frac{L_0 - L}{L - L_i} \quad (4.33)$$

where  $\varepsilon_{\max}$  is the maximum strain of the material, *i.e.* the strain at zero porosity. The author then used a second order polynomial regression, as defined by Eqn. 4.34.

$$P_t = b_0 + b_1.CR + b_2.CR^2 \quad (4.34)$$

$b_0, b_1, b_2$  : coefficients

Luciano (1983) (see [24]), who intended to determine the saturation pressure of the felts by varying the nature of the fibers that constitute the felt, found the following relation between the porosity of the material and the applied pressure:

$$\phi = \frac{\phi^*}{\varrho_6.P_t^{\varrho_7} - 1} \quad (4.35)$$

where  $\phi^*$  is the porosity at 0.2 kPa, and  $\varrho_6$  and  $\varrho_7$  are parameters of the model. Four years after Luciano's findings, Ballard came to the model described hereafter when trying to characterize the felt compressibility:

$$\sigma = \varrho_8 \cdot \left[ L - L_{\min} + \left( \frac{\sigma_{\max}}{\varrho_8} \right)^{-\frac{1}{\varrho_9}} \right]^{-\varrho_9} \quad (4.36)$$

where  $\varrho_8$  and  $\varrho_9$  are parameters of the model and,  $L_{\min}$  is the felt thickness corresponding to the maximum applied stress,  $\sigma_{\max}$ .

The models mentioned so far were suggested according to the analysis of the stress-strain behavior of the materials under quasi-static pressing conditions. In such experimental conditions, it was assumed a negligible hydraulic pressure. This is not valid, however, for the dynamic compression of the felt inside the press nip where the hydraulic pressure may, in certain cases, overcome the applied pressure. El-Hosseiny [8] studied the behavior of felts under dynamic compression and measured the hydraulic pressure developed inside the fibrous mat. He then subtracted the hydraulic pressure to the total applied pressure to obtain the pressure withstood by the structure of the material, *i.e.* the structural pressure. Finally,

he came to the following relation between the normalized structural pressure,  $P_t^*$ , with the corresponding normalized strain,  $\varepsilon^*$ :

$$P_t^* = \left[ \frac{b_3 \cdot (\varepsilon^* - \varepsilon^{pl})}{(1 - \varepsilon^*) + b_3 \cdot (\varepsilon^* - \varepsilon^{pl})} \right]^{b_4} \quad (4.37)$$

where  $\varepsilon^{pl}$  is the permanent or irreversible strain, and  $b_3$  and  $b_4$  are parameters of the model.

Like El-Hosseiny, Kataja *et al* [20] inferred from their experimental research that Terzaghi's principle was valid, *i.e.* the total applied pressure can be split up into two parts, the hydraulic and the structural pressure. The aim of the study was to investigate the pressure equilibrium inside a saturated fibrous mat, and the authors came to the following relation between the structural pressure and the corresponding deformation of the material:

$$P_{st} = P_{st}^o \left[ \frac{(b_5 - 1) \cdot \left( \frac{\varepsilon}{\varepsilon_{exp}} \right)}{b_5 - \frac{\varepsilon}{\varepsilon_{exp}}} \right]^{b_6} \quad (4.38)$$

where  $b_5$ ,  $b_6$ ,  $P_{st}^o$ ,  $\varepsilon_{exp}$  are parameters determined from the experiments.

Particularly interesting is the work performed some years ago by Lopez [24]. The aim of the study was to investigate the response of press felts to different compression/decompression tests and to evaluate the rheological character of the uncompressed felts under study. To accomplish that the author began by performing creep tests. The responses obtained by Lopez allowed to advance the idea of a viscoelastic behavior, and a Kelvin-Voigt model in series with a Maxwell model was suggested to describe such behavior. For the most general case of linear viscoelastic material the total strain, or deformation, is the sum of three essentially separate parts: the immediate elastic deformation, the delayed elastic deformation and the Newtonian flow, which is identical with the deformation of a viscous liquid obeying Newton's law of viscosity. If the material shows linear behavior the magnitude of each strain is exactly proportional to the magnitude of the applied stress, so that a creep compliance  $J(t)$  can be defined, for a step input, as:

$$J(t) = \frac{\varepsilon(t)}{\sigma} = J_1 + J_2 + J_3 = \quad (4.39)$$

$$= \frac{1}{E_A} + \frac{t}{\mu_A} + \frac{1}{E_B} \cdot \left[ 1 - \exp\left(-\frac{E_B}{\mu_B} \cdot t\right) \right] \quad (4.40)$$

where  $E_A$ ,  $\mu_A$ ,  $E_B$ , and  $\mu_B$  are the elastic and viscous parameters of the model, as illustrated in Figure 4.4.

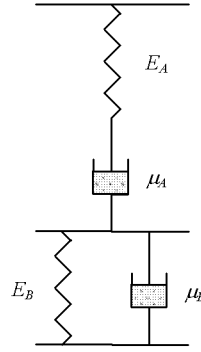


Figure 4.4: Schematic representation of a Voigt-Kelvin unit and a Maxwell unit arranged in series as suggested by Lopez [24] (this serves only as an example of a viscoelastic model).

The elastic and viscous parameters obtained by Lopez are, however, restricted to the tested felt samples, and can not be extrapolated to felts with the most diverse characteristics. Furthermore, Lopez performed tests of multistep stress relaxation in order to validate the models proposed by Osterberg, Swain, Luciano or Ballard, without success however. When an instantaneous strain is applied to an ideal elastic solid a finite and constant stress will be recorded. For a linear viscoelastic solid subjected to an instantaneous strain the initial stress will be proportional to the applied strain and will decrease with time, at a rate characterized by the relaxation time. This behavior is called stress relaxation. Lopez, performed consecutive compression tests without decompress the samples in each step, and emphasized that the discrepancies between the experimental data and the models suggested by the other authors were in part due to differences in the method employed. By observing the results obtained, Lopez suggested the model presented hereafter, valid for both the compression and the decompression phases:

$$L = b_7 \cdot P_t^{-b_8} \quad (4.41)$$

where  $b_7$  and  $b_8$  are parameters characterizing the felt. Finally, Lopez reinforced the idea of a viscoelastic behavior of felts according to the hysteresis observed in the compression/decompression curves (see Figure 4.5). Although of great interest, the previous results could not illustrate the felt behavior to compression in a common paper machine due to the extremely different time scale of the events. In order to investigate the compression of new and used felts in real paper machine operating conditions, Lopez performed a set of tests in a rheometer. By doing so, the author could reproduce the same stress level and frequency of application of that stress, and the nip dwell time. An alternative experimental procedure to creep and relaxation is therefore to subject the felt sample to an alternating stress and simultaneously measure the strain. For linear viscoelastic behavior, when the equilibrium is reached, the stress and the strain will both vary sinusoidally, but the strain lags behind the stress. Therefore, the stress and the strain may be expressed as:

$$\sigma(t) = \sigma_1 \cdot \cos(\omega_1 \cdot t + \delta_1) \quad (4.42)$$

$$\varepsilon(t) = \varepsilon_1 \cdot \cos(\omega_1 \cdot t) \quad (4.43)$$

where  $\sigma_1$  and  $\varepsilon_1$  are the amplitude of the stress and the corresponding strain,  $\omega_1$  is the angular frequency and  $\delta_1$  the phase lag. Expanding Eqn. 4.42 the stress can be considered to consist of two components: (i) of magnitude  $\sigma_1 \cdot \cos(\delta_1)$  in phase with the strain, and (ii) of magnitude  $\sigma_1 \cdot \sin(\delta_1)$ ,  $90^\circ$  out of phase with the strain. The stress-strain relationship can therefore be defined by a quantity  $G'$  and  $G''$  as follows:

$$\sigma = \varepsilon_1 \cdot G' \cdot \sin(\omega_1 \cdot t) + \varepsilon_1 \cdot G'' \cdot \cos(\omega_1 \cdot t) \quad (4.44)$$

where,

$$G' = \frac{\sigma_1}{\varepsilon_1} \cdot \cos(\delta_1) \text{ and } G'' = \frac{\sigma_1}{\varepsilon_1} \cdot \sin(\delta_1) \quad (4.45)$$

$G'$ , which is in phase with the strain, is called the storage modulus because it defines the energy stored in the specimen due to the applied strain, and  $G''$ , which is  $90^\circ$  out of phase with the strain, defines the dissipation of energy and is called

the loss modulus. The complex modulus notation not only has a mathematical basis in viscoelasticity theory, but it also has a straightforward interpretation. Thus, the real part of the complex modulus  $G^* = G' + iG''$  is associated with elastic energy storage, whereas the imaginary part is associated with energy dissipation, or damping. The energy dissipated per cycle,  $\Delta Energy$ , is calculated as

$$\Delta Energy = \oint \sigma . d\varepsilon = \int_0^{\frac{2\pi}{\omega}} \sigma . \frac{d\varepsilon}{dt} dt \quad (4.46)$$

Substituting for  $\sigma$  and  $\varepsilon$ ,

$$\begin{aligned} \Delta Energy &= \omega . \varepsilon_1^2 \int_0^{\frac{2\pi}{\omega}} \left[ G' . \sin(\omega_1 . t) . \cos(\omega_1 . t) + \dots \right. \\ &\quad \left. \dots + G'' . \cos^2(\omega_1 . t) \right] dt = \end{aligned} \quad (4.47)$$

$$= \pi . G'' . \varepsilon_1^2 \quad (4.48)$$

If the integral is evaluated over a quarter-cycle rather than over the complete period, the first term of Eqn. 4.47 gives the maximum stored elastic energy, *Energy*:

$$Energy = \frac{1}{2} G' . \varepsilon_1^2 \quad (4.49)$$

Hence, by Eqn. 4.48 and 4.49,

$$\frac{G''}{G'} = \tan(\delta_1) = \frac{\Delta Energy}{2\pi . Energy} \quad (4.50)$$

The ratio  $\frac{\Delta Energy}{Energy}$  is called the specific loss

$$\frac{\Delta Energy}{Energy} = 2\pi . \tan(\delta_1) . \quad (4.51)$$

The property,  $G^*$  is a complex modulus which depends on the properties of the material, *i.e.*, the elastic and viscous properties characterized by the parameters of a viscoelastic model like that of Kelvin-Voigt. In that sense,  $|G^*|$  is given by:

$$|G^*| = \sqrt{G'^2 + G''^2} . \quad (4.52)$$

Lopez used an apparatus able to apply a sinusoidal stress to the felt samples and to register the dynamic response of the material. The experiments were

performed with five dry samples in series at room temperature, on which a pre-stress of 5 MPa and a sinusoidal force of 25 N at an angular frequency of 31.5 Hz were applied. The apparatus allows the measurement of the thickness of the felt, the phase lag, and a parameter  $B_m$  that characterizes the resistance of the felt to compression under dynamic conditions. It is worth noting that the higher the parameter  $B_m$ , the lower will be the capability of the felt to absorb the vibrations observed in a real paper machine. In this sense, Lopez studied both new and used felts in order to investigate the influence of the number of compression cycles on that parameter,  $B_m$ , which will be designated by rigidity modulus hereafter. From the experiments, Lopez observed that the variation of  $B_m$  was more significant for used felts, *i.e.* between 37 and 153 % variation in respect to new felts of the same type. The author therefore suggested a different behavior to compression of felts in a paper machine as the felt becomes aged. Typical values of  $B_m$  are in the order of  $10^{-5}$  N.m<sup>-1</sup> for the felts studied, and the phase lag observed was less than 5 ° which the author attributed to a somewhat less pronounced viscous behavior.

Finally, Lopez repeated the experiments in a static press, for different levels of compression by gradually increasing the applied stress on the felt samples. The author then came to a power law relationship between the applied stress and the corresponding strain imposed to the felt samples, as already mentioned above (see Eqn. 4.41).

Again, if one takes the compressibility of a material to be the variation of its thickness with pressure, as defined by Eqn. 4.28, and consider the model used by Chevallier [5] and Lopez [24] (Eqn. 4.41), the compressibility of the felt,  $N$ , is given as follows:

$$\frac{\partial L}{\partial P_t} = -\frac{b_8 \cdot L}{P_t} \quad (4.53)$$

$$\Rightarrow N = \frac{b_8}{P_t} \quad (4.54)$$

The magnitude of  $N$  thus allows to compare felts with different characteristics: the lower  $N$  is, less compressible is the felt, which seems to enable dewatering in the paper machine. On the other hand, a more compressible felt tend to absorb the vibrations of the paper machine more easily. It should be pointed out that  $b_8$

does not depend on the applied stress. Instead, it shows how the material deforms or behaves when subjected to a given stress. Being the slope of the curve

$$\log L = \log b_7 - b_8 \cdot \log P_t \quad (4.55)$$

it is not surprising that great deformations may be achieved even for low compressible materials.

Lopez also emphasized that Eqn. 4.41 is valid for new felts or at least felts that have been subjected to few compression/decompression cycles. The relationship is not valid, however, after one million cycles have been imposed to the press felts. In fact, as the felt becomes aged, the relation gradually changes from a power law to a linear relation, and the hysteresis seems to disappear almost completely (see Figure 4.5). Lopez suggested that the aging effect obtained for the felts tested was in fact very similar to that of a real paper machine.

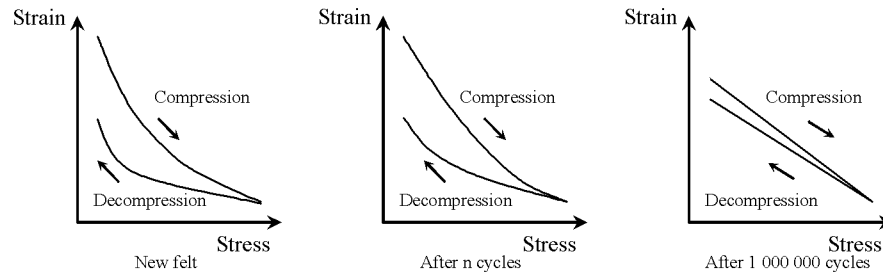


Figure 4.5: Strain-stress curves characteristic of the aging process applied to press felts.

The following section intends to summarize the experimental work performed with press felts from Albany Nordiskafilt AB. The research work was divided into two main parts: determination of felt permeability and compressibility under static and dynamic conditions, respectively.

## 4.2 Analysis of felt permeability and compressibility

Characterization of fibrous structures, and felts in particular, has been the subject of many scientific works. Felt structure plays an important role on mechanical



and physical properties, such as permeability and is of major importance in developments to improve press section efficiency. Often in pressing studies, the flow resistance due to the felt structure is either related to physical parameters following an empirical law or not taken into account at all. In fact, a recent theory presented by I'Anson and Ashworth [15] postulates that felt permeability in modern paper machines is not a major factor for the efficiency of water removal. The authors advance the idea of a differentiated-permeability surface layer existing on the sheet side facing the press felt and able to affect the level of dewatering. Their results suggest that the differences in dryness can be explained solely in terms of surface contact. Despite this, the structure of the felt remains a matter of vast research in terms of its water stock capacity, and problems of rewetting and uniformity of pressure application. In addition, the analysis of fluid flow inside the felt is still based on the knowledge of its permeability tensor, *i.e.* the permeability both in the thickness direction towards the holes of the pressing surface, and along the in-plane direction of the felt.

In the past three decades, a number of researchers have published reports which mathematically describe the dynamics of water flow in a press nip. The authors obtained expressions derived purely from mechanisms perceived to govern the phenomena of fluid flow through porous media, others have presented regression analysis of experimental data and obtained empirical expressions which relate material moisture content to some press variables. The subject of this section is related only to the second method of analysis, hence the phenomenological approach will be discussed in following sections.

### 4.2.1 Permeability tests

It is worth remember at this point, that permeability is divided into absolute permeability, defined as the permeability of a phase if it occupied the entire void volume of the porous material, and the relative permeability which depends only on the saturation level of that same phase. The permeability tensor of a phase “*i*”,  $K_i$  may then be expressed as a function of its components, according to Eqn. 4.56:

$$\underline{K}_i = k_{ri} \cdot \underline{K} \quad (4.56)$$

This study focus the experimental determination of transversal absolute per-

meability of felt samples specially designed for impulse drying. In this sense, a transversal permeameter device proprietary of EFPG was used (see [41] for more details). The apparatus imposes a flow perpendicular to the felt plane direction in order to measure the transverse permeability of the felt. The permeability measurement is carried out in two steps: firstly, the permeameter is calibrated by performing a blanc test from which water flow rate, head losses and strain of the porous plates are collected; then, a water-saturated felt sample is placed in the test cell and the above mentioned parameters are registered. The felt samples under study were provided by Albany Nordiskafilt within the framework of the Joule III Non-Nuclear Energy Programme sponsored by the European Commission. This type of felt is used in the third press of the paper machine and must meet two important requirements: (i) to provide an even pressure distribution on the paper surface and; (ii) to resist to high temperatures and high loading and strain rates. Albany International developed a proprietary fiber suitable for these severe conditions. The material is based on a commercial PA6.6 staple fiber, which is cross-linked in a proprietary and patented process. This process was further optimized during the Joule III project to obtain a well-defined and well-controlled cross-linking level of the fibers. It is important to note that there is always a balance between low cross-linking level giving flattening and sintering, and high cross-linking level giving high temperature resistance and brittleness. In addition, flattening and melting of the fibers of the felt surface increase the risk of paper sticking to the felt causing instability of the paper sheet after the press nip. Experiments carried out by Albany showed that severe felt wear was obtained with the treated fibers in cases when the felt had been in contact with the roll at very high temperature (over 300 °C), without a paper sheet acting as a heat protection. However, experiments performed during the present work show no evidence of such high temperatures in the paper/felt interface, which means that the effect of temperature on the felt surface is not of utmost significance, at least to the present operating conditions. In fact, the temperature in that interface was always lower than 200 °C, which seems to be acceptable. Furthermore, the base weave of the felt samples provided by Albany is more open than the fiber web in contact with the paper, so that together with the pores of the sintered material underneath the felt, the base weave should have enough void volume in compressed state in order to handle the water from the sheet. Three samples of felt No. 249031 from Albany were used in this work. Table 4.1 shows

some properties of samples named as D, 11 and 12.

The samples were preconditioned by the manufacturer and at the EFPG they were soaked in water for one hour previously to being submitted to the permeability tests. The compressive stress exerted onto the felt samples varied from about 0.3 to 5 MPa.

In the apparatus developed by Thibault at EFPG, a linear displacement transducer with 10 mm measurement range and 10  $\mu\text{m}$  accuracy allows the felt thickness measurement. The water flow rate is measured by weighting and timing a volume of water coming from the overflow of the vase which is connected to a guard area, *i.e.* the central region of the test cell available for flow. The transversal permeability factor is then deduced from these results using Darcy's relation.

Table 4.1: Felt properties.

| Felt No.  | Fiber material | Grammage             | Initial thickness |
|-----------|----------------|----------------------|-------------------|
|           |                | [g.m <sup>-2</sup> ] | [mm]              |
| 2490311-D | nylon          | 1383                 | 4.035             |
| 249031-11 | nylon          | 1366                 | 3.665             |
| 249031-12 | nylon          | 1405                 | 3.660             |

## Results and discussion

For each experiment performed at a given applied pressure, the results obtained both for the felt sample and the blanc trial were fitted by two linear relations, which may be represented by the two following equations:

$$\Delta P_{Total,Felt} = R_{Felt}.Q + \mathfrak{S} \quad (4.57)$$

$$\Delta P_{Total,Blanc} = R_{Blanc}.Q + \mathfrak{S}' \quad (4.58)$$

where  $\mathfrak{S}$  and  $\mathfrak{S}'$  are characteristic of the pressure measuring equipment,  $R_{Felt}$  and  $R_{Blanc}$  are the slope of each linear regression (see Figure 4.6 as an example; the results obtained for each felt are summarized on Tables D.1, D.2 and D.3 in **Appendix D**).

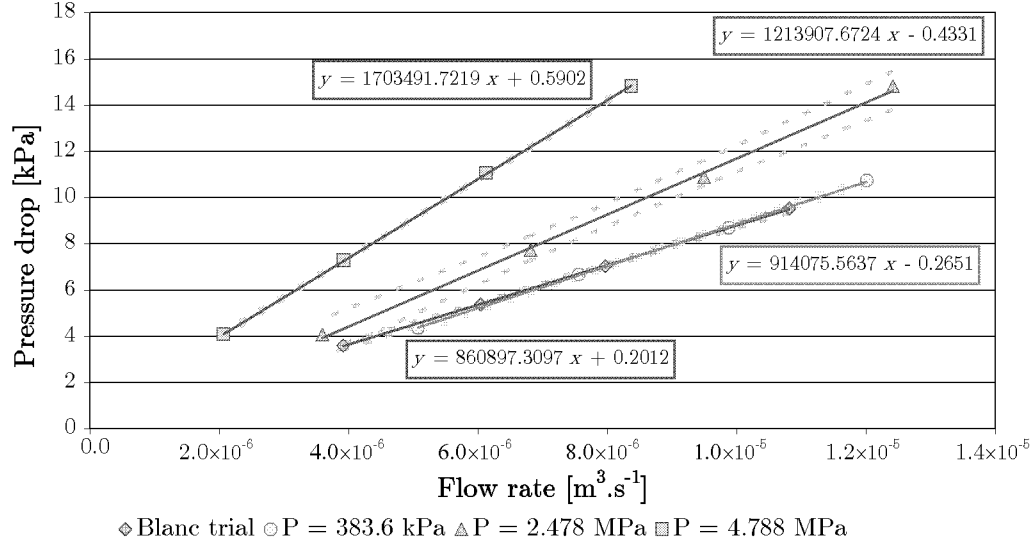


Figure 4.6: Total pressure drop versus flow rate for felt sample No. 249031-D at different pressure levels. Solid lines correspond to regression lines obtained by the method of least squares; dashed lines represent the upper and lower limits of the 95 % confidence interval for each linear regression.

As  $\mathfrak{S}$  and  $\mathfrak{S}'$  are almost identical (an error lower than 2 % was verified), it may be assumed that the pressure drop across the felt sample,  $\Delta P_{Felt}$ , is given by:

$$\Delta P_{Felt} = Q \cdot (R_{Felt} - R_{Blanc}) \quad (4.59)$$

In addition, in order to check the validity of Darcy's relation, the fluid velocity (flow rate per unit area) is plotted against the pressure gradient across the thickness of the felt sample (Figure 4.7).

The linearity found between the superficial velocity of the fluid and the pressure gradient across the felt in the transversal direction emphasizes the validity of Darcy's relation. Then, plotting the pressure drop in the felt against the quantity  $\frac{\mu \cdot L \cdot Q}{A} = \text{"Factor"}$  according to Darcy's relation, the transversal permeability factor is given by the slope of the linear regression obtained by the least squares method (see Figure 4.8 as an example; the results obtained for each felt are summarized on Tables D.4, D.5 and D.6 in **Appendix D**).

In summary, the transversal permeability factor obtained for three felt samples used throughout the impulse drying tests performed in the framework of the

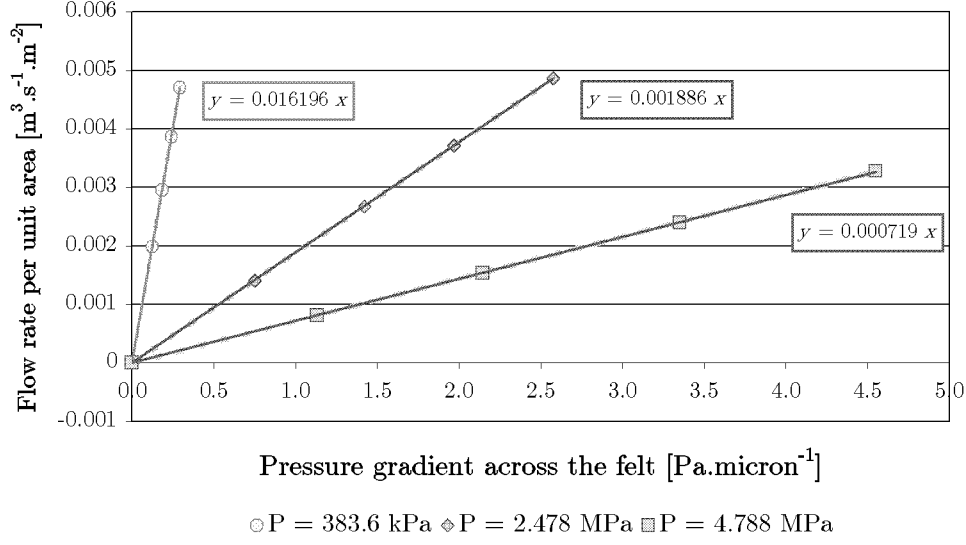


Figure 4.7: Flow rate per unit area,  $Q/A$ , versus pressure gradient,  $\Delta P/L$  at different compression levels, obtained for felt No. 249031-D. The linear regression emphasizes the validity of Darcy's relation. Solid lines correspond to regression lines obtained by the method of least squares; dashed lines represent the upper and lower limits of the 95 % confidence interval for each linear regression.

present thesis, is presented for each level of compression on Table 4.2. It is worth noting that each experiment is performed at a given pressure, which induces a different level of compression in the felt sample. Therefore, the porosity of the sample will be subsequently lower as the applied pressure is increased. The total porosity of the sample, defined as the ratio of the void volume,  $V_{voids}$ , to the total volume of the mat is given by Eqn. 4.60:

$$\phi = \frac{V_{voids}}{V} = 1 - \frac{m_{s,nylon}}{A \cdot L \cdot \rho_{f,nylon}} \quad (4.60)$$

where  $m_{s,nylon}$  is the dry mass of the felt sample and  $\rho_{f,nylon}$  the specific density of the nylon fibers ( $1141 \text{ kg} \cdot \text{m}^{-3}$ ).

Finally, the transversal permeability factor was correlated with the porosity of the felt samples used in this study. For that purpose, simple exponential and power laws currently employed in similar circumstances were used. The Kozeny-Carman model was also used, even knowing that the relation is only valid for porosities in the range of 0.50-0.90. The correlations obtained may then be used in the pressing model developed hereafter for the impulse drying of paper in which

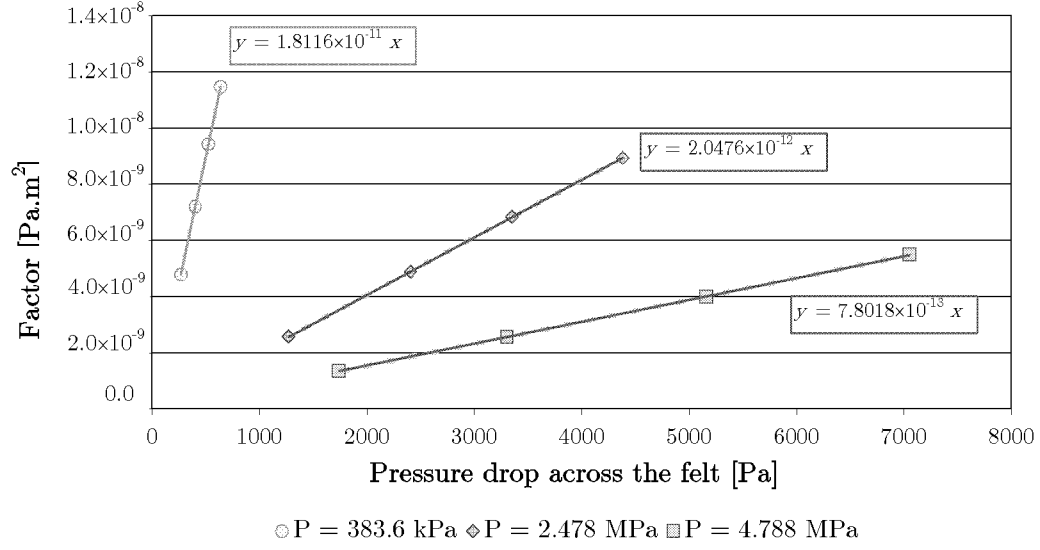


Figure 4.8: “Factor” =  $\mu.L.Q/A$  versus the pressure drop across the felt sample No. 249031-D at different compression levels. Solid lines correspond to regression lines obtained by the method of least squares; dashed lines represent the upper and lower limits of the 95 % confidence interval for each linear regression.

felt plays an important role in the dewatering process. Figures 4.9 and 4.10, represent the exponential and power fittings of the experimental data, according to the following expressions:

$$K = K_0 \cdot \exp(\Pi_0 \cdot \phi) \quad (\text{Exponential law}) \quad (4.61)$$

$$K = K'_0 \cdot \phi^{\Pi'_0} \quad (\text{Power law}) \quad (4.62)$$

where  $K_0$ ,  $K'_0$ ,  $\Pi_0$  and  $\Pi'_0$  are parameters of the model.

The two graphs emphasize a quite good agreement between transversal permeability and felt porosity according to both models, except for the data concerning felt No. 249031-11, for which no fitting was possible. This is ascribed to the experimental error when determining the transversal permeability at the lowest compression level, *i.e.* corresponding to a porosity of 0.432 (see Figure 4.9 or 4.10). In fact, this compression level should correspond to a higher permeability value, even higher than that obtained for the two remaining felts, No. 249031-D and No. 249031-12, as felt No. 249031-11 has the lowest grammage and should, therefore, be more permeable (as observed in the initial trend of the

Table 4.2: Transversal permeability factor of the felt samples for different levels of compression.

| Felt No.  | Applied pressure<br>[MPa] | Thickness<br>[mm] | Permeability factor<br>[ $\mu\text{m}^2$ ] | Porosity<br>[-] |
|-----------|---------------------------|-------------------|--------------------------------------------|-----------------|
| 2490311-D | 0.3836                    | 2.198             | 18.116                                     | 0.448           |
|           | 2.478                     | 1.696             | 2.0476                                     | 0.285           |
|           | 4.788                     | 1.543             | 0.78018                                    | 0.214           |
| 249031-11 | 0.3605                    | 2.108             | 5.3415                                     | 0.432           |
|           | 2.455                     | 1.646             | 2.8328                                     | 0.272           |
|           | 4.917                     | 1.504             | 1.3505                                     | 0.204           |
| 249031-12 | 0.3682                    | 2.274             | 8.8478                                     | 0.458           |
|           | 2.463                     | 1.863             | 1.4754                                     | 0.339           |
|           | 4.830                     | 1.706             | 0.84376                                    | 0.278           |

data in Figures 4.9 and 4.10).

When trying to fit the experimental data to the Kozeny-Carman model, it was observed that the model overestimates the permeability for the same felt porosity. The three sets of predicted values (Figure 4.11) were obtained using Eqn. 4.5, which implies the knowledge of the Kozeny factor and the volume specific surface of the porous medium. The first parameter,  $k_k$ , was estimated using three distinct approaches: (i)  $k_k$  is constant and equal to 5.5, according to Ingmanson *et al* [16]; (ii) and (iii)  $k_k$  is given by Eqn. 4.8 according to the parameters proposed by Davies [6] and Ingmanson *et al* [16].

The volume specific surface of the felt is more complex to determine because one needs to know its constituents as well as the grammage of the different layers that constitute the felt [5]. As the study of felt structure and properties was not in the scope of the present work a simple approach will be used to estimate  $S'_v$ . As the information related to the properties of the felt samples used in the present work are scarce, it was decided to use the data collected by Chevallier for nylon felts of  $1325 \text{ g.m}^{-2}$  grammage in a non-compacted stage, using mercury porosimetry. The author found a value of  $0.0540 (\pm 0.0024) \text{ m}^2.\text{g}^{-1}$  for the mass specific surface of the felt,  $S'_m$ , defined as the ratio of the volume specific surface of the fibers that constitute the network to the density of the network. When submitting the felt to a pressure of 5 MPa he found the value  $0.0460 \text{ m}^2.\text{g}^{-1}$ . He also determined the mass specific surface by stereometry using image analysis, from which the value  $0.0488 \text{ m}^2.\text{g}^{-1}$  was obtained for a non-compacted

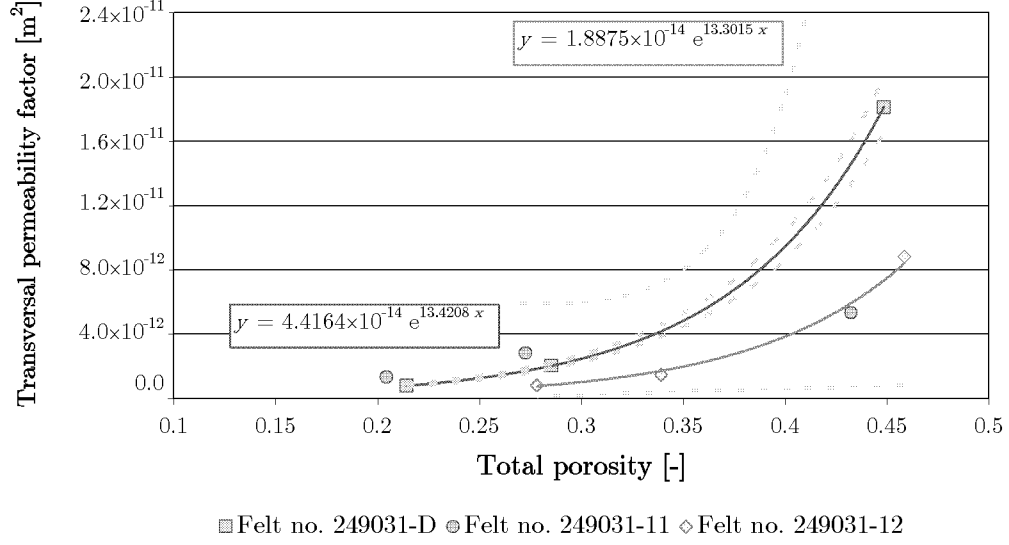


Figure 4.9: Exponential fitting of transversal permeability experimental data. Solid lines correspond to regression lines obtained by the method of least squares; dashed lines represent the 95 % confidence intervals for each regression.

felt. Observing his results he suggested that the pressure imposed by the mercury inside the test chamber slightly separates the nylon fibers, thus eliminating the contact surfaces between fibers. Therefore, Chevallier suggests that the values obtained by porosimetry correspond not to the mass specific surface of the felt but to that of its constituents, *i.e.* the nylon fibers. For simplicity it will be assumed a mean value of  $0.0540 \text{ m}^2.\text{g}^{-1}$  for the mass specific surface of the nylon fibers,  $S'_{m,nylon}$ , [5]. In addition, the volume specific surface of the fibers,  $S'_f$ , will be given by:

$$S'_f = S'_{m,nylon} \cdot \rho_{f,nylon} = 616.14 \text{ cm}^{-1} \quad (4.63)$$

The volume specific surface of the felt may then be determined as:

$$S'_v = S'_f \cdot (1 - \phi) \quad (4.64)$$

Therefore,  $S'_v$  is calculated for each level of compression imposed to the felt samples of the study, allowing to determine its transversal permeability factor according to the Kozeny-Carman model (Eqn. 4.5) and accounting for the dependence of  $k_k$  and  $S'_v$  on porosity.



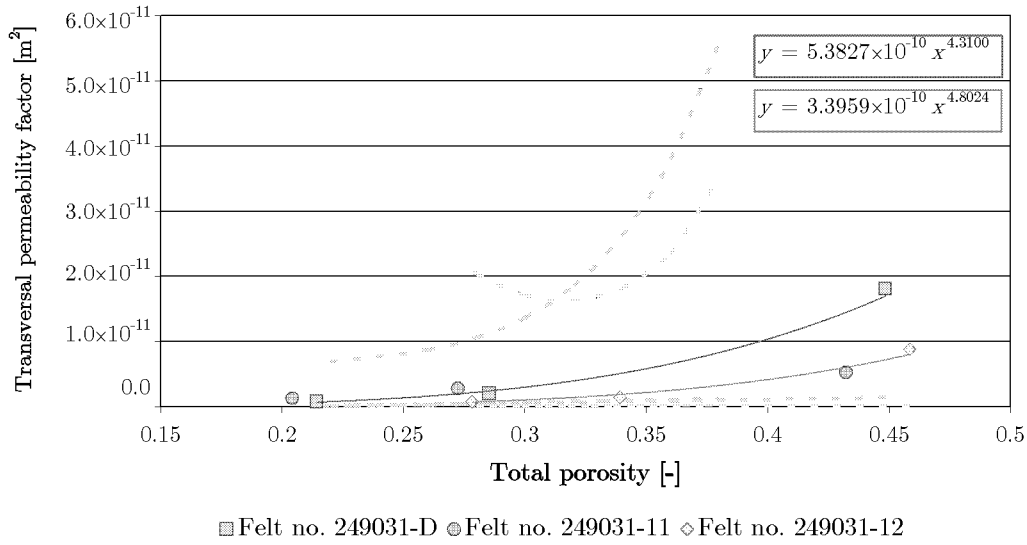


Figure 4.10: Power law fitting of transversal permeability experimental data. Solid lines correspond to regression lines obtained by the method of least squares; dashed lines represent the 95 % confidence intervals for each regression.

Figure 4.11, therefore represents the experimental data collected throughout the present study, and fitted to exponential and power laws, and data estimated according to the Kozeny-Carman model for the same compression level. As expected, the Kozeny-Carman model does not represent the transversal permeability of the felts under study. This is in part due to the fact that the range of porosity is well below that in which the model is valid. Nevertheless, experimental and estimated data seem to follow the same trend. Also in Figure 4.11, the exponential relation obtained by Thibault for a felt similar to felt No. 249031 used in the present study is presented. The discrepancies observed between the two experimental studies may be attributed to the fact that two of the samples, felts No. 249031-11 and -12, had been submitted to several impulse drying tests prior to the permeability tests, which induced a different level of compaction mainly observed on the face of the felt contacting the paper sample in the press nip. On the contrary, felt No. 249031-D was a new felt, thus presented the highest transversal permeability factor. Another possible reason for the different trend may be associated to experimental error when determining the permeability at the lowest level of compression, or even to differences in the internal structure of the felt. As illustrated in Figure 4.11, the transversal permeability of felt

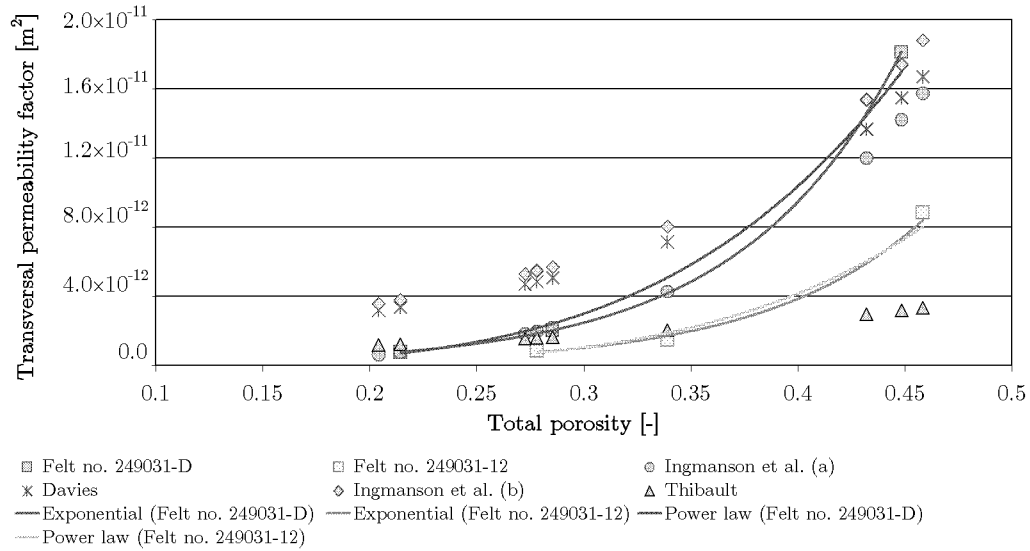


Figure 4.11: Transversal permeability factor versus total porosity. Data report to experimental (filled squares) and predicted values: (i) according to the Kozeny-Carman model and using different approaches to determine the Kozeny-Carman factor and (ii) using exponential and power fittings.

No.249031-D measured at lower porosities is very similar to that of Thibault's felt sample. However, this is no longer true for higher porosities when the felt is in an almost uncompressed state.

For comparison, the permeability results obtained by Silvy and Butel [36] for felt samples from SCAPA Scandia are also presented. In their study, five felts, different in the design of their fabric and the batt fiber diameter, have been investigated. The samples were wet conditioned by 500 cycles at a pressure of 5 MPa and then submitted to the permeability tests in a transversal permeameter developed by Chevallier [5]. The results for a pressure range from 0.36 to 3.34 MPa are represented in Figure 4.12. The authors also found a decreasing exponential law for the dependence of the permeability factor on the pressure of compaction, or reversely an increasing exponential law in terms of felt porosity.

## Conclusions

In conclusion, one may say that the transversal permeability factors of the felts under study are well represented by an exponential law. The resulting correlations will be used to predict the absolute permeability of the felt sample in the impulse

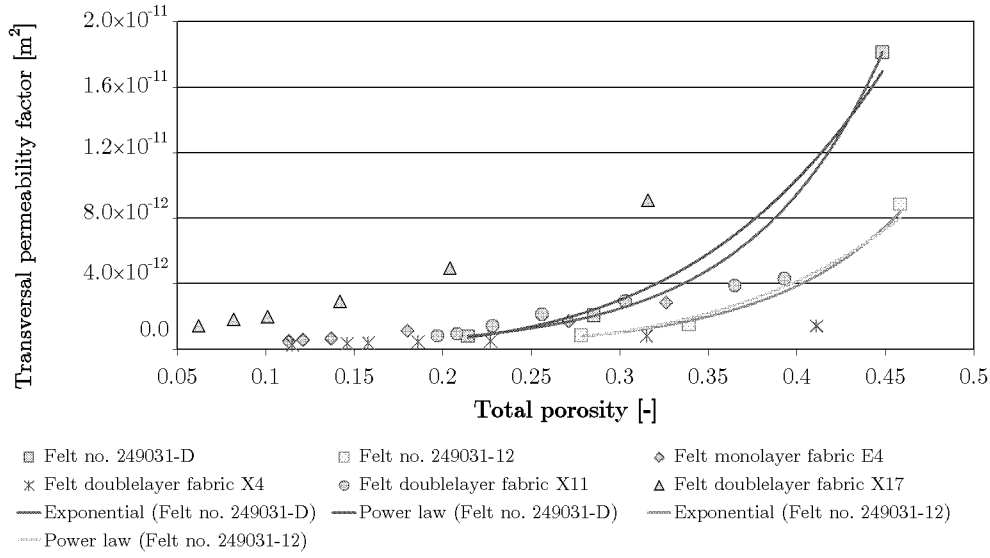


Figure 4.12: Transversal permeability factor versus total porosity. A comparison is made between experimental data obtained by Silvy and Butel [36] (fitted to exponential laws) and the permeability values experimentally determined in the present study (filled squares).

drying model simulations.

#### 4.2.2 Compressibility tests

This section comprises two independent experimental programs, with the same objective, however. In fact, the main purpose of the work presented hereafter is to get some insight into the rheology of the felt samples used in the previous permeability tests. For that purpose, tests of compressibility under quasi-static and dynamic conditions were performed. The preliminary information obtained here will be used in the development of the consolidation theoretical model for the press felt.

##### Compressibility tests under quasi-static conditions

During the permeability tests, the thickness of the felt samples was recorded as a function of the applied stress. These results allowed the investigation of the densification process of the felts under quasi-static conditions. Although the level of stress imposed to the felt is similar to that of a real paper machine,

the time-scale is far different, which makes it difficult to infer about the real consolidation process of the material. Nevertheless, the information is useful in order to compare their behavior to compression, and also to find a correlation between the thickness of the felt and the applied stress in order to determine the level of stress that induces the incompressible thickness, *i.e.* the thickness of the felt at zero porosity.

**Results and discussion** The data obtained at the equilibrium for each level of stress is represented in Figure 4.13. The results clearly show the high compressibility of the porous material in the initial phase of the compression process, followed by a gradually decreasing tendency to compress. This behavior is particularly visible for samples No. 249031-D and -11. In fact, the initial thickness of these two samples differ in about  $370\text{ }\mu\text{m}$ , but at the highest level of compression the samples have almost the same thickness. This is mainly due to the fact that felt No. 249031-D has been submitted to less compression/decompression cycles than felt No. 249031-11, which makes it more soft and compressible. On the other hand, felts No. 249031-12 and -11 have been subjected to the same experimental conditions and therefore present a very similar initial thickness. Surprisingly, these two samples experienced a somewhat different consolidation process, as the two corresponding curves tend to separate at a higher compression level. This may be explained in terms of the incompressible thickness of the samples.

The incompressible thickness,  $L_i$ , is calculated as the ratio of the grammage of the sample to the specific density of the material that constitutes it. In fact, felt No. 249031-12 presents the highest incompressible thickness, as illustrated on Table 4.3. This means that the sample has a higher amount of solids, which leads to a higher resistance to compression. This is even confirmed by the similarity of the grammage of samples 249031-D and -11.

Table 4.3: Incompressible thickness of the felt samples.

| Felt No.  | Grammage<br>[g.m <sup>-2</sup> ] | Initial thickness<br>[mm] | Incompressible thickness<br>[mm] |
|-----------|----------------------------------|---------------------------|----------------------------------|
| 2490311-D | 1383                             | 4.035                     | 1.213                            |
| 249031-11 | 1366                             | 3.665                     | 1.198                            |
| 249031-12 | 1405                             | 3.660                     | 1.232                            |

Romatier and Silvy [32] studied the compressibility of wet paper webs and

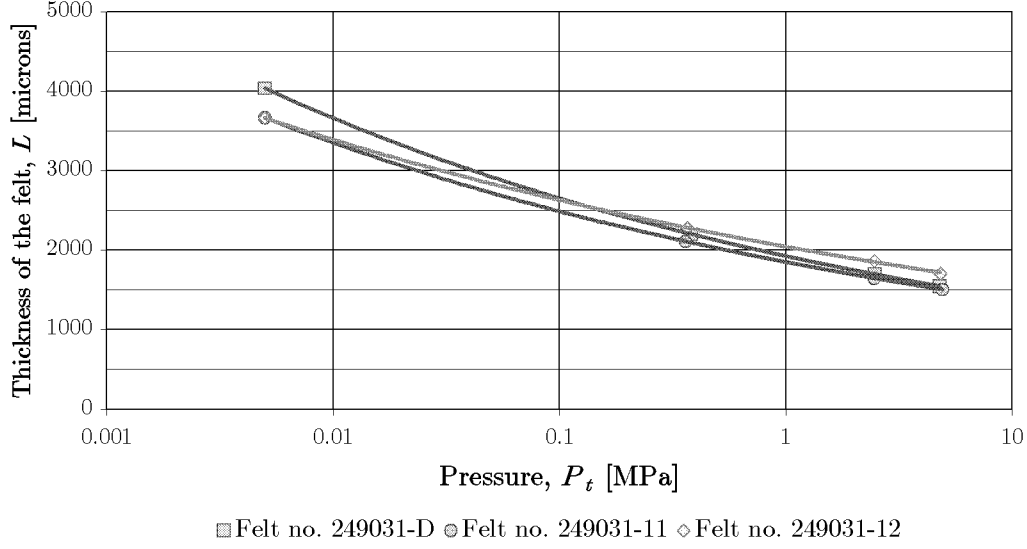


Figure 4.13: Thickness of the felt samples at equilibrium versus applied pressure.

defined its compressibility as the variation in volume for a small increase of pressure as already stated (see Eqn. 4.28), although in terms of thickness. Making use of what is defined as the dry basis density of the material,  $\rho_{dry}$ ,

$$\rho_{dry} = \frac{Gr}{L} \quad (4.65)$$

and substituting Eqn. 4.65 into Eqn. 4.28, the compressibility of the material is then expressed as:

$$N = \frac{1}{\rho_{dry}} \cdot \left( \frac{\partial \rho_{dry}}{\partial P_t} \right)_T \quad (4.66)$$

On the other hand, it is known that many fibrous materials exhibit a compression behavior represented by a power law, *i.e.*:

$$\rho_{dry} = \rho_{dry}^* \cdot \left( \frac{P_t}{P_t'} \right)^{cf} \quad (4.67)$$

where  $cf$  (denoted as  $b_8$  in Eqn. 4.41) is the compressibility factor and  $\rho_{dry}^*$  is the dry basis density of the fibrous material for  $P_t = P_t'$ , being  $P_t'$  a reference value. Again, making reference to the work of Chevallier [5] and using Eqns. 4.65 and 4.67, it is possible to express the thickness of the felt as:

$$L = \frac{Gr}{\rho_{dry}^*} \cdot \left( \frac{P_t}{P'_t} \right)^{-cf} \quad (4.68)$$

Moreover, the compressibility of the felt may now be determined as:

$$N = \frac{cf}{P_t} \quad (4.69)$$

from which one may conclude that the compressibility of the material is inversely proportional to the applied pressure, *i.e.* the variation of volume is gradually decreasing as the pressure level increases. The compressibility of a given material is characterized by its rigidity modulus,  $E^*$  defined as:

$$E^* = \frac{1}{N} \quad (4.70)$$

As it was previously said, the incompressible thickness of the felt is determined at zero porosity, therefore it makes all sense writing Eqn. 4.68 as:

$$L = L_i \cdot \left( \frac{P_t}{P'_t} \right)^{-cf} \quad (4.71)$$

$$\text{with } L_i = \frac{Gr}{\rho_{f,nylon}} \quad (4.72)$$

$P'_t$  is, therefore, the stress that has to be imposed to the felt sample to induce a stage of zero porosity. The parameters  $P'_t$  and  $cf$  were determined according to the method of least squares through the following expression:

$$\ln \left( \frac{L}{L_i} \right) = \ln (P'_t)^{cf} - cf \cdot \ln P_t \quad (4.73)$$

The parameters of the relation defined by Eqn. 4.71 are illustrated in Figures 4.14, 4.15, and summarized on Table 4.4 for each of the three felt samples under study.

In summary, the static analysis highlighted the resistance to compression of felt samples with different compression/decompression histories. In fact, felts submitted to longer compression/decompression cycles exhibited lower compressibility, *i.e.* they gradually tend to compress less as the applied pressure increases. This is also clear when the level of pressure applied to sample No. 249031-12, which is a more compact structure, is compared with that applied to the remaining felt samples to attain a similar incompressible thickness (see Table 4.4).

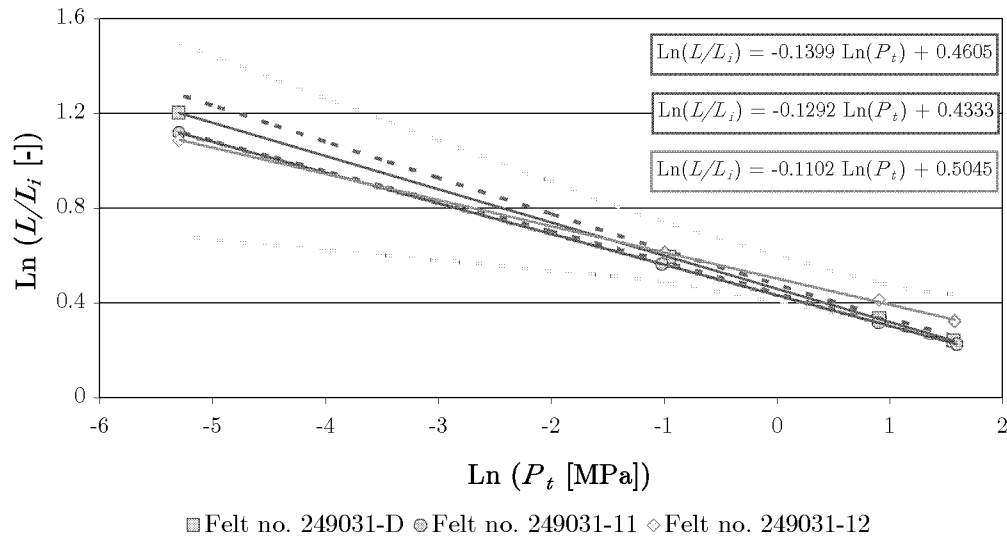


Figure 4.14:  $\text{Ln}(L/L_i)$  versus  $\text{Ln}(P_t)$  for each felt sample. Solid lines correspond to regression lines obtained by the method of least squares; dashed lines represent the 95 % confidence intervals for each regression.

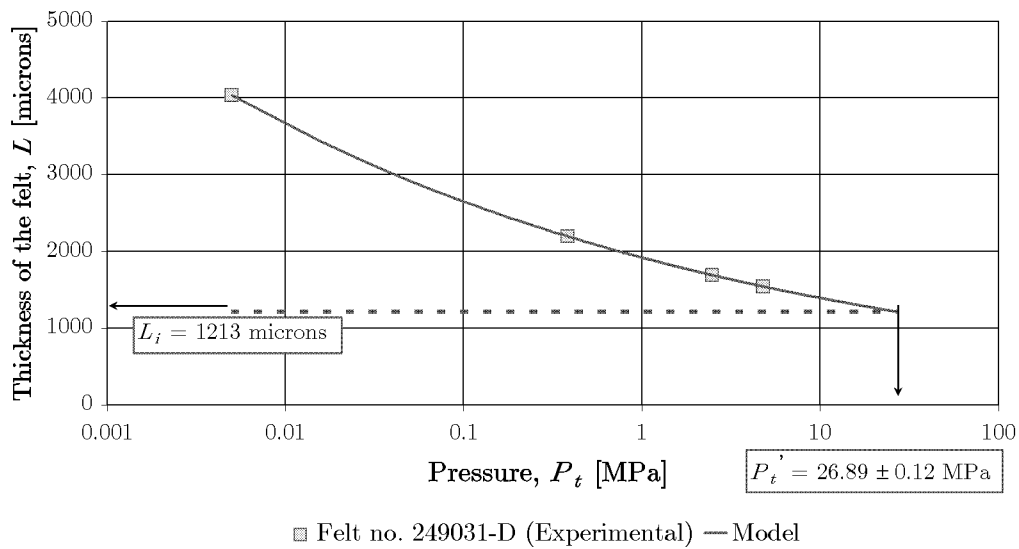


Figure 4.15: Thickness of the felt No. 249031-D at equilibrium versus applied pressure. The incompressible thickness and the parameter  $P'_t$  are emphasized on the graph.

Table 4.4: Parameters of the model represented by Eqn. 3.71.

| Felt No.  | Incompressible thickness, $L_i$ | $cf$   | $P'_t$           | Rigidity modulus, $E^*$ |
|-----------|---------------------------------|--------|------------------|-------------------------|
|           | [mm]                            | [-]    | [MPa]            | [MPa]                   |
| 2490311-D | 1.213                           | 0.4605 | $26.89 \pm 0.12$ | $P_t / 0.4605$          |
| 249031-11 | 1.198                           | 0.4333 | $28.63 \pm 0.00$ | $P_t / 0.4333$          |
| 249031-12 | 1.232                           | 0.5045 | $97.38 \pm 0.07$ | $P_t / 0.5045$          |

A similar approach may also be used to express the porosity of the felt as a function of the applied stress exerted on the material. Making reference to Eqn. 4.60, the porosity is expressed in terms of the incompressible thickness as follows:

$$\phi = \frac{V - V_s}{V} = 1 - \frac{L_i}{L} \quad (4.74)$$

Thus, from Eqns. 4.71 and 4.74 one may write:

$$\phi = 1 - \left( \frac{P_t}{P'_t} \right)^{cf} \quad (4.75)$$

The figure presented hereafter represents the evolution of porosity with the applied pressure. The parameters  $cf$  and  $P'_t$  used are those presented on Table 4.4.

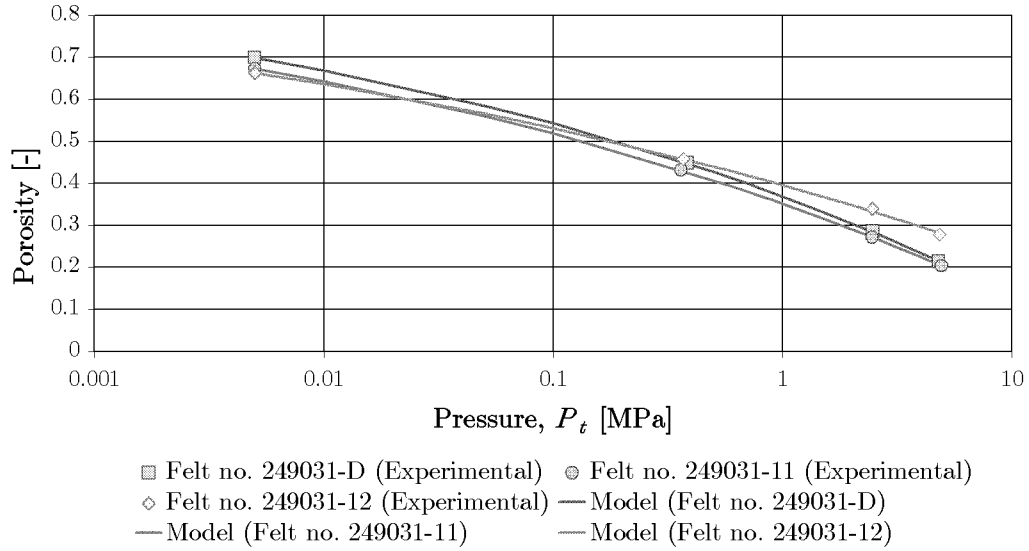


Figure 4.16: Porosity of the felt samples versus the applied pressure. Solid lines correspond to the model represented by Eqn. 4.75, for each felt sample.



Although the previous analysis is of utmost importance, and allows to define variation laws for felt porosity and thickness as a function of the applied stress, as well as to determine some physical parameters for different levels of compaction and use, it doesn't allow to investigate the response of the material under dynamic pressing conditions.

### Compressibility tests under dynamic conditions

In the previous section, the response to compression of felt samples with different degrees of compaction was investigated. However, the apparatus used to perform the tests did not allow to apply a certain level of stress over a short period of time, as in the case of a paper machine. In order to investigate the compression of new and used felts under operating conditions similar to those of a real paper machine, a set of tests was carried out in a rheometer. By doing so, it is possible to operate similar stress levels and frequencies of application of the stress.

The experimental work presented hereafter was performed on a rheometer device proprietary of EFPG. The rheometer Métravib (see Figure 4.17) allows a maximum force of 100 N to be applied on the material, which implies that the material has to be pre-compressed under a known level of static pressure and then submitted to small sinusoidal deformations. By doing so, the level of pressure exerted on the felt sample is within the range of pressure typical of a paper machine.

The felt samples with 20 mm of diameter are prepared and placed inside the sample holder. The samples are tested under dry conditions and at two different temperatures, 25 and 50 °C approximately. The sample holder is composed of two parallel plates joined by means of five springs that can be adjusted in order to exert a known level of pre-stress on the felt sample. Knowing the elastic constant of the springs and measuring the deformation imposed, it is possible to determine the level of pre-stress. As the springs are adjusted manually, care must be taken to guarantee the parallelism between the two plates of the sample holder. Additionally, the parameter  $B_m$  (as defined previously on Section 4.1.1) of the felt samples must be lower than  $4 \cdot 10^6 \text{ N.m}^{-1}$ ; otherwise there is the risk of measuring the  $B_m$  of the apparatus itself. For a single sample of 20 mm diameter,  $B_m$  easily reaches  $10^7 \text{ N.m}^{-1}$  [24]. Therefore, several samples must be tested simultaneously, and for that purpose three felt samples were joined in series. The corresponding  $B_m$  value of the set will be given by:

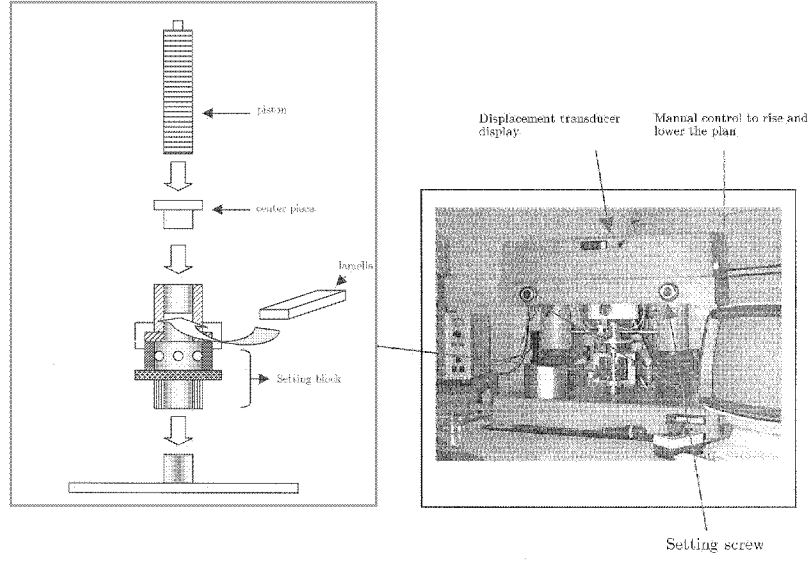


Figure 4.17: Photograph of the rheometer MÉTRAVIB and schematic view of the sample holder (taken from [27]).

$$\frac{1}{(B_m)_{measured}} = \sum_i^n \frac{1}{B_{m_i}} \quad i = 1, 2, \dots, n \quad (4.76)$$

where  $B_{m_i}$  is the parameter for each sample in the series arrangement. If one now assumes that  $B_{m_1} \simeq B_{m_2}, \dots, \simeq B_{m_n}$ , the  $B_m$  value of a single sample may be determined simply as:

$$\frac{1}{(B_m)_{measured}} = \frac{1}{B_{m_1}} + \frac{1}{B_{m_2}} + \frac{1}{B_{m_3}} \simeq \frac{3}{(B_m)_{sample}} \quad (4.77)$$

or else,

$$(B_m)_{sample} = 3.(B_m)_{measured} \quad (4.78)$$

As several felt samples are being used, one may question about the parallelism between the plates of the sample holder, and infer about the experimental error due to that procedure on the Young's modulus of the samples, which is a function of the parameter  $B_m$  and thickness of the sample. Lopez [24], reported a 5 % error for the measurement of the thickness and 10 % for the parameter  $B_m$ . This means, according to Lopez experiments, that the Young's modulus of the samples

may be affected by an error of 20 %, which is considerable. In addition, the author advanced some factors that may influence the  $B_m$  measurement, namely the duration of the experiment or the frequency of application of the stress, the magnitude of the pre-stress, and also the temperature and moisture level of the samples. In the present work, the influence of the three former parameters will be studied.

**Results and discussion** As mentioned in the previous section, the rheometer allows to measure the bulk modulus,  $B_m$ , related to the fractional change in volume, and the loss angle,  $\delta_1$ . These parameters were studied for a new and a previously conditioned felt sample, at two levels of compression and temperature as summarized on Table 4.5, and for frequencies,  $\omega_1$ , in the range of 7.8-500 Hz.

Table 4.5: Experimental conditions for the dynamic tests.

| Felt No. | Type of felt    | Temperature           | Pre-stress | Dynamic additional force |
|----------|-----------------|-----------------------|------------|--------------------------|
|          |                 | [°C]                  | [MPa]      | [N]                      |
| 249031-7 | New             | 22, 51 (23, 50.4 )    | 3.95       | 30 (50)                  |
| 249031-A | Pre-conditioned | 22.6, 50.7 (22, 50.7) | 2.76       | 30 (50)                  |

The storage modulus,  $G'$ , is then determined as a function of  $B_m$  (for a single sample),  $\cos \delta_1$ , and a shape factor  $F_f$  according to the following expression [24], [1]:

$$G' = B_m \cdot F_f \cdot \frac{L}{A_e} \cdot \cos \delta_1 \quad (4.79)$$

where  $A_e$  is the surface area exposed to the stress, and  $F_f$  is given as:

$$F_f = \frac{1}{1 + 2 \left( \frac{D_{felt}}{4L} \right)^2} \quad (4.80)$$

where  $D_{felt}$  is the felt diameter.

Firstly, a series of preliminary tests were performed in order to study the influence of frequency of stress application, pre-stress magnitude, time and temperature. As already mentioned, the rheological behavior of felts is highly influenced by the number of compression/decompression cycles. For that very reason it was decided to compare the results obtained for a new and a pre-conditioned felt.

Some studies tend to emphasize the viscoelastic behavior of felts. Others consider them as elastic solids showing a permanent deformation, *i.e.* exhibiting an hysteresis in their stress/strain diagrams. In fact, many composites exhibit time-dependent viscoelastic behavior under load, and this is particularly true for composites having polymeric constituents, like felts. Polymeric materials, which are known to be viscoelastic, may behave like fluids or solids, depending on the time scale and/or the temperature. These materials are viscoelastic at room temperature, and the viscoelastic effects become stronger as the temperature approaches the glass transition temperature. Another important issue is the definition of linear elastic and linear viscoelastic material behavior. A linear elastic solid exhibits a linearity between stress and strain, and this linear relationship is independent of time. A linear viscoelastic solid also exhibits a linearity between stress and strain, but the linear relationship depends on the time history of the input. Bearing this in mind, it was necessary to verify whether the bulk modulus  $B_m$ , also known as stiffness, as well as the complex modulus  $G^*$  changed significantly in time. For that purpose, felt No. 249031-A was submitted to an oscillatory frequency of 125 Hz, using a total compressive stress of 2.92 MPa. The dynamic test was performed at 50 °C for about 12 minutes. The results illustrated in Figure 4.18 show no evidence of a significant change of the complex modulus or the stiffness of the material. Although the time scale of the experiment is rather short compared to the lifetime of the felt in a real paper machine, it is clear that for this operating conditions the felt under study exhibits a rheological behavior more like an elastic solid and less as a viscoelastic material. In addition, the loss factor is rather low, and corresponds to a phase lag less than 5 °. This fact suggests that the loss modulus,  $G''$ , is not very significant, which reinforces the idea of an elastic behavior of the felt under study in the present operating conditions.

Observing Figures 4.19 and 4.20 one may conclude that the stiffness of the felt samples remain almost independent of frequency at very low frequencies, but changes rapidly at higher frequency values. One may then say that the speed of a real paper machine plays an important role in the development of felts stiffness and eventually other mechanical properties. This effect was even more pronounced for the new felt samples, since a variation of about 60 % was observed, against a 40 % increase for the pre-conditioned samples at the highest frequency values (see Figure 4.21). However, these values must be considered

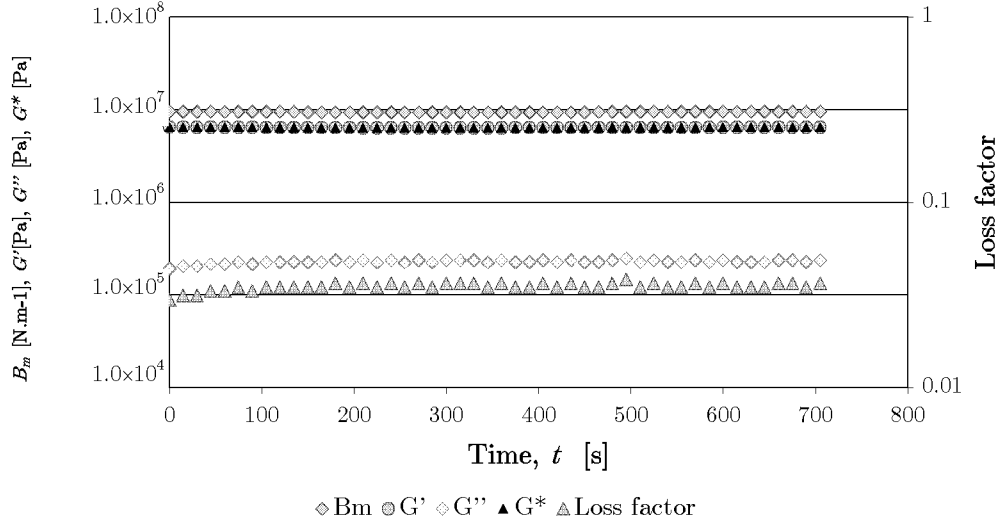


Figure 4.18: Time dependence of  $B_m$ ,  $G^*$ ,  $G'$ ,  $G''$  and  $\tan \delta_1$ . The test was performed at  $T = 50$  °C,  $\omega_1 = 125$  Hz and  $\sigma_T = 2.92$  MPa.

carefully as the level of pre-stress of the samples was quite different. In fact, the preconditioned felt samples were submitted to a pre-stress of 2.76 MPa whereas the new felts were pre-stressed at 3.95 MPa. Therefore, a higher stiffness would be expected for the samples submitted to a higher level of stress, as illustrated in Figure 4.19 or 4.20; an additional force of 50 N produces a higher stiffness than a 30 N force, which is clearly visible for felt No. 249031-7; this is not so evident for felt No. 249031-A as the material is already stiffer and a small increase in load does not produce a significant increase of the modulus. The results presented in Figure 4.20 for felt No. 249031-A are very similar, yet slightly higher than those obtained for felt No. 249031-7 with an additional force of 30 N, which suggests that a considerably higher stiffness would be obtained for the former felt if the same level of pre-stress had been applied.

Lopez [24] also studied the influence of frequency of oscillation on the stiffness of industrial felt samples, and reported an increase of 9.1 % of the modulus when the frequency was increased from 5 to 125 Hz, which is in accordance with the results presented here (see Figure 4.21).

It is also known that temperature influences the bulk modulus of a viscoelastic material. From a practical viewpoint, the temperature dependence of polymer properties is of paramount importance because plastics and rubbers show very

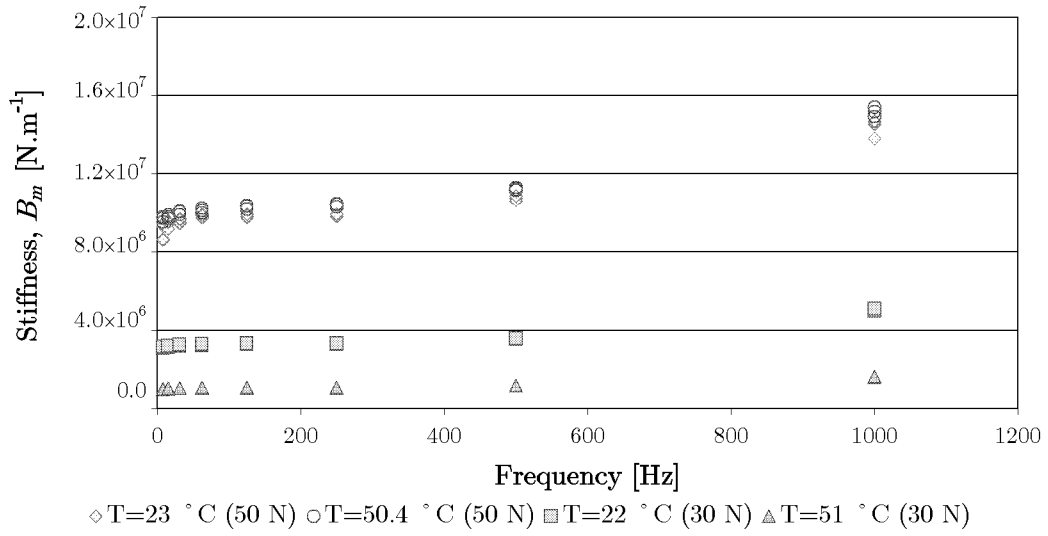


Figure 4.19: Stiffness versus oscillation frequency. The results were obtained for felt samples No. 249031-7 at two levels of additional stress, 30 and 50 N, and two different temperatures, around 20 and 50 °C.

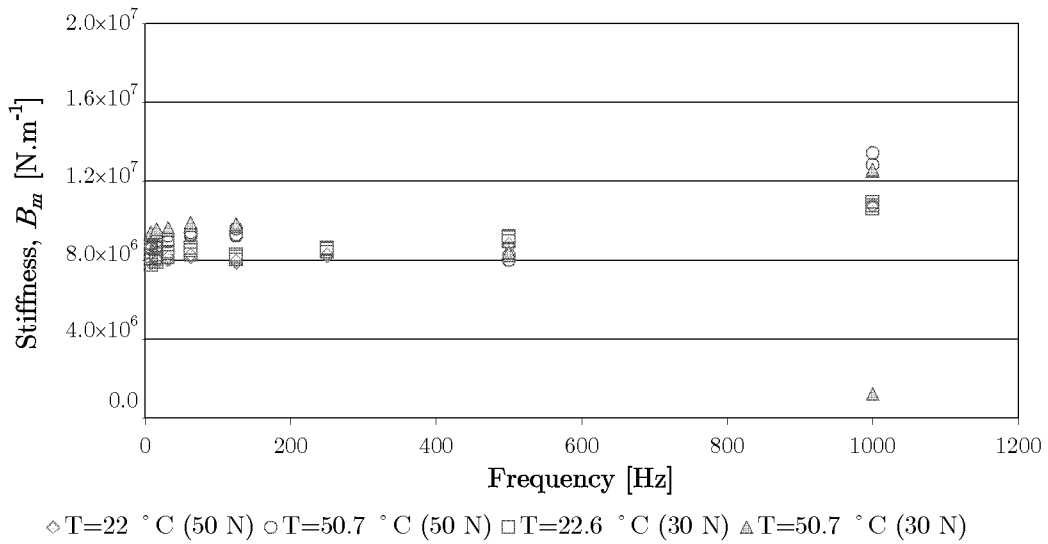


Figure 4.20: Stiffness versus oscillation frequency. The results were obtained for felt samples No. 249031-A at two levels of additional stress, 30 and 50 N, and two different temperatures, around 20 and 50 °C.

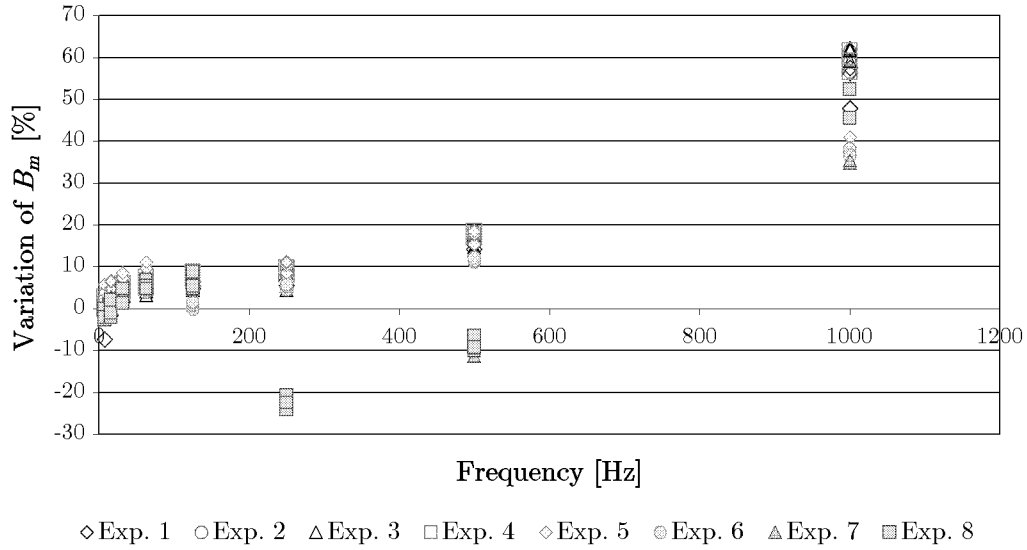


Figure 4.21: Stiffness variation of felts 249031-7 (open symbols) and A (filled symbols), in relation to the values obtained at 7.8 Hz.

large changes in properties with changing temperature. In fact, there is one primary transition, usually called the glass transition, which involves a large decrease in modulus. Lopez reported a 45 % decrease in stiffness operating from 20 to 80 °C at 31.5 Hz [24]. In the present study, the conclusions are not so straightforward, as a 90 % decrease was observed for new felt samples operated at 22 and then at 51 °C (see Figure 4.19), and a slight inverse tendency was reported for the remaining operating conditions. It should also be mentioned that the glass transition temperature of nylon is around 90 °C, thus far above the operating temperature.

Consider now the variation of  $G'$ ,  $G''$  and  $\tan \delta_1$  with frequency, for a viscoelastic solid which shows no flow (Figure 4.22). At very low frequencies the material is rubber-like and has a low modulus  $G'$  which is independent of frequency. At the highest frequencies the material is glassy, with a modulus probably about  $10^9$  Pa, which is again independent of frequency. In the intermediate region, where the material behaves viscoelastically, the modulus will increase with frequency. In this region,  $G''$  rises to a maximum value, close to the frequency at which  $G'$  is changing most rapidly with frequency. In addition, the loss factor  $\tan \delta_1$ , will be zero at low and high frequencies, where stress and strain are in phase for the

rubbery and glassy states. The loss factor also has a maximum in the viscoelastic region, but this occurs at a lower frequency than that in  $G''$ .

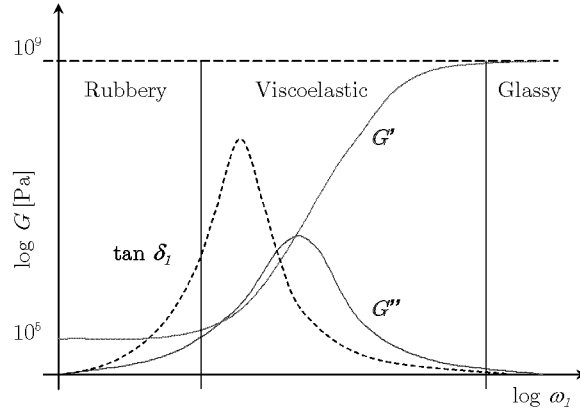


Figure 4.22: The complex modulus  $G^* = G' + iG''$  as a function of frequency  $\omega_1$  (adapted from [44]).

Observing Figures 4.23, 4.24, 4.25 and 4.26 it is reasonable to assume that both felt samples, new and preconditioned, behave as an elastic solid under the current operating conditions. In fact the storage modulus  $G'$  remains almost independent of frequency in the range of 7.8 to 1000 Hz. Although the viscoelastic effect is expected to appear at a higher frequency level, the material under study does not behave viscoelastically in the range of frequencies tested. Another important remark is that the complex modulus  $G^*$  remains very close to the storage modulus since  $G''$ , which is a measure of the energy dissipated, is significantly lower than  $G'$ . The loss factor  $\tan \delta_1$  also has a small value, always less than 0.1 in that frequency region, which emphasizes the slight viscoelastic character of the material. Again, an increase around 10 % of the loss factor was reported for the felt sample No. 249031-7 tested at 50.4 °C.

Finally, some rheological properties obtained for the new and preconditioned felt samples, are summarized on Table 4.6. The results report to a frequency of oscillation of 31.2 Hz since it is within the range of frequencies typical of the impulse drying technique. In fact, this frequency corresponds to a dwell time in the order of 30 ms, which is very close to the time scale operated in the impulse drying experiments described in the present study.



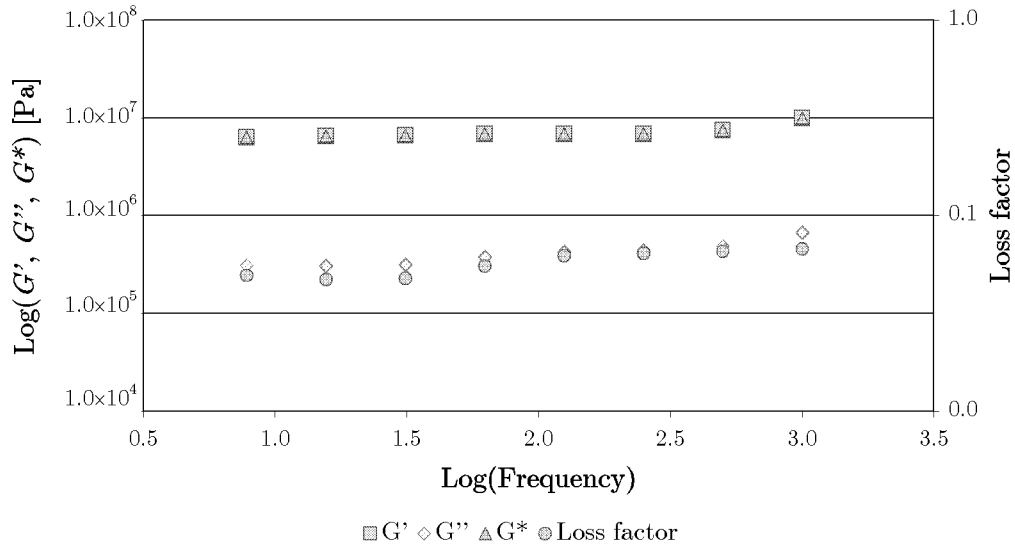


Figure 4.23: The complex modulus  $G^* = G' + iG''$  and its components as a function of frequency  $\omega_1$ . The test was performed with felt samples No. 249031-7 at  $T = 23$  °C and  $\sigma_T = 4.11$  MPa.

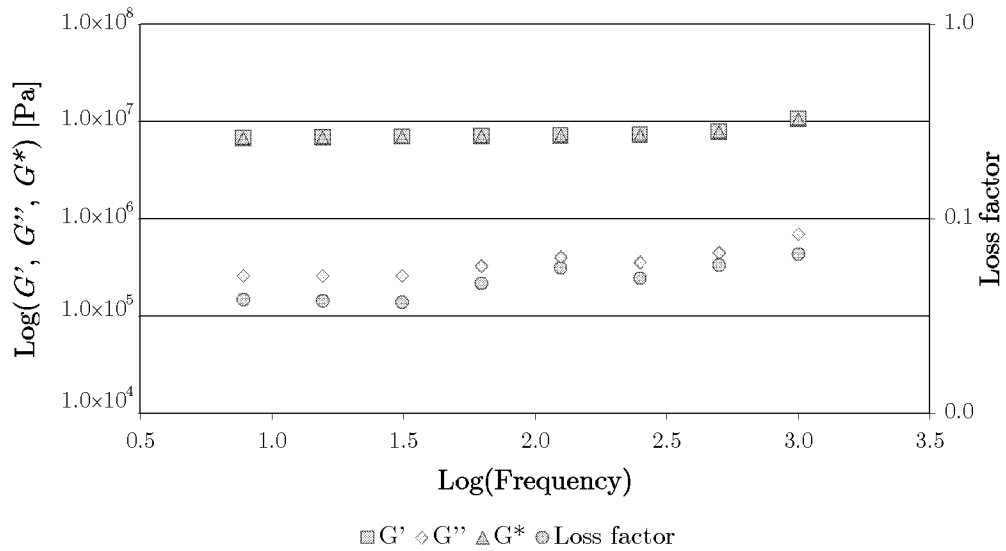


Figure 4.24: The complex modulus  $G^* = G' + iG''$  and its components as a function of frequency  $\omega_1$ . The test was performed with felt samples No. 249031-7 at  $T = 50.4$  °C and  $\sigma_T = 4.11$  MPa.

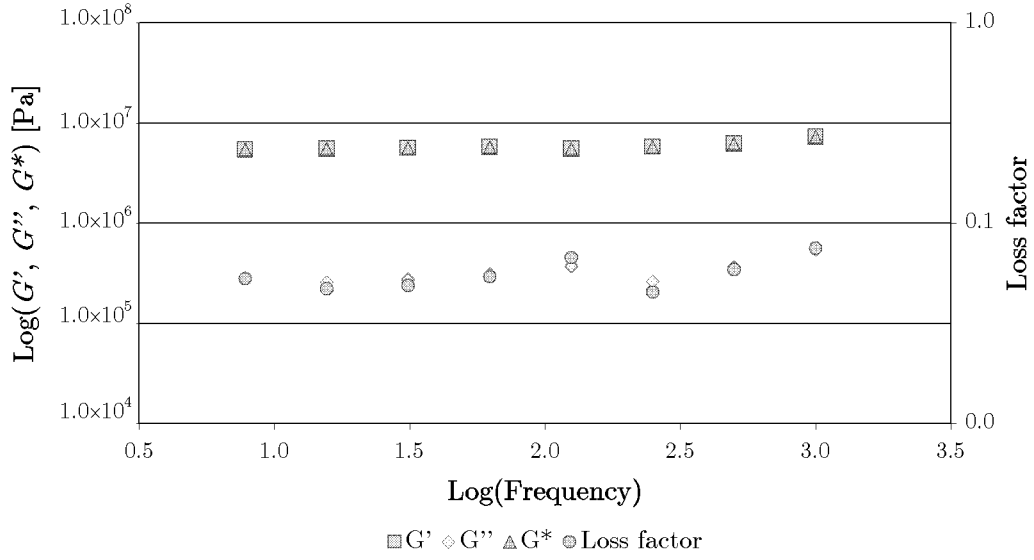


Figure 4.25: The complex modulus  $G^* = G' + iG''$  and its components as a function of frequency  $\omega_1$ . The test was performed with felt samples No. 249031-A at  $T = 22.6$  °C and  $\sigma_T = 2.86$  MPa.

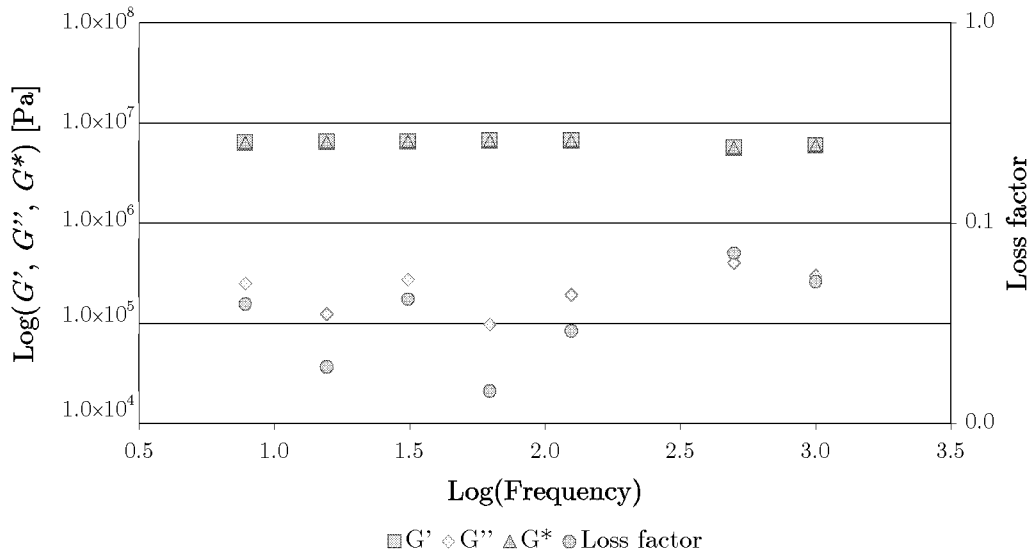


Figure 4.26: The complex modulus  $G^* = G' + iG''$  and its components as a function of frequency  $\omega_1$ . The test was performed with felt samples No. 249031-A at  $T = 50.7$  °C and  $\sigma_T = 2.86$  MPa.

Table 4.6: Rheological properties obtained at a frequency of 31.2 Hz.

| Felt No. | Temperature | Total stress | Stiffness,<br>$Bm$   | Storage<br>modulus, $G'$ | Loss<br>modulus, $G''$ | Complex<br>modulus, $G^*$ | Loss factor,<br>$\tan \delta_1$ |
|----------|-------------|--------------|----------------------|--------------------------|------------------------|---------------------------|---------------------------------|
|          | [°C]        | [MPa]        | [N.m <sup>-1</sup> ] | [MPa]                    | [MPa]                  | [MPa]                     | [-]                             |
| 249031-7 | 23          | 4.11         | $9.61 \times 10^6$   | 6.66                     | 0.318                  | 6.67                      | 0.0477                          |
|          | 50.4        | 4.11         | $1.00 \times 10^7$   | 6.96                     | 0.259                  | 6.96                      | 0.0373                          |
| 249031-A | 22          | 2.92         | $8.10 \times 10^6$   | 5.51                     | 0.321                  | 5.52                      | 0.0582                          |
|          | 50.7        | 2.92         | $9.04 \times 10^6$   | 6.15                     | 0.376                  | 6.16                      | 0.0612                          |

## Conclusions

This section allowed to determine the experimental parameters of compressibility of the felts used throughout the impulse drying experiments presented later in this chapter. The quasi-static analysis also allowed to obtain variation laws of felt's thickness and porosity as a function of the applied stress.

Some rheological properties of nylon felts were also described in this section, namely the storage, loss and complex moduli, as well as the loss factor. All these parameters were determined by dynamic analysis of new and used felts under operating conditions as close as possible to those typical of the impulse drying process. The results obtained in the present study are in accordance to what was reported by other researchers, and tend to emphasize the elastic behavior of the nylon felts pressed under the current conditions of temperature, applied stress and frequency of application of that stress. Although nylon is known as a viscoelastic material, one may assume that the viscoelastic effect is not of major importance here. It is also worth noting that, as expected, the rheological properties did not change significantly within the range of temperatures used. The magnitude of the applied stress and the frequency were, in fact, the major factors influencing the rheological properties.

## 4.3 Impulse drying experiments

This section is divided in two parts, the first aiming to present the experimental results in terms of water retention capacity of the felts tested, expressed as the water uptake rate per unit area, and the second being dedicated to the evaluation of felts behavior to compression when submitted to the impulse drying tests performed in the laboratory press.

### 4.3.1 Evaluation of the water uptake rate for the felt under study

#### Materials and methods

In this part of the study, the transient temperature and thickness profiles of 12 felt samples, undergoing compression at a peak pressure in the range 5-6 MPa, were investigated. The experimental conditions were such that the pulse length was approximately 30 ms. A micro thermocouple was carefully placed at the top surface of the felt sample allowing the local temperature to be recorded as a function of time in a range of temperatures from 25 to 350 °C (see Figure 4.27). The temperature was also recorded at the felt/sintered metal plate interface but no increase of temperature was recorded even for the highest operating temperature. This last procedure was then abandoned as it was extremely difficult to keep the thermocouple in conditions to function properly.

As already described in **Chapter 2**, a paper sample is placed on the top of the felt and the resulting sandwich is then pressed. Weighting the felt sample before and after the pressing event it is possible to determine the amount of water expressed from the paper sample and absorbed by the felt. As no significant water flow is observed from the bottom side of the felt, it is reasonable to determine the water uptake rate per unit area,  $WUR$ , expressed in kg H<sub>2</sub>O/m<sup>2</sup>s, as follows:

$$WUR = \frac{\dot{m}}{A} = \frac{\Delta MR^F \cdot m_{dry}^F}{\Delta t \cdot A} \quad (4.81a)$$

where  $\Delta MR^F$  and  $m_{dry}^F$  represent the difference in moisture ratio experienced by the felt and its dry mass, respectively.

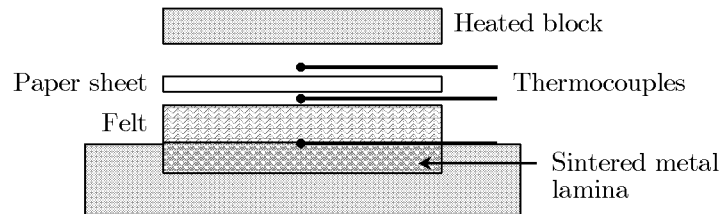


Figure 4.27: Schematic illustration of the mat consisting of a felt and a paper sample, with inserted thermocouples.

Paper samples made from different pulp types, with different grammages and

refining levels were used to test the water retention capacity of the felts under study. Their characteristics are summarized on Table 4.7. This procedure aims also to evaluate the amount of water expressed from the different paper samples into the felt, and study the influence of temperature and initial moisture ratio of the paper samples on that parameter.

Table 4.7: Paper samples characteristics.

| Pulp type           | Grammage<br>[g.m <sup>-2</sup> ] | Refining level<br>[°SR] | Initial moisture content<br>[%] |
|---------------------|----------------------------------|-------------------------|---------------------------------|
| Eucalyptus globulus | 60, 80                           | 25, 40                  | 60-70                           |
| Pinus pinaster      | 60, 80                           | 25, 40                  | 60-70                           |

In addition, the properties of the felt samples tested in the present study are listed on Table 4.8. The initial thickness of the felt samples is presented here as a reference value since it depends on the number of compression/decompression cycles imposed to the samples. Being so, it was decided to present the values obtained during the first thickness measurement, *i.e.* the initial value observed during the first impulse drying experiment operated on each felt sample. In the subsequent experiments the actual felt thickness was measured and used in the calculations to obtain the actual density of the felt samples as well as the thickness profiles.

Table 4.8: Properties of the felt samples used to evaluate the water uptake rate.

| Felt No. | Grammage<br>[g.m <sup>-2</sup> ] | Incompressible<br>thickness<br>[mm] | Initial<br>thickness<br>[mm] | Felt No.  | Grammage<br>[g.m <sup>-2</sup> ] | Incompressible<br>thickness<br>[mm] | Initial<br>thickness<br>[mm] |
|----------|----------------------------------|-------------------------------------|------------------------------|-----------|----------------------------------|-------------------------------------|------------------------------|
| 249031-1 | 1460                             | 1.289                               | 4.038                        | 249031-7  | 1395                             | 1.224                               | 4.004                        |
| 249031-2 | 1289                             | 1.131                               | 3.776                        | 249031-8  | 1282                             | 1.125                               | 3.853                        |
| 249031-3 | 1507                             | 1.322                               | 3.660                        | 249031-9  | 1194                             | 1.047                               | 3.510                        |
| 249031-4 | 1341                             | 1.176                               | 3.765                        | 249031-10 | 1338                             | 1.174                               | 3.952                        |
| 249031-5 | 1448                             | 1.270                               | 3.990                        | 249031-11 | 1366                             | 1.198                               | 3.665                        |
| 249031-6 | 1393                             | 1.222                               | 3.660                        | 249031-12 | 1405                             | 1.232                               | 3.660                        |

## Results and discussion

The moisture ratio of the felt samples was determined before and after the impulse drying experiment. For that purpose, the samples were weighted at both stages

of the test and finally placed in an oven at 40 °C to determine the dry mass of the samples. The moisture ratio was then determined as the amount of water present in the felt sample divided by its dry mass.

It is worth noting that extensive data was collected from the experimental results, and for that reason a representative case will be presented hereafter. The remaining results are listed on Tables E.1 to E.24 in **Appendix E**. Among the operating conditions tested in the present work, those corresponding to the most extreme situation in terms of temperature were selected, *i.e.* when samples were pressed at 350 °C. The results are summarized on Table 4.9 and refer to felt samples numbered from 1 to 6 and 60 g.m<sup>-2</sup> paper samples made from *Eucalyptus globulus* pulp refined at 25 °SR.

Table 4.9: Moisture ratio of the felt samples prior and after the impulse drying event.

| T = 25 °C |                               |                               | T = 350 °C |                               |                               |
|-----------|-------------------------------|-------------------------------|------------|-------------------------------|-------------------------------|
| Felt No.  | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.   | MR <sub>in</sub>              | MR <sub>out</sub>             |
|           | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |            | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1  | 0.13774                       | 0.13928                       | 249031-1   | 0.13771                       | 0.17727                       |
| 249031-2  | 0.16820                       | 0.16896                       | 249031-2   | 0.16820                       | 0.20965                       |
| 249031-3  | 0.12930                       | 0.13089                       | 249031-3   | 0.12933                       | 0.16870                       |
| 249031-4  | 0.16454                       | 0.16645                       | 249031-4   | 0.16443                       | 0.20075                       |
| 249031-5  | 0.14823                       | 0.15355                       | 249031-5   | 0.14827                       | 0.18558                       |
| 249031-6  | 0.14712                       | 0.15440                       | 249031-6   | 0.14722                       | 0.16402                       |

Although the results presented on the previous table serve only as an example, it is worth noting that the remaining cases, at least for the hardwood samples, all show the same trend in terms of temperature dependency. In fact, it was observed an increase in felt's moisture ratio with increasing temperature, which means that more water was removed from the paper sample. For the cases in which softwood paper samples were pressed together with the felt, the trend is not so clear. This is even more notorious observing Figures 4.28 and 4.29 where the water uptake rate per unit area is plotted against temperature for paper samples with different grammages and refining levels. There, it is clear an increase of the water uptake rate per unit area, *i.e.* the amount of water retained by the felt per unit area in a given period of time, with increasing temperature.

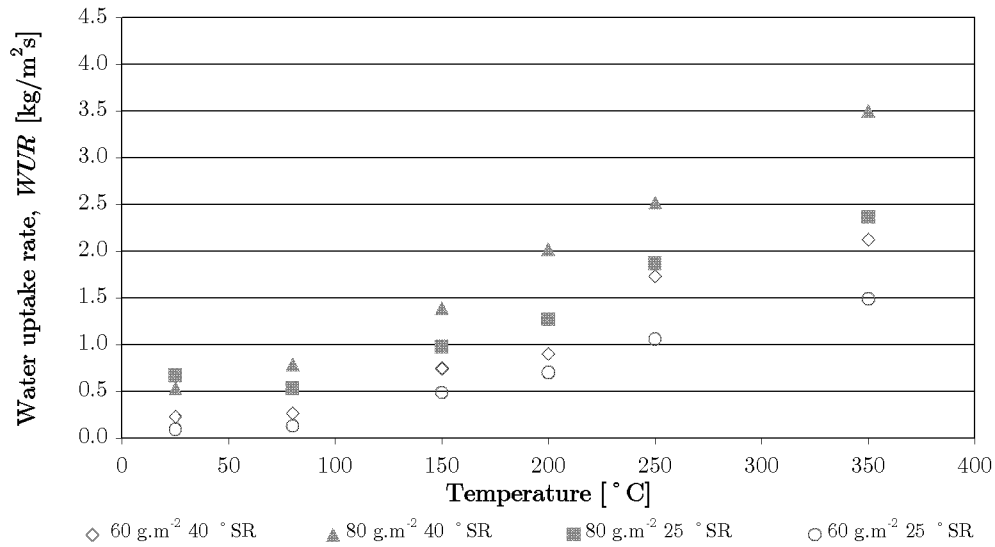


Figure 4.28: Water uptake rate per unit area as a function of temperature for hardwood paper samples of different grammages and refining levels.

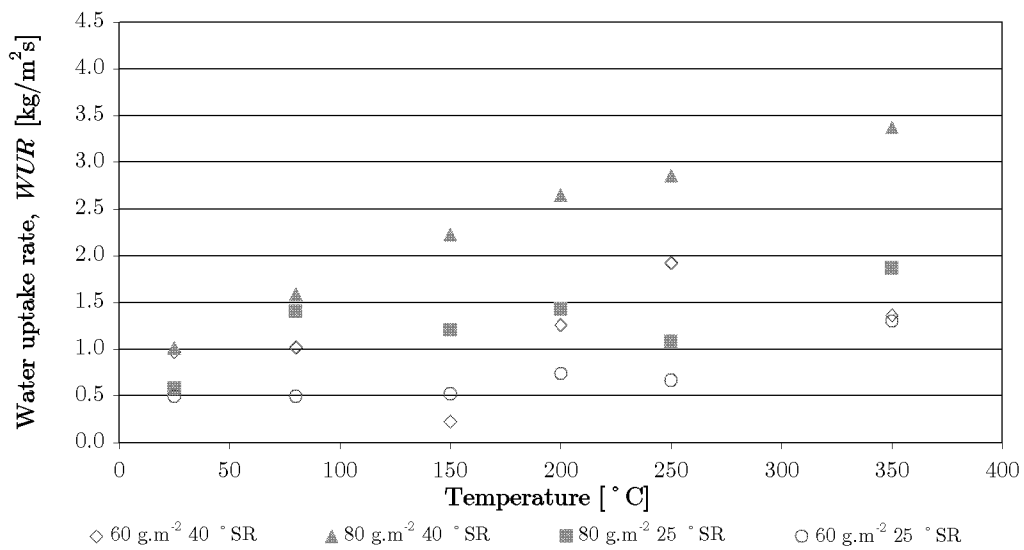


Figure 4.29: Water uptake rate per unit area as a function of temperature for softwood paper samples of different grammages and refining levels.

The results illustrated in Figures 4.28 and 4.29 follow a very similar trend to those presented in **Chapter 2** (see Figures 2.32 and 2.33) expressing the

*total* water removal rate per unit area for different paper grades. In fact, water removal rate clearly increases with temperature and refining level, following the same trend as dryness increase, but the main idea to retain here is that sheets with the same moisture ratio and higher grammage have more water available to be removed.

The analysis is not so easy for the case where *Pinus pinaster* paper samples were used. The felt water uptake rate does not follow a clear tendency with increasing temperature, with the exception for the case where 80 g.m<sup>-2</sup> 40 °SR paper sheets were used (again see Figures 2.33 and 4.29). Although water uptake rate remains higher for heavy weight sheets pressed at temperatures ranging from room temperature to about 200 °C, the results become scattered for higher temperatures. Still, paper sheets beaten to a higher extent present higher water removal rates, which follows the trend presented also for *Eucalyptus globulus* paper. As previously, the behavior of *Pinus pinaster* paper samples is ascribed to some runnability problems with the platen press when operating at 150 °C and above.

Figures 4.30, 4.31, 4.32 and 4.33 reinforce the conclusions presented above, *i.e.* water uptake rate depends greatly on the ingoing moisture ratio of the paper samples. A trend of decreasing water uptake rate for decreasing ingoing moisture ratio was observed, which is explained by the lower amount of water available. Additionally, if the ingoing moisture ratio is close to the water retention value, it could be expected that water removal would be less as most of the water is bound to the fiber structure and is therefore not so easily removed. Instead, at higher temperature and ingoing moisture ratio, the amount of water in the interstitial space is higher and easily removed as the web becomes more conformable and the water viscosity is reduced, which facilitates water removal. Therefore, more water is pressed towards the felt.

As expected, higher water uptake rates were achieved for higher Schopper-Riegler degrees and grammages, as more water is available to be removed. Although somewhat scattered, the data for softwood paper samples still present a similar behavior to that of hardwood samples (see Figure 4.33).

If one now evaluates the water fraction taken by the felt from the paper web at different operating temperatures, it is not possible to draw a firm conclusion on the influence of both temperature and ingoing moisture ratio of the paper



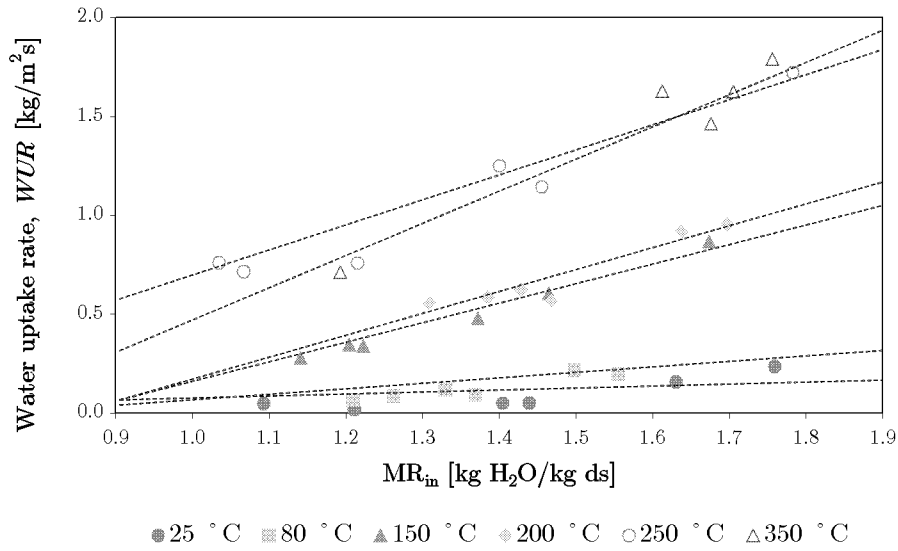


Figure 4.30: Water uptake rate per unit area versus ingoing moisture ratio for 60  $\text{g.m}^{-2}$  *Eucalyptus globulus* paper at various temperatures. Refining level 25 °SR.

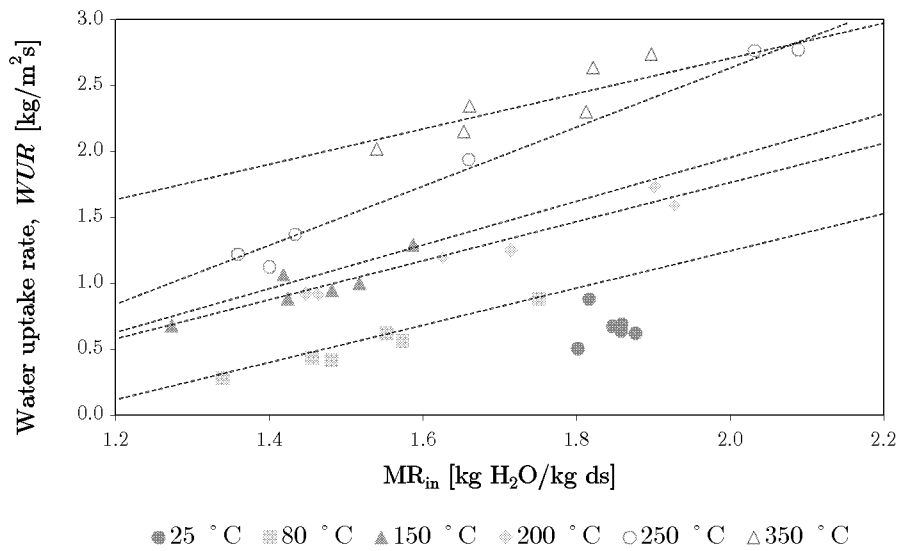


Figure 4.31: Water uptake rate per unit area versus ingoing moisture ratio for 80  $\text{g.m}^{-2}$  *Eucalyptus globulus* paper at various temperatures. Refining level 25 °SR.

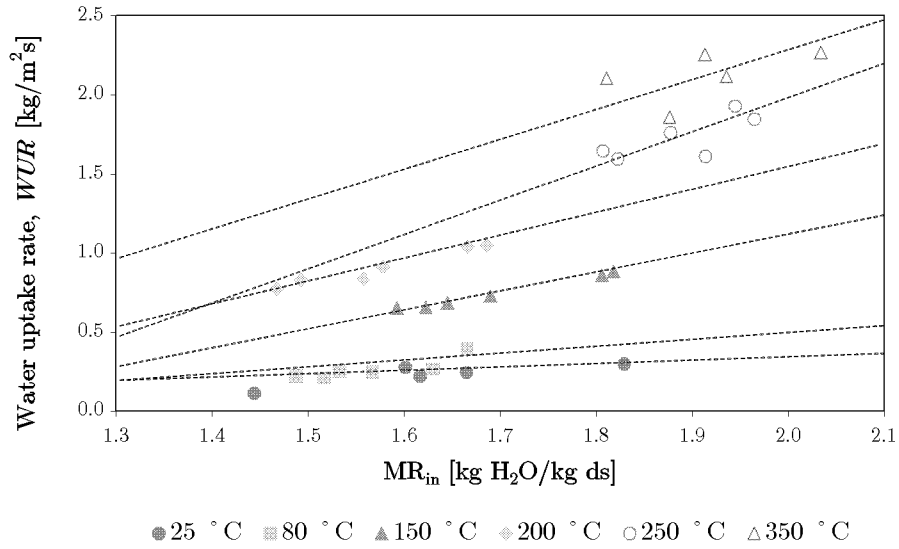


Figure 4.32: Water uptake rate per unit area versus ingoing moisture ratio for  $60 \text{ g.m}^{-2}$  *Eucalyptus globulus* paper at various temperatures. Refining level 40 °SR.

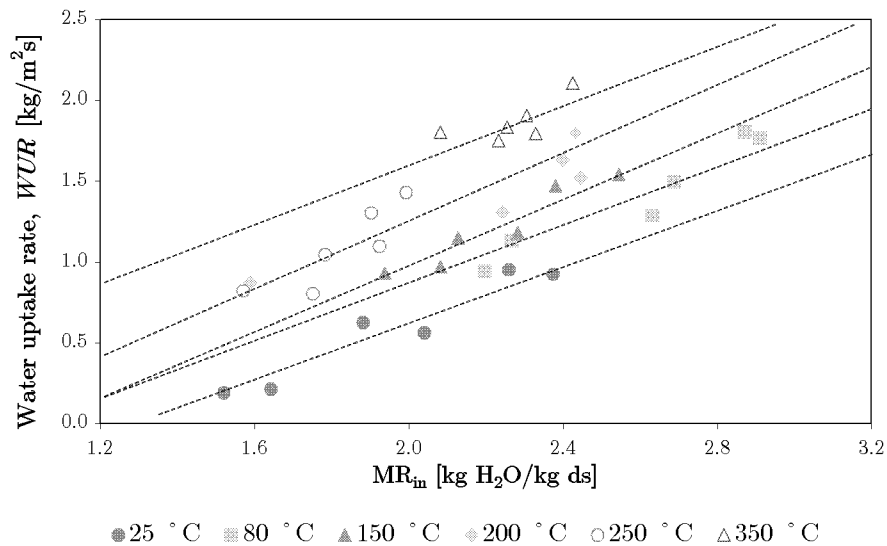


Figure 4.33: Water uptake rate per unit area versus ingoing moisture ratio for  $80 \text{ g.m}^{-2}$  *Pinus pinaster* paper at various temperatures. Refining level 25 °SR.

samples. However, it seems to exist two distinct regions that characterize different water removal mechanisms. In fact, this is clearly observed in Figures 4.34, 4.35 and 4.36. Here, the ratio  $WUR/WR_{tot}$ , expressed in %, was plotted against the ingoing moisture ratio of the paper samples and for increasing temperature levels. This representation gives an idea of the amount of water that is retained by the felt and what is removed due to temperature effects. A remark that is worth to note is that the fraction of water taken by the supporting felt is, in fact, higher for increasing ingoing moisture ratios. This is confirmed by the results obtained for  $60 \text{ g.m}^{-2}$  and  $80 \text{ g.m}^{-2}$  softwood paper samples made from *Eucalyptus globulus* pulp beaten to 25 °SR, for which the amount of water taken by the supporting felt lies between 14 and 74 %, and 37 and 83 % of the total water removed from the paper sample, respectively. Additionally, for  $60 \text{ g.m}^{-2}$  softwood paper samples made from *Eucalyptus globulus* pulp beaten to 40 °SR values in the range of 35 to 80 % were obtained. However, if one tries to find a relation between this ratio and the grammage and refining level of the paper samples no clear picture can be draw. In fact, it seems there is almost no dependence of dewatering rate on the refining level and grammage, as the water removal rate depends mainly on the roll surface temperature, the press load and the ingoing moisture content [22].

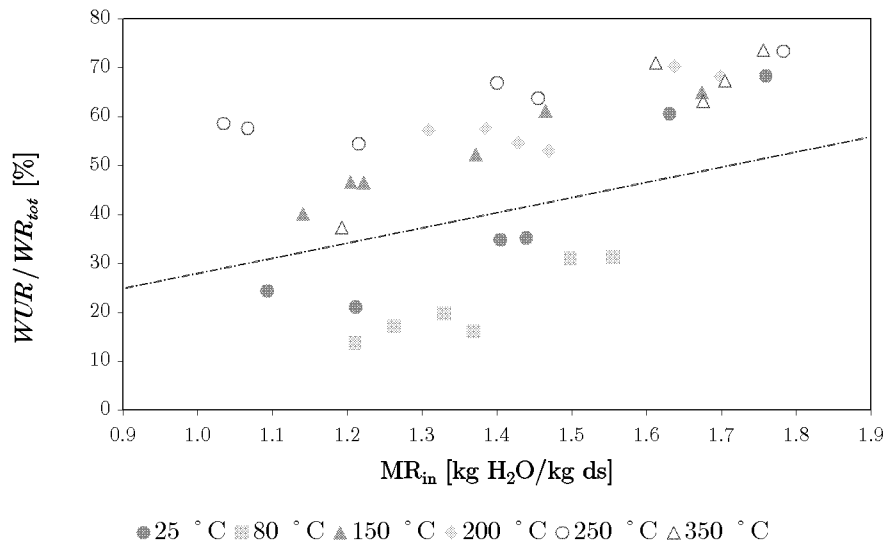


Figure 4.34: Contribution of the supporting felt for the total water removal rate per unit area, as a function of temperature and ingoing moisture ratio of  $60 \text{ g.m}^{-2}$  25 °SR *Eucalyptus globulus* paper samples.

Another important remark is that, for a given operating temperature, the water fraction taken by the felt increases with the amount of water available within the paper sample, and this is verified even at high temperatures, which means that the preferred mode for water removal is the flow of water out from the paper sample towards the felt. Temperature seems to play a less important role in water removal, at least for the present operating conditions.

Moreover, for a given moisture ratio level, an increase in temperature leads to a higher water uptake rate by the supporting felt. However, this is only notorious if one compares what happens at temperatures below and above 80 °C, approximately. In fact, there is a clear separation of the trend lines at this temperature level, except for some data obtained at 25 °C which may have been overdetermined (see Figures 4.35 and 4.36). Observing Figures 4.34, 4.35 and 4.36, one may say that for a given moisture level, there is no significant differences among the results obtained at those high temperatures. This suggests that the increase of the total water removal rate with temperature results not only from the evaporation effect but also from the enhanced consolidation of the material due to water viscosity reduction and increased conformability of the cellulosic network.

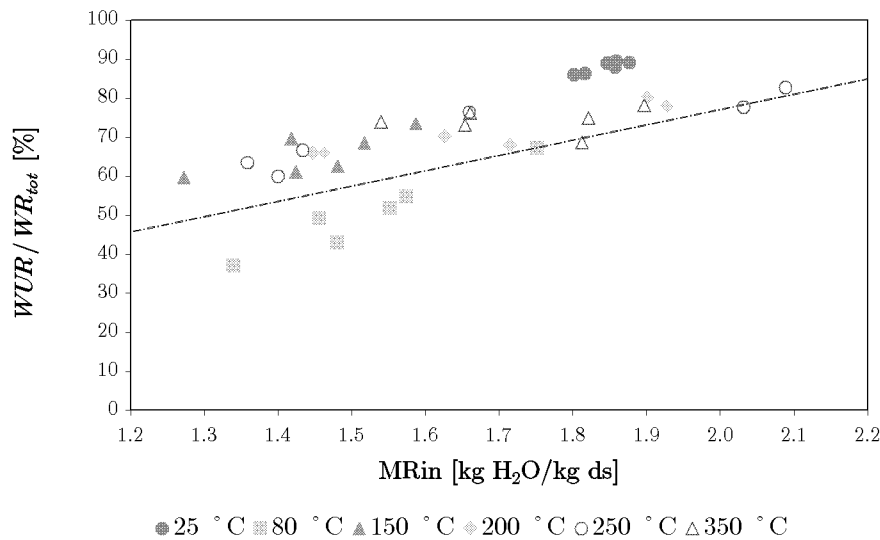


Figure 4.35: Contribution of the supporting felt for the total water removal rate per unit area, as a function of temperature and ingoing moisture ratio of 80 g.m<sup>-2</sup> 25 °SR *Eucalyptus globulus* paper samples.

Nevertheless, the results also indicate that the amount of water leaving the paper samples is mostly taken by the supporting felt even at high temperatures. This is not surprising, as part of the evaporated water is trapped within the paper sheet during the pressing event and may occasionally leave the sheet towards the press felt, thus contributing to the its water uptake capacity (this is most notorious in Figure 4.36).

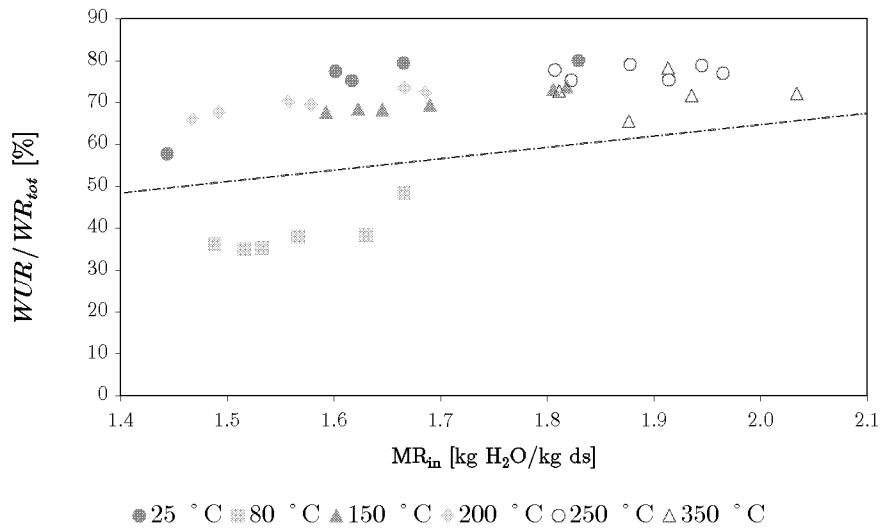


Figure 4.36: Contribution of the supporting felt for the total water removal rate per unit area, as a function of temperature and ingoing moisture ratio of 60 g.m<sup>-2</sup> 40 °SR *Eucalyptus globulus* paper samples.

### 4.3.2 Evaluation of the effect of some operating conditions on the consolidation process of felt in the press nip. Presentation of some experimental results.

This section aims to present some typical experimental results obtained from the impulse drying tests performed in the laboratory press, and also to study the effect of the operating conditions such as temperature, applied stress and pulse shape on the mechanical response of the material, *i.e.* the supporting felt. To accomplish this, a set of experiments performed at different operating conditions, and representative of the experiments, was selected. As no significant differences

in behavior were found between the felt samples, the results presented hereafter refer mainly to felt sample No. 249031-12.

As described in **Chapter 2**, during the impulse drying experiments the felt samples were submitted to a press pulse similar to those operated in a roll-press-nip. The pulse lengths and peak pressures typically used are listed in Table 4.10, together with the remaining operating conditions and felt physical properties.

Table 4.10: Felt properties and operating conditions in impulse drying experiments.

| Felt No.  | Grammage<br>[g.m <sup>-2</sup> ] | Incompressible<br>thickness<br>[mm] | Initial<br>thickness<br>[mm] | MR <sub>in</sub><br>[kg H <sub>2</sub> O/kg ds] | Temperature<br>[°C]           | Pulse length<br>[ms] | Peak Pressure,<br>$\sigma_0$ [MPa] |
|-----------|----------------------------------|-------------------------------------|------------------------------|-------------------------------------------------|-------------------------------|----------------------|------------------------------------|
| 249031-12 | 1405                             | 1.232                               | 3.660                        | $\approx$ 0.15                                  | 25, 80, 150,<br>200, 250, 350 | $\approx$ 30         | $\approx$ 5-6                      |

The results obtained from the compression event under typical operating conditions for felt No. 249031-12 are presented hereafter. It should be mentioned that each operating condition was tested at least four times, and each experiment was evaluated separately as the pressure profiles differ slightly from one test to another.

In this study, the transient temperatures of the heated plate and at the top surface of the felt sample undergoing compression were measured, as well as the applied pressure and the corresponding thickness evolution of the felt sample. Figure 4.37 illustrates the results obtained for felt No.249031-12 pressed at 350 °C. The peak pressure reached 5.2 MPa and the nip length was 31 ms. Moreover, the initial thickness of the sample was 3.660 mm and its ingoing moisture ratio was 0.1491 kg H<sub>2</sub>O/kg ds.

The temperature of the heated plate was set to 350 °C and it remained almost constant throughout the pressing event, although a slight decrease would be expected at the moment of contact with the felt sample that was at room temperature. In fact, the thermocouple that monitored the temperature of the heated plate was not sufficiently close to the outer surface contacting the felt samples. Therefore, in the subsequent discussion of temperature profiles it will be assumed that this is the real temperature of the contacting surface.

As for the temperature evolution on the top surface of the sample some remarks should be made. Firstly, the temperature recorded at the moment of

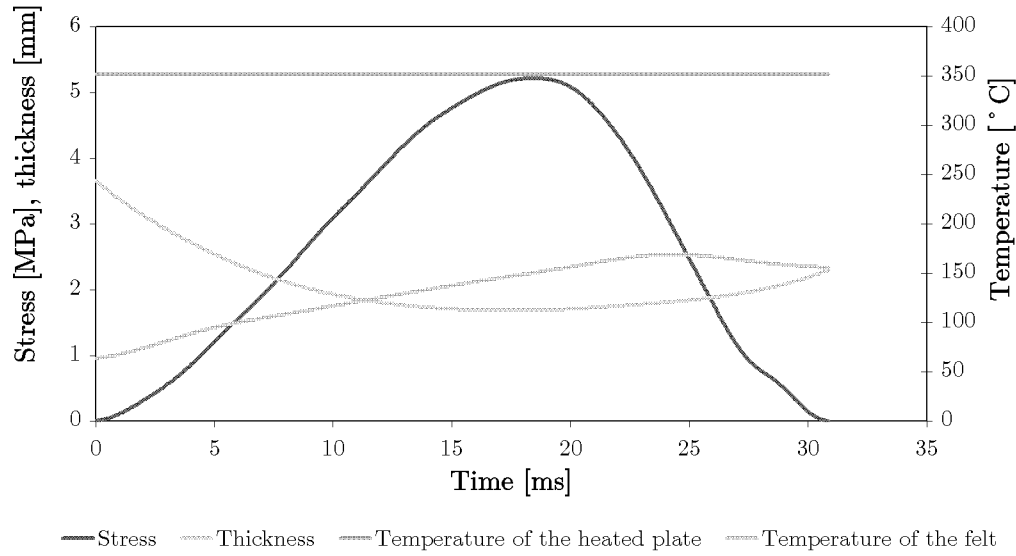


Figure 4.37: Time evolution of pressure, felt thickness, and temperature both on the heated plate and on the top surface of the felt sample No. 249031-12.

contact is about 64 °C, which is relatively high and may be explained by the exposure of the sample, and consequently the microthermocouple placed on its top surface, to the extremely high temperature of the heated plate during the few milliseconds prior to nip closing. Another reason for such high temperature at the initial stage of the pressing event relates to the time zero definition itself. As previously explained in **Chapter 2**, the moment of contact was assumed to be that corresponding to a certain level of pressure exerted on the nip. Therefore, the felt sample is in fact contacting the heated surface prior to the moment that is set as the beginning of the pressing event. Figure 4.37 also shows a gradual increase of temperature on the surface of the sample, reaching a maximum of about 170 °C after 24 ms. Afterwards, there is a slight decrease of temperature corresponding to the final decompression phase.

Most of the previous research has been focused on the pressure release control in order to prevent web delamination. Some authors [28], [25], [30], suggest that during impulse drying water in the web is heated and pressurized so that it exists as a subcooled liquid just prior to nip opening or eventually some milliseconds before it. The increasing compression rates used in impulse drying cause an increase in hydraulic pressure, which tends to shift the boiling point of water

and prevents steam generation. As the nip is opened, the water inside the web continues to be heated by contact with the hot surface while experiencing a sudden drop in applied pressure. Steam is then generated by flashing and can be partially vented through the backing material only. As more heat is added to the steam trapped inside the web, the steam becomes superheated and a sudden increase in temperature near the hot plate is expected (as already discussed in **Chapter 3**). When load is completely removed and nip opens, the steam near the top surface of the sample may now escape towards the hot plate.

As shown in Figure 4.37, with a pulse length of approximately 31 ms, no clear evidence of steam generation was found during the pressing event. It is speculated that the amount of liquid water within the felt sample is probably too low to generate steam enough to produce a measurable property change. However, local steam generation may actually take place within the fibrous network as the hydraulic pressure generated should not be sufficiently high to prevent phase change. In addition, the typical temperature increase at the end of the impulse pressing event for high grammage paper webs was not observed. As previously discussed, Petrini [30] reported peak temperatures as soon as the applied pressure is released. However, his data refer to wet paper samples of 120, 200 and 300 g.m<sup>-2</sup> pressed with a 28 ms extended press pulse at 300 °C. Moreover, Lucisano [25] found the same behavior for SBK sheets with grammage of 500 g.m<sup>-2</sup>, although the experiments were performed with somewhat longer press pulses. None of the authors reported peaks in the internal temperature when working with samples with grammage lower than 120 g.m<sup>-2</sup>. In the present case, however, the internal structure of the material facilitates the water flow both in the thickness direction and through the lateral edges of the sample. In fact, the felt samples have a quite low apparent density, around 0.35 kg.m<sup>-3</sup>, which means that liquid water or steam may eventually escape from the region near the hot plate towards the sintered metal plate. Then, it would not be surprising the absence of peak temperatures, as water would probably not be trapped in the hot region. Obviously, this analysis only makes sense if one considers that the temperature measured on the top surface of the felt sample is somehow representative of what happens in the felt layer closest to the interface with the heated plate. In fact, this assumption is not totally unreal if one considers the extremely small dimensions of the thermocouples used in the present work. On the basis of the experimental results it is suggested that the metal junction of the thin ther-



mocouple is in fact measuring the temperature at the outer layer of the felt and not the temperature at the interface line. Otherwise, the recorded temperature would be significantly higher.

The following figures intend to highlight some particular details concerning the mechanical behavior of the felt samples submitted to the extreme conditions of impulse drying. Figures 4.38, 4.39 and 4.40 compare two press pulses and the corresponding felt responses to compression. The fibrous mat showed to be highly compressible as at the point of maximum pressure the thickness of the samples had reduced to approximately half of its initial value. This compression behavior was already observed in the quasi-static compressibility tests performed with the permeability test device (see Figure 4.13).

Comparing Figures 4.38 and 4.39, one observes that the point of minimum thickness arises slightly after the point of maximum applied pressure as predicted by Wahlström [43]. However, the present understanding of pressing mechanisms is that the consolidation of a wet porous web may be compression restricted or, on the other hand, controlled by fluid flow across the medium, according to the analogy illustrated in Figure 3.2 (**Chapter 3**). The experimental results thus suggest that the dominating carrier of the press load is the fiber network, although the fluid contribution cannot be neglected, which explains the slight time delay.

Figure 4.40 represents the typical stress-strain (or thickness) diagram for the felt samples used in the present work. The hysteresis observed is characteristic of some porous materials in which fluid flow plays an important role in the consolidation process. In fact, for low moisture ratio webs the applied load is mainly carried by the solid material. Then, as the medium is further compressed a given hydraulic pressure develops within the fluid and forces its way out. From this point on the load is carried by the solid structure and part of the fluid that remained within the porous material. This suggests that even after the point of maximum applied pressure the web may be further compressed to a minimum thickness. In the decompression phase the thickness follows a different trend as the moisture conditions and the porous structure have changed.

From the mathematical modeling point of view this deformation behavior has often been referred to as viscoelastic, although previous experiments tend to emphasize the dominant elastic character of the felts under study. It should be pointed out, however, that the recovery of the felt sample continued for a rather

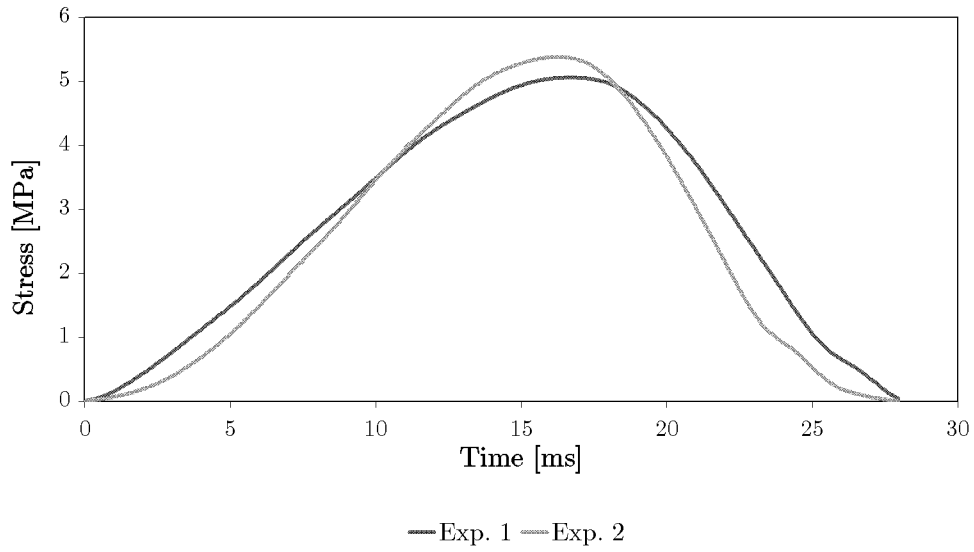


Figure 4.38: Experimental stress pulses applied on felt No. 249031-12 at 150 °C. Peak pressure: (Exp. 1) 5.1 MPa; (Exp. 2) 5.4 MPa.

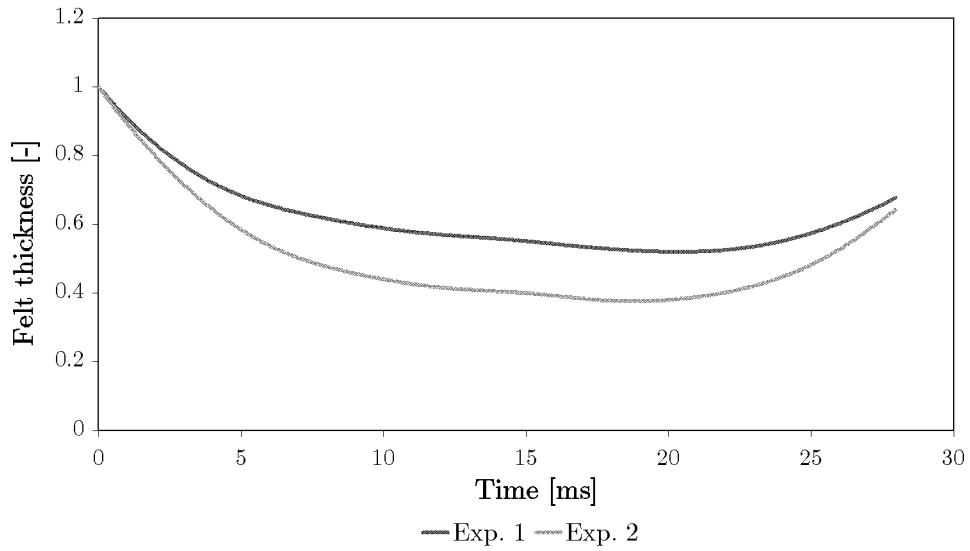


Figure 4.39: Normalized thickness,  $L/L_{z0}$ , of felt No. 249031-12 submitted to press pulses illustrated in Figure 4.38. Minimum thickness: (Exp. 1) 1.902 mm; (Exp. 2) 1.374 mm.

long time after unloading, but this is mainly ascribed to the recovery of the fiber network itself and less to the viscoelastic character of its constituents. On the basis of these findings, it seems reasonable to consider a viscoelastic approach in the development of the mechanical model for this material, as explained further ahead in the text.

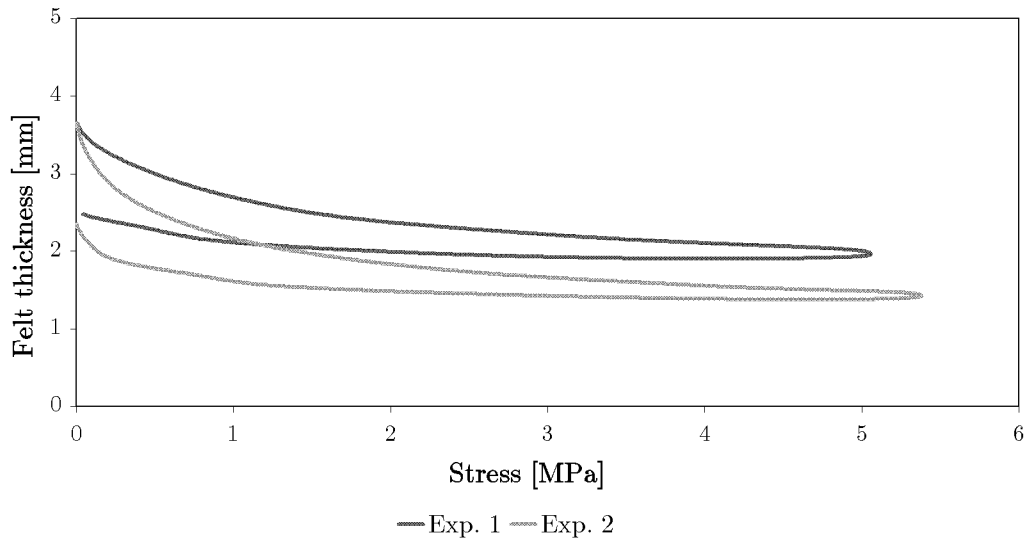


Figure 4.40: Hysteresis behavior of felt thickness against applied stress. The curves refer to data presented in Figures 4.38 and 4.39 for felt sample No. 249031-12 pressed at 150 °C.

Additionally, it is clear that the strain not only depends on the applied stress, but also on the history of the compression. Figure 4.41 shows different pressure pulses with approximately the same peak pressure and pulse length. The influence of pulse shape in the mechanical response of the material is clearly seen in Figure 4.42. In fact, the higher stress rate imposed to the felt during the initial stage of the pressure pulse (Exp. 3) induces an increase in felt resistance to compression. As a result the minimum normalized thickness attained in Exp. 3 is significantly higher than those observed during Exp. 1 and 2 (see Figure 4.42), which correspond to very similar pressure pulses. In fact, increasing the stress rate, the fluid may not have enough time to escape from the network, which means that the trapped air and water may then contribute to the increased compression resistance of the material. This stress-strain behavior emphasizes, once more, the importance of flow resistance in addition to the fiber mat resistance to

compression.

Additionally, Exp. 1 and 2 described in Figure 4.41 were performed with the felt sample No. 249031-D, which has lower density than felt No. 249031-12 although of higher initial thickness (see Figure 4.43). This too could partially explain the difference in the stress-strain behavior, as a denser fibrous mat tends to be more compression resistant. It is believed, however, that this reason alone could not explain such difference in behavior.

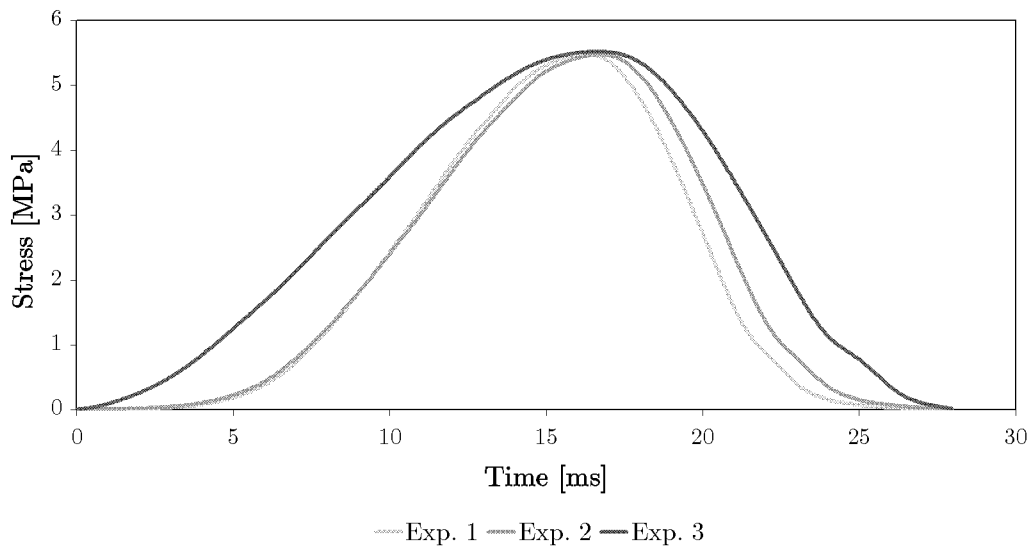


Figure 4.41: Experimental stress pulses applied on felts No. 249031-12 (dark blue line) and 249031-D (red and green lines) at 200 °C. Peak pressure: (Exp. 1) 5.5 MPa; (Exp. 2) 5.5 MPa; (Exp. 3) 5.5 MPa.

The effect of temperature on the dynamic compression behavior of the felt was also investigated. For that purpose, some experiments performed at different operating temperatures, but with very similar pressure pulses were selected. Observing the results presented in Figure 4.44 and 4.45 it seems there is no temperature effect on the consolidation of the porous material. However, one cannot draw a firm conclusion in this respect as a few other factors play an important role in the pressing event, such as for instance, felt moisture ratio, local grammage and pulse shape. Unfortunately, no other set of experiments performed with the same felt sample gave so similar pressure pulses at different temperatures, which makes it difficult to evaluate the temperature effect under the present operating conditions.

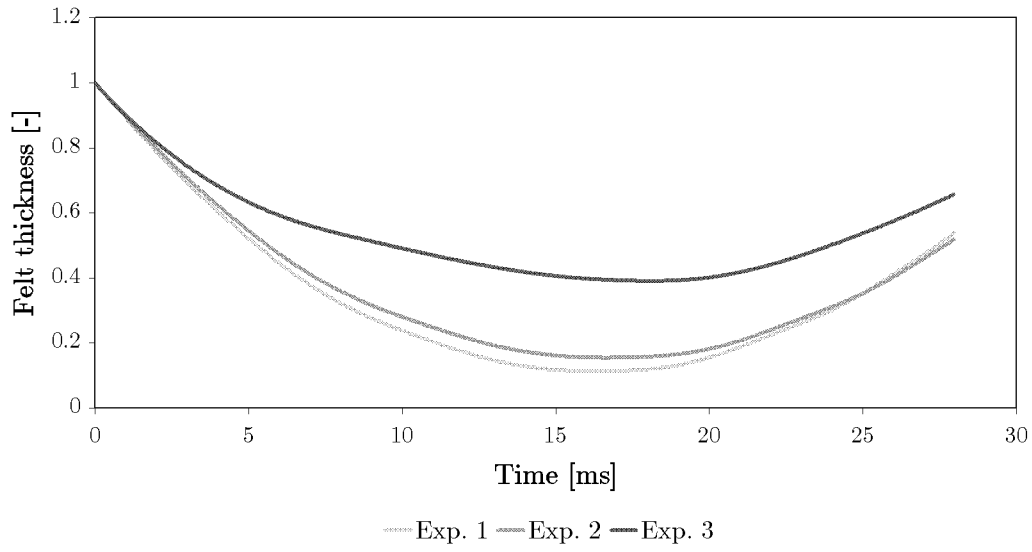


Figure 4.42: Normalized thickness,  $L/L_{z_0}$ , of felts No. 249031-12 (dark blue line) and 249031-D (red and green lines) submitted to press pulses illustrated in Figure 4.41. Minimum thickness: (Exp. 1) 0.453 mm; (Exp. 2) 0.620 mm; (Exp. 3) 1.426 mm.

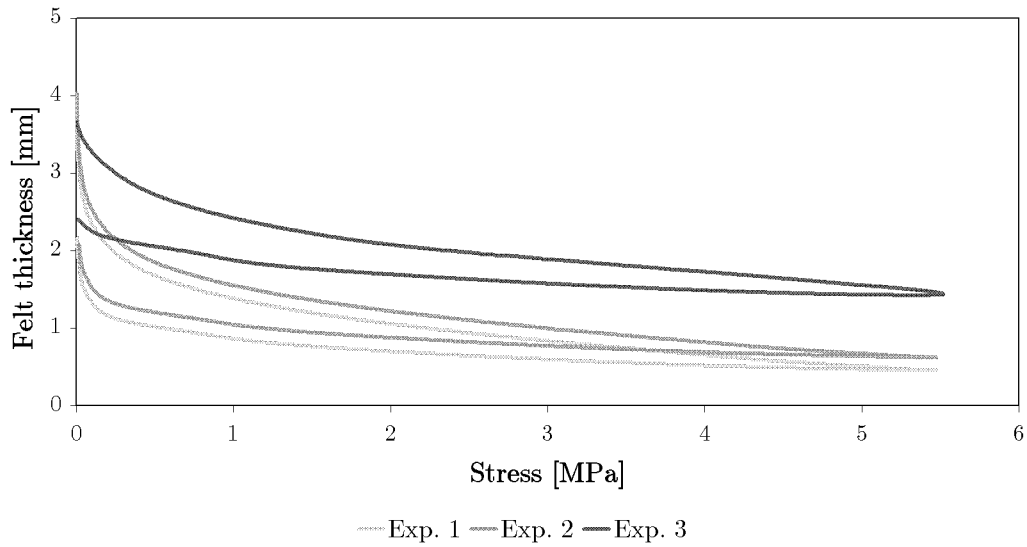


Figure 4.43: Hysteresis behavior of felt thickness against applied stress. The curves refer to data presented in Figures 4.41 and 4.42 for felt samples No. 249031-12 (dark blue line) and 249031-D (red and green lines) pressed at 200 °C.

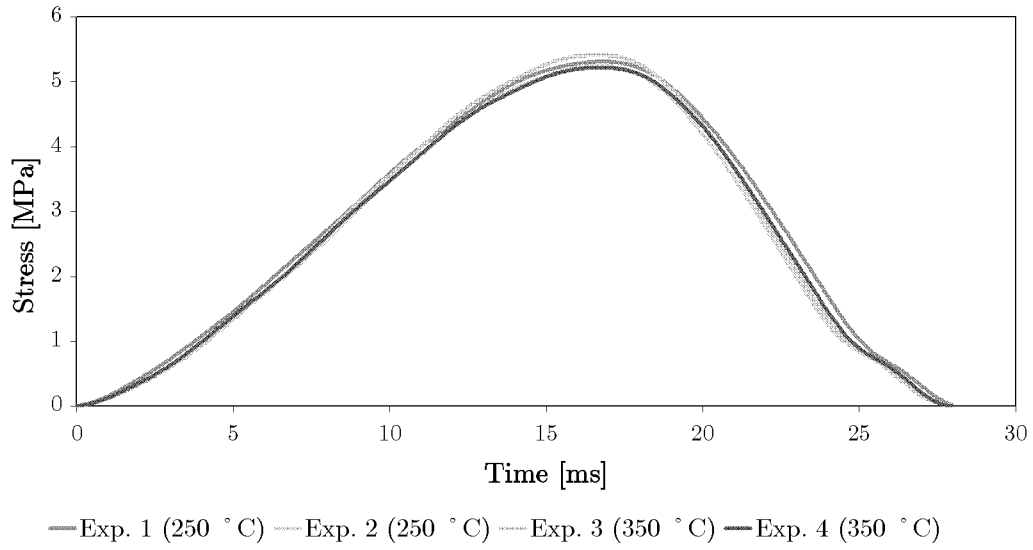


Figure 4.44: Experimental stress pulses applied on felt No. 249031-12 at 250 °C and 350 °C. Peak pressure: (Exp. 1) 5.3 MPa; (Exp. 2) 5.2 MPa; (Exp. 3) 5.4 MPa; (Exp. 4) 5.2 MPa.

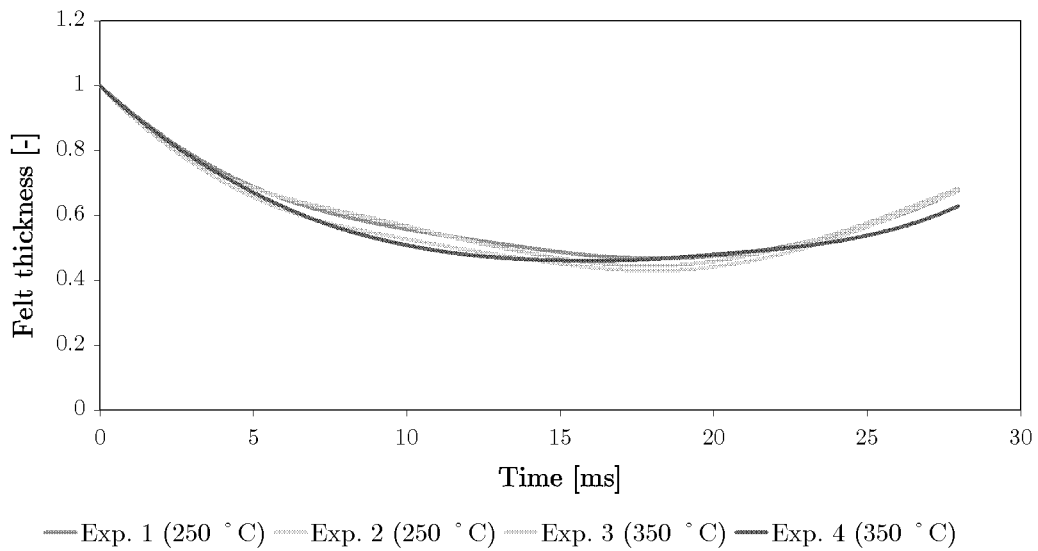


Figure 4.45: Normalized thickness,  $L/L_{z0}$ , of felt No. 249031-12 submitted to press pulses illustrated in Figure 4.44. Minimum thickness: (Exp. 1) 1.711 mm; (Exp. 2) 1.570 mm; (Exp. 3) 1.626 mm; (Exp. 4) 1.684 mm.

Finally, Figure 4.46 is presented here just to compare the stress-strain behavior of felt sample No. 249031-12, pressed at 250 and 350 °C, to that observed at lower operating temperatures, *i.e.* 150 and 200 °C (see Figure 4.40 and 4.43 - Exp. 3). Although there are no clear findings about the temperature effect on mat compression, the response of the material follows a somewhat well defined pattern. In fact, during the compression phase of the pressing event the material deforms to a minimum thickness of about 1.5 mm, and this level of strain is observed in all the experiments in which the maximum applied stress was above 5.1 MPa. However, the unloading phase shows some dissimilarities in felt's behavior: at 150 °C there is a thickness plateau in the early stage of decompression; as the temperature increases this plateau tends to disappear, which may indicate a faster recovery of the mat. At the end of the pressing event the recorded thickness of the felt sample was approximately the same for all the experiments, *i.e.*  $\simeq 2.5$  mm, which indicates an average permanent strain around 30 %. However, after load release the mat continues to expand, thus reducing the permanent strain.

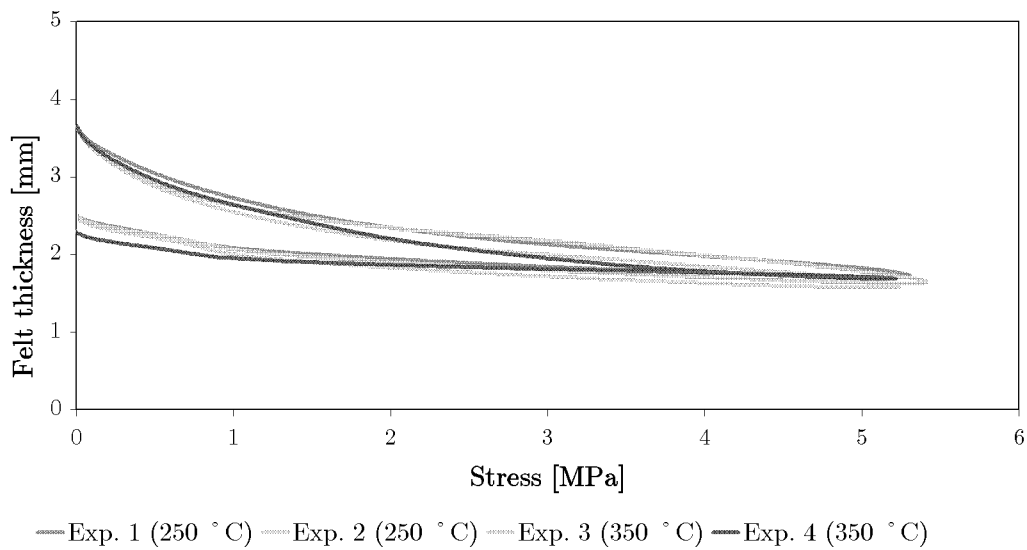


Figure 4.46: Hysteresis behavior of felt thickness against applied stress. The curves refer to data presented in Figures 4.44 and 4.45 for felt sample No. 249031-12 pressed at 250 and 350 °C.

## 4.4 A mechanical model for felt in impulse drying

A mechanical model for felt in compression is required in order to be able to estimate its deformation when subjected to impulse drying. Such information may then be integrated into a global model comprising both paper and felt compression behavior in a press nip. The scope of this work is to understand the fiber network rheological behavior under uniaxial compression, to develop a mathematical model able to describe the observed behavior with the help of some measurable variables such as felt thickness, applied stress and moisture and temperature conditions and, finally, to verify if the theoretical model can be used to predict the felt behavior under different pressing conditions.

Due to the viscoelastic nature of the material that constitute the felts used in modern paper machines, and also its network structure close to that of a cellular solid, it seems reasonable to follow the approach used to model the mechanical behavior of paper. Although the viscous parameter found in the rheological tests performed with the Métravib apparatus is not of great significance, its effect will be taken into account in the mechanical model. Being so, a viscoelastoplastic model was used to represent the uniaxial compression of the felts under study in the present work.

Similarly to what was done for paper, the effect of some model parameters on the mechanical response of the felt will be studied. For that purpose, the heat and mass transfer will only be included in the model in a subsequent stage of the study. For the moment, the influence of such parameters will be analyzed in terms of thickness evolution of the felt as well as its density profile in the thickness direction. The validation of the model will be performed using the results obtained from the compression tests carried out to simulate impulse drying, as explained in **Chapter 2** and **Section 4.3.2**.

The assumptions made to model the behavior of paper under uniaxial compression are considered to be valid for the mechanical model of the felt, except the assumptions referring to both elastic and viscous parameters of the felt constituent, *i.e.* nylon. In fact, the temperature and moisture dependence was not taken into account when estimating either the elasticity modulus or the viscous parameter of nylon. Instead, the experimental values obtained from the rheologi-



cal tests performed with the rheometer Métravib were used (see **Section 4.2.2**). In order to estimate the rheological parameters of each individual control domain, it is assumed that felt is formed by nylon fibers, liquid water removed from the paper/felt interface and an ideal mixture of air and water vapor.

Following the same procedure as that used to derive the partial time derivative equations of the mechanical model for paper, the constitutive equations of the model for felt may be summarized as follows, where the superscript “ $F$ ” refers to the felt:

$$\frac{\partial \mathbf{z}_{ijk}^F}{\partial \theta} = \frac{\Delta \mathbf{z}_0^F}{2\mathbf{L}_z^F} \left( \frac{\partial \varepsilon_{ijk}^F}{\partial \theta} + 2 \sum_{l=1}^{k-1} \frac{\partial \varepsilon_{ijl}^F}{\partial \theta} \right) - \frac{\mathbf{z}_{ijk}^F}{\mathbf{L}_z^F} \frac{\partial \mathbf{L}_z^F}{\partial \theta} \quad (4.82a)$$

$$\text{where } \frac{\partial \varepsilon_{ijk}^F}{\partial \theta} = \frac{1}{\mathbf{H}_0^F \left( \mathbf{E}_{ijk}^F + \varepsilon_{ijk}^F \cdot \frac{\partial \mathbf{E}_{ijk}^F}{\partial \varepsilon_{ijk}^F} \right)} \frac{\partial \boldsymbol{\sigma}_{ij}^F}{\partial \theta} + \frac{\mathbf{V}_0^F}{\boldsymbol{\mu}_{ijk}^F} \cdot \boldsymbol{\sigma}_{ij}^F \quad (4.82b)$$

$$\text{Initial condition} \quad : \quad \theta = 0; \quad \varepsilon_{ijk}^F = 0; \quad \mathbf{z}_{ijk}^F = \frac{k - 0.5}{N_k^F}. \quad (4.82c)$$

$$\frac{\partial \boldsymbol{\sigma}_{ij}^F}{\partial \theta} = \mathbf{H}_0^F \mathbf{E}_{ij}^F \frac{\partial \mathbf{L}_z^F}{\partial \theta} - \mathbf{H}_0^F \mathbf{V}_0^F \frac{\mathbf{E}_{ij}^F}{\boldsymbol{\mu}_{ij}^F} \boldsymbol{\sigma}_{ij}^F \quad (4.83a)$$

$$\text{Initial condition} \quad : \quad \theta = 0; \quad \boldsymbol{\sigma}_{ij}^F = 0; \quad \mathbf{L}_z^F = 1. \quad (4.83b)$$

$$\frac{\partial \mathbf{L}_z^F}{\partial \theta} = \frac{1}{\mathbf{H}_0^F \mathbf{E}_T^F} \frac{\partial \boldsymbol{\sigma}_T^F}{\partial \theta} + \frac{\mathbf{V}_0^F}{\boldsymbol{\mu}_T^F} \boldsymbol{\sigma}_T^F \quad (4.84a)$$

$$\text{Initial condition} \quad : \quad \theta = 0; \quad \mathbf{L}_z^F = 1. \quad (4.84b)$$

As in the case of paper, the dependent variables are the vertical position,  $z_{ijk}^F$ , the compressive stress in each column,  $\sigma_{ij}^F$ , and the thickness of the felt,  $L_z^F$ .

**Numerical solution** The numerical solution of the resulting set of equations was obtained according to the procedure adopted for the resolution of the paper mechanical model. The spatial discretization followed the same approach of control domains: one fourth of the web was discretized in 1000 points, 10 in each direction, each grid point corresponding to a control domain. The C++-based subroutine built for this case used the same parameters as those selected for the

mechanical model for paper. However, the resolution of the present PDEs showed to be less time consuming, as some physical properties of the felt were taken as constants, thus reducing the complexity of the problem.

**Results and discussion** The mechanical model was used to predict the evolution of thickness, elastic and viscous moduli and density, in time and at any given position inside a felt sample. Several simulation runs were carried out and in each case the applied pressure pulse recorded in the experiment (see Figure 4.47) was used as an input to the model. The results presented hereafter correspond to a typical compression event performed at room temperature. Once more, the objective here was to test the applicability of the cellular solids approach to the estimation of the mechanical properties of felts. The effect of temperature will therefore be evaluated in the integrated model presented in **Chapter 5**.

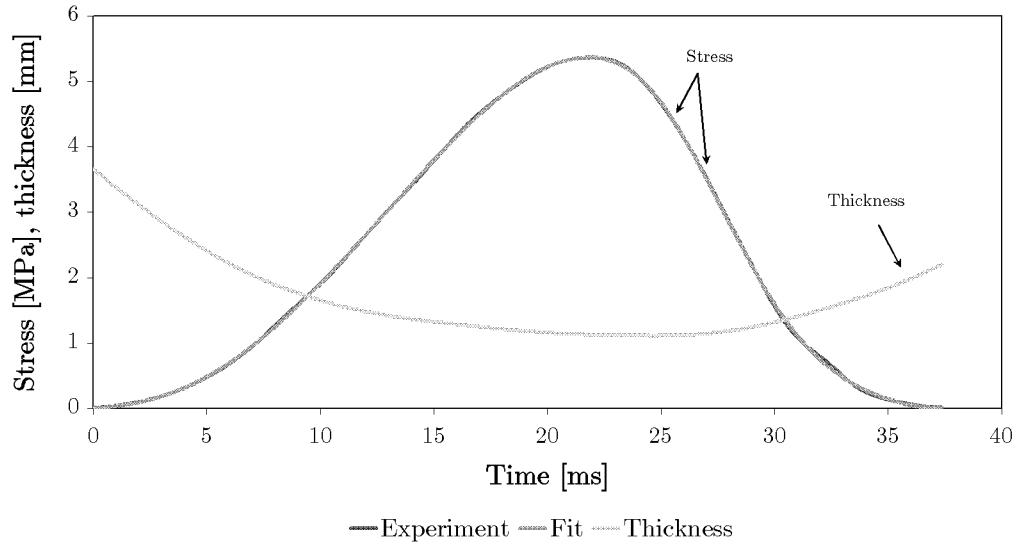


Figure 4.47: Stress pulse imposed to a felt No. 249031-12. Temperature:  $\approx 25$  °C; pulse length: 37 ms; peak pressure: 5.3 MPa; moisture ratio: 0.18 kg H<sub>2</sub>O/kg ds.

The experimental stress pulse was fitted to the following expression:

$$\sigma_T = \begin{cases} \sigma_0 (fp_0 + fp_1.\theta + fp_2.\theta^2 + \dots + fp_5.\theta^5 + fp_6.\theta^6) & \theta < \theta_m \\ \sigma_0 (fp_7 + fp_8.\theta + fp_9.\theta^2 + \dots + fp_{12}.\theta^5 + fp_{13}.\theta^6) & \theta \geq \theta_m \end{cases} \quad (4.85)$$

where  $\theta$  is the dimensionless time and  $\theta_m$  correspond to the point of maximum stress. The fitting parameters are summarized on Table 4.11 and the main operating conditions used in the experiments on Table 4.12. For simplicity, the results presented hereafter will be expressed in terms of dimensionless time defined as time divided by its corresponding value at the point of maximum applied stress. Additional felt characteristics are given on Table 4.13.

Table 4.11: Stress fitting parameters

| Fitting parameters |              |              |               |              |               |             |
|--------------------|--------------|--------------|---------------|--------------|---------------|-------------|
| $fp_0$             | $fp_1$       | $fp_2$       | $fp_3$        | $fp_4$       | $fp_5$        | $fp_6$      |
| 0                  | 0.182921     | 1.267666     | 28.139506     | -88.460746   | 111.906331    | -61.962560  |
| $fp_7$             | $fp_8$       | $fp_9$       | $fp_{10}$     | $fp_{11}$    | $fp_{12}$     | $fp_{13}$   |
| 651.602095         | -5202.952054 | 17088.374554 | -29497.289576 | 28237.901987 | -14232.784514 | 2955.153220 |

Table 4.12: Operating conditions used in the simulation runs.

|                                  |                                    |
|----------------------------------|------------------------------------|
| Temperature of the pressing head | $T_p = 25\text{ }^{\circ}\text{C}$ |
| Pulse length                     | $\tau = 37\text{ ms}$              |
| Peak pressure                    | $\sigma_0 = 5.3\text{ MPa}$        |
| Pulse shape                      | Roll                               |

Table 4.13: Felt properties used in the simulation runs

|                         |                                              |
|-------------------------|----------------------------------------------|
| Initial thickness       | $L_{z_0} = 3.660\text{ mm}$                  |
| Initial moisture ratio  | $MR_{in} = 0.18\text{ kg H}_2\text{O/kg ds}$ |
| Grammage                | $Gr = 1507.5\text{ g.m}^{-2}$                |
| Density of nylon fibers | $\rho_{nylon} = 1141\text{ kg.m}^{-3}$       |
| Bound water             | $y_b = 5\%$                                  |

The performance of the mechanical model was evaluated in terms of thickness evolution of the felt sample, its density, gas pressure, water liquid volume fraction and elastic modulus. It should be remembered that, at this stage of the model development, no property gradients in the thickness direction of the felt are expected as the heat and mass transfer is not included. As for the estimation of the elasticity modulus of each representative volume element, the micromechanical approach used for paper was also used here to determine the elastic parameters for felt. *i.e.*, the solid (nylon fibers + bound water), liquid and gas phases are assembled in parallel.

Similar to what was done for paper, the influence of some model parameters on the mechanical behavior of felts was evaluated by performing a series of simulation runs using the C<sup>++</sup>-based subroutine included in **Appendix F**. For that purpose different values of the viscous parameter and fiber elasticity modulus were considered in the analysis. Once more, the contribution of the liquid phase to the elasticity modulus of the composite was not overseen.

The influence of the above mentioned parameters and material properties is presented hereafter.

- The effect of fiber viscous parameter

The influence of the viscous parameter on the performance of the viscoelastoplastic model for felt was studied by performing a series of simulation runs using two different values of  $\mu_{nylon}$ : (i) that obtained from the experiments carried out with the rheometer Métravib,  $\mu_{nylon} = 2.5$  MPa.s and (ii) a lower value,  $\mu_{nylon} = 0.25$  MPa.s. Additionally, the elasticity modulus of liquid water used here was  $E_l = 2,068$  MPa (Runs 1 and 2) and  $E_l = 0.25 \times 206.8$  MPa (Run 3).

It is then clear from Figures 4.48 and 4.49 that the viscous parameter of the nylon fibers plays an important role in the consolidation of the mat. In fact, Run 1 shows almost no deformation, whereas in Run 2 the thickness of the web decreases to a minimum value after the point of maximum stress and remains constant till the end of the press pulse. In the later case no web expansion is observed as pressure is released. This viscous behavior is more pronounced when the water elasticity modulus is decreased (Run 3; with  $\mu_{nylon} = 2.5$  MPa.s). As liquid water offers less resistance to compression the web deforms to a higher extent, but when the minimum thickness is attained it follows the same trend as in Run 2. It seems clear though that even for the highest value of  $\mu_{nylon}$  the mechanical behavior of the mat is predominantly affected by the presence of water. It should be pointed out however that if the mass transfer was to be considered here, the mat would probably expand at the end of the press pulse as a result of moisture ratio decrease. Bearing this in mind, it seems reasonable to consider  $\mu_{nylon} = 2.5$  MPa.s in the subsequent simulation runs, as it gives thickness profiles closer to those observed in the experiments.

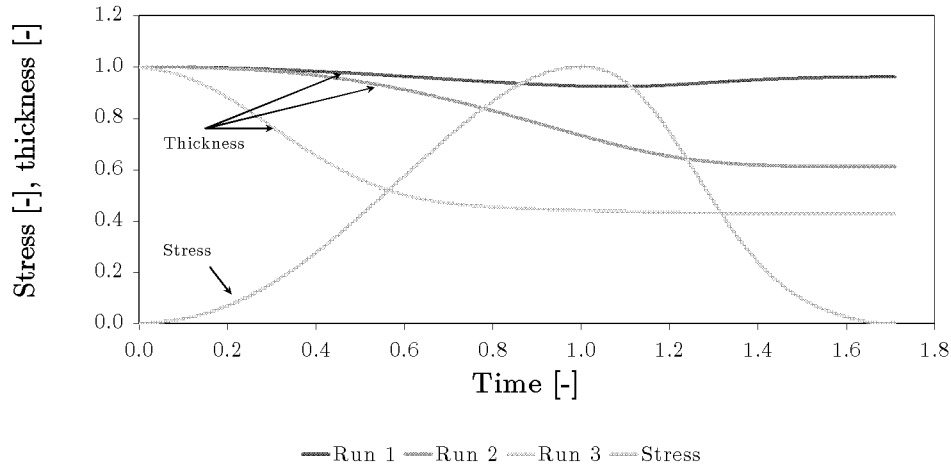


Figure 4.48: Applied stress and predicted thickness evolution for felt No. 249031-12 at 25 °C. The results were obtained for different values of the viscous parameter  $\mu_{nylon}$  and water elasticity modulus  $E_l$ . Run 1:  $\mu_{nylon} = 2.5$  MPa.s,  $E_l = 2,068$  MPa; Run 2:  $\mu_{nylon} = 0.25$  MPa.s,  $E_l = 2,068$  MPa; Run 3:  $\mu_{nylon} = 2.5$  MPa.s,  $E_l = 0.25 \times 206.8$  MPa. Additional parameters:  $C_2 = 0.5$ ;  $MR_{in} = 0.18$  kg H<sub>2</sub>O/kg ds;  $E_s = 6.66$  MPa.

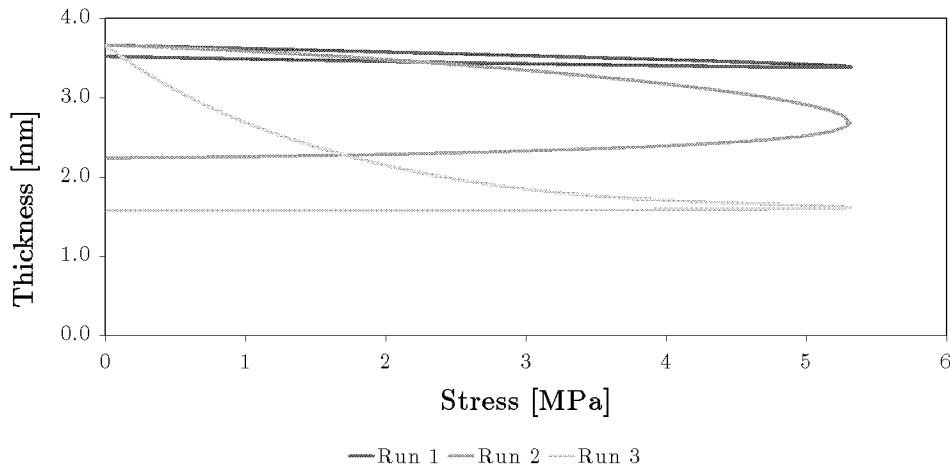


Figure 4.49: Predicted stress-strain behavior for felt No. 249031-12 at 25 °C. The results were obtained for different values of the viscous parameter  $\mu_{nylon}$  and water elasticity modulus  $E_l$ . Run 1:  $\mu_{nylon} = 2.5$  MPa.s,  $E_l = 2,068$  MPa; Run 2:  $\mu_{nylon} = 0.25$  MPa.s,  $E_l = 2,068$  MPa; Run 3:  $\mu_{nylon} = 2.5$  MPa.s,  $E_l = 0.25 \times 206.8$  MPa. Additional parameters:  $C_2 = 0.5$ ;  $MR_{in} = 0.18$  kg H<sub>2</sub>O/kg ds;  $E_s = 6.66$  MPa.

- The effect of water elasticity modulus

In order to evaluate the effect of water elasticity modulus, the mechanical behavior of the felt sample was simulated setting  $E_l = 2,068$  MPa (Run 6 in Figure 4.50),  $0.15 \times 2,068$ ,  $0.1 \times 2,068$ ,  $0.075 \times 2,068$ ,  $0.05 \times 2,068$ , and  $0.025 \times 2,068$  MPa (Run 1 in Figure 4.50). Similarly to what was found for paper, this parameter has a significant influence on the mechanical response of the felt material, as illustrated in Figures 4.50 to 4.55. In terms of thickness, similar trends were observed, except for the lowest value of  $E_l$  (Run 1), which gave the highest strain levels. As already mentioned, the influence of  $E_l$  is most notorious in terms of its contribution to the elasticity modulus of the composite. Figure 3.41 in **Chapter 3** shows clear evidence of that. The elasticity modulus of the composite is significantly lower for the lowest value of  $E_l$ .

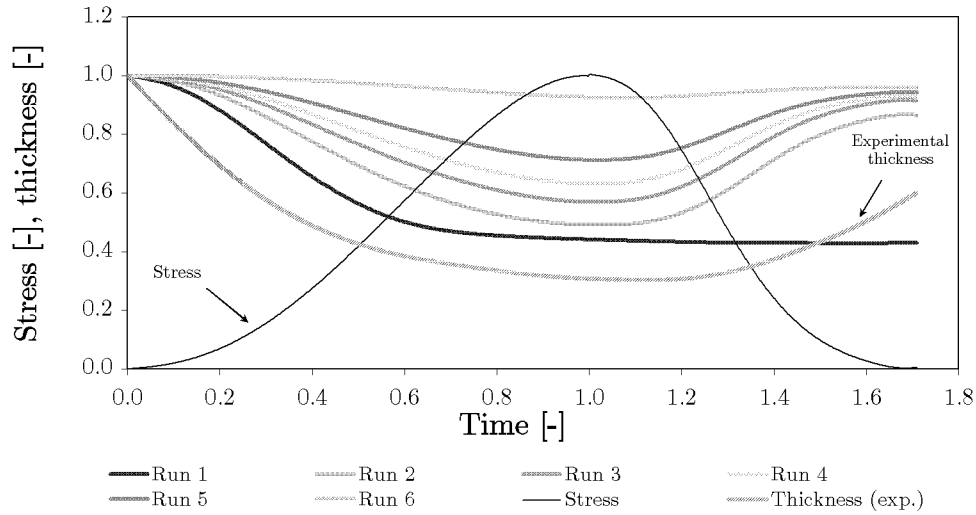


Figure 4.50: Applied stress and predicted thickness evolution for felt No. 249031-12 at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 1:  $E_l = 0.025 \times 2,068$  MPa; Run 2:  $E_l = 0.05 \times 2,068$  MPa; Run 3:  $E_l = 0.075 \times 2,068$  MPa; Run 4:  $E_l = 0.1 \times 2,068$  MPa; Run 5:  $E_l = 0.15 \times 2,068$  MPa; Run 6:  $E_l = 2,068$  MPa. Additional parameters:  $C_2 = 0.5$ ;  $MR_{in} = 0.18$  kg H<sub>2</sub>O/kg ds;  $E_s = 6.66$  MPa;  $\mu_{nylon} = 2.5$  MPa.s. The experimental thickness profile is presented here for comparison.

At the mid-nip the modulus is also affected by the increase of the gas pressure. This rise in pressure is ascribed to the entrapment of gas inside the porous mater-

ial. It should be remembered that no heat or mass transfer is being considered at this point of the work, and that the simulation results cannot accurately describe the materials behavior. It only serves as a first approach to the integrated model presented in **Chapter 5**.

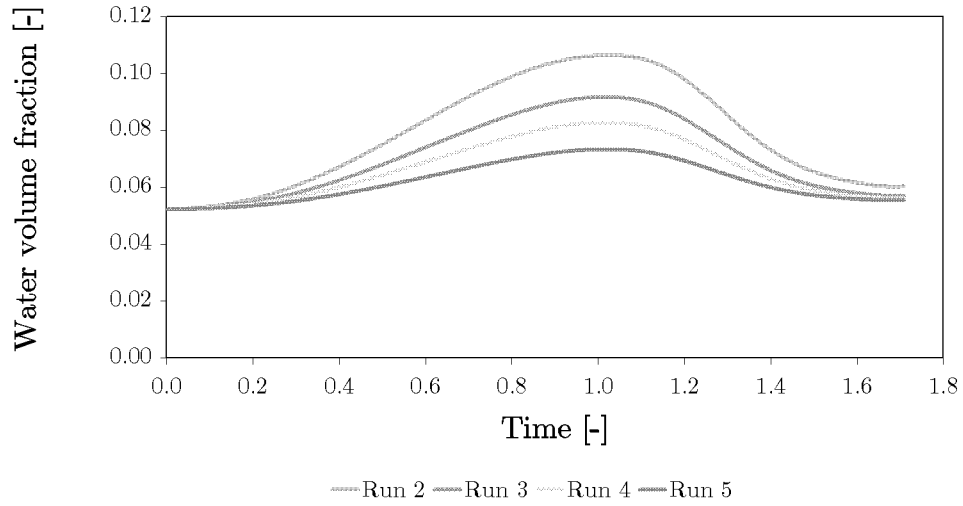


Figure 4.51: Predicted water volume fraction evolution for felt No.249031-12 at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 2:  $E_l = 0.05 \times 2,068$  MPa; Run 3:  $E_l = 0.075 \times 2,068$  MPa; Run 4:  $E_l = 0.1 \times 2,068$  MPa; Run 5:  $E_l = 0.15 \times 2,068$  MPa. Additional parameters:  $C_2 = 0.5$ ;  $MR_{in} = 0.18$  kg H<sub>2</sub>O/kg ds;  $E_s = 6.66$  MPa;  $\mu_{nylon} = 2.5$  MPa.s.

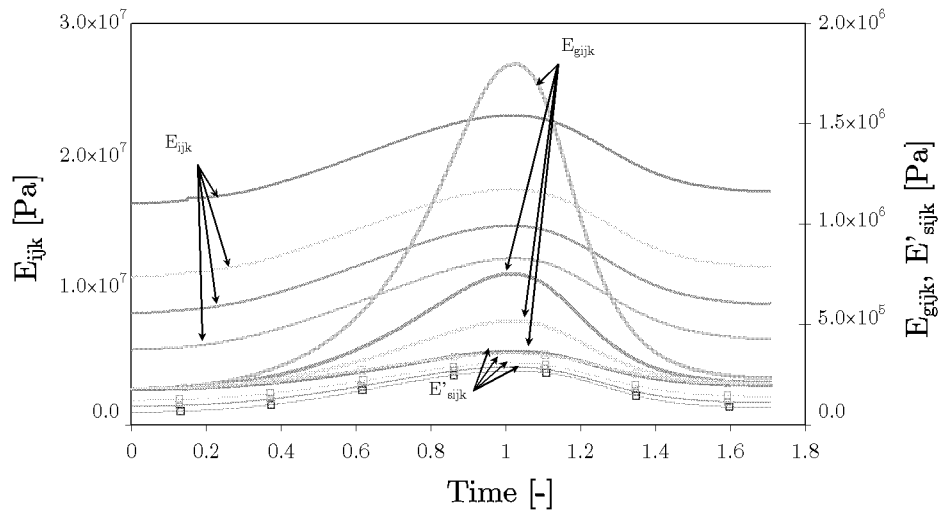


Figure 4.52: Predicted contribution of the gas and solid phases to the elastic parameter of felt No. 249031-12 pressed at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 2 (blue):  $E_l = 0.05 \times 2,068$  MPa; Run 3 (red):  $E_l = 0.075 \times 2,068$  MPa; Run 4 (orange):  $E_l = 0.1 \times 2,068$  MPa; Run 5 (green):  $E_l = 0.15 \times 2,068$  MPa. Additional parameters:  $C_2 = 0.5$ ;  $MR_{in} = 0.18$  kg H<sub>2</sub>O/kg ds;  $E_s = 6.66$  MPa;  $\mu_{nylon} = 2.5$  MPa.s.



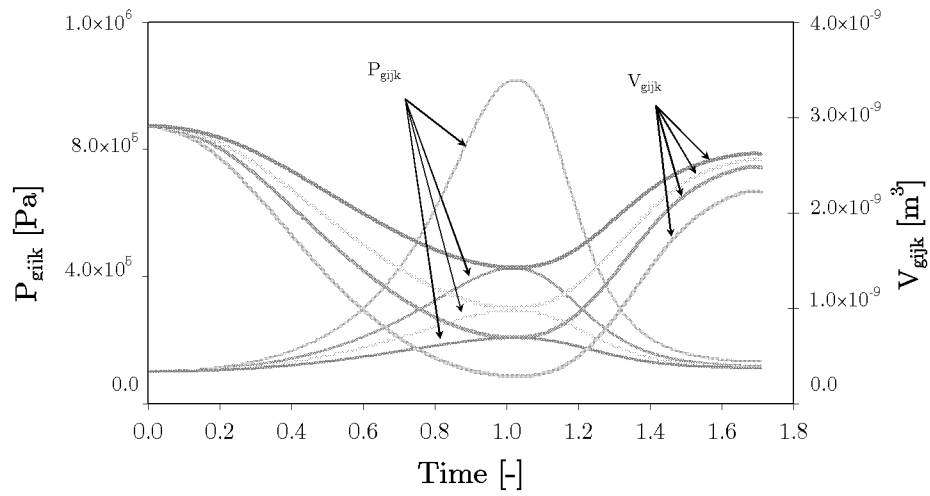


Figure 4.53: Predicted volume of the gas phase and its corresponding pressure inside felt No. 24031-12 during a pressing event performed at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 2 (blue):  $E_l = 0.05 \times 2,068$  MPa; Run 3 (red):  $E_l = 0.075 \times 2,068$  MPa; Run 4 (orange):  $E_l = 0.1 \times 2,068$  MPa; Run 5 (green):  $E_l = 0.15 \times 2,068$  MPa. Additional parameters:  $C_2 = 0.5$ ;  $MR_{in} = 0.18$  kg H<sub>2</sub>O/kg ds;  $E_s = 6.66$  MPa;  $\mu_{nylon} = 2.5$  MPa.s.

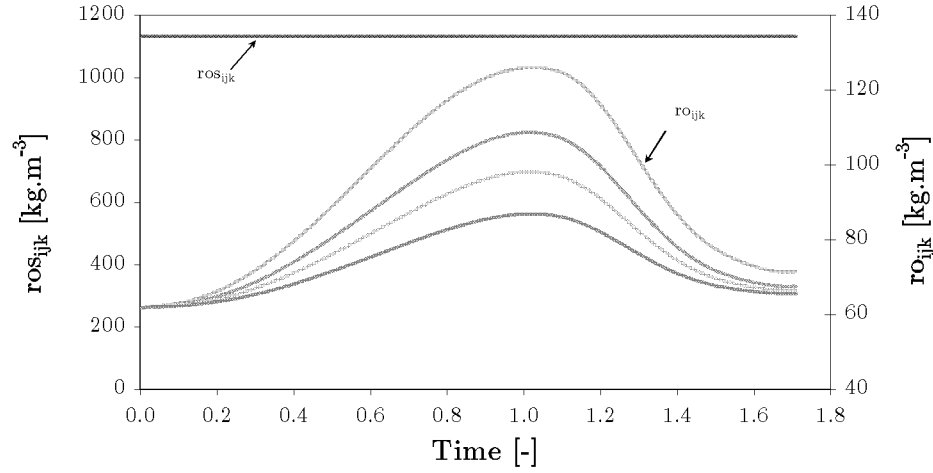


Figure 4.54: Prediction of apparent and solid phase densities of felt No. 24031-12 during a pressing event performed at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 2 (blue):  $E_l = 0.05 \times 2,068$  MPa; Run 3 (red):  $E_l = 0.075 \times 2,068$  MPa; Run 4 (orange):  $E_l = 0.1 \times 2,068$  MPa; Run 5 (green):  $E_l = 0.15 \times 2,068$  MPa. Additional parameters:  $C_2 = 0.5$ ;  $MR_{in} = 0.18$  kg H<sub>2</sub>O/kg ds;  $E_s = 6.66$  MPa;  $\mu_{nylon} = 2.5$  MPa.s.

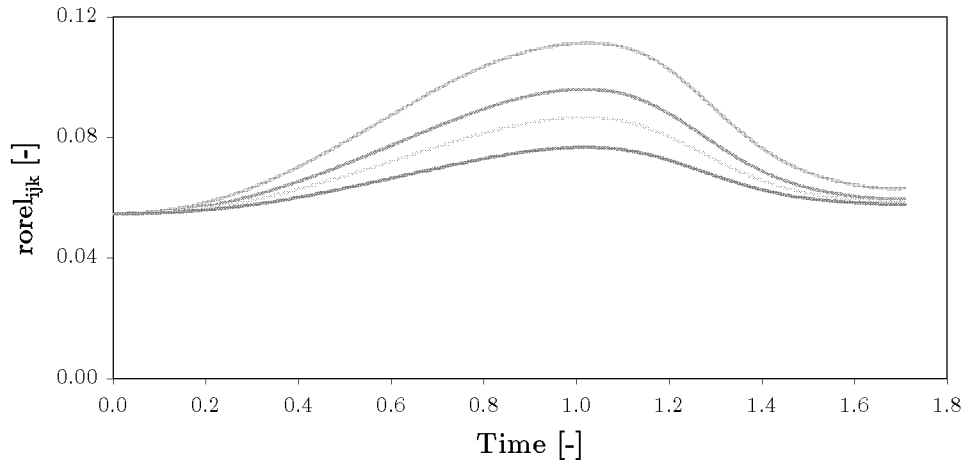


Figure 4.55: Prediction of the relative density of felt No. 24031-12 during a pressing event performed at 25 °C. The results were obtained for different values of the water elasticity modulus  $E_l$ . Run 2 (blue):  $E_l = 0.05 \times 2,068$  MPa; Run 3 (red):  $E_l = 0.075 \times 2,068$  MPa; Run 4 (orange):  $E_l = 0.1 \times 2,068$  MPa; Run 5 (green):  $E_l = 0.15 \times 2,068$  MPa. Additional parameters:  $C_2 = 0.5$ ;  $MR_{in} = 0.18$  kg H<sub>2</sub>O/kg ds;  $E_s = 6.66$  MPa;  $\mu_{nylon} = 2.5$  MPa.s.

**Concluding remarks** A mathematical model of the stress-strain behavior of moist felts was presented here. Model simulations show that the mechanical behavior of the material greatly depends on fiber viscous parameter and water elasticity modulus. Although less water is present than in the case of wet paper webs, the liquid water plays an important role in felt consolidation. Therefore, the correct estimation of its elastic properties would certainly benefit the modeling work. Nevertheless, it was possible to get some insight into the stress-strain behavior of the felt samples under study. The main discrepancies between the experimental data and the simulation results are observed at the early stage of compression and at the end of the decompression phase, where water and gas should be allowed to flow through the porous media. Despite this rough approximation, the model suggests a certain level of strain at mid nip close to that observed experimentally. It is therefore believed that a proper mass transfer model could improve the mathematical description of felt's behavior to dynamic compression.

## 4.5 Conclusions

The present chapter was dedicated to the study of felts especially conceived to operate at high temperature conditions as those used in impulse drying. Although the purpose of the work was not the study of its internal structure and chemical composition, a brief experimental study was performed in respect to its permeability and compressibility as well as to its rheological characteristics. The results from this experimental work were subsequently used in the development of the mathematical models presented in this thesis, namely the transversal permeability, and the rheological parameters obtained from the rheometer Métravib.

From the experimental findings, felt samples are assumed to behave almost as an elastic material, since the viscous parameter is relatively low and the phase angle observed in the rheology experiments is not significant. However, in the presence of moisture the felt behaves more as a viscoelastic solid. This change in behavior is mainly attributed to the additional resistance to compression given by the liquid water. Consequently, felt was assumed to behaved viscoelastically. The permanent strain observed at the end of the compression event is somehow fictitious as the web continues to expand after load has been removed. Nevertheless, the model intends to represent the stress-strain behavior of the material

inside the press nip, and to achieve that goal a certain level of permanent strain has to be considered.

Then, the water uptake rate under extreme operating conditions was evaluated and compared to that of conventional wet pressing. The main conclusion to retain is that felts play a fundamental role in the paper dewatering process, and its water removal capacity is somehow enhanced by increasing the operating temperature.

Finally, a mathematical description of the materials' behavior to dynamic compression was presented. The simulation results obtained for the typical operating conditions of impulse drying in terms of peak pressure and pulse length show some agreement with the experimental results. However, different operating temperatures must be simulated in order to validate the model. Additionally, a proper heat and mass transfer model must be included so that an accurate description of the consolidation of the material may be obtained.

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# Chapter 5

## Global Model

### 5.1 Introduction

After the study of paper in terms of the main heat and mass transfer mechanisms taking place under the extreme operating conditions of impulse drying, together with the analysis of the mechanical behavior of paper and felt, it was important to understand the interaction of these in the press nip of a paper machine. Integrating all the information collected from the experimental work and simulation runs performed in the previous chapters was the fundamental step to the development of a global mechanical model, which includes heat and mass transfer with phase change, for the consolidation process of paper and felt.

In the pressing process in a roll press, the paper web is squeezed together with one or more press felts between two rolls exerting a mechanical pressure on both materials. During the compression phase water will flow from the paper web into the felt forced by a positive hydraulic pressure gradient. At the end of the press nip, when load is being released, the hydraulic pressure gradient will become negative, which may result in some rewetting caused by the back-flow of water and air from the felt to the paper web. Furthermore, if applying a heated press roll an energy flow from the roll to the paper web will be established at the moment the web makes contact with the press roll. Depending on the temperature and pressure conditions imposed to the paper web/felt sandwich steam may be generated inside the paper web and ultimately induce web delamination. It has been shown, however, that proper temperature/pressure control may prevent steam generation in the press nip.

## 5.2 Model development

The global model presented hereafter is based on the same assumptions made for the development of the theoretical models for paper and felt presented in **Chapter 3** and **4**, respectively. The model intends to represent the heat and mass transfer phenomena that may occur inside paper and felt when submitted to the high-intensity conditions of impulse drying, as well as their mechanical behavior under such conditions. In an attempt to simplify the model, it was assumed geometric symmetry, *i.e.* two planes of symmetry were considered, the vertical mid-planes. This simplification implies that the lateral edges of both paper and felt are exposed to the same ambient conditions; only the top and bottom surfaces of the mat are submitted to different operating conditions. Consequently, only one fourth of the total mat needs to be modelled.

The geometry of the calculation domain of the model is shown in Figure 5.1. It consists of a sandwich formed by paper and felt, in contact with the heated platen press. Since the platen press is not included in the calculation domain, its surface temperature was considered constant during the whole process.

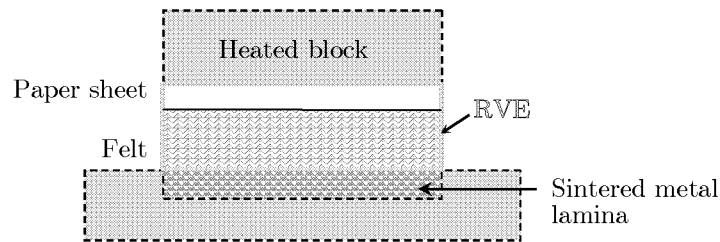


Figure 5.1: Schematic view of the geometry of the model domain.

In the model construction the following assumptions were considered:

- the model is three-dimensional, although the consolidation of the paper web and felt occurs in the thickness direction only, and no lateral deformations are assumed;
- the media are composed of three phases, solid, liquid and gas, and local thermodynamic equilibrium is assumed; any heat and mass transfer resistance among the different phases are neglected;

- the gas phase is formed by air and water vapor that may eventually be generated during the process, and it exists in the extra-fiber pore space; additionally, it behaves as an ideal gas;
- the liquid phase is composed of water; the convective flow of gas and liquid phases are assumed to follow the Darcy's relation;
- the solid phase for paper is formed by cell wall material from the cellulose fibers, additive and water adsorbed on the fiber surface; the effect of fiber swelling due to water adsorption has been neglected; the solid phase for felt is formed by nylon fibers and 5% (kg H<sub>2</sub>O/kg ds) bound water;
- paper and felt are assumed to be isotropic in the in-plane direction;
- the consolidation of the mat is induced by the applied mechanical pressure as the compression event is pressure controlled;
- the physical properties depend on temperature, moisture ratio and local steam pressure; transport properties that are dependent on changing physical properties can also vary with time and space; the mechanical properties (elastic and viscous parameters) also depend on the local temperature and moisture ratio of the material; inside each RVE no property change is assumed;
- although cellulosic fibers may plasticize within the layers near the hot plate, no additional heat transfer resistance is considered;
- the heat transferred to the paper sheet comes, exclusively, from the heated pressing head; no internal heat generation is assumed, which means that the energy transferred from the cure reaction of some additives added to the pulp suspension is neglected;
- moisture can exist in any of the three different phases: a vapor in the gas, as free liquid, or as bound water within the porous solid matrix;
- if free liquid is present (*i.e.* above the fiber saturation point) the vapor and bound phases remain saturated at the local temperature, and the free liquid water is in equilibrium with its saturated vapor; in the absence of liquid (*i.e.* below fiber saturation point), bound water concentration and gas phase composition obey to a sorption isotherm at local temperature;

- the main heat and mass transfer mechanisms are:
  1. ordinary heat conduction between the heated plate surface and the interior layers of the paper (the time of exposure to the heat source is neglected), and to the felt;
  2. convective heat and mass transfer: the driving forces of the water removal mechanism in impulse drying are the pressure and the temperature. The applied pressure results in an hydraulic pressure gradient in the thickness direction of paper causing a compression and a water flow, which in turn is enhanced by increasing the temperature of the web. Also, the higher temperature of the heated plate compared to that of the paper web causes a heat flux into the sheet. This heats up the water and the fiber network, and when the temperature is equal to the saturation temperature at the corresponding hydraulic pressure, vapor is formed. The pressure gradient between the surface and the core of the web results in a flow of heat and vapor to the inner layers of the web, thus increasing its temperature. As a positive pressure differential is established from the interior of the web to the lateral edges, a mixture of air and water will flow through the edges of the web;
  3. phase change of water either from the adsorbed or liquid state into vapor; the diffusion mechanism of bound water was not considered in the model;
- the capillary pressure is determined according to the equivalent pore theory developed by Silvy and Butel [4]; relative permeabilities are introduced for both fluids as a function of water effective saturation;
- the press felt has a uniform initial moisture ratio of about 0.15 kg H<sub>2</sub>O/kg ds;
- both paper and felt are assumed to behave as viscoelastoplastic materials.

Prior to present the constitutive equations of the model it should be pointed out that the medium is comprised of two different materials, paper and felt, but for modeling purposes they will be envisaged as a single porous material

with different physical properties at the interface paper/felt. This boundary will be defined by the number of layers initially set for each medium. This simplification allows to consider the same discretization grid in the thickness direction, as illustrated in Figure 5.2. Here,  $L_z$  is the total thickness of the sandwich paper+felt.

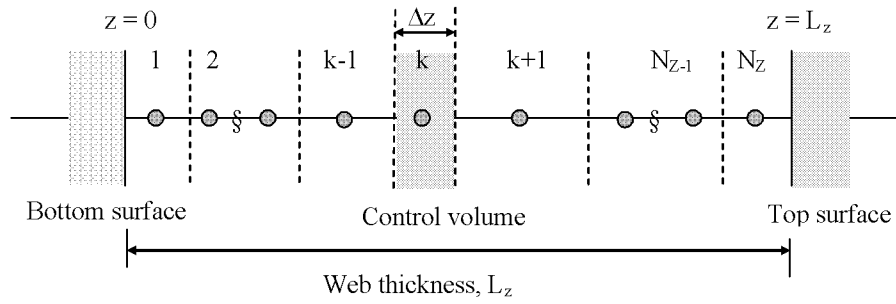


Figure 5.2: Discretization in the thickness direction of the mat;  $N_k$  is the total number of considered grid points.

Another point of particular interest is the description of the saturation in the felt during the compression and expansion phases. It is accepted that during the compression phase of the pressing operation all the water emerging from the paper web surface will gradually fill up the void volume inside the felt up to total saturation. In this approach, all the water removed from the paper web is assumed to be collected on top of the paper/felt interface, until total saturation is reached. This means that if the felt becomes completely saturated during the pressing event, then it is assumed that water can leave the bottom surface of the felt to the sintered metal lamina without any additional resistance. In the expansion phase the problem is more complex. One of two situations may occur: (i) water stays at the paper/felt interface during expansion (assuming low forces between felt fibers and water); (ii) water will move upwards with the expanding felt structure (thus assuming strong forces between felt fibers and water). These two approaches are illustrated in Figures 5.3 and 5.4.

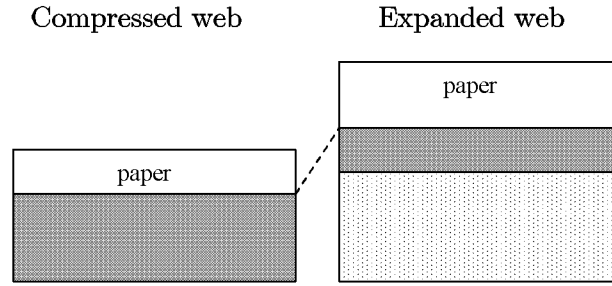


Figure 5.3: Schematic view of the compression/expansion phases of the mat during the pressing event (approach 1).

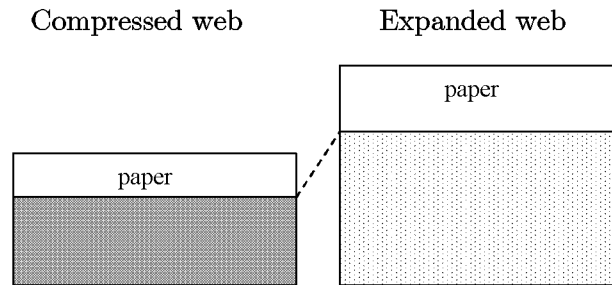


Figure 5.4: Schematic view of the compression/expansion phases of the mat during the pressing event (approach 2).

In the first approach, a thin layer of water at the paper/felt interface will create a significant hydraulic pressure drop resulting in a limited back flow. But as the back flow is totally saturated, the rewet may be significant. On the other hand, the second approach assumes that the felt pores at the interface are unsaturated, thus resulting in a lower pressure drop over the felt. In this case the back flow towards the paper web will be higher but the net flux of water may be lower.

### 5.2.1 Model equations

The development of the mathematical model for the uniaxial compression of the mat comprised of paper and felt follows the same approach as that presented for the global model of paper (see **Chapter 3, Section** “A proposed global model for the consolidation of water saturated paper webs in high-intensity processes”).

Therefore the constitutive model equations will be given in dimensionless variables, and its derivation is avoided here for simplification (for more detailed information, see **Chapter 3**).

It is however important to remember the definition of the model variables and parameters in their dimensionless form prior to present the constitutive model equations and the corresponding initial and boundary conditions.

Therefore, the spatial variables  $x$  and  $y$ , corresponding to the coordinates in the in-plane direction of the mat, are normalized by the initial values of its half length,  $L_{x_0}$ , and half width,  $L_{y_0}$ , respectively. The  $z$ -coordinate is normalized by the actual total thickness of the mat (paper + felt),  $L_z(t)$ , according to the transformation of Landau:

$$\mathbf{X} = \frac{x}{L_{x_0}} \quad (5.1a)$$

$$\mathbf{Y} = \frac{y}{L_{y_0}} \quad (5.1b)$$

$$\Rightarrow \mathbf{Z} = \frac{z}{L_z(t)} \quad (5.1c)$$

Additionally, time is normalized by the length of the press pulse and the physical and transport properties for the three main directions are divided by their corresponding initial values. It must be noted that the reference values of local properties are evaluated according to the vertical position, *i.e.* whether it corresponds to the paper or felt zone. As an example, if the reference value of the elasticity modulus is to be calculated at the grid point corresponding to  $k = 1$  (felt zone) in order to determine  $\mathbf{E}_{221}$ , the elasticity modulus of the felt must be used. This procedure was adopted for each local transport and physical property. The dimensionless variables and parameters of the mechanical model are then defined in a similar way to that presented in **Chapter 3** for paper.

$$\mathbf{L}_z = \frac{L_z}{L_{z_0}} \quad \Delta \mathbf{z}_{ijk} = \frac{\Delta z_{ijk}}{L_{z_0} \mathbf{L}_z} \quad \Delta \mathbf{z}_0 = \frac{\Delta z_0}{L_{z_0}} = \frac{1}{N_k}$$

$$\theta = \frac{t}{\tau} \quad \sigma_T = \frac{\sigma_T}{\sigma_0} \quad \sigma_{ij} = \frac{\sigma_{ij}}{\sigma_0}$$

$$\mathbf{E}_T = \frac{E_T}{E_0} \quad \mathbf{E}_{ij} = \frac{E_{ij}}{E_0} \quad \mathbf{E}_{ijk} = \frac{E_{ijk}}{E_0}$$

$$\mu_T = \frac{\mu_T}{\mu_0} \quad \mu_{ij} = \frac{\mu_{ij}}{\mu_0} \quad \mu_{ijk} = \frac{\mu_{ijk}}{\mu_0}$$

For the variables and parameters of the heat and mass transfer model a similar procedure was adopted. For simplicity, the dimensionless variables and parameters are presented here as if the mat was formed by paper only. However, the mat region has to be identified prior to the calculation of the reference values of such variables. For instance, the subscript “p” in some physical properties may denote the felt or the paper material, according to the vertical position at which the property is to be evaluated.

$$\begin{aligned}
\mathbf{T} &= \frac{T-T_{amb}}{T_p-T_{amb}} & \mathbf{T}_0 &= \frac{T_{amb}}{T_p-T_{amb}} & \phi_g &= \frac{\phi_g}{\phi_{g0}} & \phi_l &= \frac{\phi_l}{\phi_{l0}} \\
\rho_g &= \frac{\rho_g}{\rho_{g0}} & \rho_l &= \frac{\rho_l}{\rho_{l0}} & \rho_v &= \frac{\rho_v}{\rho_{g0}} & \rho_p &= \frac{\rho_p}{\rho_{p0}} \\
\mathbf{C}_p &= \frac{C_p}{C_{p0}} & \mathbf{C}_{pg} &= \frac{C_{pg}}{C_{pg0}} & \mathbf{C}_{pl} &= \frac{C_{pl}}{C_{pl0}} & \rho_{dry} &= \frac{\rho_{dry}}{\rho_0} \\
\lambda_{px} &= \frac{\lambda_{px}}{\lambda_{pz0}} & \lambda_{py} &= \frac{\lambda_{py}}{\lambda_{pz0}} & \lambda_{pz} &= \frac{\lambda_{pz}}{\lambda_{pz0}} \\
\mathbf{v}_{gx} &= \frac{v_{gx}}{v_{gz0}} & \mathbf{v}_{gy} &= \frac{v_{gy}}{v_{gz0}} & \mathbf{v}_{gz} &= \frac{v_{gz}}{v_{gz0}} & v_{gz0} &= \frac{L_{z0}}{\tau} \\
\mathbf{v}_{lx} &= \frac{v_{lx}}{v_{lz0}} & \mathbf{v}_{ly} &= \frac{v_{ly}}{v_{lz0}} & \mathbf{v}_{lz} &= \frac{v_{lz}}{v_{lz0}} \\
\mathbf{D}_x^{eff} &= \frac{D_x^{eff}}{D_{0z}^{eff}} & \mathbf{D}_y^{eff} &= \frac{D_y^{eff}}{D_{0z}^{eff}} & \mathbf{D}_z^{eff} &= \frac{D_z^{eff}}{D_{0z}^{eff}} \\
\mathbf{P}_v &= \frac{P_v}{P_0} & \mathbf{P}_g &= \frac{P_g}{P_0} & \mathbf{P}^{sat} &= \frac{P^{sat}}{P_0} \\
\mathbf{K}_{gx} &= \frac{K_{gx}}{K_{gz0}} & \mathbf{K}_{gy} &= \frac{K_{gy}}{K_{gz0}} & \mathbf{K}_{gz} &= \frac{K_{gz}}{K_{gz0}} \\
\mathbf{K}_{lx} &= \frac{K_{lx}}{K_{lz0}} & \mathbf{K}_{ly} &= \frac{K_{ly}}{K_{lz0}} & \mathbf{K}_{lz} &= \frac{K_{lz}}{K_{lz0}} \\
\mu_g &= \frac{\mu_g}{\mu_{g0}} & \mu_l &= \frac{\mu_l}{\mu_{l0}} & \mathbf{R}_x &= \frac{L_{z0}}{L_{x0}} & \mathbf{R}_y &= \frac{L_{z0}}{L_{y0}}
\end{aligned}$$

The following dimensionless numbers are also defined as:



$$\begin{aligned}
\mathbf{H}_0 &= \frac{E_0}{\sigma_0} & \mathbf{V}_0 &= \frac{\tau \cdot \sigma_0}{\mu_0} \\
\mathbf{Fo}_z &= \frac{\lambda_{pz_0} \tau}{\rho_{p0} C_{p0} L_{z0}^2} & \mathbf{Fo}_x &= \mathbf{R}_x^2 \mathbf{Fo}_z & \mathbf{Fo}_y &= \mathbf{R}_y^2 \mathbf{Fo}_z \\
\mathbf{Pe}_{gz} &= \frac{\rho_{g0} C_{pg0} v_{gz_0} L_{z0}}{\lambda_{pz_0}} & \mathbf{Pe}_{lz} &= \frac{\rho_{l0} C_{pl0} v_{lz_0} L_{z0}}{\lambda_{pz_0}} \\
\mathbf{Pe}_{mgz} &= \frac{v_{gz_0} L_{z0}}{\phi_{g0} D_{0z}^{eff}} & \mathbf{Pe}_{mgx} &= \frac{\mathbf{Pe}_{mgz}}{\mathbf{R}_x} & \mathbf{Pe}_{mgy} &= \frac{\mathbf{Pe}_{mgz}}{\mathbf{R}_y} \\
\mathbf{Fo}_{mz} &= \frac{\phi_{g0} D_{0z}^{eff} \tau}{L_{z0}^2} & \mathbf{Fo}_{mx} &= \mathbf{R}_x^2 \mathbf{Fo}_{mz} & \mathbf{Fo}_{my} &= \mathbf{R}_y^2 \mathbf{Fo}_{mz} \\
\mathbf{Np}_{gz} &= \frac{P_0 K_{gz_0} \tau}{\mu_{g0} L_{z0}^2} & \mathbf{Np}_{gx} &= \mathbf{R}_x^2 \mathbf{Np}_{gz} & \mathbf{Np}_{gy} &= \mathbf{R}_y^2 \mathbf{Np}_{gz} \\
\mathbf{Np}_{lz} &= \frac{P_0 K_{lz_0} \tau}{\mu_{l0} L_{z0}^2} & \mathbf{Np}_{lx} &= \mathbf{R}_x^2 \mathbf{Np}_{lz} & \mathbf{Np}_{ly} &= \mathbf{R}_y^2 \mathbf{Np}_{lz} \\
\dot{\mathbf{M}} &= \frac{\tau \dot{M}}{\rho_{p0}} & \dot{\mathbf{M}}_v &= \frac{\tau \dot{M}}{\rho_{v0}} & \dot{\mathbf{M}}_l &= \frac{\tau \dot{M}_l}{\rho_{l0}} \\
\dot{\mathbf{M}}_b &= \frac{\tau \dot{M}_b}{\rho_0} & \rho_{v0} &= \frac{M M_v P_0}{R(T_p - T_{amb})}
\end{aligned}$$

The constitutive equations of the global model and the corresponding initial and boundary conditions, may then be written as follows, in terms of dimensionless variables.

Considering the operating conditions in terms of temperature and applied pressure, as well as the higher moisture content of the paper samples tested, it was assumed, for simulation purposes, that the paper web remains above the fiber saturation point even at the highest temperature of pressing. This means that all the vapor formed inside the paper web comes from the liquid water and no adsorbed water is vaporized. A similar approach is defined for the felt. In fact, the liquid water inside the felt pores tend to remain in the liquid state as no temperature recordings above 100 °C were obtained from the experiments performed at moderate temperatures. At the highest operating temperatures however the interface paper/felt crossed the boundary of 100 °C, which means that steam may be generated unless the hydraulic pressure is kept high enough to prevent it.

In summary, the global model considers the following dependent variables:

- heat and mass transfer: five dependent variables (temperature, water vapor pressure, gas pressure, volume fraction of liquid water and moisture ratio);
- mechanical behavior: three dependent variables (the vertical position, the stress level in each representative column of the mat, and the total thickness of the web).

The corresponding model equations are:

- heat and mass transfer: one energy balance, three mass balances (vapor, gas and liquid) and one equation describing vapor-liquid saturation equilibrium;
- mechanical behavior: one equation that relates the vertical position and local deformation, one to determine the stress developed in each representative column of the mat, and finally one equation for the total thickness of the mat (**paper+felt**).

### Mechanical constitutive equations

The vertical position for each  $ijk$  representative volume element:

$$\frac{\partial \mathbf{Z}_{ijk}}{\partial \theta} = \frac{\Delta \mathbf{z}_0}{2\mathbf{L}_z} \left( \frac{\partial \varepsilon_{ijk}}{\partial \theta} + 2 \sum_{l=1}^{k-1} \frac{\partial \varepsilon_{ijl}}{\partial \theta} \right) - \frac{\mathbf{Z}_{ijk}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \quad (5.2a)$$

$$\text{where } \frac{\partial \varepsilon_{ijk}}{\partial \theta} = \frac{1}{\mathbf{H}_0 \left( \mathbf{E}_{ijk} + \varepsilon_{ijk} \frac{\partial \mathbf{E}_{ijk}}{\partial \varepsilon_{ijk}} \right)} \frac{\partial \boldsymbol{\sigma}_{ij}}{\partial \theta} + \frac{\mathbf{V}_0}{\boldsymbol{\mu}_{ijk}} \boldsymbol{\sigma}_{ij} \quad (5.2b)$$

$$\text{Initial condition} \quad : \quad \theta = 0; \quad \varepsilon_{ijk} = 0; \quad \mathbf{Z}_{ijk} = \frac{k - 0.5}{N_k} \quad (5.2c)$$

The applied stress in every  $ij$  column:

$$\frac{\partial \boldsymbol{\sigma}_{ij}}{\partial \theta} = \mathbf{H}_0 \mathbf{E}_{ij} \frac{\partial \mathbf{L}_z}{\partial \theta} - \mathbf{H}_0 \mathbf{V}_0 \frac{\mathbf{E}_{ij}}{\boldsymbol{\mu}_{ij}} \boldsymbol{\sigma}_{ij} \quad (5.3a)$$

$$\text{Initial condition} \quad : \quad \theta = 0; \quad \boldsymbol{\sigma}_{ij} = 0; \quad \mathbf{L}_z = 1 \quad (5.3b)$$

The total thickness of the mat (paper+felt):

$$\frac{\partial \mathbf{L}_z}{\partial \theta} = \frac{1}{\mathbf{H}_0 \mathbf{E}_T} \frac{\partial \boldsymbol{\sigma}_T}{\partial \theta} + \frac{\mathbf{V}_0}{\mu_T} \boldsymbol{\sigma}_T \quad (5.4a)$$

$$\text{Initial condition} \quad : \quad \theta = 0; \quad \mathbf{L}_z = 1 \quad (5.4b)$$

**The energy conservation equation**

$$\begin{aligned} \frac{\partial \mathbf{T}}{\partial \theta} = & -\frac{\mathbf{F} \mathbf{o}_z}{\rho_p C_p} \left( \mathbf{R}_x^2 \frac{\partial \varphi_{tx}}{\partial \mathbf{X}} + \mathbf{R}_y^2 \frac{\partial \varphi_{ty}}{\partial \mathbf{Y}} + \frac{1}{\mathbf{L}_z} \frac{\partial \varphi_{tz}}{\partial \mathbf{Z}} \right) - \frac{\dot{\mathbf{M}} (\Delta H_{vap} + Q_l)}{\rho_p C_{p0} C_p (T_p - T_{amb})} - \dots \\ & \dots - \frac{\mathbf{T} + T_0}{\rho_p} \frac{\partial \rho_p}{\partial \theta} + \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left( \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} + \frac{\mathbf{T} + T_0}{\rho_p} \frac{\partial \rho_p}{\partial \mathbf{Z}} \right) \end{aligned} \quad (5.5)$$

*Heat fluxes*

$$\varphi_{tx} = -\lambda_{px} \frac{\partial \mathbf{T}}{\partial \mathbf{X}} + \left( \frac{\mathbf{P} \mathbf{e}_{gz}}{\mathbf{R}_x} \rho_g \mathbf{v}_{gx} C_{pg} + \frac{\mathbf{P} \mathbf{e}_{lz}}{\mathbf{R}_x} \rho_l \mathbf{v}_{lx} C_{pl} \right) (\mathbf{T} + T_0) \quad (5.6a)$$

$$\varphi_{ty} = -\lambda_{py} \frac{\partial \mathbf{T}}{\partial \mathbf{Y}} + \left( \frac{\mathbf{P} \mathbf{e}_{gz}}{\mathbf{R}_y} \rho_g \mathbf{v}_{gy} C_{pg} + \frac{\mathbf{P} \mathbf{e}_{ly}}{\mathbf{R}_y} \rho_l \mathbf{v}_{ly} C_{pl} \right) (\mathbf{T} + T_0) \quad (5.6b)$$

$$\varphi_{tz} = -\frac{\lambda_{pz}}{\mathbf{L}_z} \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} + (\mathbf{P} \mathbf{e}_{gz} \rho_g \mathbf{v}_{gz} C_{pg} + \mathbf{P} \mathbf{e}_{lz} \rho_l \mathbf{v}_{lz} C_{pl}) (\mathbf{T} + T_0) \quad (5.6c)$$

**The conservation equation for water vapor**

$$\begin{aligned} \dot{\mathbf{M}}_v = & \mathbf{F} \mathbf{o}_{m_z} \left( \mathbf{R}_x^2 \frac{\partial \varphi_{vx}}{\partial \mathbf{X}} + \mathbf{R}_y^2 \frac{\partial \varphi_{vy}}{\partial \mathbf{Y}} + \frac{1}{\mathbf{L}_z} \frac{\partial \varphi_{vz}}{\partial \mathbf{Z}} \right) + \dots \\ & \dots + \frac{\phi_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_v}{\partial \theta} - \frac{\phi_g \mathbf{P}_v}{(\mathbf{T} + T_0)^2} \frac{\partial \mathbf{T}}{\partial \theta} + \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \phi_g}{\partial \theta} - \dots \\ & \dots - \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left( \frac{\phi_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}} - \frac{\phi_g \mathbf{P}_v}{(\mathbf{T} + T_0)^2} \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} + \dots \right. \\ & \left. \dots + \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \phi_g}{\partial \mathbf{Z}} \right) \end{aligned} \quad (5.7)$$

*Vapor fluxes*

$$\varphi_{vx} = -\frac{\mathbf{D}_x^{eff} \phi_g}{\mathbf{T} + T_0} \left( \frac{\partial \mathbf{P}_v}{\partial \mathbf{X}} - \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \mathbf{X}} \right) + \frac{\mathbf{P}_{mgz}}{\mathbf{R}_x} \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \mathbf{v}_{gx} \quad (5.8a)$$

$$\varphi_{vy} = -\frac{\mathbf{D}_y^{eff} \phi_g}{\mathbf{T} + T_0} \left( \frac{\partial \mathbf{P}_v}{\partial \mathbf{Y}} - \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \mathbf{Y}} \right) + \frac{\mathbf{P}_{mgz}}{\mathbf{R}_y} \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \mathbf{v}_{gy} \quad (5.8b)$$

$$\varphi_{vz} = -\frac{\mathbf{D}_z^{eff} \phi_g}{\mathbf{L}_z (\mathbf{T} + T_0)} \left( \frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}} - \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} \right) + \mathbf{P}_{mgz} \frac{\mathbf{P}_v}{\mathbf{T} + T_0} \mathbf{v}_{gz} \quad (5.8c)$$

**The conservation equation for the gas phase**

$$\begin{aligned} \frac{\partial \mathbf{P}_g}{\partial \theta} &= -\frac{\mathbf{N} \mathbf{P}_{gz}}{\phi_g} \left( \mathbf{R}_x^2 \frac{\partial \varphi_{gx}}{\partial \mathbf{X}} + \mathbf{R}_y^2 \frac{\partial \varphi_{gy}}{\partial \mathbf{Y}} + \frac{1}{\mathbf{L}_z} \frac{\partial \varphi_{gz}}{\partial \mathbf{Z}} \right) (\mathbf{T} + T_0) + \dots \\ &\dots + \frac{\mathbf{M}_v (\mathbf{T} + T_0)}{\phi_g} + \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \theta} - \frac{\mathbf{P}_g}{\phi_g} \frac{\partial \phi_g}{\partial \theta} + \dots \\ &\dots + \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left( \frac{\partial \mathbf{P}_g}{\partial \mathbf{Z}} - \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} + \frac{\mathbf{P}_g}{\phi_g} \frac{\partial \phi_g}{\partial \mathbf{Z}} \right) \end{aligned} \quad (5.9)$$

*Gas fluxes*

$$\varphi_{gx} = -\frac{\mathbf{K}_{gx}}{\mu_g} \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_g}{\partial \mathbf{X}} \quad (5.10a)$$

$$\varphi_{gy} = -\frac{\mathbf{K}_{gy}}{\mu_g} \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_g}{\partial \mathbf{Y}} \quad (5.10b)$$

$$\varphi_{gz} = -\frac{\mathbf{K}_{gz}}{\mu_g} \frac{\mathbf{P}_g}{\mathbf{T} + T_0} \frac{\partial \mathbf{P}_g}{\partial \mathbf{Z}} \quad (5.10c)$$

**The conservation equation for the liquid phase**

$$\begin{aligned} \frac{\partial \phi_l}{\partial \theta} &= -\frac{\mathbf{N} \mathbf{p}_{lz}}{\rho_l} \left( \mathbf{R}_x^2 \frac{\partial \varphi_{lx}}{\partial \mathbf{X}} + \mathbf{R}_y^2 \frac{\partial \varphi_{ly}}{\partial \mathbf{Y}} + \frac{1}{\mathbf{L}_z} \frac{\partial \varphi_{lz}}{\partial \mathbf{Z}} \right) - \frac{\mathbf{M}_l}{\rho_l} - \frac{\phi_l}{\rho_l} \frac{\partial \rho_l}{\partial \theta} + \dots \\ &\dots + \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left( \frac{\partial \phi_l}{\partial \mathbf{Z}} + \frac{\phi_l}{\rho_l} \frac{\partial \rho_l}{\partial \mathbf{Z}} \right) \end{aligned} \quad (5.11)$$

Water fluxes

$$\varphi_{lx} = -\frac{\rho_l K_{lx}}{\mu_l} \left( \frac{\partial P_g}{\partial X} - \frac{\partial P_c}{\partial X} \right) \quad (5.12a)$$

$$\varphi_{ly} = -\frac{\rho_l K_{ly}}{\mu_l} \left( \frac{\partial P_g}{\partial Y} - \frac{\partial P_c}{\partial Y} \right) \quad (5.12b)$$

$$\varphi_{lz} = -\frac{\rho_l K_{lz}}{\mu_l} \frac{1}{L_z} \left( \frac{\partial P_g}{\partial Z} - \frac{\partial P_c}{\partial Z} \right) \quad (5.12c)$$

### 5.2.2 Initial conditions

Initial conditions have to be set on temperature and water, gas and vapor concentrations everywhere in the paper web and in the felt.

Paper region

$$T(X, Y, Z \neq 1, 0) = 0 \quad (5.13a)$$

$$T(X, Y, Z = 1, 0) = 1 \quad (5.13b)$$

$$P_g(X, Y, Z, 0) = \frac{P_{amb}}{P_0} \quad (5.14)$$

*Above fiber saturation point:* paper is assumed to be above the fiber saturation point throughout the pressing event. Additionally, no steam generation is expected to occur before pressure release.

$$P_v(X, Y, Z, 0) = P^{sat}(T = 0) \quad (5.15)$$

$$\phi_l(X, Y, Z, 0) = (\phi_{l_0})^P \quad (5.16)$$

Felt region

$$T(X, Y, Z, 0) = 0 \quad (5.17)$$

$$P_g(X, Y, Z, 0) = \frac{P_{amb}}{P_0} \quad (5.18)$$

$$\mathbf{P}_v(\mathbf{X}, \mathbf{Y}, \mathbf{Z}, 0) = \mathbf{P}_v(MR = MR_{in}; \mathbf{T} = 0) \quad (5.19)$$

$$\phi_l(\mathbf{X}, \mathbf{Y}, \mathbf{Z}, 0) = (\phi_{l_0})^F \quad (5.20)$$

### 5.2.3 Boundary conditions

The boundaries of the model can be divided into six parts with potentially different conditions, as represented in Figure 5.5.

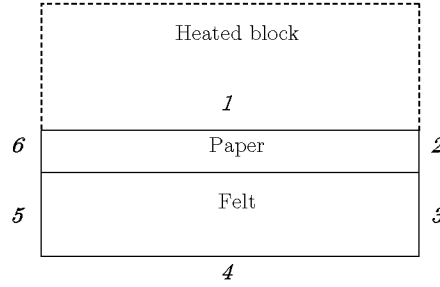


Figure 5.5: Boundaries of the model.

- The boundaries 2,3 and 5,6 are similar. Therefore, the boundary conditions for paper and felt are the same; the only difference is in the material properties.

*Boundaries 2,3:*

$$\mathbf{T}(1, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (5.21a)$$

$$\mathbf{T}(\mathbf{X}, 1, \mathbf{Z}, \theta) = 0 \quad (5.21b)$$

$$\mathbf{P}_g(1, \mathbf{Y}, \mathbf{Z}, \theta) = \frac{P_{amb}}{P_0} \quad (5.22a)$$

$$\mathbf{P}_g(\mathbf{X}, 1, \mathbf{Z}, \theta) = \frac{P_{amb}}{P_0} \quad (5.22b)$$

$$\frac{\partial \phi_l}{\partial \mathbf{X}}(1, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \text{ (fluid discontinuity, } v_{l_x} = 0) \quad (5.23a)$$

$$\frac{\partial \phi_l}{\partial \mathbf{Y}}(\mathbf{X}, 1, \mathbf{Z}, \theta) = 0 \text{ (fluid discontinuity, } v_{l_y} = 0) \quad (5.23b)$$

Boundary 2:

$$\mathbf{P}_v(1, \mathbf{Y}, \mathbf{Z}, \theta) = \mathbf{P}^{sat}(\mathbf{T} = 0) \quad (5.24a)$$

$$\mathbf{P}_v(\mathbf{X}, 1, \mathbf{Z}, \theta) = \mathbf{P}^{sat}(\mathbf{T} = 0) \quad (5.24b)$$

Boundary 3:

$$\mathbf{P}_v(1, \mathbf{Y}, \mathbf{Z}, \theta) = \mathbf{P}_v(MR = MR_{in}; \mathbf{T} = 0) \quad (5.25a)$$

$$\mathbf{P}_v(\mathbf{X}, 1, \mathbf{Z}, \theta) = \mathbf{P}_v(MR = MR_{in}; \mathbf{T} = 0) \quad (5.25b)$$

*Boundaries 5,6:*

$$\frac{\partial \mathbf{T}}{\partial \mathbf{X}}(0, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (5.26a)$$

$$\frac{\partial \mathbf{T}}{\partial \mathbf{Y}}(\mathbf{X}, 0, \mathbf{Z}, \theta) = 0 \quad (5.26b)$$

$$\frac{\partial \mathbf{P}_v}{\partial \mathbf{X}}(0, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (5.27a)$$

$$\frac{\partial \mathbf{P}_v}{\partial \mathbf{Y}}(\mathbf{X}, 0, \mathbf{Z}, \theta) = 0 \quad (5.27b)$$

$$\frac{\partial \mathbf{P}_g}{\partial \mathbf{X}}(0, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (5.28a)$$

$$\frac{\partial \mathbf{P}_g}{\partial \mathbf{Y}}(\mathbf{X}, 0, \mathbf{Z}, \theta) = 0 \quad (5.28b)$$

$$\frac{\partial \phi_l}{\partial \mathbf{X}}(0, \mathbf{Y}, \mathbf{Z}, \theta) = 0 \quad (5.29a)$$

$$\frac{\partial \phi_l}{\partial \mathbf{Y}}(\mathbf{X}, 0, \mathbf{Z}, \theta) = 0 \quad (5.29b)$$

• The boundary denoted as 1 is impermeable. Therefore, the mass fluxes are set to zero. Through Darcy's relation this is equivalent to vanish the gas and vapor pressure gradients as well as that of liquid water volume fraction. The heat flow through the boundary is continuous.

$$\mathbf{T}(\mathbf{X}, \mathbf{Y}, 1, \theta) = 1 \quad (5.30)$$

$$\frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, 1, \theta) = 0 \quad (5.31)$$

$$\frac{\partial \mathbf{P}_g}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, 1, \theta) = 0 \quad (5.32)$$

$$\frac{\partial \phi_l}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, 1, \theta) = 0 \text{ (impermeable surface, } K_{l_z} = 0) \quad (5.33)$$

• The boundary 4 is open to water, gas and vapor flow. During the compression phase the fluids can leave the felt with no external resistance; when the nip opens the felt will expand and some gas or liquid has to flow into the felt. For unsaturated felts the saturation is lowest at the felt/sintered metal lamina interface and it may be assumed that the amount of liquid water entering the felt can be neglected.

$$\mathbf{T}(\mathbf{X}, \mathbf{Y}, 0, \theta) = 0 \quad (5.34)$$

$$\mathbf{P}_v(\mathbf{X}, \mathbf{Y}, 0, \theta) = \mathbf{P}_v(MR = MR_{in}; \mathbf{T} = 0) \quad (5.35)$$

$$\mathbf{P}_g(\mathbf{X}, \mathbf{Y}, 0, \theta) = \frac{P_{amb}}{P_0} \quad (5.36)$$

$$\frac{\partial \phi_l}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, 0, \theta) = 0 \text{ (fluid discontinuity, } v_{l_z} = 0) \quad (5.37)$$

Additionally, the paper/felt interface is assumed to be saturated in order to avoid fluid discontinuity.

$$\bullet S_{l,eff} = 1 \quad \frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, \mathbf{Z}^*, \theta) = 0 \text{ (saturated interface)} \quad (5.38)$$

$$\bullet S_{l,eff} = 1 \quad \frac{\partial \mathbf{P}_g}{\partial \mathbf{Z}}(\mathbf{X}, \mathbf{Y}, \mathbf{Z}^*, \theta) = 0 \text{ (saturated interface)} \quad (5.39)$$

where  $\mathbf{Z}^*$  denotes the dimensionless  $z$ -coordinate at the paper/felt interface.



### Equilibrium equations

As the liquid water is assumed to be in equilibrium with its saturated vapor within the paper web, the following equation may be written:

$$\frac{\partial \mathbf{P}_v}{\partial \theta} = \frac{\partial \mathbf{P}^{sat}}{\partial \theta} = \left( \frac{\partial \mathbf{P}^{sat}}{\partial \mathbf{T}} \right) \left( \frac{\partial \mathbf{T}}{\partial \theta} \right) + \frac{\mathbf{Z}}{\mathbf{L}_z} \frac{\partial \mathbf{L}_z}{\partial \theta} \left[ \frac{\partial \mathbf{P}_v}{\partial \mathbf{Z}} - \left( \frac{\partial \mathbf{P}^{sat}}{\partial \mathbf{T}} \right) \left( \frac{\partial \mathbf{T}}{\partial \mathbf{Z}} \right) \right] \quad (5.40)$$

Additionally, the amount of adsorbed water, in equilibrium with the water vapor in the pores, may then be determined by the sorption isotherm for a given local temperature inside the paper web, according to the equation of Nadler *et al* [2] (see Eqn. 3.212 or alternatively Eqn. 3.213).

$$MR_{eq}(\mathbf{X}, \mathbf{Y}, \mathbf{Z}, \theta) = MR_{eq}(HR = 1; \mathbf{T}) \quad (5.41)$$

### 5.2.4 Numerical solution

In order to solve the model constitutive equations the same finite-differences approach as in **Chapter 3** was used, and the resulting set of ODEs was numerically integrated using a specialized solver for stiff equations based on the Gear method developed by Hindmarsh [1]. Following the procedure described by Patankar [3] to discretize the right-hand side of the constitutive equations, a scheme of first order central differences was used for the conduction/diffusion terms, and the upwind difference technique was employed for the discretization of the convective terms, which in this case means that variables are attributed the upstream values in relation to the direction of the flux. A backward difference scheme was used for the vertical temperature gradient term in the energy balance, as some numerical problems came up when high platen temperatures were used. This was attributed to the sudden temperature increase at the beginning of the pressing event. Using this discretization method the problem of boundaries inconsistency is solved, as the time derivatives are evaluated at the grid points, whereas the heat and mass fluxes are determined at the boundaries of the RVE (as a result of the central differences scheme).

In the finite difference solution method, the paper web was divided into 1,000 uniform RVEs (corresponding to 10 grid points in each direction) and the felt was divided into 500 RVEs (a sensitivity analysis has shown that 5 grid points in the thickness direction of felt were adequate).

The DLSODES subroutine was integrated in a C<sup>++</sup>-based program containing the constitutive equations of the heat and mass transfer model together with the differential equations describing the mechanical behavior of the material and all the relations required to determine the transport and physical properties at any point in the paper web and in the felt.

### 5.3 Results and discussion

The following paragraphs summarize the main experimental results in terms of temperature, web thickness and applied pressure recordings obtained during the impulse drying of paper with a felt sample acting as a backing material. The results refer to 60 and 80 g.m<sup>-2</sup> wet paper samples made from hardwood or softwood pulps beaten either to 25 or 40 °SR. The felt samples used in this set of experiments were similar to those used in the experimental investigations previously presented. For simplicity, the material properties and operating conditions are presented on Tables 5.1 and 5.2.

The main purpose of this part of the work was to infer about the possibility of steam generation inside the mat formed by paper and felt and pressed under the extreme operating conditions of impulse drying. Additionally, it serves as a database for model validation. This constitutes the second part of the present section. The results from the impulse drying experiments described in **Chapter 2**, and presented hereafter, were compared with model simulations in order to verify the global model predictions and to derive appropriate parameter values. The results of these activities are summarized here.

Table 5.1: Material properties.

|                        |                                       |
|------------------------|---------------------------------------|
| Paper                  |                                       |
| Grammage               | 60 and 80 g.m <sup>-2</sup>           |
| Refining level         | 25 and 40 °SR                         |
| Additive content       | -                                     |
| Initial moisture ratio | ≈ 1.5 - 2.3 kg H <sub>2</sub> O/kg ds |
| Pulp furnish           | bleached hardwood pulp                |
| Felt                   |                                       |
| Grammage               | 1400 - 1500 g.m <sup>-2</sup>         |
| Initial moisture ratio | ≈ 0.15 kg H <sub>2</sub> O/kg ds      |

Table 5.2: Operating conditions.

|                                  |                                            |
|----------------------------------|--------------------------------------------|
| Temperature of the pressing head | $T_p = 25, 80, 150, 200, 250$ and $350$ °C |
| Pulse length                     | $\tau \approx 30 - 50$ ms                  |
| Peak pressure                    | $\sigma_0 \approx 5 - 6$ MPa               |
| Pulse shape                      | Roll                                       |

### 5.3.1 Experimental results

The transient temperature profiles of the mat, formed by paper and felt undergoing compression in the temperature range of 25-350 °C, were analyzed together with its mechanical response to a pressure pulse similar to that presented in Figure 5.6 obtained for a pressing event performed at 350 °C. It should be mentioned that each operating condition was tested at least six times, and each experiment was evaluated separately as the pressure profiles differ from one test to another. As an example, Figure 5.6 illustrates the results obtained for a 60 g.m<sup>-2</sup> unsaturated paper sample made from bleached hardwood pulp beaten to 25 °SR, and felt sample No. 249031-12. The peak pressure was about 5.4 MPa and the nip length 34 ms.

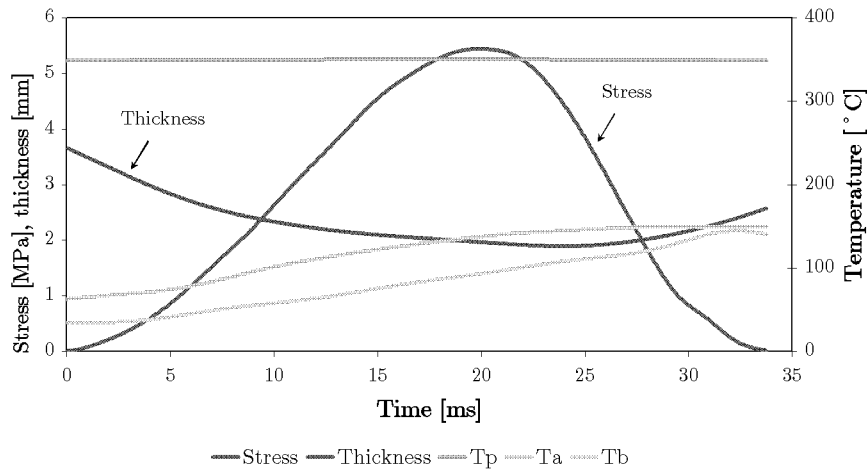


Figure 5.6: Time evolution of pressure, mat thickness, temperature of the heated plate ( $T_p$ ) and at the interfaces heated plate/paper ( $T_a$ ) and paper/felt ( $T_b$ ). The results refer to the impulse drying of a 25 °SR 60 g.m<sup>-2</sup> hardwood unsaturated paper sample together with felt sample No. 249031-12. The duration of the press pulse was 34 ms with a peak pressure of 5.4 MPa. The plate temperature was set to 350 °C.

Figures 5.7 to 5.12 show the results of measurements performed with  $60 \text{ g.m}^{-2}$  unsaturated paper samples pressed from room temperature up to  $350^\circ\text{C}$ . In all the experiments illustrated hereafter, felt No. 249031-12 was used as the supporting material of the paper sample.

The temperature of the heated plate was monitored as well as the temperature at the interfaces heated plate/paper and paper/felt (according to Figure 2.21 in **Chapter 2**). The major conclusion drawn from the experimental temperature profiles is that there is no clear evidence of steam generation inside the nip, even in the region of the paper web closest to the heated surface. In fact, for paper webs pressed under such a short period of time and at temperatures equal or below  $200^\circ\text{C}$ , the thermocouples did not reach the  $100^\circ\text{C}$  barrier, whereas at  $250$  and  $350^\circ\text{C}$  both interfaces, defined above, were exposed to a temperature higher than that limit. This means that vapor could actually be formed for temperatures of  $250^\circ\text{C}$  or above. It is, however, advanced that a sufficient hydraulic pressure level is developed in order to prevent steam generation inside the nip. As discussed previously in **Chapters 3** and **4**, a sudden increase in temperature at the final stage of the decompression phase has been reported as an evidence of vapor formation (see Figures 3.86 to 3.88 in **Chapter 3**), but this behavior was observed for press pulses longer than those analyzed in the present case. It is then advanced that the increased compression rate (shorter press pulses) tends to increase the hydraulic pressure in most of the paper sheet, thus preventing or minimizing steam generation in the press nip. Additionally, liquid water is suggested to be present in the web until the pressure is totally released.

As for the mechanical response of the mat formed by paper and felt, the observations are very similar to those drawn for felt (see **Chapter 4**). In fact, the mat behaves almost as if paper was not present, which is not surprising when comparing the initial thickness of paper and felt (for the present case, felt is at least 10 times thicker than paper). The presence of paper is most notorious in what heat and mass transfer is concerned. Here, paper plays a fundamental role as it acts as an additional resistance to heat transfer in the thickness direction of the mat.

The left-hand side of Figures 5.7 to 5.12 illustrates the mat response to compression under similar press pulses but with slightly different peak pressure magnitudes. The overall conclusion is that the fibrous mat is highly compressible

as at the point of maximum pressure the thickness of the mat had reduced to approximately half of its initial thickness (strain in the range 0.4-0.6). Moreover, the point of minimum thickness arises slightly after the point of maximum applied pressure, suggesting that although the main carrier of the press load is the fiber network, the fluid contribution cannot be neglected and is actually seen as the main contributor to the slight time delay. In fact, this is partially ascribed to the time taken to squeeze water out of the porous material. It was also mentioned in **Chapter 4** that an increase in the stress rate induces an increase in felt resistance to compression, as the fluid may not have enough time to escape from the mat. The entrapped air and water may then contribute to the increased compression resistance of the material, as suggested from Figures 5.7, 5.8 and 5.9.

In the decompression phase the thickness of the mat follows a different trend as the moisture conditions and the porous structure are no longer the same. At the end of the pressing event the recorded thickness of the mat indicates a permanent strain between 30 and 40 %, approximately. However, this is only valid in the context of the in nip analysis, as after load release the mat continues to expand and the strain level attained no longer refers to the consolidation mechanisms occurred within the press nip.

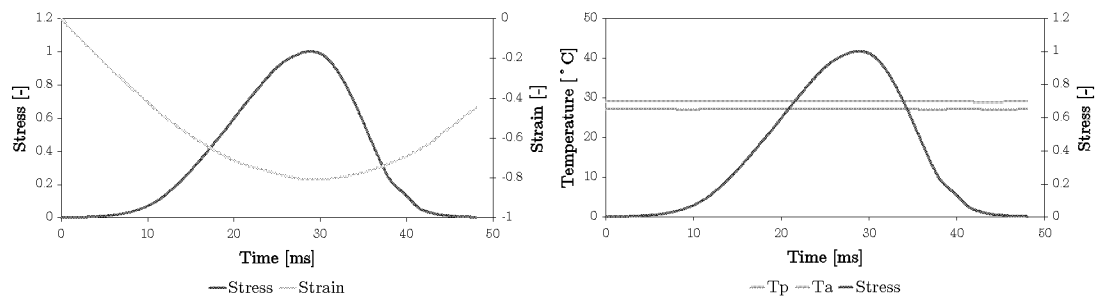


Figure 5.7: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 48 ms with a peak pressure of 5.5 MPa. The plate temperature was set to room temperature. **Right:** The corresponding temperature profiles obtained during the press drying of a  $60 \text{ g.m}^{-2}$  25 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature and  $T_a$  the temperature at the paper/heated plate interface.

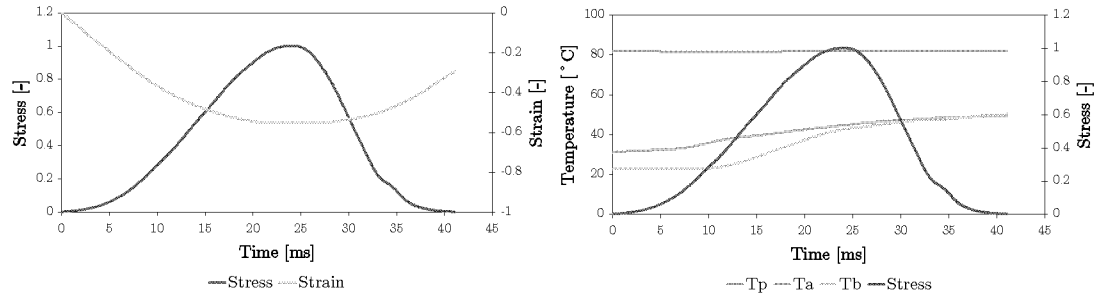


Figure 5.8: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 41 ms with a peak pressure of 5.3 MPa. The plate temperature was set to 80 °C. **Right:** The corresponding temperature profiles obtained during the press drying of a 60 g.m<sup>-2</sup> 25 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature,  $T_a$  and  $T_b$  the temperature at the paper/heated plate and paper/felt interfaces.

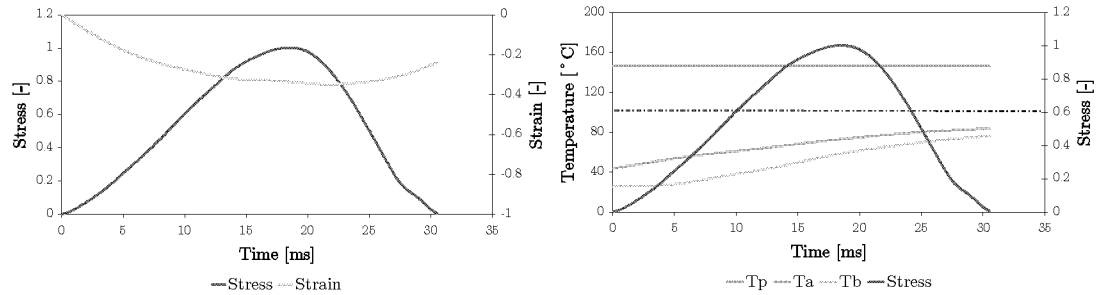


Figure 5.9: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 31 ms with a peak pressure of 5.2 MPa. The plate temperature was set to 150 °C. **Right:** The corresponding temperature profiles obtained during the press drying of a 60 g.m<sup>-2</sup> 25 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature,  $T_a$  and  $T_b$  the temperature at the paper/heated plate and paper/felt interfaces.

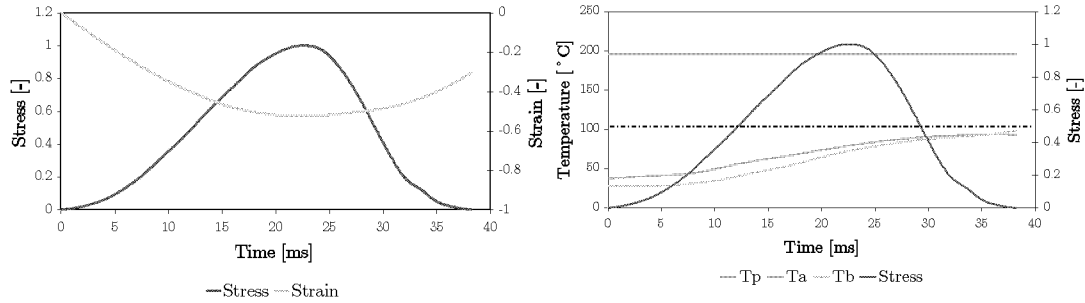


Figure 5.10: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 38 ms with a peak pressure of 5.5 MPa. The plate temperature was set to 200 °C. **Right:** The corresponding temperature profiles obtained during the press drying of a 60 g.m<sup>-2</sup> 25 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature,  $T_a$  and  $T_b$  the temperature at the paper/heated plate and paper/felt interfaces.

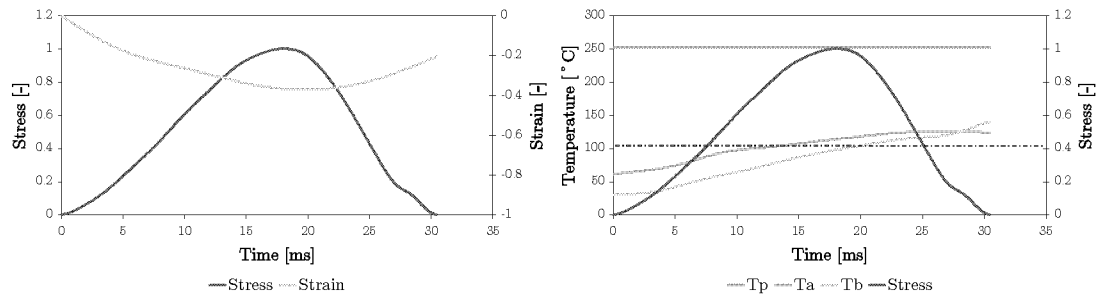


Figure 5.11: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 31 ms with a peak pressure of 5.2 MPa. The plate temperature was set to 250 °C. **Right:** The corresponding temperature profiles obtained during the press drying of a 60 g.m<sup>-2</sup> 25 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature,  $T_a$  and  $T_b$  the temperature at the paper/heated plate and paper/felt interfaces.

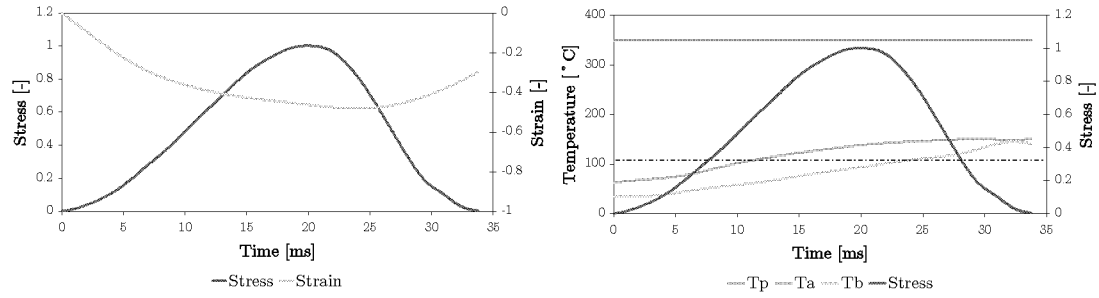


Figure 5.12: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 34 ms with a peak pressure of 5.4 MPa. The plate temperature was set to 350 °C. **Right:** The corresponding temperature profiles obtained during the press drying of a 60 g.m<sup>-2</sup> 25 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature,  $T_a$  and  $T_b$  the temperature at the paper/heated plate and paper/felt interfaces.

The impulse drying analysis was also extended to higher paper grammages, namely 80 g.m<sup>-2</sup>. In terms of mechanical behavior no significant changes were observed when compared to the response of the 60 g.m<sup>-2</sup> paper samples. The main differences were observed in the temperature profiles.

The effect of paper grammage is clearly illustrated in Figures 5.13 to 5.16: an increase in paper grammage tends to shift the temperature profiles at the paper/felt interface to lower temperatures, as a result of the increased heat and mass transfer resistance created by the additional amount of fibers and water (considering the same moisture ratio). As expected, there are no major dissimilarities between the temperature readings at the platen/paper interface observed for both sets of experiments, *i.e.* using either 60 or 80 g.m<sup>-2</sup> paper samples.



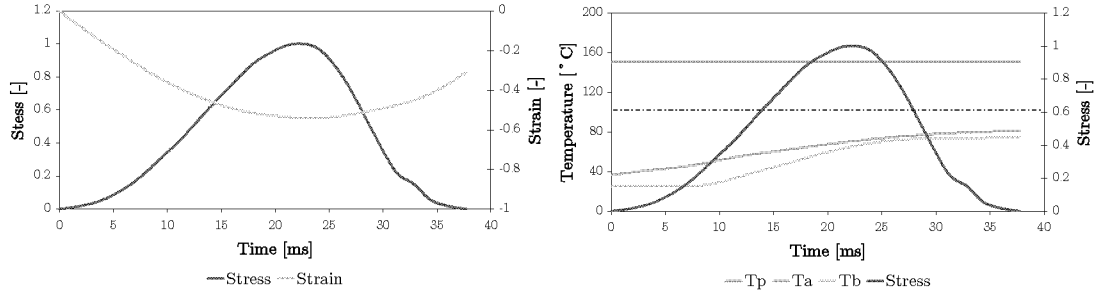


Figure 5.13: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 38 ms with a peak pressure of 5.3 MPa. The plate temperature was set to 150 °C. **Right:** The corresponding temperature profiles obtained during the press drying of a 80 g.m<sup>-2</sup> 40 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature,  $T_a$  and  $T_b$  the temperature at the paper/heated plate and paper/felt interfaces.

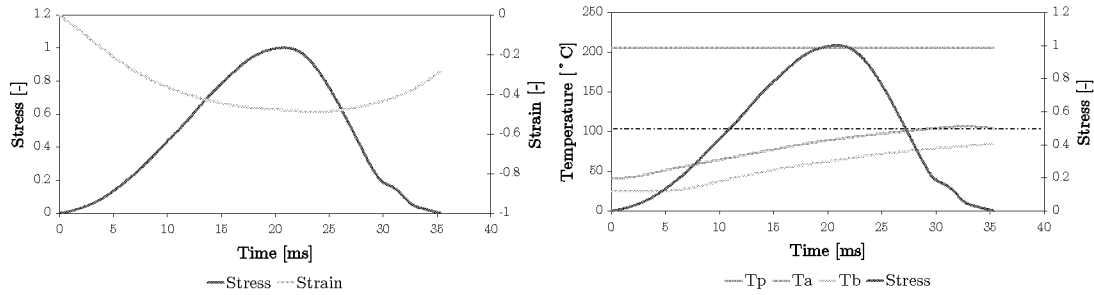


Figure 5.14: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 35 ms with a peak pressure of 5.2 MPa. The plate temperature was set to 200 °C. **Right:** The corresponding temperature profiles obtained during the press drying of a 80 g.m<sup>-2</sup> 40 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature,  $T_a$  and  $T_b$  the temperature at the paper/heated plate and paper/felt interfaces.

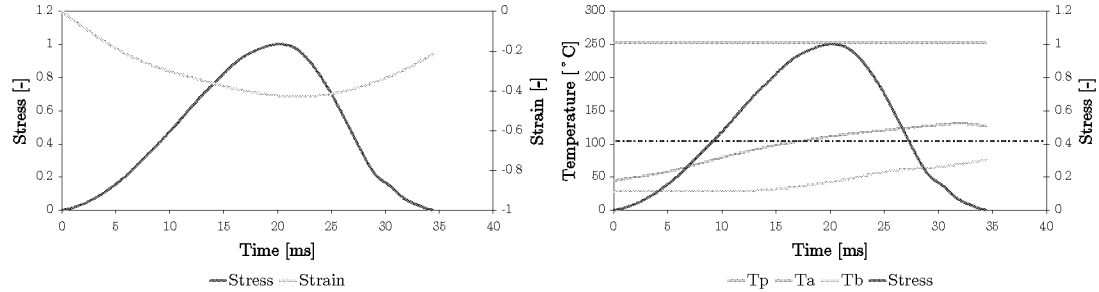


Figure 5.15: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 34 ms with a peak pressure of 5.1 MPa. The plate temperature was set to 250 °C. **Right:** The corresponding temperature profiles obtained during the press drying of a  $80 \text{ g.m}^{-2}$  40 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature,  $T_a$  and  $T_b$  the temperature at the paper/heated plate and paper/felt interfaces.

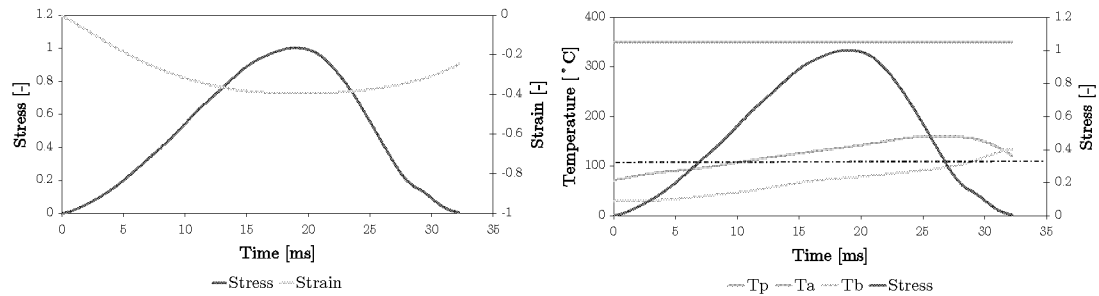


Figure 5.16: **Left:** Experimental applied stress and the corresponding web strain evolution throughout the pressing event. The duration of the press pulse was 32 ms with a peak pressure of 5.0 MPa. The plate temperature was set to 350 °C. **Right:** The corresponding temperature profiles obtained during the press drying of a  $80 \text{ g.m}^{-2}$  40 °SR hardwood wet paper web together with felt sample No. 249031-12.  $T_p$  represents the platen temperature,  $T_a$  and  $T_b$  the temperature at the paper/heated plate and paper/felt interfaces.

### 5.3.2 Simulations

The global model was used to predict the evolution of the dependent variables of the heat and mass transfer model for both paper and felt. Temperature, gas and vapor pressure and moisture ratio as well as those properties related to the mechanical model (web thickness and, stress and density profiles) are presented for a typical impulse drying event. The model performance was evaluated for the high-intensity pressing conditions summarized on Table 5.2, imposing the same press pulse as that illustrated in Figure 5.6 to a sandwich formed by a wet paper web and a felt sample. The description of the mat (paper + felt) main properties is presented on Table 5.1.

Some of the model predictions for these high-intensity conditions are presented in the following figures, namely those obtained at 150 and 350 °C, the latter case being the most representative of the operating conditions typically used in impulse drying. Figures 5.17, 5.18 and 5.19 illustrate the results obtained at 150 °C for the variables related to the mechanical model, *i.e.* the total thickness of the sheet,  $L_z$ , the applied stress  $\sigma_{ij}$ , and the local density,  $\rho_{ijk}$ . The remaining figures, 5.20 to 5.34, refer to the time evolution of the variables of the heat and mass transfer model, and their horizontal and vertical profiles within paper and felt pressed at 150 °C. Therefore, Figures 5.17 to 5.34 report to a simulation run performed for the operating conditions and material properties presented on Table 5.3.

Table 5.3: Material properties and operating conditions used in a simulation run.

| Paper                  |                                   | Operating conditions                                        |
|------------------------|-----------------------------------|-------------------------------------------------------------|
| Grammage               | 60 g.m <sup>-2</sup>              | Temperature of the pressing head<br>T <sub>p</sub> = 150 °C |
| Refining level         | 25 °SR                            |                                                             |
| Additive content       | -                                 | Pulse length                                                |
| Initial moisture ratio | ≈ 2.1 kg H <sub>2</sub> O/kg ds   | τ ≈ 31 ms                                                   |
| Pulp furnish           | bleached hardwood pulp            | Peak pressure                                               |
| Felt                   |                                   | 5.2 MPa                                                     |
| Grammage               | 1405 g.m <sup>-2</sup>            | Pulse shape                                                 |
| Initial moisture ratio | ≈ 0.146 kg H <sub>2</sub> O/kg ds | Roll                                                        |

The comparison between predicted and measured strain of the mat formed by paper and felt pressed at 150 °C is shown in Figure 5.17. Qualitatively, the agreement is satisfactory but the model tends to over-predict the level of strain attained during the pressing event. Further, the agreement is clearly greater in the initial stage of the compression, and major discrepancies start to appear as

the mat is further heated and compressed. Once pressure is released the model tends to follow the experimental data. For high temperatures, when evaporation is expected, the model tends to shift even further from the experimental results (see Figure 5.35). It is then advanced that the larger discrepancies are related to difficulties in accurately describe paper and felt properties at high temperatures.

The information obtained from the model can give insights about the mechanisms that are active in the nip. An interesting example concerns the slight time delay of the strain curve predicted by the model in respect to the point of maximum applied stress. This is also in agreement with the experimental findings, and seems to emphasize the viscoelastic behavior of the materials studied here under the selected operating conditions.

Figures 5.18 and 5.19 illustrate the evolution of the density profiles of the composite as a function of time and at different vertical positions within the mat, highlighting the stratification phenomena often reported in the literature. At the beginning of the pressing event, the consolidation of the paper sample is somehow prevented by the action of the liquid water present within the fibrous material. Additionally, the high stress rate applied to the web builds up the hydraulic pressure in the extra-fiber space during the compression phase, thus contributing to the increase of the material's resistance to compression.

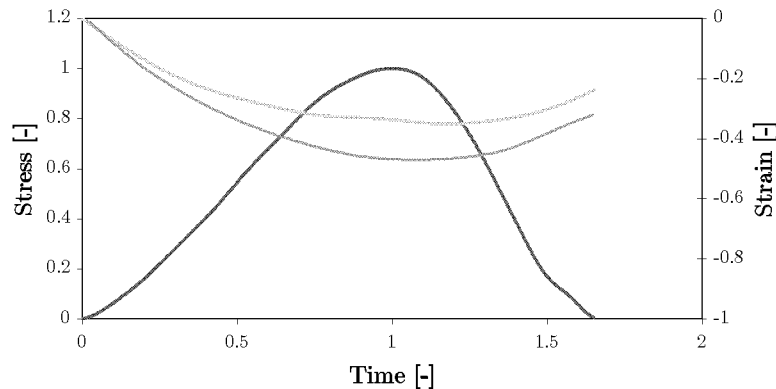


Figure 5.17: Comparison between the experimental data (light green line) and the mathematical prediction (red line) for the total web thickness. The peak pressure was 5.2 MPa, the pulse length 31 ms and the pressing temperature 150 °C. The corresponding stress pulse is also presented (blue line).

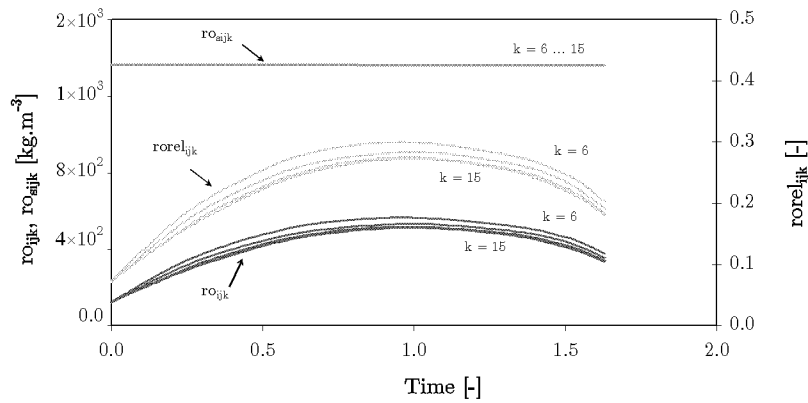


Figure 5.18: Model predictions for the apparent, relative and solid phase densities of a 60 g.m<sup>-2</sup> 25 °SR hardwood paper web pressed at 150 °C together with felt sample No. 249031-12. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa. Densities are plotted for different vertical positions within paper:  $k = 6$  denotes the layer in the paper region near the paper/felt interface and  $k = 15$  the layer near the heated platen press.

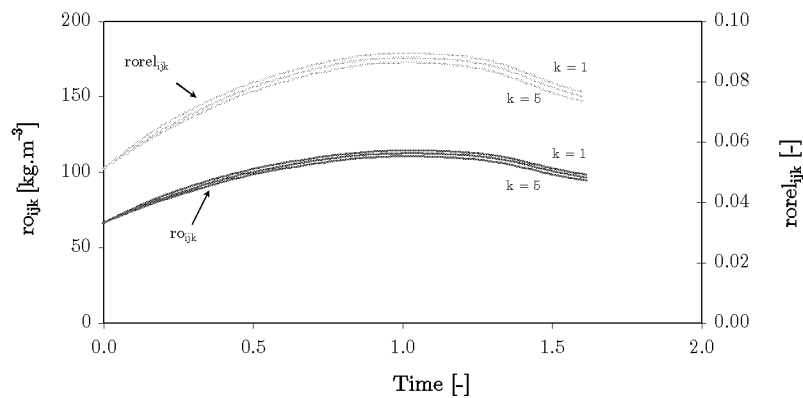


Figure 5.19: Model predictions for the apparent and relative densities of felt sample No. 249031-12. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa. Densities are plotted for different vertical positions within felt:  $k = 1$  denotes the felt layer near the sintered metal plate, and  $k = 5$  the felt layer near the paper/felt interface.

The interaction between viscous flow forces and fibers result in a structural stress onto the fiber network. This structural stress accumulates and increases in the flow direction, *i.e.* towards the press felt. Additionally, the water flow through the fiber network requires a drop in hydraulic pressure as its driving force. Both structural stress and hydraulic pressure therefore vary in the flow direction and are responsible for the stratification phenomenon shown in Figures 5.18 and 5.19. In fact, the highest compaction of the paper sample was found near the permeable paper/felt interface, where hydraulic pressure is minimum. In contrast to that, only part of the applied stress is supported by the solid material at the heated plate/paper interface, with the major part of the stress being supported by the fluid (high hydraulic pressure). These same findings are also valid for the felt material, although the density gradient in the thickness direction is not so evident. This is not surprising since both felt sides are in contact with permeable surfaces - paper at the top surface and the sintered metal plate beneath. Furthermore, the viscous flow forces are less important since the amount of liquid water is considerably lower than in the case of wet paper. This results in a more even stress distribution in the thickness direction of the felt sample, thus leading to a less pronounced density gradient.

Observing the three previous figures, it may be concluded that the heat and mass transfer model together with the mathematical description of the mechanical behavior of paper and felt, describe with some accuracy the consolidation process. At the initial stage of the pressing event both paper and felt deform to a great extent at a relatively low stress. Then, as a result of fiber stiffness and water resistance to compression, the strain rate decreases and the thickness remains almost constant as the stress is further increased. Again, this is in close agreement with the mechanical behavior of the cellular solids, *i.e.* the initial deformation stage corresponding to the linear elastic and cellular collapse phases, followed by a consolidation mechanism in which a higher level of stress is required to further deform the web. When the applied stress is suddenly released the web gradually expands but not to its initial state, which suggests a certain level of permanent strain at the end of the pressing event.

In addition, the simulation study showed that the mat consolidation also plays a fundamental role on the heat and mass transfer process. Figure 5.20 illustrates the temperature distribution in the thickness direction of the mat (paper + felt)

as predicted by the model. For comparison the experimental results obtained for the same operating conditions are also presented.

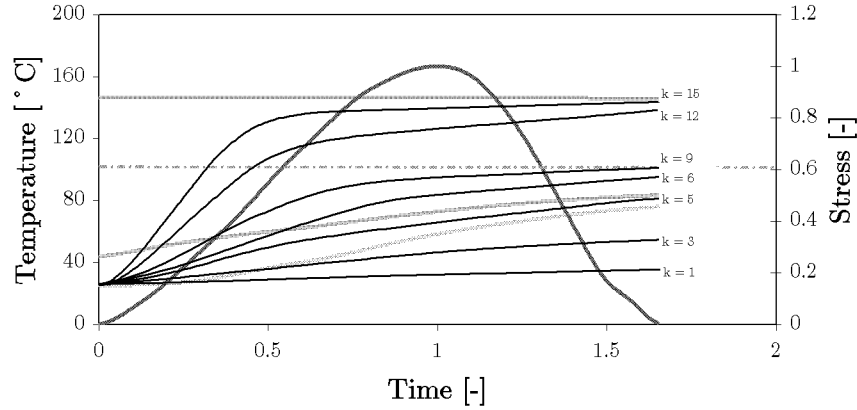


Figure 5.20: Experimental temperature profiles obtained for a 25 °SR 60 g.m<sup>-2</sup> hardwood paper web subjected, together with felt sample No. 249031-12, to a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C (Tp: magenta; Ta: orange; Tb: light green (as defined in Figure 2.21)). The results of a simulation run for the same operating conditions and materials properties are also presented (solid black lines). The predicted values were obtained for the vertical middle plane of the web (paper and felt) at different vertical positions:  $k = 1$  denotes the layer in the felt region near the backing sintered metal plate,  $k = 5$  the felt layer near the paper/felt interface,  $k = 6$  the layer in the paper region near the same interface, and  $k = 15$  the paper layer close to the heated platen press.

In the very beginning of the press pulse it is observed a steep temperature increase in the superficial layers of the paper sheet close to the hot platen. This is ascribed to the temperature gradient established between the two surfaces, which induces an extremely high heat flux to the wet paper sample. As for the inner layers of paper sheet the increase in temperature is more gradual and starts a few milliseconds after nip closing as heat has to be transported in the thickness direction. At this initial stage warming up is dominated by heat conduction through the paper sheet, a process that requires time. Since the nip residence time is relatively short (31 ms) the heat penetration through the porous material is believed to be still in progress near the end of the pressing event. In the felt region the temperature increase is even more gradual. In fact, for a pressing temperature of 150 °C, the felt surface contacting the sintered metal plate remains almost at

room temperature during the entire pressing event, and no model predictions indicate temperatures above 100 °C. This is not the case, however, for the paper sample. Actually, the warming up process is far more intensive in the paper layers near the hot platen, where temperature easily crosses the 100 °C barrier.

Additionally, heat is also transferred by convection. The more the mat is compressed the more water will be transported from the layers near the hot platen towards the cold side of the felt, thus exchanging its heat with the fibers while passing through the porous structure. As the inner layers of the mat are continuously heated, the temperature gradient in the thickness direction decreases as well as the heat flux from the top surface of the paper sheet. As a consequence the temperature increase becomes more gradual near the end of the pressing operation. A low viscosity of water, as a result of the increased temperature inside the wet porous network, is also very beneficial for efficient dewatering since it reduces the flow resistance.

Observing the model predictions of the horizontal and vertical temperature profiles for both paper and felt, pressed under the current operating conditions, it is advanced that the heat transfer occurs predominantly in the thickness direction of the mat, as illustrated in Figures 5.21 to 5.24. In fact, the horizontal profiles are nearly constant for both materials during the entire pressing event (see Figures 5.21 and 5.22), whereas the vertical temperature profiles indicate the existence of important temperature gradients in the thickness direction of the mat. One of the explanations for this preferred path of heat transfer is the direction of pressure application, which seems to force heat towards the bottom side of the mat (convective heat transfer). Additionally, conductive heat transfer is related to the temperature gradient established between the top surface of the paper sheet contacting the heated platen and the cold side of the felt sample near the sintered metal plate. The higher the temperature gradient the higher will be the potential for heat transfer. In fact, as the mat is being compressed, heat flows towards the inner layers of paper and felt, thus decreasing the temperature gradient in the thickness direction. As a result, the conductive heat flux is most significant during the initial stages of the pressing event, and this is even more notorious for the paper sample (see Figures 5.23 and 5.24). In contrast, no significant temperature gradients are found in the in-plane direction of the mat.



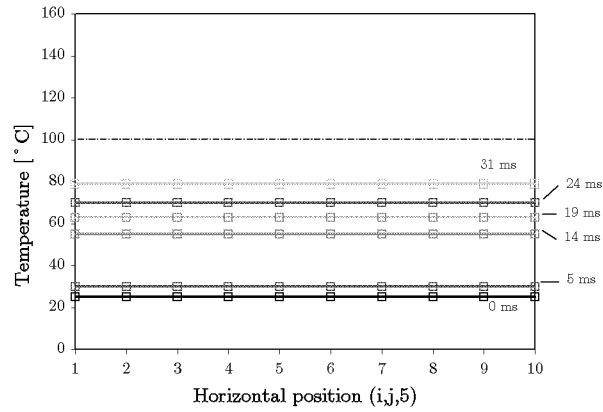


Figure 5.21: Horizontal temperature profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Temperature is plotted for the layer denoted by  $k = 5$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the felt sample. Results are also presented for different stages of the pressing event.

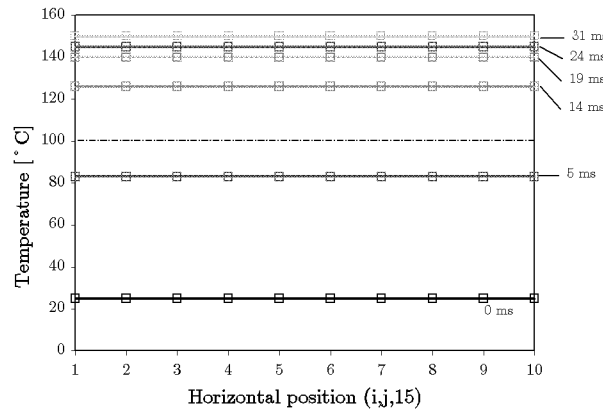


Figure 5.22: Horizontal temperature profiles predicted by the model for a 60  $\text{g.m}^{-2}$  25 °SR hardwood paper sample. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Temperature is plotted for the layer denoted by  $k = 15$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper sample. Results are also presented for different stages of the pressing event.

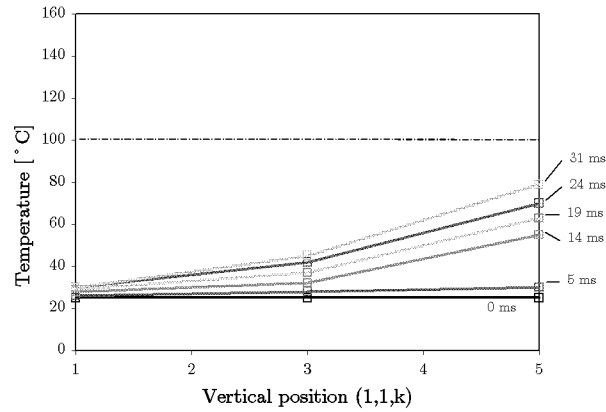


Figure 5.23: Vertical temperature profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Temperature is plotted for the vertical middle plane of the sample at different vertical positions:  $k = 1$  denotes the layer in the felt region near the backing sintered metal plate,  $k = 5$  the felt layer near the paper/felt interface. Results are also presented for different stages of the pressing event.

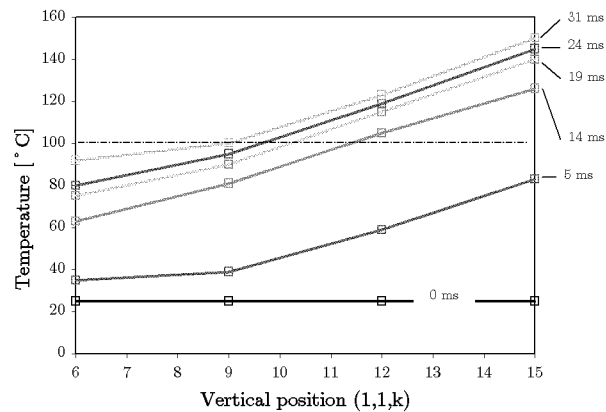


Figure 5.24: Vertical temperature profiles predicted by the model for a 60 g.m<sup>-2</sup> 25 °SR hardwood paper sample. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Temperature is plotted for the vertical middle plane of the sample at different vertical positions:  $k = 6$  denotes the layer in the paper region near the backing felt sample, and  $k = 15$  the paper layer near the heated paten press. Results are also presented for different stages of the pressing event.

According to the model predictions, the temperature in the layers of the paper region near the heated platen crossed the 100 °C limit. This is not the case for the felt sample however, where temperature reaches a maximum value around 80 °C. In contrast, temperatures up to 150 °C are reported for paper, which could indicate internal steam generation. In fact, during the compression of the mat an hydraulic pressure builds up inside the porous structure, thus shifting the water boiling temperature and preventing steam generation. If vapor was formed near the outer surface of the mat and additional resistance to heat transfer would appear. The porosity of the medium is also seen as an important factor in the development of steam in the pore space as it directly affects the permeability of the medium. As the web is being compressed, its void space decreases, as well as its permeability. If water is trapped inside the porous medium, an increase in temperature may therefore generate steam. This does not seem to be the case, however.

As the mat is being compressed the internal gas pressure builds up as a consequence of web thickness reduction (see Figures 5.25 and 5.26 for both felt and paper). As no additional vapor is assumed to be generated during the pressing event, for the actual pressing temperature of 150 °C, its contribution to the increase of the gas pressure is not considered. In fact, the partial vapor pressure inside the felt sample is significantly lower and its increase results once more from the decreasing porosity of the medium as it is compressed. It should be noted that felt has a low moisture ratio and the pore space is mainly occupied by moist air. This tends to flow primarily in the vertical direction towards the sintered metal plate, although a horizontal gas pressure gradient is established in the in-plane direction of the felt sample (Figures 5.29 and 5.31). In fact, at the initial stage of the compression event the gas is forced to flow towards the cold side of the felt as a result of pressure application. As the material is further compressed, the gas is forced to leave the porous medium through the lateral edges as well. However, the permeability of the medium is lower in the in-plan direction and the gas flux is reduced, thus increasing its pressure in the central region of the sample (see Figure 5.29). Figures 5.30 and 5.32 illustrate a similar behavior of the gas phase inside the paper sample. As the material presents a high moisture ratio, the amount of liquid water in the interfiber space will be partially responsible for the increased resistance to compression. Being a more closed structure, when compared to that of felt, the gas will tend to remain trapped inside the porous

network. As a result the gas pressure increases far beyond the atmospheric limit. If one compares the horizontal and vertical gas pressure profiles of both paper and felt, some interesting conclusions can be drawn: (i) the gas pressure increase in the central region of the sample is most notorious for paper as a result of air and vapor entrapment; (ii) at the end of the pressing event, the gas phase near the lateral edges of the felt sample tend to be close to atmospheric conditions; (iii) the vertical gas pressure profiles obtained for paper are steeper, which is not surprising since the material is significantly less permeable to fluid flow.

As no steam generation is assumed at the present conditions, the horizontal vapor profiles are nearly constant for both paper and felt (see Figures 5.27 and 5.28). A pressure increase with time is however observed as a consequence of volume reduction of the mat. Again, the pressure levels are significantly higher for paper.

The predicted moisture ratio evolution with time at different vertical positions inside felt sample is presented in Figure 5.33. The moisture distribution is a consequence of liquid water flow in the thickness direction towards the sintered metal plate (only liquid water is able to flow across the paper/felt interface as a result of the fluid continuity assumption established for modeling purposes). Furthermore, due to the stratification process the bottom layers have a lower amount of liquid water per kg of dry mass. As expected, the top layers of the felt present a higher moisture ratio as liquid water is being transferred from the bottom layers of the paper sample contacting the felt. During the compression phase the moisture ratio increases as a consequence of fluid flow towards the felt and the uneven consolidation of the porous material in the thickness direction. As the applied pressure is released, the mat expands and some back flow towards the paper sheet may actually take place, thus decreasing the felt moisture ratio near the interface.

Finally, for the moisture distribution within paper, similar conclusions may be drawn from Figure 5.34: it is also a consequence of liquid water flow in the thickness direction of the web, and of the stratification process. During the compression phase of the pressing event, the moisture ratio decreases as liquid water is leaving the paper sample. This decrease is more pronounced in the bottom layers near the felt. In addition, in the expansion phase the applied mechanical pressure is decreased and the web will expand as the fluid fills up the created void volume (rewetting). This is observed in the moisture ratio profile at

the layer close to the felt (layer denoted as  $k = 6$  in Figure 5.34).

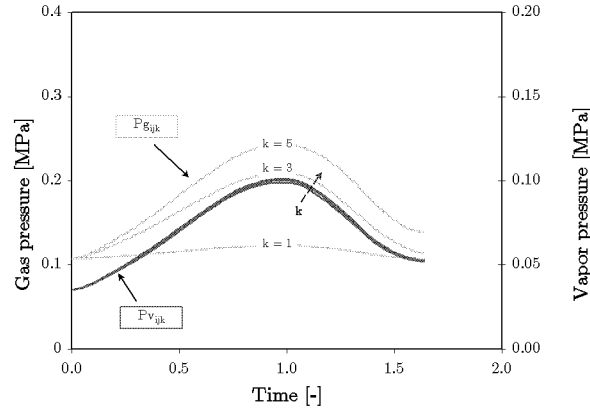


Figure 5.25: Predicted gas and vapor pressure values inside felt sample No. 249031-12. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Pressure is plotted for the vertical middle plane of the felt sample at different vertical positions:  $k = 1$  denotes the layer in the felt region near the backing sintered metal plate,  $k = 5$  the felt layer near the paper/felt interface.

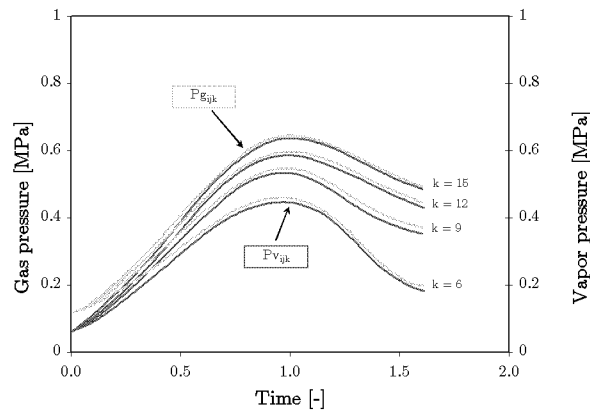


Figure 5.26: Predicted gas and vapor pressure values inside a 60 g.m<sup>-2</sup> 25 °SR hardwood paper sample. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Pressure is plotted for the vertical middle plane of the paper sample at different vertical positions:  $k = 6$  denotes the layer in the paper region near the backing felt sample, and  $k = 15$  the paper layer near the heated paten press.

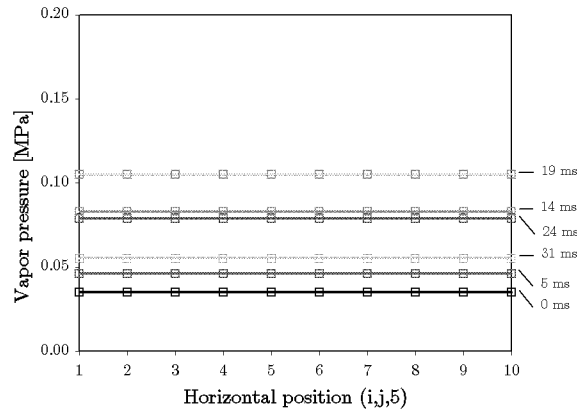


Figure 5.27: Horizontal vapor pressure profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Vapor pressure is plotted for the layer denoted by  $k = 5$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the felt sample. Results are also presented for different stages of the pressing event.

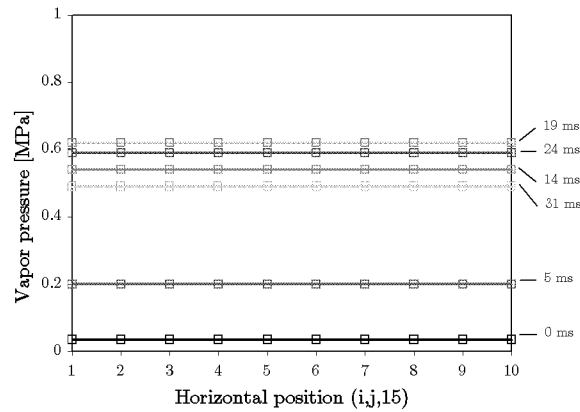


Figure 5.28: Horizontal vapor pressure profiles predicted by the model for a 60 g.m<sup>-2</sup> 25 °SR hardwood paper sample. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Vapor pressure is plotted for the layer denoted by  $k = 15$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper sample. Results are also presented for different stages of the pressing event.

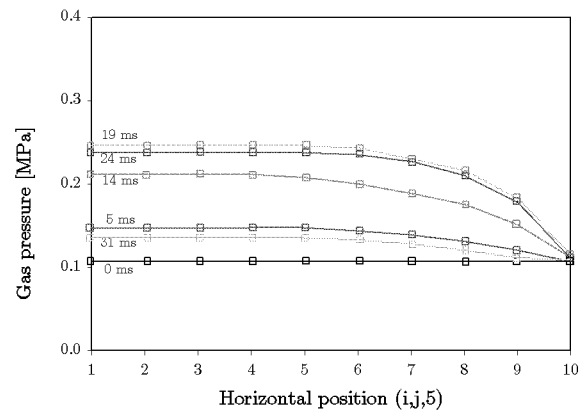


Figure 5.29: Horizontal gas pressure profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Gas pressure is plotted for the layer denoted by  $k = 5$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the felt sample. Results are also presented for different stages of the pressing event.

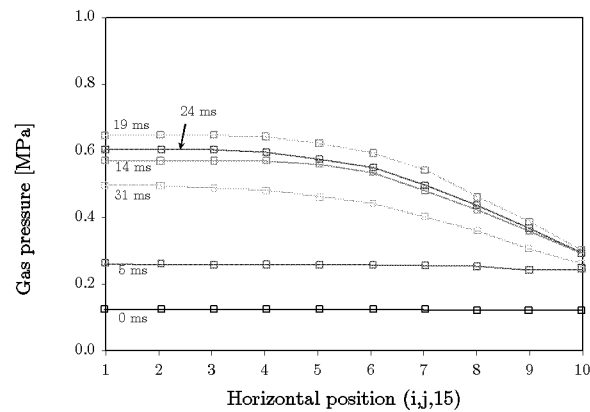


Figure 5.30: Horizontal gas pressure profiles predicted by the model for a 60  $\text{g.m}^{-2}$  25 °SR hardwood paper sample. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Gas pressure is plotted for the layer denoted by  $k = 15$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper sample. Results are also presented for different stages of the pressing event.

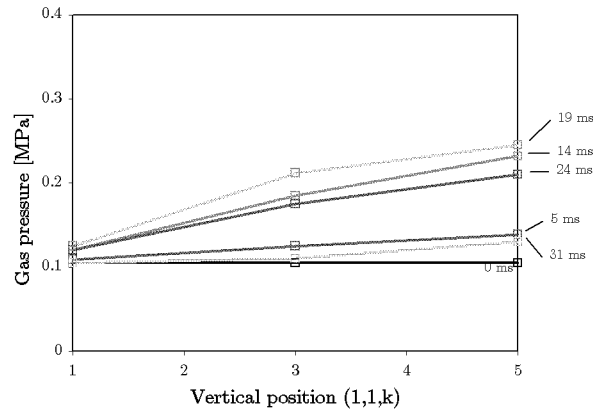


Figure 5.31: Gas pressure profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Gas pressure is plotted for the vertical middle plane of the sample at different vertical positions:  $k = 1$  denotes the layer in the felt region near the backing sintered metal plate,  $k = 5$  the felt layer near the paper/felt interface. Results are also presented for different stages of the pressing event.

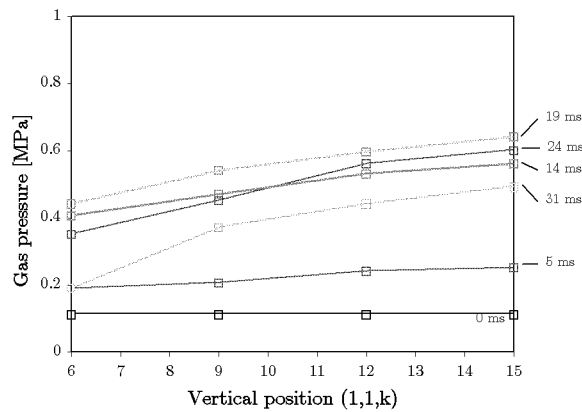


Figure 5.32: Gas pressure profiles predicted by the model for a 60 g.m<sup>-2</sup> 25 °SR hardwood paper sample. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Gas pressure is plotted for the vertical middle plane of the sample at different vertical positions:  $k = 6$  denotes the layer in the paper region near the backing felt sample, and  $k = 15$  the paper layer near the heated paten press. Results are also presented for different stages of the pressing event.



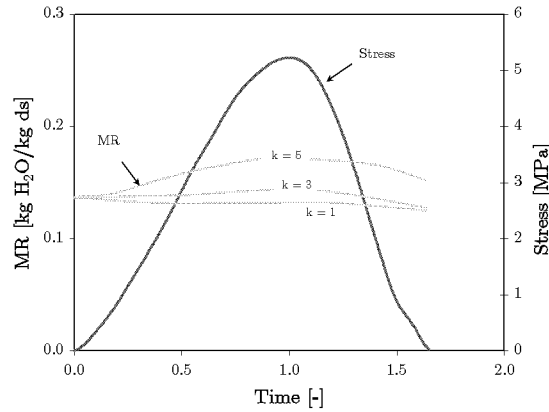


Figure 5.33: Predicted moisture ratio evolution with time at different vertical positions inside felt sample No. 249031-12. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Moisture ratio is plotted for the vertical middle plane of the felt sample at different vertical positions:  $k = 1$  denotes the layer in the felt region near the backing sintered metal plate,  $k = 5$  the felt layer near the paper/felt interface. The pressure pulse applied on the sample is also presented.

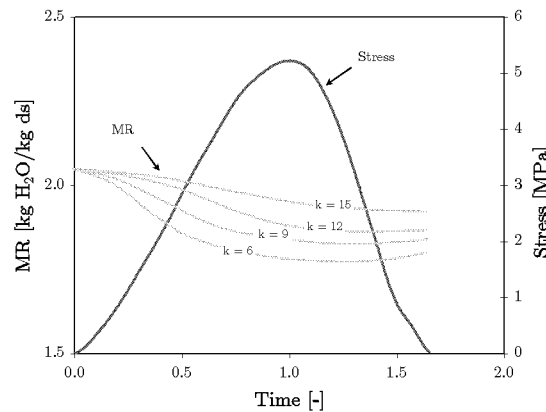


Figure 5.34: Predicted moisture ratio evolution with time at different vertical positions inside a 60 g.m<sup>-2</sup> 25 °SR hardwood paper sample. The results were obtained for a press pulse of 31 ms with a peak pressure of 5.2 MPa at 150 °C. Moisture ratio is plotted for the vertical middle plane of the paper sample at different vertical positions:  $k = 6$  denotes the layer in the paper region near the backing felt sample, and  $k = 15$  the paper layer near the heated paten press. The pressure pulse applied on the web is also presented.

To get a view on the potential of the impulse technology the results of a simulation run performed for typical operating conditions are presented here. Figures ?? to 5.52 report to that simulation run obtained for the operating conditions and material properties presented on Table 5.4. Basically, the main conclusions in terms of mat deformation and density evolution are the same as those drawn for the previous case, *i.e.* the results obtained at a lower temperature of pressing (150 °C). Therefore, an exhaustive description of Figures ??, 5.36 and 5.37 is avoided here. The main difference, which is worth to note, is the slight strain recovery at the final stage of the pressing event. This behavior has often been referred in the literature as a consequence of flash expansion, and indicates that steam generation may have taken place at nip opening.

Table 5.4: Material properties and operating conditions used in a simulation run.

| Paper                  |                                           | Operating conditions                               |
|------------------------|-------------------------------------------|----------------------------------------------------|
| Grammage               | 60 g.m <sup>-2</sup>                      | Temperature of the pressing head<br>$T_p = 350$ °C |
| Refining level         | 25 °SR                                    |                                                    |
| Additive content       | -                                         | Pulse length                                       |
| Initial moisture ratio | $\approx 1.9$ kg H <sub>2</sub> O/kg ds   | $\tau \approx 34$ ms                               |
| Pulp furnish           | bleached hardwood pulp                    | Peak pressure<br>5.4 MPa                           |
| Felt                   |                                           |                                                    |
| Grammage               | 1405 g.m <sup>-2</sup>                    | Pulse shape                                        |
| Initial moisture ratio | $\approx 0.131$ kg H <sub>2</sub> O/kg ds | Roll                                               |

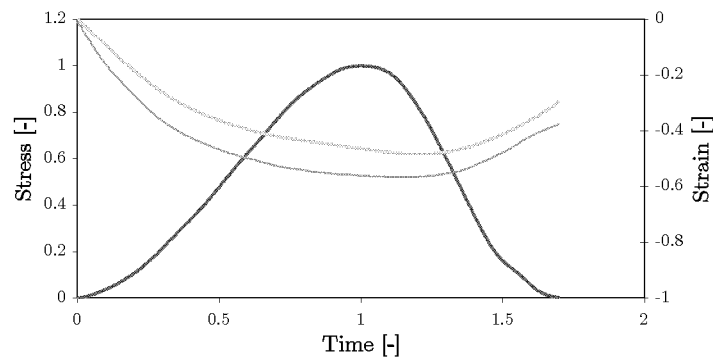


Figure 5.35: Comparison between the experimental data (light green line) and the mathematical prediction (red line) for the total web thickness. The peak pressure was 5.4 MPa, the pulse length 34 ms and the pressing temperature 350 °C. The corresponding stress pulse is also presented (blue line).

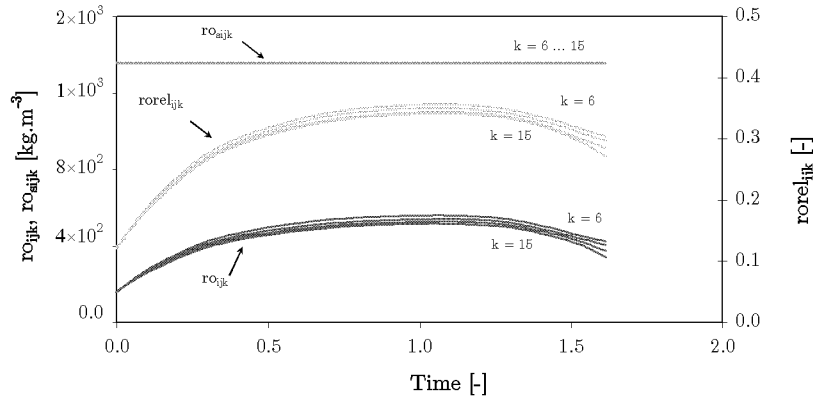


Figure 5.36: Model predictions for the apparent, relative and solid phase densities of a 60 g.m<sup>-2</sup> 25 °SR hardwood paper web pressed at 350 °C together with felt sample No. 249031-12. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa. Densities are plotted for different vertical positions within paper:  $k = 6$  denotes the layer in the paper region near the paper/felt interface and  $k = 15$  the layer near the heated platen press.

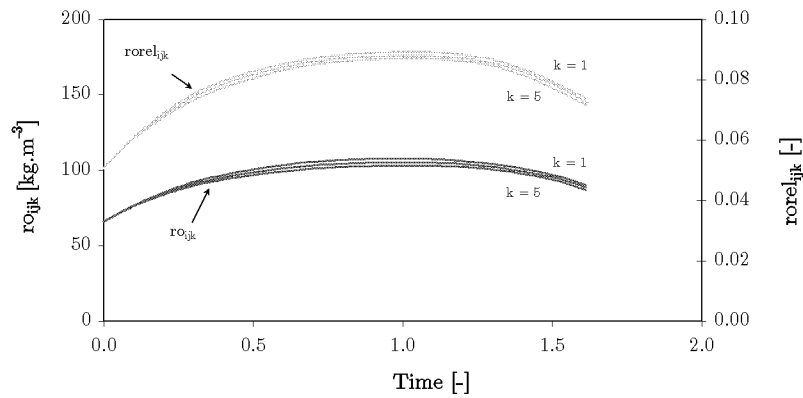


Figure 5.37: Model predictions for the apparent and relative densities of felt sample No. 249031-12. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa. Densities are plotted for different vertical positions within felt:  $k = 1$  denotes the felt layer near the sintered metal plate, and  $k = 5$  the felt layer near the paper/felt interface.

The amount and severity of flash expansion depends on the temperature gradient at the beginning of the expansion phase of the pressing event. As it may be observed in Figure 5.38, the temperature profiles predicted by the model during a simulation run using a pressing temperature of 350 °C, are very steep for the paper layers near the heated platen press. In fact, even the top layers of the felt sample crossed the 100 °C barrier. This suggests that steam generation may actually take place inside the mat at these operating conditions. It is, however, advanced that a sufficiently high hydraulic pressure is created and maintained during the compression stage and almost at the end of the expansion phase of the press drying event.

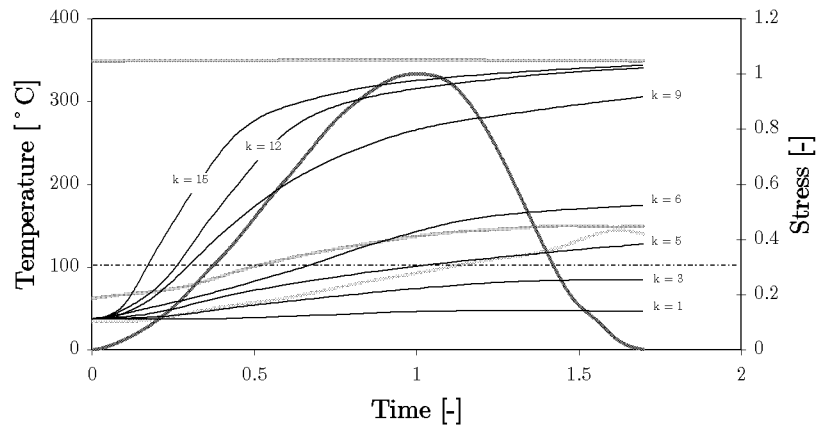


Figure 5.38: Experimental temperature profiles obtained for a 25 °SR 60 g.m<sup>-2</sup> hardwood paper web subjected, together with felt sample No. 249031-12, to a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C (Tp: magenta; Ta: orange; Tb: light green (as defined in Figure 2.21)). The results of a simulation run for the same operating conditions and materials properties are also presented (solid black lines). The predicted values were obtained for the vertical middle plane of the web (paper and felt) at different vertical positions: k = 1 denotes the layer in the felt region near the backing sintered metal plate, k = 5 the felt layer near the paper/felt interface, k = 6 the layer in the paper region near the same interface, and k = 15 the paper layer close to the heated platen press.

At the end of the press nip the mechanical pressure drops steeply back to atmospheric conditions. Accordingly, steam formation will occur if the saturated pressure associated with the local temperature in the mat exceeds the hydraulic pressure. This seems to be the case for the example reported here. In fact, the

layers in the paper region near the heated platen easily reach and cross 300 °C. Since the saturation pressure increases rapidly with temperature, an increase of the heated platen temperature above 250 °C will enable steam generation also for higher press loads. The effect of steam generation will be a local increase of the hydraulic pressure in the pores, which in turn will enhance water flow through the paper sheet. However, this effect is believed to occur only in the few milliseconds just prior to nip opening, as no clear evidence of web expansion is observed prior to that in the simulation results. In fact, Figure 5.36 shows some evidence of steam formation, as the apparent density of the top layers of the paper sheet suddenly decreases, just before the end of the press pulse. It is then advanced, that a very high hydraulic pressure is developed in the surface layers of the paper sheet near the heated platen press during almost the entire press drying event.

Figures 5.39 to 5.42 illustrate the horizontal and vertical temperature profiles predicted by the model for an impulse drying event of both paper and felt at 350 °C. With these fast compression rates there should be no evidence of steam formation, at least for low grammage paper sheets, as it is the present case. For short pulses the hydraulic pressure generated inside the mat is expected to be high enough to prevent steam formation as the increase of the hydraulic pressure, due to either web stratification or viscoelastic effects, tends to shift the boiling point of water to higher temperatures and prevent steam generation. One explanation for the model predictions in terms of steam formation during the decompression phase of the pressing event is the over-prediction of the temperature profiles. Major discrepancies found between the predicted and measured temperatures inside paper and felt (see Figure 5.38) may be partially attributed to the absence of a heat transfer resistance coefficient and over-simplified boundary conditions defined in the theoretical model for the paper/heated platen interface. A more accurate description of the temperature profiles inside the mat would certainly indicate a lower temperature range, which would enable the prevention of steam formation in the nip for the present operating conditions.

As observed in the simulation run performed with a pressing temperature of 150 °C, the heat transfer is preferably established in the thickness direction of both paper and felt. In fact, the horizontal temperature profiles are nearly constant, whereas in the vertical direction significantly temperature gradients are observed (this is more notorious for the paper sample as it contacts the heated platen press). Figure 5.42 shows, in fact, extremely high temperature profiles

inside the paper sheet. It is believed, however, that a small amount of vapor may actually be formed at the very end of the pressing event, when pressure is removed.

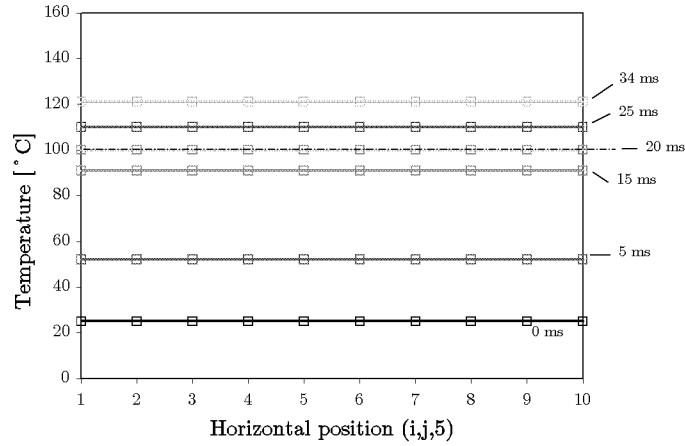


Figure 5.39: Horizontal temperature profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Temperature is plotted for the layer denoted by  $k = 5$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the felt sample. Results are also presented for different stages of the pressing event.

The effect of steam generation within the paper layers near the hot surface will be the increase of local vapor and gas pressure, which in turn will enhance dewatering towards the press felt. Qualitatively, the results obtained here in terms of horizontal and vertical pressure profiles show no significant deviations from those obtained at 150 °C. The major difference refers to the gas and vapor pressure levels determined for the paper sample pressed at the highest temperature. In fact, steam formation at the paper side in contact with the hot platen induces a higher gas pressure gradient in the thickness direction of the porous network (see Figures 5.44 and 5.50), whereas nearly constant vapor pressure profiles are still observed in the in-plane direction (Figure 5.46). The horizontal gas pressure profiles (Figure 5.48) are qualitatively similar to those previously presented at 150 °C. As no steam generation is expected inside the felt sample, the gas and vapor pressure evolution follows the same trend as that observed at lower temperature

(see Figures 5.43, 5.45, 5.47 and 5.49).

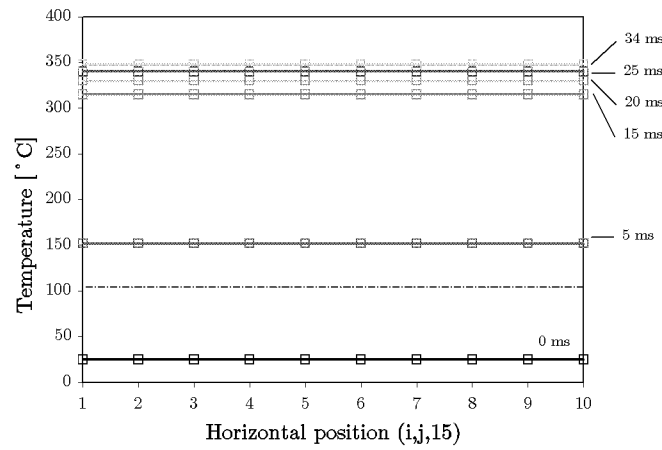


Figure 5.40: Horizontal temperature profiles predicted by the model for a 60 g.m<sup>-2</sup> 25 °SR hardwood paper sample. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Temperature is plotted for the layer denoted by  $k = 15$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper sample. Results are also presented for different stages of the pressing event.

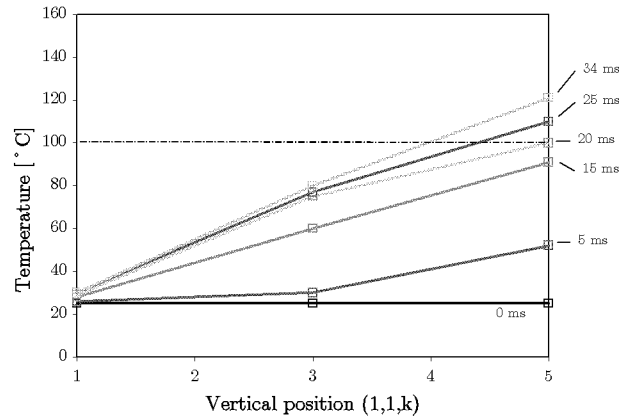


Figure 5.41: Vertical temperature profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Temperature is plotted for the vertical middle plane of the sample at different vertical positions:  $k = 1$  denotes the layer in the felt region near the backing sintered metal plate,  $k = 5$  the felt layer near the paper/felt interface. Results are also presented for different stages of the pressing event.

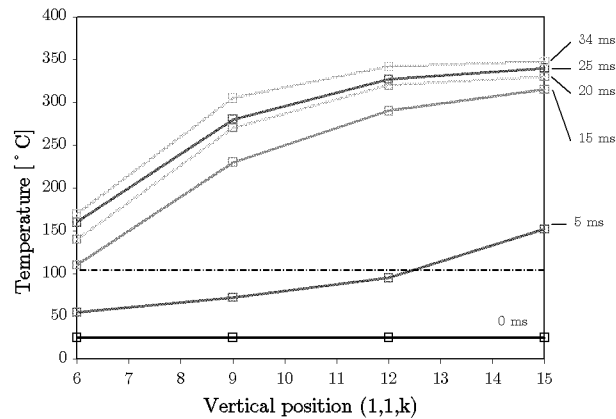


Figure 5.42: Vertical temperature profiles predicted by the model for a 60 g.m<sup>-2</sup> 25 °SR hardwood paper sample. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Temperature is plotted for the vertical middle plane of the sample at different vertical positions:  $k = 6$  denotes the layer in the paper region near the backing felt sample, and  $k = 15$  the paper layer near the heated paten press. Results are also presented for different stages of the pressing event.



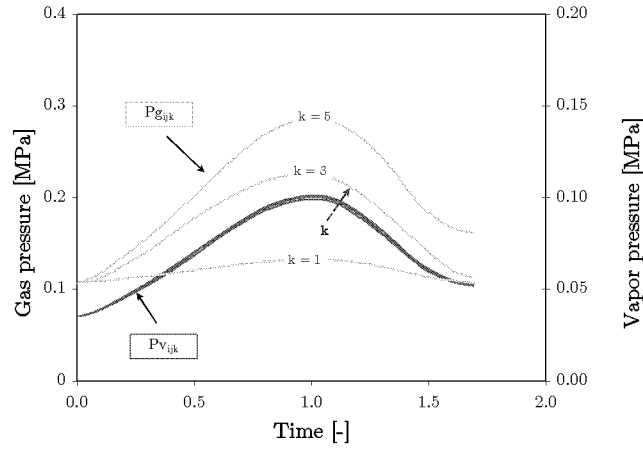


Figure 5.43: Predicted gas and vapor pressure values inside felt sample No. 249031-12. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Pressure is plotted for the vertical middle plane of the felt sample at different vertical positions:  $k = 1$  denotes the layer in the felt region near the backing sintered metal plate,  $k = 5$  the felt layer near the paper/felt interface.

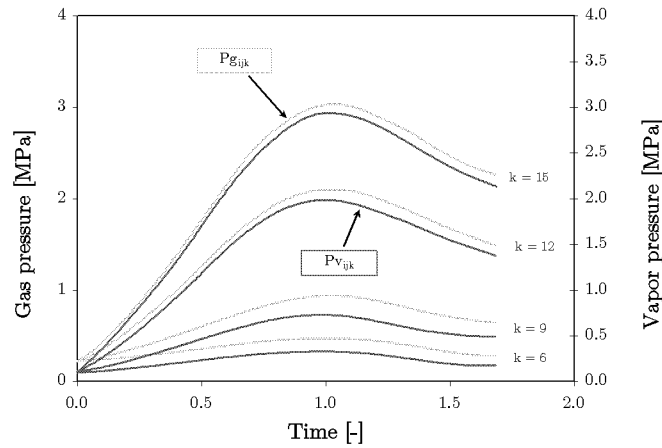


Figure 5.44: Predicted gas and vapor pressure values inside a 60 g.m<sup>-2</sup> 25 °SR hardwood paper sample. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Pressure is plotted for the vertical middle plane of the paper sample at different vertical positions:  $k = 6$  denotes the layer in the paper region near the backing felt sample, and  $k = 15$  the paper layer near the heated paten press.

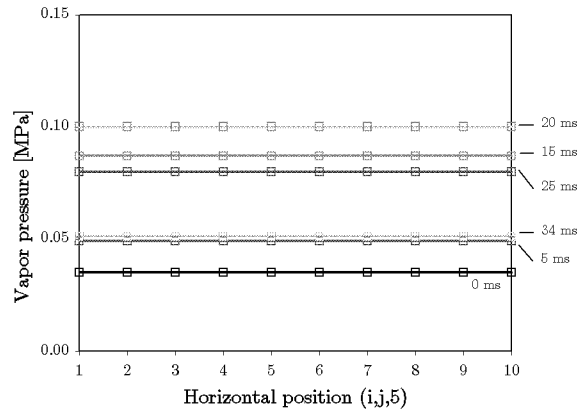


Figure 5.45: Horizontal vapor pressure profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Vapor pressure is plotted for the layer denoted by  $k = 5$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the felt sample. Results are also presented for different stages of the pressing event.

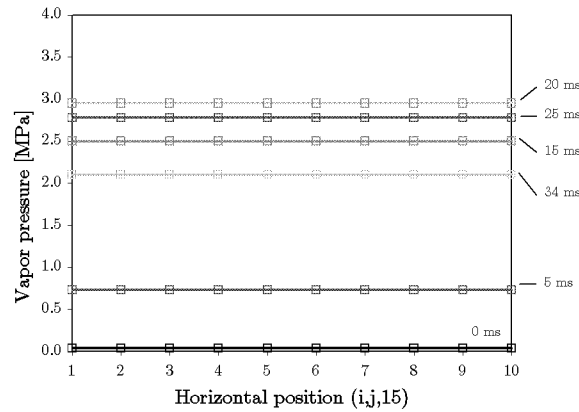


Figure 5.46: Horizontal vapor pressure profiles predicted by the model for a 60  $\text{g.m}^{-2}$  25 °SR hardwood paper sample. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Vapor pressure is plotted for the layer denoted by  $k = 15$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper sample. Results are also presented for different stages of the pressing event.

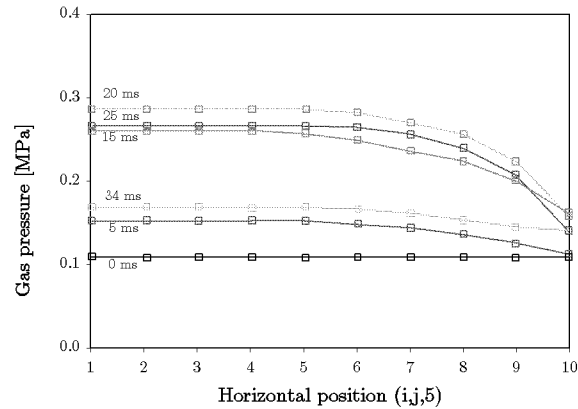


Figure 5.47: Horizontal gas pressure profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Gas pressure is plotted for the layer denoted by  $k = 5$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the felt sample. Results are also presented for different stages of the pressing event.

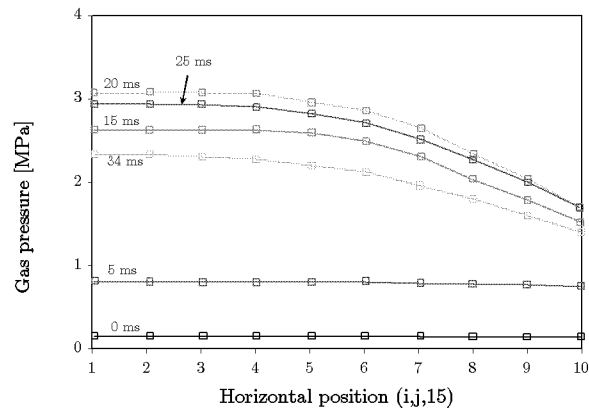


Figure 5.48: Horizontal gas pressure profiles predicted by the model for a 60  $\text{g.m}^{-2}$  25 °SR hardwood paper sample. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Gas pressure is plotted for the layer denoted by  $k = 15$  at different in-plane locations:  $i = 1$  (or  $j = 1$ ) denotes the region adjacent to the center of the sample and  $i = 10$  (or  $j = 10$ ) corresponds to the region near the lateral edge of the paper sample. Results are also presented for different stages of the pressing event.

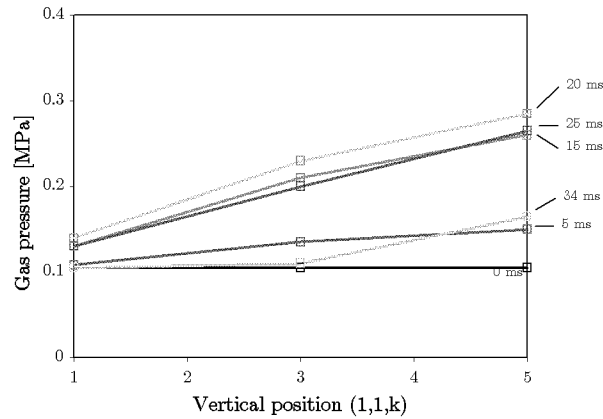


Figure 5.49: Gas pressure profiles predicted by the model for felt sample No. 249031-12. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Gas pressure is plotted for the vertical middle plane of the sample at different vertical positions:  $k = 1$  denotes the layer in the felt region near the backing sintered metal plate,  $k = 5$  the felt layer near the paper/felt interface. Results are also presented for different stages of the pressing event.

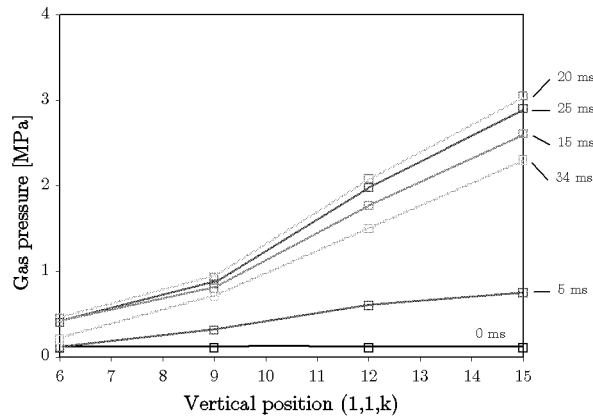


Figure 5.50: Gas pressure profiles predicted by the model for a 60 g.m<sup>-2</sup> 25 °SR hardwood paper sample. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Gas pressure is plotted for the vertical middle plane of the sample at different vertical positions:  $k = 6$  denotes the layer in the paper region near the backing felt sample, and  $k = 15$  the paper layer near the heated paten press. Results are also presented for different stages of the pressing event.

Finally, Figures 5.51 and 5.52 refer to the moisture ratio evolution during the pressing event for both felt and paper, respectively. Besides a lower range of moisture ratio predicted by the model for the felt sample at this high temperature, no major differences from the results obtained at 150 °C are worth to be mentioned. Both temperature effects and stratification are advanced here as the main causes for the decreasing moisture ratio gradient in the thickness direction of the felt sample. For paper, the picture is altogether different, however. In fact, as a steam layer is expected to be generated (although based in over-predicted results) near the hot platen, a considerable decrease in moisture ratio is observed in the paper region close to that interface. At the final stage of the decompression phase the moisture ratio tends to decrease further as a consequence of flashing at unloading. In the proximity of the felt, temperature never exceeds 170 °C, which means that steam generation can be avoided if a sufficient hydraulic pressure is maintained in the pores. As liquid water is leaving the paper sample towards the felt, the moisture ratio tends to decrease but to a moderate rate.

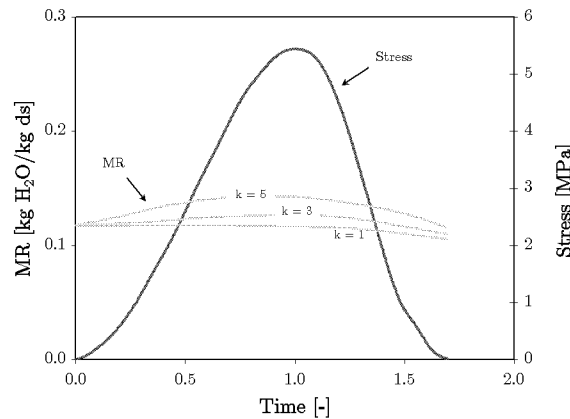


Figure 5.51: Predicted moisture ratio evolution with time at different vertical positions inside felt sample No. 249031-12. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at 350 °C. Moisture ratio is plotted for the vertical middle plane of the felt sample at different vertical positions:  $k = 1$  denotes the layer in the felt region near the backing sintered metal plate,  $k = 5$  the felt layer near the paper/felt interface. The pressure pulse applied on the sample is also presented.

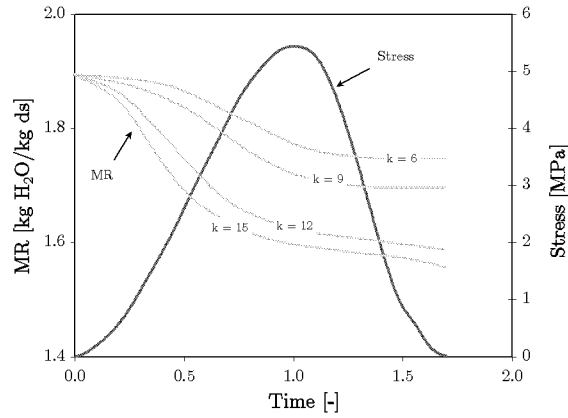


Figure 5.52: Predicted moisture ratio evolution with time at different vertical positions inside a  $60 \text{ g}\cdot\text{m}^{-2}$   $25^\circ\text{SR}$  hardwood paper sample. The results were obtained for a press pulse of 34 ms with a peak pressure of 5.4 MPa at  $350^\circ\text{C}$ . Moisture ratio is plotted for the vertical middle plane of the paper sample at different vertical positions:  $k = 6$  denotes the layer in the paper region near the backing felt sample, and  $k = 15$  the paper layer near the heated paten press. The pressure pulse applied on the web is also presented.

## 5.4 Conclusions

A global model for the consolidation process of paper and felt at high-intensity conditions is presented here. The model takes into account the convective movement of vapor and liquid apart from the known transport mechanisms of capillary flow of liquid and heat conduction. The inclusion of the convective vapor and liquid flow makes the model more suitable for simulating high intensity drying techniques. The model is general in the sense that it can predict changes in the state of the mat due to a pressure pulse of arbitrary shape and length, under a wide range of temperature conditions. The model can simulate changes in the local density of the mat, and other structural properties as the mat passes the press nip.

The predictive capability of the model has been evaluated with data from a laboratory platen press. At low operating temperatures the model gives good predictions of mat density, gas pressure, liquid water volume fraction, internal web temperature and vapor pressure. However, at the highest temperatures tested in the present work some important discrepancies are observed between the experimental results and the simulations. This is in part attributed to inappropriate model parameter estimation. Additionally, some physical properties would require better estimates at those extreme conditions.

Although the model presents some limitations it forms a good basis for discussions about the direction in which impulse drying research should focus to achieve improved dewatering rates with minimal energy demand. For instance, to optimize the mechanical dewatering process it would be beneficial to warm up the paper web/felt interface in order to decrease water viscosity where it has to leave the web. Additionally, it is suggested that at the end of the nip it would be better to have moderate temperatures inside the web to limit the amount of flash expansion.





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## Chapter 6

# Conclusions and recommendations for future work

The mechanisms of impulse drying have been widely discussed in the literature since the technique was conceived in the early '70s. It is seen as a promising web consolidation technique that combines the effect of mechanical pressure and intense heat to remove water from a paper web. Although there is a large body of information in the literature on the water removal and heat transfer mechanisms involved in such a complex process as impulse drying, the interaction between heat and water within paper is still a matter of some controversy. Despite the longstanding debate whether a steam front develops at the hot roll surface and displace any unbound water from the wet web or, on the other hand, impulse events can be interpreted as a combination of high-temperature pressing and rapid flash evaporation, experimental evidence confirming these theories is not easy to find.

Therefore, one of the main goals of the present work was to get an additional insight into the dewatering process of paper under the extreme conditions of impulse drying. For that purpose, an extensive experimental program was carried out in a platen press, covering different operating conditions in terms of temperature, peak pressure and nip residence time. As expected, experimental findings suggest that evaporative effects play a fundamental role in the dewatering process and in the physics of impulse technology. Furthermore, this experimental analysis seems to confirm an emerging theory based on the concept of “*flashing-assisted displacement dewatering*” (Lucisano, 2002), which unifies the two main theoretical approaches put forward in the literature. It is then suggested that little or

no steam generation occurs prior to the point of maximum applied pressure, in contrast with what was formerly advanced by other authors.

The results of experiments performed with embedded thermocouples in 240 and 320 g.m<sup>-2</sup> paper webs pressed from room temperature up to 350 °C over medium to long press pulses ( $\Delta t = 120$  and 2000 ms) revealed that for a platen temperature of 150 °C or above, almost all the thermocouples crossed the atmospheric boiling point of water, which may indicate that steam is formed. Different conclusions were drawn from the results obtained for similar paper webs pressed over a short period of time ( $\Delta t = 75$  ms). Here, platen temperatures of 150 °C or below did not induce steam generation, as the temperature inside the paper sheet remained under 100 °C. Similar press pulses ( $\Delta t = 75$  ms) applied on lower grammage sheets (60 and 80 g.m<sup>-2</sup>) showed, at temperatures above 200 °C, a sudden increase in temperature inside the web when the mechanical load was released. This suggests that thin sheets tend to exhibit phase change just prior to the end of the pressing event.

When even shorter pulses ( $\Delta t = 30$  ms) were applied to 60 g.m<sup>-2</sup> sheets, no clear evidence of such temperature increase was found, except for platen temperatures around 250 °C and above. It is then advanced that the high compression rate causes an increase in the hydraulic pressure inside the porous material, which shifts the boiling point of water and prevents steam generation. Then, when the mechanical load is released, the hydraulic pressure decreases and if the local temperature is higher than the saturation temperature corresponding to the local hydraulic pressure, liquid water flashes to vapor. This was found to occur at the very end of the impulse events performed with thin sheets at temperatures of 250 and 350 °C.

In light of the experimental findings it is then suggested that impulse drying may be envisaged as a hot pressing process followed by evaporative flashing at pressure release. This points to the existence of steam only in conjunction with flashing at the decompression phase of the impulse event, confirming the theory proposed by Macklem and Pulkowski (1988) as well as the experimental findings of Zavaglia and Lindsay (1989).

Apart from the experimental investigation of the internal temperature profiles of paper pressed under typical operating conditions of impulse drying, the present work aimed at evaluating the water removal efficiency of the process for the same conditions. The difference between the ingoing and outgoing dryness of samples

made from different pulp furnishes was determined for the temperature range of 25-350 °C. A continuous increase of gain in dryness was observed with increasing temperature of pressing for the particular case of low grammage paper sheets made from hardwood bleached kraft pulp. A gain in dryness was also observed for sheets made from softwood unbleached pulps, but the general trend was not so clear as in the former case.

In order to infer about the influence of some parameters, such as the ingoing moisture ratio, paper grammage, refining level, temperature, and additive content, the total water removal rate per unit area was used as an efficiency parameter. The results reported in this thesis confirm previous results obtained in other laboratory-scale experiments. In fact, the  $WR_{tot}$  clearly increases with temperature and refining level, following the same trend as dryness increase, but the main idea to retain here is that paper sheets with the same ingoing moisture ratio and higher grammage have more water available to be removed. It may then be concluded that the total water removal rate per unit area does not depend on sheet grammage but on the amount of water inside the paper web. As expected, the water removal rate is a strong function of the heat transfer to the paper web due to hot pressing effects, *i.e.* it enhances water flow by decreasing its viscosity, and increases fiber flexibility and conformability, therefore improving sheet consolidation. As for the performance of additive-containing paper sheets no firm conclusion can be drawn. In fact, sheets tend to delaminate or stick to the heated plate, making water removal evaluation impracticable. A result of utmost importance was the achievement of a significant increase in dryness of additive-free paper coming out of the pressing unit working at the high-intensity conditions of impulse drying. Moreover, no glass transition of the material is expected to occur within the range of temperature and moisture ratio conditions in the press nip, except maybe for the unbleached paper samples when pressed under very high temperature conditions and for a long period of time.

In light of the experimental findings a rheological model was developed for paper. The first approach aimed to represent the mechanical response of paper to compression, taking into account the flow resistance of liquid water, vapor and air within the fibrous network. At the risk of some simplification, the proposed model was represented by a mechanical analogue comprised of three elements coupled in series and in parallel: (i) one element is purely elastic (recoverable); (ii) the other is plastic (the unrecoverable strain is associated with the internal

structure of the material); and (iii) the third element is viscous (time-dependent). Paper is then envisaged as a “viscoelastoplastic” material.

The model proposed represents the behavior of the composite subjected to a uniaxial load at different operating temperatures, although at this stage the heat and mass transfer model was not included. Obviously, this first approach does not represent the true mechanical behavior of paper, but served as a basis to test the *cellular materials* approach to estimate the local mechanical properties of the composite, *i.e.* the elastic parameters.

The viscoelastoplastic model was used to predict the evolution of thickness, elastic and viscous moduli of the composite as well as its density with time and at any given position of the high moisture ratio paper web. As expected, the model predictions did not agree, in an acceptable way, with the experimental results of uniaxial compression carried out in the laboratory platen press. The integration of the heat and mass transfer was, therefore, of utmost importance.

The second approach, based on the fundamental laws of thermodynamics and fluid flow in porous media, was found to qualitatively predict the heat and mass transfer phenomena taking place within paper pressed at low to moderate operating temperatures. In fact, the performance of the global model for paper was analyzed for the typical operating conditions of impulse drying in terms of pressure application, but not for the high temperature conditions used in the process due to the lack of experimental data corresponding to temperatures above 150 °C. Instead, this was done for the validation of the integrated global model presented later for both paper and felt. Despite the limitations in terms of validation, the actual model was used to simulate the evolution of web thickness, densities, internal web temperature, moisture content and, gas and vapor pressure inside the paper web.

The results of the simulation runs allowed to get more insight into the dewatering and consolidation mechanisms taking place within paper, and emphasized the fundamental role of the heat and mass transfer phenomena in the consolidation process of the fiber network. In terms of temperature predictions, the model overestimates the temperature profiles in the web layers near the hot platen, which may be related to the boundary conditions defined in the model, namely the absence of a heat transfer coefficient for the paper/heated platen interface.

Subsequently, a mathematical model for the rheological behavior of the supporting felt was also derived and compared with the experimental results from

dynamic compression trials. The model was developed based on a preliminary study of felt's permeability and compressibility. From this experimental study it was concluded that although the material that constitutes the felt is predominantly elastic, the network behaves viscoelastically in the presence of moisture. It is suggested that this behavior is related to the network structure and fluid flow effects. The permanent strain observed in the final stage of the compression event is somehow fictitious as the mat continues to expand after load has been removed. Nevertheless, as the model intended to represent the stress-strain behavior of the material in the press nip, a viscoelastoplastic micromechanical model was also considered here in order to account for a certain level of permanent strain.

The simulation results obtained for the typical temperature and load conditions of impulse drying showed some agreement with the experimental results. However, a proper heat and mass transfer model must be included in order to accurately describe the consolidation of the material. This was also implemented during the development of the global model presented at the end of this thesis.

Finally, a global 3D unsteady state model was proposed for the high-intensity pressing of paper and felt. The global model is based on the same assumptions made for the development of the theoretical models previously presented for paper and felt, and it intends to represent the heat and mass transfer phenomena taking place inside the mat formed by the two materials submitted to the high-intensity conditions of impulse drying, as well as their mechanical response to compression under such conditions.

The validation of the model was accomplished by comparing the results from the simulation runs to the experimental data obtained in the laboratory platen press. A sensitivity analysis of the model indicates that the predicted moisture ratio of the mat is mostly influenced by the moisture content, water saturation and rheological properties of the ingoing mat.

At low operating temperatures the model gives good predictions of mat density, gas pressure, liquid water volume fraction, internal web temperature and vapor pressure. At high temperatures, however, the model presents some discrepancies from the experimental results, which may be attributed to several factors such as, for instance, inappropriate model parameter estimation, oversimplified assumptions made during the development of the theoretical model, and experimental error inherent to the pressing process. Additionally, some physical properties of the materials would require better estimates at those high temper-

atures, which is sometimes impracticable.

As a conclusion, the model can give considerable information about changes in the state of the mat formed by paper and felt as they pass through the press nip and some insights about the mechanisms that are active in such a complex process. Despite the complexity of the model and the discrepancies found, it gives quite reasonable predictions over a wide range of pressing temperatures. Finally, on the base of model experiments and simulation runs performed in this work, it is suggested that the heat and mass transfer phenomena involved in impulse drying may be explained in terms of the recently proposed theory of “flashing-assisted displacement dewatering” (Lucisano, 2002).

Although the knowledge concerning the phenomena involved in the impulse drying process has increased tremendously over the years, modeling and simulation of the process must be continued. Improvements and extensions are required to describe the physics of the post-nip stage of the process and to clarify the amount and severity of flash expansion. As the highest temperature occurs at the paper side in contact with the heated plate, the application of coatings with special thermal properties (high thermal mass) at this interface would influence the interface temperature as well as the distribution inside the sheet and most probably reduce the effect of flash expansion.



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## APPENDICES

(STUDY OF THE RHEOLOGY OF DEFORMABLE  
POROUS MEDIA:  
APPLICATION TO PAPER PRODUCTION)



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# Chapter 7

## Nomenclature

|                                     |                                                                                                                    |
|-------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| $A$                                 | contact surface area                                                                                               |
| $a', a''$                           | constants                                                                                                          |
| $a_{f,1}, a_{f,2}$                  | Fourier coefficients, with the subscript “ $f$ ” denoting fibers, and “1” and “2” being the fiber orientation axes |
| $b', b''$                           | constants                                                                                                          |
| $C_1$                               | geometric constant of proportionality                                                                              |
| $CD$                                | cross-machine direction                                                                                            |
| $cc_1, cc_2, cc_3$                  | constants                                                                                                          |
| $C_{ij}$                            | extensional stiffnesses of the laminate for $i, j = 1, 2, 6$                                                       |
| $C_{csty}$                          | final consistency                                                                                                  |
| $C_{csty,L}$                        | limiting consistency                                                                                               |
| $C_{csty,S}$                        | initial consistency                                                                                                |
| $D_{mosaic}$                        | diameter of the cylindrical phase region in the mosaic model                                                       |
| $e_1, e_2, e_3, e_4, e_5$ and $e_6$ | structural parameters of a honeycomb-like cell                                                                     |
| $E$                                 | elastic or Young’s modulus                                                                                         |
| $E_{cw}$                            | elastic or Young’s modulus of the cell wall material                                                               |
| $E_x, E_y$                          | the axial and transverse elastic modulus of the composite                                                          |
| $E_{x_0}, E_{y_0}$                  | the initial axial and transverse elastic modulus of the composite                                                  |
| $E_z$                               | Young’s modulus in the thickness direction of the sheet                                                            |
| $E_1, E_2$                          | fiber axial and transverse elastic modulus (“1” and “2” being the fiber orientation axes)                          |
| $E_{1,cw}, E_{2,cw}$                | axial and transverse elastic modulus of the cell wall material                                                     |
| $E_{hemi}$                          | elastic modulus of the hemicellulose matrix                                                                        |
| $E_{x,fibrils}, E_{y,fibrils}$      | axial and transverse elastic modulus of the microfibrils                                                           |
| $E_m$                               | Young’s modulus of the matrix                                                                                      |
| $E_{cellulose}$                     | Young’s modulus of cellulose inclusions                                                                            |
| $E_{1,cellulose}, E_{2,cellulose}$  | axial and transverse elastic modulus of the cellulose inclusions                                                   |
| $E_f$                               | fiber elastic modulus                                                                                              |
| $E_{lignin}$                        | lignin elastic modulus                                                                                             |

|                                    |                                                                                   |
|------------------------------------|-----------------------------------------------------------------------------------|
| $E_{2t}, E_{2c}$                   | fiber tangent modulus (second slope) in tension and compression                   |
| $f(\Omega)$                        | probability density function of $\Omega$                                          |
| $F_{h,x} = F_{h,1}$                | hygroscopic force in the machine direction                                        |
| $F_{h,y} = F_{h,2}$                | hygroscopic force in the cross-machine direction                                  |
| $F_{mec,x}, F_{mec,y}, F_{mec,xy}$ | mechanical force resultants in the machine, cross-machine and in-plane directions |
| $G_{xy,fibrils}$                   | the shear modulus of the microfibrils                                             |
| $G_{hemi}$                         | shear modulus of the hemicellulose matrix                                         |
| $G_{xy}$                           | in-plane shear modulus of the composite                                           |
| $G_{12}$                           | in-plane shear modulus                                                            |
| $G_m$                              | matrix shear modulus                                                              |
| $G_{12,cellulose}$                 | shear modulus of the cellulose inclusions                                         |
| $G_{12,cw}$                        | in-plane shear modulus of the cell wall                                           |
| $G_{xy,b}$                         | bond shear elastic modulus                                                        |
| $G_{2,b}$                          | bond tangent modulus                                                              |
| $Gr$                               | grammage                                                                          |
| $H_0, H_1$                         | test hypothesis                                                                   |
| $I$                                | pressure impulse                                                                  |
| $K^*$                              | specific permeability                                                             |
| $K_0^*$                            | initial specific permeability                                                     |
| $k_k$                              | Kozeny factor                                                                     |
| $L_{mosaic}$                       | side length of the representative volume element in the mosaic model              |
| $L_{fiber}$                        | fiber length                                                                      |
| $L_f, L_b$                         | bounds at which the transitions to bond and fiber occur                           |
| $L$                                | total thickness                                                                   |
| $L_0$                              | initial thickness                                                                 |
| $MD$                               | machine direction                                                                 |
| $M_i$                              | constants ( $i = 1, \dots, 6$ )                                                   |
| MR                                 | moisture ratio                                                                    |
| $MR_{in}$                          | ingoing moisture ratio                                                            |
| $MR_{out}$                         | outgoing moisture ratio                                                           |
| $N$                                | compressibility factor                                                            |
| $n_A, n_B$                         | characteristic constants of the pulp                                              |
| $P'$                               | probability                                                                       |
| $P_0$                              | reference pressure                                                                |
| $P_{g0}$                           | initial pressure of the gas phase                                                 |
| $P_t$                              | compressive pressure                                                              |
| $P_{atm}$                          | atmospheric pressure                                                              |
| $Q$                                | water flow rate                                                                   |
| $\bar{Q}_{ij}$                     | transformed reduced-ply stiffness                                                 |

|                  |                                                        |
|------------------|--------------------------------------------------------|
| $RH$             | relative humidity                                      |
| $R_w$            | rewetting factor                                       |
| $S'_{ij}$        | off-axis compliance elements of the cell-wall material |
| $S'_v$           | specific surface area                                  |
| $^{\circ}SR$     | Schopper-Riegler or refining degree                    |
| $t$              | time                                                   |
| $T$              | temperature                                            |
| $T'$             | the Student t variable                                 |
| $V_{segs}$       | volume of fiber segments                               |
| $V_{bonds}$      | volume of bonds                                        |
| $W(\varepsilon)$ | strain energy density function                         |
| $W_{CD}$         | strain energy density function in the $CD$ direction   |
| $W_{MD}$         | strain energy density function in the $MD$ direction   |

### Greek letters

|                                |                                                                                               |
|--------------------------------|-----------------------------------------------------------------------------------------------|
| $\bar{\beta}_j$                | transformed coefficient of hygroexpansion of a ply                                            |
| $\beta'_1, \beta'_2$           | coefficients of hygroexpansion of the laminate ("1" and "2" being the fiber orientation axes) |
| $\hat{\beta}_1, \hat{\beta}_2$ | $y$ intercept on the $y$ -axis and the slope of the linear regression line, respectively      |
| $\Delta'x, \Delta'y$           | $x$ -axis and $y$ -axis displacements                                                         |
| $\Delta z_k$                   | thickness of the $k$ -th ply in the laminate                                                  |
| $\Delta MC$                    | incremental moisture content                                                                  |
| $\Delta P$                     | pressure drop across the medium                                                               |
| $\Delta P_{Total}$             | total pressure drop                                                                           |
| $\Delta P_{Felt}$              | total pressure drop across the felt sample                                                    |
| $\varepsilon_{ij}$             | strain tensor                                                                                 |
| $\varepsilon_f$                | fiber strain                                                                                  |
| $\varepsilon$                  | strain                                                                                        |

|                                                  |                                                                       |
|--------------------------------------------------|-----------------------------------------------------------------------|
| $\varepsilon_{xy}$                               | shear strain                                                          |
| $\varepsilon_x$                                  | strain in the machine direction                                       |
| $\varepsilon_y$                                  | strain in the cross-machine direction                                 |
| $\varepsilon'_x, \varepsilon'_y$                 | moisture-induced strains of the laminate in the MD and CD             |
| $\varepsilon_{yield,ft}, \varepsilon_{yield,fc}$ | fiber yield strain in tension and compression                         |
| $\varepsilon_{yield,b}$                          | bond yield strain                                                     |
| $\varepsilon_{xy,b}$                             | bond shear strain                                                     |
| $\eta_E, \eta_G$                                 | parameters of the model                                               |
| $\Theta$                                         | parameter of the limiting consistency model                           |
| $\vartheta, \vartheta_E, \vartheta_G$            | shape factors for the reinforcing elements                            |
| $\mu$                                            | dynamic viscosity of the fluid                                        |
| $\nu_{cw}$                                       | Poisson's ratio of the cell wall material                             |
| $\nu$                                            | Poisson's ratio                                                       |
| $\nu_{xy,fibrils}, \nu_{xy,hemi}$                | the Poisson's ratios of the microfibrils and hemicellulose            |
| $\nu_{xy} = \nu_{12}$                            | Poisson's ratio of the composite in the in-plane direction            |
| $\nu_z$                                          | Poisson's ratio in the thickness direction of the sheet               |
| $\nu_m$                                          | Poisson's ratio for the matrix                                        |
| $\nu_{hemi}$                                     | Poisson's ratio of hemicellulose                                      |
| $\nu_{lignin}$                                   | Poisson's ratio of lignin                                             |
| $\nu_{12,cw}$                                    | Poisson's ratio of the cell wall in the in-plane direction            |
| $\nu_{12,cellulose}$                             | Poisson's ratio of the cellulose inclusions in the in-plane direction |
| $\Pi$                                            | "orientation parameter" of the microfibrils                           |
| $\pi_1^*, \pi_2^*, \pi_3^*$                      | parameters                                                            |
| $\Omega$                                         | orientation angle of a fiber with respect to the MD                   |
| $\rho$                                           | apparent density of the material                                      |
| $\rho_{rel}$                                     | relative density                                                      |
| $\rho_s$                                         | density of the solid phase                                            |
| $\rho_{cw}$                                      | density of the cell wall material                                     |
| $\rho_f$                                         | fiber density                                                         |
| $\rho_{sheet}$                                   | apparent sheet density                                                |
| $\rho'_0$                                        | density of the material for a zero compressive stress                 |
| $\rho_0$                                         | apparent density (dry basis)                                          |
| $\sigma^2$                                       | variance                                                              |
| $\sigma_{ij}$                                    | stress tensor                                                         |
| $\sigma_f$                                       | fiber stress                                                          |
| $\sigma_{xy}$                                    | shear stress                                                          |
| $\sigma_x$                                       | stress in the machine direction                                       |
| $\sigma_y$                                       | stress in the cross-machine direction                                 |
| $\sigma_{yield,ft}, \sigma_{yield,fc}$           | fiber yield stress in tension and compression                         |
| $\sigma_{xy,b}$                                  | bond shear stress                                                     |
| $\sigma$                                         | stress                                                                |

---

|                                                   |                                                                                                                                     |
|---------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| $\sigma_{el}$                                     | elastic collapse stress                                                                                                             |
| $\sigma_{pl}$                                     | plastic collapse stress                                                                                                             |
| $\sigma_{ycw}$                                    | yield stress of the cell wall material                                                                                              |
| $\sigma_{yield,b}$                                | bond yield stress                                                                                                                   |
| $\bar{\sigma}_f$                                  | average fiber stress                                                                                                                |
| $\nu$                                             | kinematic viscosity                                                                                                                 |
| $\phi$                                            | total porosity or void fraction                                                                                                     |
| $\phi_{cw}$                                       | volume fraction of the cell wall                                                                                                    |
| $\phi_{voids}$                                    | volume fraction of voids in the sheet                                                                                               |
| $\phi_{RVE,segs},$<br>$\phi_{RVE,bonds}$          | volume fractions of fiber segments and bonds in<br>the representative volume element                                                |
| $\phi_{fibrils}, \phi_{hemi},$<br>$\phi_{lignin}$ | volume fraction of the microfibrils, hemicellulose<br>and lignin in the cell wall                                                   |
| $\phi_{Hemi}, \phi_{Lignin}$                      | volume fractions of hemicellulose and lignin in the matrix                                                                          |
| $\phi_{cellulose}, \phi_m$                        | volume fractions of cellulose and matrix in the cell wall                                                                           |
| $\phi_V$                                          | water volume ratio (defined as the ratio of the water volume<br>to the volume occupied by the oven-dried pulp fibers in the<br>mat) |
| $\Psi$                                            | normalized elastic and shear moduli                                                                                                 |



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# Appendix A

## Mechanical Models

### A.1 Continuum models

Modeling of the heterogeneous structure of paper presents substantial obstacles because the sheet structure contains such a wide spectrum of void and fiber geometry, fiber orientations, and degrees of bonding. Accordingly, a range of micromechanical theories has emerged since the early 1950s. Steenberg (1947) (see [39]) approached the viscoelastic response of paper by a phenomenological model based on an assemblage of springs and dashpots, but the first micromechanical model was developed by Cox [9], who considered paper as a geometrical network of continuous fibers and derived the elastic properties of the sheet in terms of the axial modulus of the fibers. Many researchers such as van der Akker (1962), Kallmes *et al* (1963), Page *et al* (1979, 1980) and Perkins and Mark (1976) (see [39]) extended Cox's theory to incorporate various microscopic features of the network structure of paper, such as finite fiber length, bonds, *etc.* For low-density papers where free fiber segments are well identifiable, the network models should be more appropriate. In the case of high-density paper sheets, the fibers are closely packed and thus, the paper sheet loses its network character. Another researcher, Nissan [25] considered paper as an hydrogenbonded homogeneous solid and derived the elastic constants from a function governing the elongation of hydrogen bonds.

Continuum models based on a composite-materials approach have been developed by Salmén *et al* [31] and Schulgasser and Page [34], who considered paper as an homogeneous structure composed of cell wall material that is bonded together throughout the entire volume of the paper sheet. Although such models provide

insight into the mechanical response of paper, they cannot give quantitative predictions of elastic modulus since the presence of voids, which reduces the elastic stiffnesses [6], [11], is not taken into account.

Mann *et al* [20] and Baum *et al* [1] determined the orthotropic elastic properties of several paper materials, such as linerboard and carton stock, using the ultrasonic technique. These experimentally determined sheet properties were subsequently used by Carlsson *et al* [4] in their finite element analysis of the three-dimensional stress field of a paperboard subjected to bending. Similar approach, *i.e.* the application of experimentally determined macroscopic properties in finite element analysis, was also used by Muthuraman [24] to examine the paper cup brim forming process. In these works, only the elastic behavior of the sheet was examined. For modeling the nonlinear behavior of paper material beyond its elastic regime, a hyperelastic plate model was developed by Suhling *et al* [40].

In the work developed by Lu, Carlsson and Andersson [17] a micro-model of paper with the cell wall taken as a composite with continuous cellulose microfibrils embedded in a matrix of hemicellulose and lignin was presented. According to the authors, a sheet of paper may be seen as a composite of fiber segments, bonds and voids [2], as shown in Figure A.1. For sheets of low apparent density, the way in which the sheet responds to a load is thought to be dominated by fiber segments. For high-density sheets, with an apparent density approaching that of the fiber cell wall the mechanical deformation is assumed to be governed by the response of the bonded material.

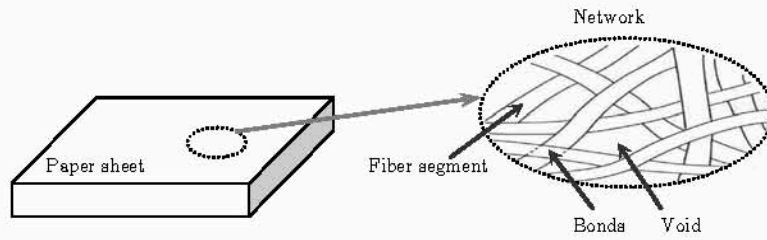


Figure A.1: Fiber segments, bonds and voids in a sheet of paper (adapted from [17]).

### A.1.1 Hyperelastic Plate Model

Suhling *et al* [40] modeled paper as an hyperelastic material. Hyperelastic or green-elastic material is defined as one for which a strain energy density function  $W(\varepsilon)$  exists. An advantage of this approach is that it is predictive in biaxial situations while allowing for stress interactions which are not directly dependent on the material's observed uniaxial response. A strain energy approach for fiber-reinforced composites has been presented by Tsai and Hahn [13] for addressing nonlinear shear behavior. Conceptually similar nonlinear elastic analysis of composites using a complementary energy density function approach have been undertaken by Pindera and Herakovich [30], and Luo and Chou [19]. The nonlinear elastic constitutive equations proposed by Suhling *et al* [40] for orthotropic media are based on a special assumed form for the strain energy density function suggested by Johnsson and Urbanik [15]. For small displacement gradient and plane stress situations the sheet stress tensor,  $\sigma_{ij}$  was reduced to the derivative of the strain energy density function with respect to the sheet strains  $\varepsilon_{ij}$ , as follows:

$$\sigma_{ij} = \frac{\partial W}{\partial \varepsilon_{ij}} (\sigma_{ij} = \sigma_{ji}) \quad (\text{A.1})$$

Following Johnsson and Urbanik, the strain energy density function of the sheet has to be determined empirically for a given paper material. An hyperbolic tangent empirical representation of the stress-strain function was used for uniaxial loading conditions, as defined by Eqn. A.2.

$$\sigma(\varepsilon) = cc_1 \tanh(cc_2 \varepsilon) + cc_3 \varepsilon \quad (\text{A.2})$$

where  $cc_1$ ,  $cc_2$  and  $cc_3$  are constants.

The previous function was fitted to experimental data of samples subjected to uniaxial loading in the machine (*MD*) and cross-machine (*CD*) directions, resulting in two stress-strain functions. These two functions were then integrated to obtain two strain energy density functions,  $W_{MD}$  and  $W_{CD}$ . However, a general strain energy density function was generated from the  $W_{MD}$  and  $W_{CD}$  using the cubic spline interpolation.

The resulting  $W$  function was then used to determine the stress-strain response of the same paper material under different loading conditions. The model prediction showed relatively good agreement with the experimental data. The orthotropic behavior of paper is primarily affected by the application of drying

restraints and fiber orientation distribution. Since the model is semi-empirical and does not address these two factors, the model could not accommodate changes in the constitutive behavior due to drying restraints and fiber orientation distribution. Therefore, for the same paper material, changes in these two factors due to the papermaking process would require another curve-fitting process to determine another strain energy density function for the same paper material. One continuum model, which attempts to address the directional dependence of the constitutive behavior of fiber orientation distribution, is the composite laminate plate model.

### A.1.2 Composite Laminate Plate Model

The elasticity of wood fibers may be predicted by recognizing the structural features of the cell wall in applying micromechanical theories coupled with classical lamination theory [5], [21], [33]. The complexity of the structural model has been limited to continuous reinforcing elements. However, irregular zones are known to exist along the length of the microfibrils [16], and the consequence of these for the mechanical properties of paper has also been discussed [26], [10]. Salmén *et al* [31] applied the classical laminate plate theory to the prediction of paper elastic properties, and treated paper as a composite of several layers of cell wall material. Each layer contains a hemicellulose matrix embedded with unidirectional cellulose microfibrils. It was assumed that the layers in the laminate are subjected to plane stress and bonded perfectly together, and that the strain components are linear functions of the thickness coordinates. With these assumptions and using the stress-strain relation for each ply, the relationships between the external forces and the moments acting on the laminate and the midplane strains can be established. The constitutive relation for a ply in a laminate will be pointed out further in this text. The fundamental steps in the cell-wall ( $S_2$  layer) calculation are first an analysis of the micromechanics of the composite material plies and then a combination of these through lamination theory to estimate the properties of the total structure of the fiber. For the micromechanical considerations, the Halpin-Tsai equations, which account for the shape of the reinforcing material, have been chosen:

$$E_x = E_{x,fibrils}\phi_{fibrils} + E_{hemi}\phi_{hemi} \quad (\text{A.3a})$$

$$\frac{E_y}{E_{hemi}} = \frac{1 + \vartheta \cdot \eta_E \cdot \phi_{fibrils}}{1 - \vartheta \cdot \phi_{fibrils}} \quad (\text{A.3b})$$

$$\frac{G_{xy}}{G_{hemi}} = \frac{1 + \vartheta \cdot \eta_G \cdot \phi_{fibrils}}{1 - \vartheta \cdot \phi_{fibrils}} \quad (\text{A.3c})$$

$$\nu_{xy} = \nu_{xy,fibrils}\phi_{fibrils} + \nu_{hemi}\phi_{hemi} \quad (\text{A.3d})$$

$$\eta_E = \frac{\frac{E_{y,fibrils}}{E_{hemi}} - 1}{\frac{E_{y,fibrils}}{E_{hemi}} + \vartheta} \quad (\text{A.3e})$$

$$\eta_G = \frac{\frac{G_{xy,fibrils}}{G_{hemi}} - 1}{\frac{G_{xy,fibrils}}{G_{hemi}} + \vartheta} \quad (\text{A.3f})$$

where,

$E_x, E_y$  = the axial and transverse elastic modulus of the composite;

$E_{x,fibrils}, E_{y,fibrils}$  = the axial and transverse elastic modulus of the microfibrils;

$G_{xy,fibrils}$  = the shear modulus of the microfibrils;

$E_{hemi}, G_{hemi}$  = the elastic and shear modulus of the hemicellulose matrix;

$\nu_{xy,fibrils}, \nu_{xy,hemi}$  = the Poisson's ratios of the microfibrils and hemicellulose;

$\phi_{fibrils}, \phi_{hemi}$  = volume fraction of the microfibrils and hemicellulose;

$\nu_{xy}$  = Poisson's ratio of the composite;

$G_{xy}$  = in-plane shear modulus of the composite;

$\vartheta$  = shape factor for the reinforcing elements ( $\vartheta = 2$  for a square array of circular fibers [12]).

In addition to the microfibrils orientation, this model also addresses the effects of moisture expansion by adding a hygroscopic force,  $F_{h,x}$  and  $F_{h,y}$ , in the machine and cross-machine directions, respectively.

From their study, Salmén *et al* [31] concluded that for isotropic sheets, the elastic modulus agrees well with the experimental results up until 80 % relative humidity (RH). However, for anisotropic papers, even at low moisture content, the model over-predicted the elastic modulus in the machine direction and under-estimated the elastic modulus in the transverse or cross-machine direction. They attributed this discrepancy at high moisture content to the break down of fiber-to-fiber bond and the microfibrils, which were not addressed in the model.

Subramanian and Carlsson [39] attributed over-estimation of the elastic modulus to the exclusion of voids from the model and this was taken into account in their modeling work using the mosaic model (as described later on in this text).

As briefly mentioned, laminate modeling of paper requires determination of the elastic constants and coefficients of hygroexpansion of the constituent plies of the laminate, and specification of the orientation of the plies with respect to the principal symmetry axes of the sheet. Summation of the contributions of each constituent ply provides the elastic and hygroexpansional responses of the laminate.

The main structural unit of a sheet of paper is a wood fiber. Wood fibers resemble a hollow tube, where the hollow region is called the lumen [41]. The cell wall consists of highly crystalline cellulose fibrils surrounded by amorphous hemicellulose and lignin. The cell wall resembles a continuous, fiber-reinforced composite, with the cellulose reinforcements embedded within a matrix of hemicellulose and lignin. The modulus of the wood fiber is largely governed by the  $S_2$  layer and its fibril angle, which ranges between  $10^\circ$  and  $30^\circ$  [27]. In the modeling of paper, Subramanian and Carlsson [39] assumed that the mechanical response of the wood fiber was entirely dominated by the  $S_2$  layer. The laminate model of paper thus considers the  $S_2$  layer as the main structural unit and not the fiber *per se*. The orientation distribution for the fibrils was calculated from the fiber-orientation-distribution function, which was experimentally determined by the later authors.

Based on the laminated-plate theory, it can be shown that the constitutive relation for such a paper sheet is

$$\begin{bmatrix} F_{mec,x} \\ F_{mec,y} \\ F_{mec,xy} \end{bmatrix} + \begin{bmatrix} F_{h,x} \\ F_{h,y} \\ 0 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & 0 \\ C_{12} & C_{22} & 0 \\ 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} \quad (A.4)$$

where,

$F_{mec,x}, F_{mec,y}, F_{mec,xy}$  = mechanical force resultants;

$C_{ij}$  = extensional stiffnesses of the laminate for  $i, j = 1, 2, 6$ ;

$\varepsilon_x, \varepsilon_y$  = normal strains;

$\varepsilon_{xy}$  = shear strain.

The effective hygroscopic forces in a paper sheet of  $n$  plies are given by an equation presented in a earlier work performed by Carlsson [3]:

$$F_{h,i} = \Delta MC \sum_{k=1}^n (\bar{Q}_{ij})_k (\bar{\beta}_j)_k \Delta z_k \quad (\text{A.5})$$

where

$F_{h,1} = F_{h,x}$ , effective hygroscopic force in MD;

$F_{h,2} = F_{h,y}$ , effective hygroscopic force in CD;

$\Delta MC$  = incremental moisture content;

$\bar{Q}_{ij}$  = transformed reduced-ply stiffness;

$\bar{\beta}_j$  = transformed coefficient of hygroexpansion of a ply, defined as the moisture-induced strain (see Eqns. A.7, A.8a and A.8b) divided by  $\Delta MC$  (see Eqns. A.9a, A.9b, A.9c);

$\Delta z_k$  = thickness of the  $k$ -th ply in the laminate.

The engineering elastic constants are determined from the laminate stiffnesses according to Salmén *et al* [31]:

$$E_x = \frac{\left[ C_{11} - \left( \frac{C_{12}^2}{C_{22}} \right) \right]}{L} \quad (\text{A.6a})$$

$$E_y = \frac{\left[ C_{22} - \left( \frac{C_{12}^2}{C_{11}} \right) \right]}{L} \quad (\text{A.6b})$$

$$\nu_{xy} = \frac{C_{12}}{C_{22}} \quad (\text{A.6c})$$

$$G_{xy} = \frac{C_{66}}{L} \quad (\text{A.6d})$$

where  $L$  is the total thickness of the laminate.

To calculate the coefficients of hygroexpansion for the laminate, Eqn. A.4, the constitutive relation is considered, but with no external forces acting:

$$\begin{bmatrix} F_{h,x} \\ F_{h,y} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{12} & C_{22} \end{bmatrix} \begin{bmatrix} \varepsilon'_x \\ \varepsilon'_y \end{bmatrix} \quad (\text{A.7})$$

where  $\varepsilon'_x$  and  $\varepsilon'_y$  are the moisture-induced strains of the laminate in the MD and CD, respectively.

The moisture-induced strains of the laminate are obtained by inversion of Eqn. A.7:

$$\varepsilon'_x = \frac{(C_{22}F_{h,x} - C_{12}F_{h,y})}{(C_{11}C_{22} - C_{12}^2)} \quad (\text{A.8a})$$

$$\varepsilon'_y = \frac{(C_{11}F_{h,y} - C_{12}F_{h,x})}{(C_{11}C_{22} - C_{12}^2)} \quad (\text{A.8b})$$

The coefficients of hygroexpansion of the laminate are then defined as:

$$\beta'_x = \frac{\varepsilon'_x}{\Delta MC} \quad (\text{A.9a})$$

$$\beta'_y = \frac{\varepsilon'_y}{\Delta MC} \quad (\text{A.9b})$$

$$\beta'_{xy} = 0 \quad (\text{A.9c})$$

The orientation of the fibers in a paper sheet is a fundamental structural variable. If the orientation angle of a fiber with respect to the MD is taken as  $\Omega$ , the relative amount of fibers oriented in an angular region around  $\Omega$  can be represented by a probability density function  $f(\Omega)$  where  $f(\Omega)d\Omega$  is the fraction of fibers between the angles  $\Omega$  and  $\Omega + d\Omega$ .

$$f(\Omega) = \frac{(1 + a_{f,1} \cos 2\Omega + a_{f,2} \cos 4\Omega)}{\pi} \quad (\text{A.10})$$

where  $a_{f,1}$  and  $a_{f,2}$  are the Fourier coefficients serving as fiber-orientation parameters, with the subscript “ $f$ ” denoting fibers, and “1” and “2” being the fiber orientation axes.

In their first study, Subramanian and Carlsson considered delignified fibers only. Cellulose fibrils were considered as transversely isotropic, while hemicellulose was considered as isotropic. The cell wall was considered as an unidirectional composite, with the matrix composed of hemicellulose and the reinforcements consisting of cellulose fibrils of circular cross section.

Based on the Halpin-Tsai micromechanics they have estimated the composite properties from the volume fractions and mechanical properties of its constituents. The following elastic constants of the cell wall (dry) were obtained:  $E_1 = 77.3$  GPa,  $E_2 = 15.8$  GPa,  $G_{12} = 3.70$  GPa, and  $\nu_{12} = 0.204$ .

According to Schapery [32] they used micromechanics to calculate the coefficients of hygroexpansion, assuming a uniform moisture content (9 %), isotropic swelling, and volume additivity for the hemicellulose matrix [31], [37], with  $\beta'_1 = 0.024$  and  $\beta'_2 = 0.50$ .



With this extensive information it was possible to establish the corresponding elastic constants of the laminate (paper) via the extensional stiffnesses  $C_{ij}$  [39]. This model demonstrates that geometric mean modulus  $(E_x E_y)^{\frac{1}{2}}$ , is independent of anisotropy, which is in agreement with experimental trends. However, the model shows a decrease in shear modulus with increased alignment of the fibrils in the machine direction, which appears to be in conflict with experimental data. The calculated elastic and shear moduli were much larger than the experimental values, which is largely attributed to the neglect of voids in the laminate model. The coefficients of hygroexpansion were in good agreement with experimental data by Salmén *et al* [31], and there was no need to correct them for the presence of voids.

Laminate and network models are based on the assumption of a uniform field of strain throughout the paper sheet. However, it is known that in reality there are great variations in local strain in a sheet under stress, as well as differences in moisture content. The bonded regions and free segments will have different stiffnesses, and there will be local concentrations of strain as a result of voids [17]. These results clearly point to the need of incorporating voids in the modeling of the elastic stiffnesses of paper, which was the subject of subsequent work of Subramanian and Carlsson.

The presence of voids in the sheet reduces its elastic moduli. Thus, any micromechanical modeling (following either network or continuum theories) of paper would be incomplete unless attention was given to the void or pore structure [2]. Corte [8] proposed that the gaps between the fibers in the paper sheet form a pore system that can be viewed as tiny cylinders extending through the thickness of the sheet. Hashin and Rosen [14] developed the “composite spheres” model to obtain the elastic properties of macroscopically isotropic two-phase materials. The model is composed of a gradation of sizes of spherical particles embedded in a continuous matrix phase. This model turned to be less useful for modeling of paper because the pores tend to be approximately cylindrical [38].

Young’s modulus and Poisson’s ratio in the thickness direction of the sheet ( $E_z$  and  $\nu_z$ ) may be estimated according to a simple linear rule of mixtures:

$$\frac{E_z}{E_m} = \frac{\nu_z}{\nu_m} = 1 - \phi_{voids} \quad (\text{A.11})$$

where the subscript “ $m$ ” represents the continuous-matrix phase and  $\phi_{voids}$  is the

volume fraction of voids in the sheet. The volume fraction of voids can be obtained from Eqn. A.24. According to Corte [8], it is reasonable to consider voids as capillary tubes oriented through the thickness. The pores are thus assumed to be cylindrical, with the axis along the thickness direction.

Data on out-of-plane elastic constants of paper are extremely rare. Nevertheless, Baum *et al* [1] estimated some parameters as shown on Table A.1.

Table A.1: Elastic constants of paper in the thickness direction (Baum *et al* (1981)).

|                             |       |
|-----------------------------|-------|
| Young's modulus $E_z$ , MPa | 300   |
| Poisson's ratio $\nu$       |       |
| $\nu_{xy}$                  | 0.011 |
| $\nu_{yz}$                  | 0.021 |
| Shear modulus $G$ , MPa     |       |
| $G_{xy}$                    | 150   |
| $G_{yx}$                    | 200   |

Christensen and Lo [7] derived exact solutions for the engineering constants for isotropic media containing spherical or cylindrical inclusions. The material is assumed to consist of three phases: the inclusions (spheres or infinitely long aligned cylinders of varying diameters such that volume filling is achieved), a spherical or cylindrical shell of matrix surrounding the inclusions, and the continuous homogeneous media in which the inclusions are embedded. This model also provides the properties in the thickness direction (z-direction).

Comparison of the results for spherical and cylindrical voids reveals that cylindrical voids result in larger modulus reductions than spherical voids. Furthermore, Poisson's ratio for a material with spherical voids is approximately equal to that of the host matrix, but it exceeds that of the matrix for a material with cylindrical voids.

Subramanian and Carlsson [38] used self-consistent micromechanical models and finite-element analysis to determine the influence of voids on the engineering constants of isotropic and orthotropic paper sheets. The analysis of voids presented in this second work quantifies the reduction factors for the elastic constants. Finite-element analysis was used to examine the influence of voids in orthotropic materials. Extensive parametric finite-element analyses were performed to generate stiffnesses of porous materials with cylindrical and spherical voids at various volume fractions and material anisotropies.

The presence of voids resulted in substantial decreases in the elastic moduli of paper, while the hygroexpansion coefficients are unaffected by voids. The elastic constants normalized with their void free (matrix) values were found to depend only slightly on the anisotropy of the matrix. Based on previous research on the structure of voids, the assumption of cylindrical pores through the thickness of the sheet appears to be most suitable for analyses predicting the elastic constants of paper [38]. The moduli exceeded the experimental values by a factor of about two. The overprediction of the moduli is most likely due to the assumption of uniform strain in the laminate model, which tends to give upper-bound estimates of the moduli. The Poisson's ratio was in close agreement with experimental values [38].

### A.1.3 “Mosaic” or “aggregate” model

The “mosaic” or “aggregate” was initially proposed by McGee and McCullough [23] for modeling short-fiber composites. McCullough pointed out that the mechanical behavior of short-fiber composites (that resemble paper) can be predicted only if a complete description of the microstructure is available [22]. Because such information rarely exists, micro models for such complex materials should be based on structural descriptors that can be evaluated experimentally. The complex and variable features of the microstructure of short-fiber composite materials led to the development of the mosaic model, in which the material is viewed as an aggregate of constituent materials. As previously pointed out, laminate and network models were based in the assumption of a uniform strain field. In reality, however, there are stiff regions that will deform less than the average strain field, and compliant regions that will undergo more deformation than the average strain field. To overcome some of these difficulties, Lu *et al* [18] presented a mosaic model of paper. This model was used to predict the elastic and hygroexpansion properties of paper. Here, paper is considered to be composed by three “phases”: fiber crossings, fiber segments and voids. The bonds or fiber crossings are assumed to have uniform strain (arranged in a parallel configuration), similar to a laminate of fiber cell wall plies, and the segments to have uniform stress behaving as cell wall material connected in series. Based on these two assumptions, they derived in the first part of their study the appropriate mechanical properties and the moisture expansion coefficients of the bonds and fiber segments.

In the micro modeling of paper, Lu, Carlsson and Andersson [17], assumed that the mechanical response of the wood fiber is entirely dominated by the  $S_2$  layer. The laminate model of paper thus considers the  $S_2$  layer as the main structural unit and not the fiber itself [38]. From their studies, they concluded that the laminate model overpredicts the elastic moduli of paper even when accounting for the void content. The overprediction of the elastic stiffnesses of paper is not surprising because the assumption of uniform strain leads to upper bounds on the elastic stiffness. Conversely, the assumption of uniform stress leads to lower bounds on the elastic stiffness.

Assembling the cell-wall elements in series (uniform stress) leads to the following expression for the effective Young's moduli ( $E_x$  and  $E_y$ ), the effective shear modulus ( $G_{xy}$ ), and Poisson's ratio,  $\nu_{xy}$ :

$$E_x = \frac{1}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} S'_{11}(\Omega) f(\Omega) d\Omega} \quad (\text{A.12a})$$

$$E_y = \frac{1}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} S'_{22}(\Omega) f(\Omega) d\Omega} \quad (\text{A.12b})$$

$$G_{xy} = \frac{1}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} S'_{66}(\Omega) f(\Omega) d\Omega} \quad (\text{A.12c})$$

$$\nu_{xy} = \frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} S'_{12}(\Omega) f(\Omega) d\Omega}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} S'_{11}(\Omega) f(\Omega) d\Omega} \quad (\text{A.12d})$$

where  $f(\Omega)$  is the probability distribution function for the orientation of fibrils, which is assumed to be symmetric with respect to the  $x$  and  $y$  axis. This function is of great importance because it accounts for the anisotropy of the network. Schulgasser and Page [34] suggested that the Cauchy distribution is appropriated for describing the fiber orientation distribution in typical machine-made papers. The Cauchy distribution is used to represent the orientation of the microfibrils and is given by,

$$f(\Omega) = \left(\frac{1}{\pi}\right) \left(\frac{1 - \Pi^2}{1 + \Pi^2 - 2\Pi \cos 2\Omega}\right) \quad (\text{A.13})$$

where  $\Pi$  is the “orientation parameter” and  $\Omega$  is the angle between the  $x$  axis (machine direction) and a microfibril in the  $S_2$  layer of the cell wall. For isotropy,  $\Pi = 0$ , and for perfect collimation of the microfibrils,  $\Pi = 1$ .

$S'_{ij}$  are the off-axis compliance elements of the cell-wall material and they can be evaluated from transformation equations from on-axis compliance elements which are in terms of the principal elastic constants of the cell wall. The calculations of elastic constants based on the series and parallel models require the elastic constants,  $S'_{ij}$ , of the cell wall as input, which are rather difficult to evaluate. A simpler evaluation was therefore suggested. As it was said before, the mechanical response of the cell wall is assumed to be dominated by the response of the  $S_2$  layer. The  $S_2$  layer is assumed to be a unidirectional composite with cellulose microfibrils embedded in a matrix consisting of hemicellulose and lignin. This matrix is seen as a mixture of hemicellulose and lignin with isotropic material properties.

The Young’s modulus of the matrix,  $E_m$ , was considered to be bounded by,

$$\frac{1}{\frac{\phi_{Hemi}}{E_{Hemi}} + \frac{\phi_{Lignin}}{E_{Lignin}}} < E_m < (E_{Hemi}\phi_{Hemi} + E_{Lignin}\phi_{Lignin}) \quad (\text{A.14})$$

where the subscripts “*Hemi*” and “*Lignin*” on  $\phi$  represent the volume fractions of hemicellulose and lignin in the matrix, respectively. The subscripts in all lower-case letters “*hemi*” and “*lignin*” on  $\phi$  represent the overall volume fractions in the cell-wall. The volume fractions of hemicellulose and lignin in the matrix are defined as:

$$\phi_{Hemi} = \frac{\phi_{hemi}}{\phi_{hemi} + \phi_{lignin}} \quad (\text{A.15a})$$

$$\phi_{Lignin} = \frac{\phi_{lignin}}{\phi_{hemi} + \phi_{lignin}} \quad (\text{A.15b})$$

Bounds on the matrix shear modulus,  $G_m = \frac{E_m}{[2(1+\nu_m)]}$ , can be obtained from the bounds on  $E_m$ . The rule of mixtures estimate the Poisson’s ratio for the matrix,

$$\nu_m = \nu_{hemi}\phi_{Hemi} + \nu_{lignin}\phi_{Lignin} \quad (A.16)$$

The elastic constants of the cell wall were then calculated using the Halpin-Tsai equations (based on the elastic properties of the cellulose inclusions,  $E_{cellulose}$ , and those of the matrix formed by lignin and hemicellulose,  $E_m$ ), as presented hereafter.

$$E_{1,cw} = E_{1,cellulose}\phi_{cellulose} + E_m\phi_m \quad (A.17a)$$

$$\frac{E_{2,cw}}{E_m} = \frac{1 + \vartheta \cdot \eta_E \cdot \phi_{cellulose}}{1 - \vartheta \cdot \phi_{cellulose}} \quad (A.17b)$$

$$\frac{G_{12,cw}}{G_m} = \frac{1 + \vartheta \cdot \eta_G \cdot \phi_{cellulose}}{1 - \vartheta \cdot \phi_{cellulose}} \quad (A.17c)$$

$$\nu_{12,cw} = \nu_{12,cellulose}\phi_{cellulose} + \nu_m\phi_m \quad (A.17d)$$

$$\eta_E = \frac{\frac{E_{2,cellulose}}{E_m} - 1}{\frac{E_{2,cellulose}}{E_m} + \vartheta} \quad (A.17e)$$

$$\eta_G = \frac{\frac{G_{12,cellulose}}{G_m} - 1}{\frac{G_{12,cellulose}}{G_m} + \vartheta} \quad (A.17f)$$

where,

$E_{1,cw}, E_{2,cw}$  = the axial and transverse elastic modulus of the cell wall material;

$E_{1,cellulose}, E_{2,cellulose}$  = the axial and transverse elastic modulus of the cellulose inclusions;

$G_{12,cellulose}$  = the shear modulus of the cellulose inclusions;

$E_m, G_m$  = the elastic and shear modulus of the hemicellulose/lignin matrix;

$\nu_{12,cellulose}, \nu_{12,m}$  = the Poisson's ratios of the cellulose inclusions and matrix;

$\phi_{cellulose}, \phi_m$  = volume fraction of the cellulose and matrix in the cell wall;

$\nu_{12,cw}$  = Poisson's ratio of the cell wall;

$G_{12,cw}$  = in-plane shear modulus of the cell wall;

$\vartheta, \vartheta_E, \vartheta_G$  = shape factor for the reinforcing elements;

$\eta_E, \eta_G$  = parameters of the model.

The input data used in the calculations of the cell wall constants are the material properties of the cellulose, hemicellulose and lignin listed in Table A.2. The calculations were based on the upper and lower bounds of  $E_m$  in order to

obtain the elastic properties of **bonds** (parallel assemblage) and **fiber segments** (series assemblage). The elastic constants of voids are assumed to be zero. Consequently, it is possible to calculate the elastic constants of the two solid phases of the mosaic model, which are to be used in the calculation of the elastic properties of the composite (Eqns. A.12a to A.12d).

Table A.2: Elastic constants and densities of cell-wall constituents (dry) (Lu, Carlsson and Andersson (1995)).

|                                      | Cellulose | Hemicellulose | Lignin |
|--------------------------------------|-----------|---------------|--------|
| Young's modulus $E$ , GPa            | -         | 8.0           | 4.0    |
| $E_1$                                | 134.0     | -             | -      |
| $E_2$                                | 27.2      | -             | -      |
| Poisson's ratio $\nu$                | -         | 0.33          | 0.33   |
| $\nu_{12}$                           | 0.1       | -             | -      |
| Shear modulus $G$ , GPa              | -         | -             | -      |
| $G_{12}$                             | 4.4       | -             | -      |
| Density, $\rho$ , kg.m <sup>-3</sup> | 1500      | 1500          | 1500   |

The complexity of the microstructure of paper makes it necessary to take a statistical approach to the geometrical analysis (if the previous evaluation method is to be used). To simplify the geometrical modeling of the material they initially considered paper composed of bonds and fiber segments only. In a paper of bonds and fibers only, the elastic constants of the bonded material are different from those of the free segments but are in the same order of magnitude [17]. Therefore, the description of the phase geometry should be less critical to prediction accuracy than it would be if the phase properties were highly dissimilar.

Being so, the distributed phase is assumed to be of cylindrical shape and to be regularly distributed throughout the volume. It is also assumed that the continuous phase is formed by bonded material, and that free segments constitute the distributed phase. The volume fractions of fiber segments and bonds in the representative volume element, denoted by  $\phi_{RVE,segs}$  and  $\phi_{RVE,bonds}$ , are:

$$\phi_{RVE,segs} = \frac{V_{segs}}{V_{segs} + V_{bonds}} = \frac{\pi D_{mosaic}^2}{4L_{mosaic}^2} \quad (A.18a)$$

$$\phi_{RVE,bonds} = \frac{V_{bonds}}{V_{segs} + V_{bonds}} = 1 - \phi_{RVE,segs} \quad (A.18b)$$

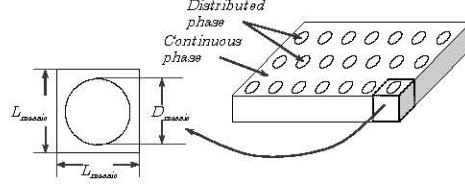


Figure A.2: The simplified representation of paper structure in the mosaic concept; the inset represents the volume element with cylindrical through-thickness inclusions (adapted from [18]).

where  $D_{mosaic}$  is the diameter of the cylindrical phase region and  $L_{mosaic}$  represents the side length of the representative volume element, as shown in Figure A.2.  $D_{mosaic}$  can be calculated rearranging Eqn. A.18a:

$$D_{mosaic} = \left( \frac{2L_{mosaic}}{\pi^{\frac{1}{2}}} \right) \left( \frac{V_{segs}}{V_{segs} + V_{bonds}} \right)^{\frac{1}{2}} \quad (A.19)$$

The in-plane elastic constants of the mosaic model are calculated using the finite element method by imposing appropriate boundary conditions on the representative volume element. Finite element analysis yields displacement of the boundaries of the representative volume element. The average strain is  $\varepsilon_x = 2 \frac{\Delta'x}{L_{mosaic}}$ , where  $\Delta'x$  is the  $x$ -axis displacement of the boundary. Assuming that paper is a macroscopically homogeneous material, the effective elastic modulus,  $E_x$  is given by Hooke's relation:

$$E_x = \frac{\sigma_x}{\varepsilon_x} \quad (A.20)$$

The Poisson's ratio,  $\nu_{xy}$  can be calculated by,

$$\nu_{xy} = \frac{\Delta'y}{\Delta'x} \quad (A.21)$$

where  $\Delta'y$  is the  $y$ -axis displacement of the boundary depicted "CD". The effective Young's modulus,  $E_y$ , is similarly calculated by application of a stress  $\sigma_y$ .

The effective shear modulus,  $G_{xy}$  is given by:

$$G_{xy} = \frac{\sigma_{xy}}{\varepsilon_{xy}} \quad (A.22)$$



The moduli  $E_x$ ,  $E_y$  and  $G_{xy}$  calculated in this way for a void-free paper are corrected for the presence of voids using results obtained for cylindrical through-thickness voids [39], [38]. The normalized elastic and shear moduli can be related to the volume fraction of voids,  $\phi_{voids}$ , by the following expression [39], [38]:

$$\Psi = 1 + \pi_1^* \phi_{voids} + \pi_2^* \phi_{voids}^2 + \pi_3^* \phi_{voids}^3 \quad (\text{A.23})$$

where  $\Psi = \frac{E_x}{E_{x0}}, \frac{E_y}{E_{y0}}, \text{ or } \frac{G_{xy}}{G_{xy0}}$ .  $E_{x0}$ ,  $E_{y0}$  and  $G_{xy0}$  are the elastic and shear moduli of the material without voids (calculated above).  $E_x$ ,  $E_y$  and  $G_{xy}$  are the corresponding values corrected for voids. The parameters  $\pi_1^*$ ,  $\pi_2^*$  and  $\pi_3^*$  are tabulated elsewhere for different moduli ratios ( $\frac{E_{x0}}{E_{y0}}$ ) [38].

Finally, the void volume fraction in a paper sheet,  $\phi_{voids}$ , can be calculated from the apparent sheet density,  $\rho_{sheet}$  [2]:

$$\phi_{voids} = 1 - \frac{\rho_{sheet}}{\rho_{cw}} \quad (\text{A.24})$$

where  $\rho_{cw}$  is the density of the cell wall material ( $\rho_{cw} = 1500 \text{ kg.m}^{-3}$ ) [38].

The predictions, performed by Lu, Carlsson and de Ruvo [18], of elastic moduli in the machine and cross-directions for papers made of bleached chemical pulp were in reasonable accordance with experimental data over a wide range of moisture contents. The mosaic model predictions of the elastic moduli were generally higher than the experimental values. This result may be attributable to microcompressions in fiber crossings, which are factors not covered by this model. The predictions of Poisson's ratio were in good agreement with experimental data. However, a more realistic geometrical representation of the microstructure of paper would probably give more accurate predictions of paper mechanical properties.

## A.2 Network models

As surveyed by Perkins [28], theoretical modeling of paperboard mechanical behavior has been undertaken using micromechanics (or network) and macromechanics (or continuum) approaches. From the micromechanics point of view, paper has been modeled as a bonded fibrous network and as a hydrogen-bonded molecular assemblage. The goal of such formulations is to predict important gross properties of a paperboard sheet from the characteristics and arrangement

of its constituents. Common bulk properties of interest include elastic moduli, Poisson's ratios, and ultimate strengths. Accurate micromechanics formulas can be used to facilitate improvements in manufacturing processes and allow tailoring of paper materials to meet particular end-use requirements.

### A.2.1 Full Plasticity Model

In micromechanical models by Perkins, paper is treated as a fiber network consisting of fiber-to-fiber bonds, free fiber segments, and voids. The load applied onto the sheet is distributed through the network at the fiber-to-fiber bond sites. Therefore, in micromechanics model, the fiber at a bond site serves as a representative load-bearing unit and is used to derive the fiber stress. In the full plasticity micromechanics model by Perkins *et al* [29], the end effects of fibers are taken into account. The fiber ends have zero axial fiber strain which increases to a maximum value at the center due to shear lag mechanism. Therefore, a gradual transition of fiber or bond from elastic to plastic state could occur along the fiber length as the applied strains increase. According to Sinha [35] there are elastic and plastic zones of fiber and bond along the fiber length, and the bounds at which this transitions occur can be determined. The equations from which the values of  $L_f$  and  $L_b$  (the bounds at which the transitions to bond and fiber occur, respectively) are solved are transcendental and have to be solved numerically. Once the boundaries have been determined, the fiber stress in each zone is then calculated, from which the sheet stress could be subsequently found.

### A.2.2 Asymptotic Fiber and Bond Model

The approach in the asymptotic fiber and bond model is similar to that in the full plasticity model, except that the fiber and bond condition is assumed to be constant throughout the fiber length [35]. When the corresponding critical strain has been reached, the fiber and bond along the entire fiber length is considered to have yielded. Thus, the end effect and shear lag mechanism is not addressed. The simplified model reduced considerably the amount of numerical calculation required. In the past, the asymptotic fiber and bond model has only been applied on the loading process of sheet in one- and two-dimensional problems [35].

Paper material behaves linear elastically at the beginning and becomes nonlinear beyond the yield point. In this model, the nonlinear sheet behavior is

triggered by the yielding of the fiber or bond in the network. Therefore, a two-slope model is used to model the constitutive behavior of fiber and bond. The constitutive behavior of cellulosic material is dependent on the rate of loading and environmental conditions such as moisture content. In micromechanic models, the constitutive behavior of fiber and bond subjected to constant loading rate is approximated with a two-slope model. In this two-slope model, the elastic modulus of fiber is the same in extension and compression. In order to address localized failure, such as fiber buckling, the compressive strength and tangent modulus (second slope) of the fiber cell wall material would be smaller than their respective tensile counterparts. The constitutive model of fiber in tension would then be given by

$$\sigma_f = E_f \varepsilon_f \quad \sigma_f < \sigma_{yft} \quad (\text{A.25a})$$

$$\sigma_f = \sigma_{yft} + E_{2t}(\varepsilon_f - \varepsilon_{yft}) \quad \sigma_f \geq \sigma_{yft} \quad (\text{A.25b})$$

and fiber in compressive loading is described by

$$\sigma_f = E_f \varepsilon_f \quad |\sigma_f| < |\sigma_{yield,ft}| \quad (\text{A.26a})$$

$$\sigma_f = \sigma_{yield,fc} + E_{2c}(\varepsilon_f - \varepsilon_{yield,fc}) \quad |\sigma_f| \geq |\sigma_{yield,ft}| \quad (\text{A.26b})$$

where,

$\sigma_f$  = fiber stress;

$\varepsilon_f$  = fiber strain;

$E_f$  = fiber elastic modulus;

$E_{2t}, E_{2c}$  = fiber tangent modulus (second slope) in tension and compression;

$\sigma_{yield,ft}, \sigma_{yield,fc}$  = fiber yield stress in tension and compression;

$\varepsilon_{yield,ft}, \varepsilon_{yield,fc}$  = fiber yield strain in tension and compression.

The same two-slope model is also applied on the bond. Therefore,

$$\sigma_{xy,b} = G_{xy,b} \varepsilon_{xy,b} \quad |\sigma_{xy,b}| < |\sigma_{yield,b}| \quad (\text{A.27a})$$

$$\sigma_{xy,b} = \sigma_{yield,b} + G_{2,b} (\varepsilon_{xy,b} - \varepsilon_{yield,b}) \quad |\sigma_{xy,b}| \geq |\sigma_{yield,b}| \quad (\text{A.27b})$$

where,

$\sigma_{xy,b}$  = bond shear stress;

$\varepsilon_{xy,b}$  = bond shear strain;  
 $G_{xy,b}$  = bond shear elastic modulus;  
 $G_{2,b}$  = bond tangent modulus;  
 $\sigma_{yield,b}$  = bond yield stress;  
 $\varepsilon_{yield,b}$  = bond yield strain.

In asymptotic fiber and bond model, as the applied stress increases, the deformation of fiber and bond could progress in two possible scenarios. In case I, bond would yield first, whereas in case II, fiber would yield first. The critical strains associated with the fiber and bond conditions may then be determined. However, this analysis is somehow extensive and will not be described in the present work.

The fiber stress expression derived for each state is also used to determine the average fiber stress for each fiber and bond condition:

$$\bar{\sigma}_f = \frac{1}{L_{fiber}} \int_0^{L_{fiber}} \sigma_f di \quad (A.28)$$

where

$\bar{\sigma}_f$  = average fiber stress;  
 $L_{fiber}$  = fiber length;  
 $i$  = coordinate axis along the fiber length.

The average fiber stress for each possible fiber and bond condition are listed elsewhere, but detailed derivation of these expressions will not be repeated here. Instead, interested reader should refer to Sinha [35]. The sheet stresses are then given by:

$$\sigma_x = \frac{\rho_{sheet}}{\rho_f} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \bar{\sigma}(\Omega) \cos^2 \Omega \cdot f(\Omega) d\Omega \quad (A.29a)$$

$$\sigma_y = \frac{\rho_{sheet}}{\rho_f} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \bar{\sigma}(\Omega) \sin^2 \Omega \cdot f(\Omega) d\Omega \quad (A.29b)$$

For application of the model in more complicated geometric and loading condition, Sinha and Perkins [36] used a combined continuum and micromechanics approach to formulate the elemental equation for finite element analysis application.

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# Appendix B

## Wet pressing models

There have been a number of mathematical models of wet pressing [11], [16], [6], [7], beginning with Campbell [2]. Most of these appear to rely greatly on experimentally predetermined data and empirical relationships and thus cannot be classified as truly fundamental or predictive models.

Campbell used a simple expression relating the applied pressure and porosity of the medium to describe the compression behavior of fiber mats under quasi-static conditions, *i.e.* assuming that the hydraulic pressure was almost inexistent and thus considering that the total applied pressure was, in fact, equal to the structural pressure of the solid material:

$$\rho = (1 - \phi) \rho_f = M_1 . P_t^{M_2} \quad (\text{B.1})$$

where,

$\rho$  = density of the material;

$\phi$  = porosity;

$\rho_f$  = density of fibers;

$P_t$  = compressive pressure;

$M_1, M_2$  = constants determined experimentally.

Several other authors have used semi-empirical relations similar to that of Campbell, to study the compressibility of bleached softwood kraft paper under static conditions [5], [3]. A somewhat different expression was introduced by Wilder to describe the creep and stress relaxation properties of paper webs, as follows [17]:

$$\rho - \rho'_0 = (M_3 + M_4 . \log t) . P_t^{M_5} \quad (\text{B.2})$$

where,

$\rho'_0$  = density of the material for a zero compressive stress;

$t$  = time;

$M_3, M_4, M_5$  = constants of the model.

Almost at the same time Asklöf *et al* expressed the static pressure applied on wet paper webs,  $P_t$  as a function of the water volume ratio  $\phi_V$ , here defined as the ratio of the water volume to the volume occupied by the oven-dried pulp fibers [1]:

$$P_t = M_6 \cdot \phi_V^{-3} \quad (\text{B.3})$$

with,  $M_6 = \text{constant} = 4.10^6 \text{ N.m}^{-2}$ .

Also, the experimental findings of Nilsson and Larsson [11], for different wood pulps, led to the following expression relating the moisture ratio of the pulp mats to the compressive pressure:

$$\text{MR} = n_A \cdot P_t^{n_B} \quad (\text{B.4})$$

where,

MR = moisture ratio;

$n_A, n_B$  = characteristic constants of the pulp.

Later, Silvy *et al* [14] and Romatier and Silvy [12] studied the consolidation of wet paper webs under quasi-static conditions and found the following relation, expressing the thickness of the paper web,  $L$ , as a function of its grammage,  $Gr$ , and the applied pressure:

$$L = \frac{Gr}{\rho_0} \left( \frac{P_t}{P_0} \right)^{-N} \quad (\text{B.5})$$

where,

$P_0$  = reference pressure;

$\rho_0$  = apparent density (dry basis) for  $P_t = P_0$ ;

$N$  = compressibility factor.

While the previous wet pressing models did not account for the effect of hydraulic pressure, the subsequent work performed by some authors emphasize the significant role of water in the compression behavior of wet paper webs. The dynamic compression behavior of water saturated paper webs was investigated

by Vomhoff [15], by exerting a roll-nip-like stress pulse onto the fibrous network. The expansion behavior was also investigated by compressing the web to a defined thickness and observing the time-dependent thickness increase after an instantaneous relief of the applied stress. Two major conclusions could be drawn from his observations: (i) the fiber network behaved basically viscoplastic during the stress pulse, and (ii) the minimum thickness was attained after the peak stress had been reached. He also observed that the fiber network behaved stiffer for shorter pulses and at lower temperatures. He then ascribed this to the water flow inside and out of the fiber walls.

McDonald *et al* [10], [9], [8] developed a model, for the press section, which gives the moisture ratio of the web leaving the press section, MR, as a function of the operating parameters of the press and the drainage properties of the fibrous material:

$$\text{MR} = \text{MR}_{in} \left( 1 + \frac{K^* \cdot N \cdot \text{MR}_{in}^N \cdot I}{v \cdot Gr^2} \right)^{-1/N} + \frac{R_w}{Gr} \quad (\text{B.6})$$

where,

$\text{MR}_{in}$  = ingoing moisture ratio;

$I$  = pressure impulse (load ( $\text{kN.m}^{-1}$ )/machine speed ( $\text{m.s}^{-1}$ ));

$v$  = kinematic viscosity;

$N$  = compressibility factor;

$K^*$  = specific permeability;

$R_w$  = rewetting factor.

The material properties affecting the water removal at the end of the press section are the compressibility factor defined as,

$$N = a' - b' - 1 \quad (\text{B.7})$$

and the specific permeability,

$$K^* = \frac{a''}{b''} \quad (\text{B.8})$$

where  $a'$ ,  $b'$ ,  $a''$  and  $b''$  are constants defined by the following relations, which are based in the assumption that permeability,  $K^*$ , and thickness are nonlinear functions of the moisture ratio of the web:

$$K = a'' . MR^{a'} = K_0^* \left( \frac{MR}{MR_{in}} \right)^{a'} \quad (B.9)$$

$$L = b'' . Gr . MR^{b'} = L_0 \left( \frac{MR}{MR_{in}} \right)^{b'} \quad (B.10)$$

with,

$K_0^*$  = initial specific permeability (before compression);

$L_0$  = initial thickness of the web.

McDonald *et al* [8] found that the dryness of the paper web was overestimated by the model when compared with the experimental data. They then introduced a rewetting factor, as in Eqn. B.6, to account for the amount of water that is reabsorbed by the paper web in the decompression phase of the pressing event.

Clos *et al* [4] presented a model for compressive dewatering based on the concept of “limiting consistency” and the Kozeny-Carman equation for permeable flow. These authors introduced the idea that for any dewatering system, there is a maximum, or limiting, consistency that can be reached regardless of how long a dewatering force is applied. This means that, the water that cannot be removed from the pulp is treated mathematically as if it was part of the fiber matrix.

The final consistency,  $C_{csty}$ , may then be expressed as follows:

$$C_{csty} = C_{csty,L} - \frac{1}{\sqrt{\Theta . \Delta P . t + \frac{1}{(C_{csty,L} - C_{csty,S})^2}}} \quad (B.11)$$

$$\text{where } \Theta = \frac{\rho^2}{\mu . k_k . S_v'^2 . Gr^2} \quad (B.12)$$

with,

$C_{csty,L}$  = limiting consistency;

$C_{csty,S}$  = initial consistency;

$\Delta P$  = pressure drop across the medium;

$\mu$  = dynamic viscosity of the fluid;

$k_k$  = Kozeny factor;

$S_v'$  = specific surface area.

The authors emphasized that the specific surface area term of the Kozeny-Carman equation is intended for impermeable solids. Taking into account that

wood fibers are highly permeable there are two specific surface areas of interest in a pulp pad: (i) the specific surface area of the pad as if the fibers were impermeable and (ii) the specific surface area of voids within the fiber. They also advanced that, in dewatering systems where individual fibers are not significantly compressed, the macro level should dominate, whereas in high consistency systems where fibers are greatly compressed, the micro level should dominate instead. Taking all these considerations into account, Clos *et al* emphasized that the limiting-consistency model fits well with experimental dewatering experimental data over a wide consistency range.

Although empirical models of wet pressing are a basis for the insight into the qualitative behavior of paper within the press section of a paper machine, they do not allow a deep evaluation over the wide operating conditions range. In this sense, it was imperative the development of theoretical models based on physical laws that could describe the material behavior in a more realistic way. Some of the most promising studies are briefly described hereafter.

Nilsson and Larsson [11] developed a theoretical wet pressing model based in the following assumptions: (i) the Darcy's law is valid; (ii) the hydraulic pressure in the felt is null; (iii) the fluid flow is perpendicular to the plan of the sheet; (iv) even saturation of the paper web; (v) there is no air flow at the point of saturation. The output of the model was the hydraulic pressure, the structural pressure, the thickness of the mat, the pressure drop and the total moisture content in the nip. However, the authors reported some difficulties concerning the convergence of the numerical method employed, especially for the case where high flow resistance was observed.

Roux and Vincent's model of the roll pressing process, while not yet accounting for realistic boundary conditions, was one of the first to rely on the physical laws governing the conservation of mass and energy, and the behavior of stress, strain, and two-dimensional, two-phase fluid (water and air) through the fiber network [13]. Roux and Vincent's applications of the model to date have already shown the deformations, water flow vectors, and pressure distributions occurring in the paper web for their assumed conditions. The main assumptions of the model developed by Roux and Vincent may then be enumerated as follows:

- the wet paper sheet exhibits complex mechanical behavior: elastoviscoplasticity. For simplicity, the skeleton figured by the fibrous network is consid-

ered as an orthotropic elastic body;

- the two interstitial fluids, water and air, are governed by Darcy's law in the interconnected pores of the porous space;
- the intra-fiber water retention value is considered constant throughout the event;
- the felt is unsaturated and incompressible.

In order to evaluate the basic parameters of the model (elasticity moduli, permeability coefficients), they carried out a program based on microscopic image analysis and ultrasonic velocity measurements. Work continued at incorporating a better computational method and accounting for permanent sheet deformation.

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# Appendix C

## The Cellular Solids Theory

### C.1 Introduction

The following section aims to describe the so-called cellular solids theory, and presents a new modeling approach to the viscous-elastic-plastic behavior of paper, envisaged here as a cellular material.

Materials with a cellular structure are widespread. Man has made use of natural ones such as wood and cork for centuries. More recently, he has made his own cellular materials in the form of *honeycombs* and *foams* which are now used in a wide range of engineering applications including thermal insulation, packaging and core materials for structural sandwich panels.

One of the simplest structure to analyze is that of a *honeycomb*-like material, made up of an array of regular, prismatic, hexagonal cells, like those of the bees. Its mechanical properties appear to be dependent on three parameters: the properties of the solid cell wall material, the volume fraction of solid (or relative density), and the geometry of the cells. More commonly, the cells are polyhedra which pack in three dimensions to fill space; these three-dimensional cellular materials are called *foams* and because of their complex structure they are a little more difficult to analyze.

The single most important feature of a cellular solid is its relative density,  $\rho_{rel}$ , which is the apparent density of the cellular material,  $\rho$ , divided by the real density of the solid of which it is made,  $\rho_s$ .

The properties of a honeycomb or a foam depend, above all else, on its relative density. Models of these properties concern themselves with the microscopic

struts and plates that make up the cell edges and faces, and the way these respond to load, or transmit heat, or dissipate energy. But models which contain microscopic parameters are not useful; the engineer cannot be expected to check on the cell-wall thickness of every foam he uses. All he or she knows is its density. So, equations which relate the cell dimensions and shape to the density are then required. The proper choice of equations depends on the dimensionality of the structure (honeycomb versus foam) and on whether (if a foam) it has open or closed cells.

The mechanical properties of cellular materials in compression are highly *non-linear* resulting from the collapse of the cellular structure. The importance of this nonlinearity is obvious to the performance of flexible foams that are used for energy absorption. Another important area for modeling the nonlinear compression properties of cellular materials is in the processing of wood-based composites.

The cellular structure of these so-called cellular materials give rise to similarities in their mechanical behavior. Their compressive stress-strain curves, for instance, all have the same characteristic shape: an initial linear elastic regime is followed by a stress plateau which continues to large strains and is terminated by a final sharp increase in stress. Each regime of behavior corresponds to a particular mechanism of cell deformation: linear elasticity to cell wall bending; the stress plateau to cell collapse by *elastic buckling*, *plastic yielding* or *brittle crushing*, depending on the nature of the cell wall material; and the final sharp increase in stress to densification of the material once the cells have almost completely collapsed. The properties of cellular solids can be understood by identifying and analyzing the mechanisms of cell deformation and collapse using methods of structural analysis. This is not the scope of the present work, however. But a brief description of the theory will be given.

Several models based on micromechanics have been developed to predict linear elastic properties of the cellular material from the cell geometry and mechanical properties of the cell wall [9], [15], [5], [12], [11], [20]. In addition, others have been formulated to predict yielding [9], [21], [3]. These theories relate the Young's modulus and yield stress of the cellular material to the Young's modulus and yield stress of the cell wall through experimentally derived constants and relative density. In addition, Maiti *et al* [14] developed deformation mode maps for the compression of elastomeric and rigid cellular materials. The col-

lapse and densification regions of the stress-strain relationships were described approximately using a relation developed from an empirical distribution of cell wall lengths.

Gibson and Ashby [7] have compared some models with data for both *honeycombs* and *foams* made from several materials such as glass, metals and polymers. Agreement was good, suggesting that the broad features of the models were correct and leading them to apply similar ideas to natural materials such as wood and wood composite materials [4], [1]. Observations of the mechanisms of deformation in wood cells have been made by Easterling using a deformation stage scanning electron microscope [4]. Compression in the tangential direction causes uniform bending and collapse by plastic yielding of the cell walls. When compression stresses are applied in the radial direction, the cells initially bend uniformly and then collapse plastically in a nonlinear manner, from the surface of the loading platen inward along the length of the specimen; a similar response has been observed in higher density woods [2]. Loading in the axial direction is different: the cells respond by contracting uniaxially. According to Bariska and Kučera (1982), at a sufficiently high strain the cells collapse by either yielding and fracturing in low density woods, or by yielding and plastic buckling in higher density woods (see [8]). Also, the theories developed by Gibson and Ashby may be particularly useful in separating the geometrical nonlinear response of the wood cells from the linear viscoelastic response of the cell wall polymers; this separation can potentially give some insights into the consolidation process of a given material.

Without doubt, the cell walls of wood either fracture or plastically yield after or when they collapse because permanent deformation remains after load is removed. However, the question arises whether the nonlinear mechanical properties can be adequately modeled assuming elastic buckling. The work developed by Wolcott *et al* [23] and Maiti *et al* [14] show that the yield strain for wood is almost independent of density. One explanation for this phenomenon is that at low relative densities, the elastic buckling strain is reached prior to reaching the fully plastic moment. At higher relative densities, when plastic hinges develop, the yield strain changes slowly with density.

### C.1.1 The mechanics of a honeycomb

If a honeycomb is compressed in-plane, the cell walls at first bend, giving linear elastic deformation. Beyond a critical strain the cells collapse by elastic buckling, plastic yielding, creep or brittle fracture, depending on the nature of the cell wall material. Cell collapse ends once the opposing cell walls begin to touch each other; as the cells close up the structure densifies and its stiffness increases rapidly. On loading out-of-plane (such that a component of stress acts parallel to the axis of the prismatic cells), the cell walls suffer compression and the moduli and collapse stresses are much larger.

The in-plane stiffnesses and strengths are the lowest because stresses in this plane make the cell walls bend. The out-of-plane stiffnesses and strengths are much larger because they require the axial compression of the cell walls. The study of in-plane properties highlights the mechanisms by which cellular solids deform and fail, whereas the out-of-plane analysis gives the additional stiffnesses which are needed for the design of honeycomb cores in sandwich panels and for the complete description of the behavior of natural honeycomb-like materials, such as wood.

The in-plane compressive stress-strain curves for an elastomeric honeycomb, an elastic-plastic honeycomb, and an elastic-brittle honeycomb have broadly similar shapes, but for different reasons. In compression, all show linear elastic regime followed by a plateau of roughly constant stress, leading into a final regime of steeply rising stress. On first loading, the cell walls bend, giving linear elasticity (provided, of course, that the cell wall itself is linear elastic). But when stress reaches a critical value, the cells begin to collapse: *in elastomeric materials collapse is by the elastic buckling of the cell walls* and so is recoverable; *in materials with a plastic yield point is by the formation of plastic hinges*; and in brittle materials it is by brittle fracture of the cell walls; the last two, of course, are not recoverable. Eventually, at high strains, the cells collapse sufficiently that opposing cell walls touch and further deformation compresses the cell wall material itself. This gives the last, steeply rising portion of the stress-strain curve labelled *densification*.

An increase of the relative density of a honeycomb increases the relative thickness of the cell walls. Then the resistance to cell wall bending and cell wall collapse goes up, giving a higher modulus and plateau stress; and the cell walls touch sooner, reducing the stress at which densification begins.

Honeycombs are much stiffer when they are loaded in the out-of-plane direction (along the cell axis). In fact, when loaded in this direction the cell walls are extended or compressed (rather than bent) and the moduli, for hexagonal honeycombs, are much larger than those calculated for the in-plane loading. The plastic collapse strengths, too, are larger, and for the same reason: that axial, as well as bending deformations are involved.

In this case the initial linear-elastic deformation involves significant axial or shear deformation of the cell walls themselves. In compression the initial linear regime is truncated by *buckling* (elastic for an elastomer, plastic for a metal or rigid polymer) and final failure is by crushing or tearing. The Young's modulus,  $E$ , which characterizes the initial slope of the stress-strain curve, for normal loading in the axial direction simply reflects the solid modulus, *i.e.* the modulus of the material from which the cell wall is made, and it is proportional to the ratio of the cell wall thickness to the length of the cell face [7],

$$\frac{E}{E_{cw}} = \frac{\rho}{\rho_{cw}} \simeq \left( \frac{e_2}{e_4} \right) \quad (\text{C.1})$$

where  $E_{cw}$  and  $\rho_{cw}$  are the Young's moduli and density of the cell wall material, respectively. The parameters  $e_2$  and  $e_4$  are the thickness and the edge length of the hexagonal cells.

The shear moduli, however, are more complicated because the stress distribution in a sheared honeycomb is not simple; each face suffers a non-uniform deformation because of the constraints imposed on it by its neighbors, and the initial plane honeycomb may not remain plane.

The out-of-plane moduli all scale as  $(e_2/e_4)$ ; that is, they depend linearly on the relative density. In this they differ from the in-plane moduli which scale as  $(e_2/e_4)^3$ . Roughly speaking, the out-of-plane moduli are larger than those in-plane by the factor of  $(e_2/e_4)^2$ , or, for typical honeycombs, a factor between 10 and 1000 [7].

The remaining out-of-plane properties are poorly investigated. Tests with a rubber model showed that an elastomeric honeycomb, compressed in the axial direction, would eventually buckle. The elastic buckling load is the sum of the loads carried by the individual cell walls, giving the elastic collapse stress  $\sigma_{el}$ :

$$\frac{(\sigma_{el})}{E_{cw}} \simeq \frac{2}{(1 - \nu_{cw}^2)} \frac{\left(\frac{e_3}{e_4} + 2\right)}{\left(\frac{e_3}{e_4} + \sin e_1\right) \cos e_1} \left(\frac{e_2}{e_4}\right)^3 \quad (C.2)$$

which, for regular hexagons, and  $\nu_{cw} = 0.3$  (a parameter of the model), becomes

$$\frac{(\sigma_{el})}{E_{cw}} = 5.2 \left(\frac{e_2}{e_4}\right)^3 \quad (C.3)$$

where  $e_3$  and  $e_1$  are as defined in Figure C.1.

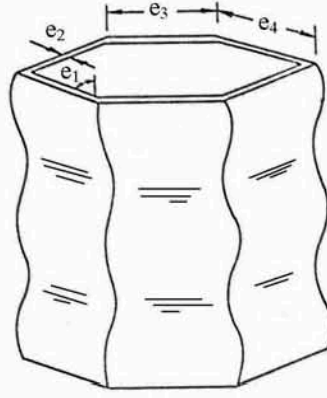


Figure C.1: The axial elastic buckling of a hexagonal cell (adapted from [7]).

If the net section stress in the plane normal to the axial direction, exceeds the yield stress  $\sigma_{ycw}$  of the cell wall material, then the cell walls will yield axially. This defines an upper limit for the plastic collapse stress of the honeycombs,  $\sigma_{pl}$ :

$$\frac{(\sigma_{pl})}{\sigma_{ycw}} = \frac{\left(\frac{e_3}{e_4} + 2\right)}{\left(\frac{e_3}{e_4} + \sin e_1\right) 2 \cos e_1} \frac{e_2}{e_4} = \frac{\rho}{\rho_{cw}} \quad (C.4)$$

This equation properly describes the axial strength in tension. But in compression this limit is seldom reached because plastic buckling occurs first.

The axial collapse of hexagonal honeycombs by plastic buckling has been treated by MacFarland [13] and later and with more detail by Wierzbicki [22]. Wierzbicki defined the stress for collapse by plastic buckling as

$$\frac{(\sigma_{pl})}{\sigma_{ycw}} = 5.6 \left(\frac{e_2}{e_4}\right)^{\frac{5}{3}} \quad (C.5)$$

for regular hexagons with a uniform wall thickness, and

$$\frac{(\sigma_{pl})}{\sigma_{ycw}} = 6.6 \left( \frac{e_2}{e_4} \right)^{\frac{5}{3}} \quad (\text{C.6})$$

for honeycombs in which two of the six cell walls are double. The stress for collapse by plastic buckling given by this equation is less than that for simple plastic compression (Eqn. C.4) when  $e_2/e_4 < 0.1$ , so for all but rather dense honeycombs the compressive collapse mode is *plastic buckling*.

So, as a conclusion, honeycombs deform by a number of different mechanisms. When loaded in-plane the cell walls at first bend, giving linear elasticity which can persist to strains as large as 10 %. This is possible because the honeycomb is like a spring: the geometry allows a large distortion of the structure with only small strains in its members (the strain in the cell wall is less, by a factor of about  $e_2/e_4$ , than that of the honeycomb as a whole). When loaded out-of-plane the cell walls are extended or compressed, and the structure is much stiffer. The complications start when linear elasticity breaks down. If the honeycomb is made of an elastomer its cell walls buckle in compression, giving a long, almost flat plateau in the stress-strain curve; if it is made of a plastic material the cell walls yield, by plastic bending for compressive in-plane loading and by plastic buckling or axial yield for compressive out-of-plane loading. This, too, gives a plateau in the stress-strain curve, though (unlike elastic buckling) the deformation associated with it is permanent.

### C.1.2 The mechanics of foams

The properties of a foam are related to its structure and to the properties of the material of which the cell walls are made. The salient structural features of a foam are its relative density, the degree to which the cells are open or closed, and their shape anisotropy ratios. The crucial cell-wall properties are the solid density, the Young's modulus, the yield strength and the fracture strength.

There is a considerable, but sometimes rather confused, literature on the mechanics of foams: part of the confusion relates to the understanding of mechanisms: some postulate mechanisms do not correspond to reality; part relates to geometric complexity. The following constitutes a brief description of the mechanics of foams when loaded in compression.

Like those for honeycombs, compressive stress-strain curves for an elastomeric, an elastic-plastic and a brittle foam show linear elasticity at low stresses followed by a long collapse plateau, truncated by a regime of densification in which the stress rises steeply. When loading is compression, the plateau is associated with collapse of the cells - by elastic buckling in elastomeric foams; by the formation of plastic hinges in a foam which yields; and by brittle crushing in a brittle foam. When the cells have almost completely collapsed opposing cell walls touch, and further strain compresses the solid itself, giving the final region of densification. Increasing the relative density of the foam increases the Young's modulus, raises the plateau stress and reduces the strain at which densification starts [7].

Superimposed on the deformation of the cell walls is the effect of fluid contained within the cells. In man-made foams, this is usually a gas, though sometimes foams are deliberately saturated with liquids. When a closed-cell foam is compressed, the cell fluid is compressed, too, giving an additional restoring force which can be calculated from Boyle's law. If, instead the cells are open and interconnected, deformation forces the fluid to flow from cell to cell, doing viscous work, and this generates a force that has to be overcome; this leads to time-dependent phenomena [7].

The mechanism of linear elasticity depends on whether the cells are open or closed. In open-cell foams, cell walls bend when the load is applied [11], [17], [16], [9]. Closed-cell foams are more complicated: if the membranes which form the cell faces do not rupture there are two additional contributions to the elastic moduli. The first arises because any deformation stretches these membranes, so that their tensile stiffness contributes to the stiffness of the foam itself [5], [17], [12], [10]. The second is caused by the compression of the cell fluid (usually air) which is trapped within the cells [6], [18]. However, there are some cases in which the closed-cell foams are made from liquid components. In such cases, surface tension can draw the material into the cell edges, leaving only a thin membrane across the cell faces, which ruptures easily. Then, although the foam has cells which are initially closed, its stiffness derives entirely from that of the cell edges, and its moduli are identical to those of an open-cell foam.

At the simplest level an open-cell foam can be modeled as a cubic array of members of length  $e_5$  and square cross-section of side  $e_6$ . Adjoining cells are staggered so that their members meet at their midpoints. The relative density of the cell is related to those dimensions by



$$\frac{\rho}{\rho_{cw}} \propto \left( \frac{e_6}{e_5} \right)^2 \quad (C.7)$$

According to the standard beam theory [19] the Young's modulus for the foam subjected to small strains is calculated by the following equation

$$\frac{E}{E_{cw}} = C_1 \left( \frac{\rho}{\rho_{cw}} \right)^2 \quad (C.8)$$

where  $C_1$  includes all of the geometric constants of proportionality and is usually taken as  $C_1 = 1$ .

For a closed-cell foam filled with gas, the membrane stresses and gas pressure contributions to the Young's modulus have to be considered, resulting in

$$\frac{E}{E_{cw}} = C_1 \phi_{cw}^2 \left( \frac{\rho}{\rho_{cw}} \right)^2 + (1 - \phi_{cw}) \left( \frac{\rho}{\rho_{cw}} \right) + \frac{P_{g0}(1 - 2\nu)}{E_{cw}(1 - \rho/\rho_{cw})} \quad (C.9)$$

where  $P_{g0}$  is the initial gas pressure,  $\phi_{cw}$  the volume fraction of the cell wall and  $\nu$  the Poisson's ratio. The three terms in Eqn. C.9 include the cell-wall bending, cell-wall stretching and gas pressure contribution to the elastic modulus.

Linear elasticity, of course, is limited to small strains, typically 5 % or less. Higher deformations may be reached in compression of elastomeric foams. The deformation is still recoverable, but it is nonlinear. The elastic collapse in foams, like that in honeycombs, is caused by the elastic buckling of the cell walls.[7]. Again, the elastic collapse and the post-collapse behavior depends on whether the foam has open or closed cells. Open-cell foams collapse at almost constant load, giving a long flat plateau. The stress at which cells begin to collapse is given by:

$$\frac{(\sigma_{el})}{E_{cw}} = 0.05 \left( \frac{\rho}{\rho_{cw}} \right)^2 \quad (C.10)$$

When foams with closed cells collapse elastically, the fluid in the cells is compressed. This can change both the collapse stress (described by Eqn. C.11) and the post-collapse behavior.

$$\frac{(\sigma_{el})}{E_{cw}} = 0.05 \left( \phi_{cw} \frac{\rho}{\rho_{cw}} \right)^2 + \frac{(P_{g0} - P_{atm})}{E_{cw}} \quad (C.11)$$

On the other hand, foams made from materials which have a plastic yield point collapse plastically when loaded beyond the linear-elastic regime. Plastic collapse as elastic buckling gives a long flat plateau but the deformation is no longer recoverable. The description of the collapse strength of open- and closed-cell plastic foams is then

- Open cells

$$\frac{(\sigma_{pl})}{\sigma_{ycw}} = 0.3 \left( \frac{\rho}{\rho_{cw}} \right)^{3/2} \quad (\text{C.12})$$

- Closed cells

$$\frac{(\sigma_{pl})}{\sigma_{ycw}} = 0.3 \left( \phi_{cw} \frac{\rho}{\rho_{cw}} \right)^{3/2} + (1 - \phi_{cw}) \left( \frac{\rho}{\rho_{cw}} \right) + \frac{(P_{g0} - P_{atm})}{\sigma_{ycw}} \quad (\text{C.13})$$

In conclusion, when an elastomeric foam is compressed, it first deforms in a linear-elastic way; then its cells buckle to give nonlinear elasticity; finally, the cells collapse completely and the stress rises steeply as the faces and edges are forced together. A plastic foam behaves in a similar way, except that linear elasticity is now followed by plastic collapse instead of elastic buckling.

Refinements to include the influence of strain-rate, temperature, or multiaxial loading are presented in detail in [7].

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# Appendix D

## Linear regression analysis

The experimental data obtained from the permeability tests for saturated felt samples are summarized in Tables D.1 to D.6.

The first step of the experimental work was to verify the linearity between the total pressure drop across the permeability test cell and the water flow rate coming out of the cell. This was done by fitting the two variables to a linear regression obtained by the method of least squares. The corresponding equation of the line may be written in the form:

$$\hat{y} = \hat{\beta}_1 + \hat{\beta}_2 x_i \quad (\text{D.1})$$

where  $x_i$  denotes the  $n$  experimental values of  $Q$  (the water flow rate), and  $\hat{y}$  the estimated values of  $y_i$ , *i.e.*  $\Delta P_{Total}$  (total pressure drop).  $\hat{\beta}_1$  and  $\hat{\beta}_2$  are the  $y$  intercept on the  $y$ -axis and the slope of the line, respectively. These two parameters of the regression may be determined as follows:

$$\hat{\beta}_1 = \frac{\sum_{i=1}^n y_i \sum_{i=1}^n x_i^2 - \sum_{i=1}^n x_i \sum_{i=1}^n x_i y_i}{n \sum_{i=1}^n x_i^2 - \left( \sum_{i=1}^n x_i \right)^2} \quad (\text{D.2})$$

$$\hat{\beta}_2 = \frac{n \sum_{i=1}^n y_i \sum_{i=1}^n x_i - \sum_{i=1}^n x_i \sum_{i=1}^n y_i}{n \sum_{i=1}^n x_i^2 - \left( \sum_{i=1}^n x_i \right)^2} \quad (\text{D.3})$$

Therefore, the resulting set of equations (one for each level of compression of the samples) may be written as,

$$\Delta P_{Total} = \hat{\beta}_1 + \hat{\beta}_2 Q \quad (D.4)$$

being  $\hat{\beta}_1$  and  $\hat{\beta}_2$  the parameters summarized in Tables D.1, D.2 and D.3.

The same approach was used to express the linear relation between the pressure drop across the felt sample and the ratio  $\frac{\mu.L.Q}{A}$  in order to determine the permeability factor. Taking  $y = \frac{\mu.L.Q}{A}$  and  $x = \Delta P_{Felt}$  the following set of equations may be written,

$$\frac{\mu.L.Q}{A} = \hat{\beta}_1 + \hat{\beta}_2 \Delta P_{Felt} \quad (D.5)$$

where  $\mu$  is the fluid viscosity,  $L$  the felt thickness,  $A$  the felt surface area and  $\Delta P_{Felt}$  the pressure drop across the felt sample. The parameters  $\hat{\beta}_1$  and  $\hat{\beta}_2$  found for each level of compaction of the felt sample are summarized in Tables D.4, D.5 and D.6.

The following step consisted in testing the compatibility of the measured and estimated values, *i.e.* checking the reliability of the fittings obtained by the least squares method. To be able to solve this problem it was necessary to use Student's  $t$  distribution. Among several applications, the  $t$  distribution may be used to find confidence limits for the ordinate of a regression line corresponding to any fixed value of  $x$ . In this regression model the  $x$ 's are chosen in advance and then one observation on  $y$  is made at each of those selected points. Repeated sampling experiments therefore imply that these same  $n$  values of  $x$  will be used each time. In addition, the regression model introduced here assumes that the  $y_i$  values are independently normally distributed with a common variance  $\sigma^2$ . As an example, the data set obtained for the permeability factor of sample No. 249031-D at the lowest level of compaction (see Table D.4, trial No.1) will be used in the description presented hereafter. Lets then consider the regression,

$$\frac{\mu.L.Q}{A} = 1.8116 \times 10^{-11} . \Delta P_{Felt} \quad (D.6)$$

Now, the residual sum of squares may be determined by

$$SS_{Res} = \sum_{i=1}^n \left( y_i - \hat{y}_i \right)^2 = 1.092109 \times 10^{-21} \quad (D.7)$$



and divided by  $n-2$  (degrees of freedom) to get the residual mean square, which is an estimate of  $\sigma^2$ :

$$\sigma^2 = MS_{\text{Res}} = \frac{SS_{\text{Res}}}{n-2} = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n-2} = \frac{1.092109 \times 10^{-21}}{4-2} = 5.460546 \times 10^{-22} \quad (\text{D.8})$$

Now that an estimate of  $\sigma^2$  was found, one can test hypotheses about the regression parameters. One can test  $H_0: \beta_2 = 0$  against  $H_1: \beta_2 \neq 0$ . Constructing the test statistic, it is possible to find that

$$T' = \frac{\hat{\beta}_2 - \beta_2}{\sqrt{\frac{MS_{\text{Res}}}{S_{XX}}}} \Big|_{H_0} = \frac{1.8116 \times 10^{-11} - 0}{\sqrt{\frac{5.460546 \times 10^{-22}}{7.576159 \times 10^4}}} = 213.4 \quad (\text{D.9})$$

where  $S_{XX}$  is given as

$$S_{XX} = \sum_{i=1}^n (x_i - \bar{x})^2 = 7.576159 \times 10^4 \quad (\text{D.10})$$

To test  $H_0: \beta_2 = 0$ , at the  $P'$  % level,  $|T'|$  is compared to the upper  $P'/2$  percentage point of the  $t$  distribution on  $n-2 = 2$  degrees of freedom,  $t_2(P'/2 \%)$ . As  $t_2(2.5 \%) = 4.303$ ,  $H_0$  may be rejected. Alternatively, one may use the p-value to reject  $H_0$ . In fact, the p-value of a statistical significance test represents the probability of obtaining values of the test statistic that are equal to or greater in magnitude than the observed test statistic. A p-value of 0.05, for example, indicates that one would have only a 5 % chance of rejecting the sample being tested if the null hypothesis was actually true. In order to determine the p-values for the present study the “Regression” pack from Excel<sup>®</sup> was used. More specifically, the p-value for the example given here was  $2.1960 \times 10^{-5}$ , which means that  $H_0$  may be rejected. It may then be concluded that  $\beta_2$  is significantly different from zero, and that there is a significant linear relationship between the two variables.

The upper and lower endpoints of a 95 % confidence interval for  $\hat{\beta}_2$  are given by

$$\hat{\beta}_2 \pm t_2(2.5\%) \cdot \sqrt{\frac{MS_{\text{Res}}}{S_{XX}}} = 1.8116 \times 10^{-11} \pm 8.4897 \times 10^{-14} \quad (\text{D.11})$$

so the 95 % confidence interval for  $\hat{\beta}_2$  is  $(1.8031 \times 10^{-11}, 1.8201 \times 10^{-11})$ .

Finally, the 95 % confidence interval for any value of  $\hat{y}_0 = \frac{\mu.L.Q}{A}$  given by Eqn. D.6 for  $x = x_0$  is given by

$$\hat{y}\Big|_{x=x_0} \pm t_{n-2}(P/2\%). \sqrt{MS_{\text{Res}} \left( \frac{1}{n} + \frac{(x_0 - \bar{x})^2}{S_{XX}} \right)} \quad (\text{D.12})$$

Taking  $t_2(2.5 \%) = 4.303$ , the confidence interval for  $\hat{y}_0 = 1.1483 \times 10^{-8}$  is

$$1.1483 \times 10^{-8} \pm 4.303. \sqrt{5.460546 \times 10^{-22} \left( \frac{1}{4} + \frac{(6.3868 \times 10^2 - 4.5887 \times 10^2)^2}{7.576159 \times 10^4} \right)} \quad (\text{D.13})$$

which gives the confidence interval for  $\hat{y}\Big|_{x=6.3868 \times 10^2}$ ,  $(1.1400 \times 10^{-8}, 1.1566 \times 10^{-8})$ .

The confidence intervals for the remaining values of  $\hat{y}$  were determined accordingly in order to obtain the upper and lower limits of the 95 % confidence interval for the linear regression.

A similar approach was done for the exponential and power law fittings corresponding to Figures 4.9 and 4.10 in **Chapter 4**.

Table D.1: Data from permeability tests for felt sample No. 249031-D (see Figure 4.6, Chapter 4).

| Trial | Experimental data                  |                           | Model           |                 | Estimate                          | Confidence interval                            |                                                |
|-------|------------------------------------|---------------------------|-----------------|-----------------|-----------------------------------|------------------------------------------------|------------------------------------------------|
|       | $Q$                                | $\Delta P_{\text{Total}}$ | $\hat{\beta}_1$ | $\hat{\beta}_2$ | $(\hat{\Delta P}_{\text{Total}})$ | $(\hat{\Delta P}_{\text{Total}})_{\text{sup}}$ | $(\hat{\Delta P}_{\text{Total}})_{\text{inf}}$ |
|       | $[\text{m}^3 \cdot \text{s}^{-1}]$ | [kPa]                     |                 |                 | [kPa]                             | [kPa]                                          | [kPa]                                          |
| Blanc | $1.0810 \times 10^{-5}$            | 9.5353                    | 0.2012          | 860897.3097     | 9.5074                            | 9.6724                                         | 9.3423                                         |
|       | $7.9730 \times 10^{-6}$            | 7.0338                    |                 |                 | 7.0652                            | 7.1644                                         | 6.9660                                         |
|       | $6.0350 \times 10^{-6}$            | 5.3661                    |                 |                 | 5.3967                            | 5.5006                                         | 5.2929                                         |
|       | $3.9086 \times 10^{-6}$            | 3.6003                    |                 |                 | 3.5661                            | 3.7206                                         | 3.4117                                         |
| No.1  | $1.2010 \times 10^{-5}$            | 1.0742                    | -0.2651         | 914075.5637     | 10.7131                           | 10.9117                                        | 10.5146                                        |
|       | $9.8774 \times 10^{-6}$            | 8.7015                    |                 |                 | 8.7635                            | 8.8975                                         | 8.6295                                         |
|       | $7.5553 \times 10^{-6}$            | 6.6806                    |                 |                 | 6.6410                            | 6.7717                                         | 6.5103                                         |
|       | $5.0728 \times 10^{-6}$            | 4.3655                    |                 |                 | 4.3718                            | 4.5769                                         | 4.1667                                         |
| No.2  | $1.2413 \times 10^{-5}$            | 1.4813                    | -0.4331         | 1213907.6724    | 14.6356                           | 15.4597                                        | 13.8115                                        |
|       | $9.4921 \times 10^{-6}$            | 1.0889                    |                 |                 | 11.0894                           | 11.6293                                        | 10.5496                                        |
|       | $6.8150 \times 10^{-6}$            | 7.7205                    |                 |                 | 7.8396                            | 8.3708                                         | 7.3084                                         |
|       | $3.5936 \times 10^{-6}$            | 4.0712                    |                 |                 | 3.9292                            | 4.7716                                         | 3.0867                                         |
| No.3  | $8.3715 \times 10^{-6}$            | 1.4823                    | 0.5902          | 1703491.7219    | 14.8510                           | 14.9891                                        | 14.7130                                        |
|       | $6.1257 \times 10^{-6}$            | 1.1066                    |                 |                 | 11.0252                           | 11.1134                                        | 10.9370                                        |
|       | $3.9225 \times 10^{-6}$            | 7.2790                    |                 |                 | 7.2721                            | 7.3632                                         | 7.1811                                         |
|       | $2.0663 \times 10^{-6}$            | 4.0908                    |                 |                 | 4.1101                            | 4.2427                                         | 3.9774                                         |

Table D.2: Data from permeability tests for felt sample No. 249031-11 (similar to Figure 4.6, Chapter 4).

| Trial | Experimental data                  |                           | Model           |                 | Estimate                          | Confidence interval                            |                                                |
|-------|------------------------------------|---------------------------|-----------------|-----------------|-----------------------------------|------------------------------------------------|------------------------------------------------|
|       | $Q$                                | $\Delta P_{\text{Total}}$ | $\hat{\beta}_1$ | $\hat{\beta}_2$ | $(\hat{\Delta P}_{\text{Total}})$ | $(\hat{\Delta P}_{\text{Total}})_{\text{sup}}$ | $(\hat{\Delta P}_{\text{Total}})_{\text{inf}}$ |
|       | $[\text{m}^3 \cdot \text{s}^{-1}]$ | [kPa]                     |                 |                 | [kPa]                             | [kPa]                                          | [kPa]                                          |
| Blanc | $1.0810 \times 10^{-5}$            | 9.5353                    | 0.2012          | 860897.3097     | 9.5074                            | 9.6724                                         | 9.3423                                         |
|       | $7.9730 \times 10^{-6}$            | 7.0338                    |                 |                 | 7.0652                            | 7.1644                                         | 6.9660                                         |
|       | $6.0350 \times 10^{-6}$            | 5.3661                    |                 |                 | 5.3967                            | 5.5006                                         | 5.2929                                         |
|       | $3.9086 \times 10^{-6}$            | 3.6003                    |                 |                 | 3.5661                            | 3.7206                                         | 3.4117                                         |
| No.1  | $1.5174 \times 10^{-5}$            | 13.8419                   | -1.9642         | 1028975.4106    | 13.6493                           | 14.5091                                        | 12.7895                                        |
|       | $1.2630 \times 10^{-5}$            | 10.8401                   |                 |                 | 11.0315                           | 11.6313                                        | 10.4318                                        |
|       | $9.3526 \times 10^{-6}$            | 7.5047                    |                 |                 | 7.6593                            | 8.2364                                         | 7.0823                                         |
|       | $6.1357 \times 10^{-6}$            | 4.5028                    |                 |                 | 4.3493                            | 5.2509                                         | 3.4477                                         |
| No.2  | $1.2453 \times 10^{-5}$            | 12.9590                   | -0.9890         | 1108798.9523    | 12.8193                           | 13.5203                                        | 12.1183                                        |
|       | $9.8272 \times 10^{-6}$            | 9.7217                    |                 |                 | 9.9074                            | 10.3733                                        | 9.4416                                         |
|       | $6.1977 \times 10^{-6}$            | 5.8075                    |                 |                 | 5.8830                            | 6.3823                                         | 5.3838                                         |
|       | $4.5514 \times 10^{-6}$            | 4.1791                    |                 |                 | 4.0576                            | 4.7066                                         | 3.4085                                         |
| No.3  | $9.5552 \times 10^{-6}$            | 12.7138                   | -0.0295         | 1336312.3181    | 12.7392                           | 12.8632                                        | 12.6151                                        |
|       | $7.2878 \times 10^{-6}$            | 9.7413                    |                 |                 | 9.7092                            | 9.7880                                         | 9.6304                                         |
|       | $5.3631 \times 10^{-6}$            | 7.1515                    |                 |                 | 7.1373                            | 7.2168                                         | 7.0577                                         |
|       | $3.2238 \times 10^{-6}$            | 4.2575                    |                 |                 | 4.2785                            | 4.4009                                         | 4.1560                                         |

Table D.3: Data from permeability tests for felt sample No. 249031-12 (similar to Figure 4.6, Chapter 4).

| Trial | Experimental data                  |                           | Model           |                 | Estimate                          | Confidence interval                            |                                                |
|-------|------------------------------------|---------------------------|-----------------|-----------------|-----------------------------------|------------------------------------------------|------------------------------------------------|
|       | $Q$                                | $\Delta P_{\text{Total}}$ | $\hat{\beta}_1$ | $\hat{\beta}_2$ | $(\hat{\Delta P}_{\text{Total}})$ | $(\hat{\Delta P}_{\text{Total}})_{\text{sup}}$ | $(\hat{\Delta P}_{\text{Total}})_{\text{inf}}$ |
|       | $[\text{m}^3 \cdot \text{s}^{-1}]$ | $[\text{kPa}]$            |                 |                 | $[\text{kPa}]$                    | $[\text{kPa}]$                                 | $[\text{kPa}]$                                 |
| Blanc | $1.0810 \times 10^{-5}$            | 9.5353                    | 0.2012          | 860897.3097     | 9.5074                            | 9.6724                                         | 9.3423                                         |
|       | $7.9730 \times 10^{-6}$            | 7.0338                    |                 |                 | 7.0652                            | 7.1644                                         | 6.9660                                         |
|       | $6.0350 \times 10^{-6}$            | 5.3661                    |                 |                 | 5.3967                            | 5.5006                                         | 5.2929                                         |
|       | $3.9086 \times 10^{-6}$            | 3.6003                    |                 |                 | 3.5661                            | 3.7206                                         | 3.4117                                         |
| No.1  | $1.2470 \times 10^{-5}$            | 12.0565                   | -0.03181        | 970083.8166     | 12.0656                           | 12.1152                                        | 12.0159                                        |
|       | $9.9666 \times 10^{-6}$            | 9.6432                    |                 |                 | 9.6366                            | 9.6701                                         | 9.6031                                         |
|       | $7.2097 \times 10^{-6}$            | 6.9749                    |                 |                 | 6.9622                            | 6.9950                                         | 6.9295                                         |
|       | $4.3412 \times 10^{-6}$            | 4.1693                    |                 |                 | 4.1795                            | 4.2306                                         | 4.1284                                         |
| No.2  | $9.1357 \times 10^{-6}$            | 13.2043                   | 0.4598          | 1398625.5791    | 13.2372                           | 13.4248                                        | 13.0496                                        |
|       | $7.2974 \times 10^{-6}$            | 10.6831                   |                 |                 | 10.6662                           | 10.7942                                        | 10.5382                                        |
|       | $5.3630 \times 10^{-6}$            | 8.0148                    |                 |                 | 7.9607                            | 8.0831                                         | 7.8383                                         |
|       | $2.9529 \times 10^{-6}$            | 4.5518                    |                 |                 | 4.5898                            | 4.7890                                         | 4.3907                                         |
| No.3  | $6.9040 \times 10^{-6}$            | 12.5764                   | 0.7839          | 1722286.7381    | 12.6745                           | 13.0990                                        | 12.2501                                        |
|       | $5.4617 \times 10^{-6}$            | 10.3103                   |                 |                 | 10.1906                           | 10.4839                                        | 9.8972                                         |
|       | $3.6006 \times 10^{-6}$            | 7.0240                    |                 |                 | 6.9852                            | 7.2714                                         | 6.6990                                         |
|       | $1.9267 \times 10^{-6}$            | 4.0417                    |                 |                 | 4.1022                            | 4.5393                                         | 3.6650                                         |

Table D.4: Data from permeability tests for felt sample No. 249031-D (see Figure 4.8, Chapter 4).

| Trial | Experimental data        |                                   | Model                    | Estimate                          |                                                | Confidence interval                            |                                |
|-------|--------------------------|-----------------------------------|--------------------------|-----------------------------------|------------------------------------------------|------------------------------------------------|--------------------------------|
|       | $\Delta P_{\text{Felt}}$ | $(\frac{\mu \cdot L \cdot Q}{A})$ |                          | $(\frac{\mu \cdot L \cdot Q}{A})$ | $(\frac{\mu \cdot L \cdot Q}{A})_{\text{sup}}$ | $(\frac{\mu \cdot L \cdot Q}{A})_{\text{inf}}$ |                                |
|       | $[\text{Pa}]$            | $[\text{Pa} \cdot \text{m}^2]$    | $\hat{\beta}_2$          | $[\text{Pa} \cdot \text{m}^2]$    | $[\text{Pa} \cdot \text{m}^2]$                 | $[\text{Pa} \cdot \text{m}^2]$                 | $[\text{Pa} \cdot \text{m}^2]$ |
| No.1  | $6.3868 \times 10^2$     | $1.1471 \times 10^{-8}$           | $1.8116 \times 10^{-11}$ | $1.148309 \times 10^{-8}$         | $1.1566 \times 10^{-8}$                        | $1.1400 \times 10^{-8}$                        |                                |
|       | $5.2526 \times 10^2$     | $9.4336 \times 10^{-9}$           |                          | $9.428321 \times 10^{-9}$         | $9.4841 \times 10^{-9}$                        | $9.3725 \times 10^{-9}$                        |                                |
|       | $4.0178 \times 10^2$     | $7.2159 \times 10^{-9}$           |                          | $7.191253 \times 10^{-9}$         | $7.2457 \times 10^{-9}$                        | $7.1368 \times 10^{-9}$                        |                                |
|       | $2.6976 \times 10^2$     | $4.7822 \times 10^{-9}$           |                          | $4.799622 \times 10^{-9}$         | $4.8851 \times 10^{-9}$                        | $4.7142 \times 10^{-9}$                        |                                |
| No.2  | $4.3821 \times 10^3$     | $8.9421 \times 10^{-9}$           | $2.0476 \times 10^{-12}$ | $8.941759 \times 10^{-9}$         | $8.9721 \times 10^{-9}$                        | $8.9114 \times 10^{-9}$                        |                                |
|       | $3.3508 \times 10^3$     | $6.8377 \times 10^{-9}$           |                          | $6.830169 \times 10^{-9}$         | $6.8578 \times 10^{-9}$                        | $6.8026 \times 10^{-9}$                        |                                |
|       | $2.4058 \times 10^3$     | $4.8804 \times 10^{-9}$           |                          | $4.895084 \times 10^{-9}$         | $4.9226 \times 10^{-9}$                        | $4.8676 \times 10^{-9}$                        |                                |
|       | $1.2686 \times 10^3$     | $2.5734 \times 10^{-9}$           |                          | $2.566593 \times 10^{-9}$         | $2.5972 \times 10^{-9}$                        | $2.5360 \times 10^{-9}$                        |                                |
| No.3  | $7.0538 \times 10^3$     | $5.4955 \times 10^{-9}$           | $7.8018 \times 10^{-13}$ | $5.485665 \times 10^{-9}$         | $5.5339 \times 10^{-9}$                        | $5.4374 \times 10^{-9}$                        |                                |
|       | $5.1615 \times 10^3$     | $3.9953 \times 10^{-9}$           |                          | $4.009295 \times 10^{-9}$         | $4.0401 \times 10^{-9}$                        | $3.9784 \times 10^{-9}$                        |                                |
|       | $3.3051 \times 10^3$     | $2.5583 \times 10^{-9}$           |                          | $2.561006 \times 10^{-9}$         | $2.5928 \times 10^{-9}$                        | $2.5292 \times 10^{-9}$                        |                                |
|       | $1.7410 \times 10^3$     | $1.3477 \times 10^{-9}$           |                          | $1.340769 \times 10^{-9}$         | $1.3872 \times 10^{-9}$                        | $1.2944 \times 10^{-9}$                        |                                |

Table D.5: Data from permeability tests for felt sample No. 249031-11 (similar to Figure 4.8, Chapter 4).

| Trial | Experimental data        |                                   | Model                    | Estimate                          | Confidence interval                            |                                                |
|-------|--------------------------|-----------------------------------|--------------------------|-----------------------------------|------------------------------------------------|------------------------------------------------|
|       | $\Delta P_{\text{Felt}}$ | $(\frac{\mu \cdot L \cdot Q}{A})$ |                          | $(\frac{\mu \cdot L \cdot Q}{A})$ | $(\frac{\mu \cdot L \cdot Q}{A})_{\text{sup}}$ | $(\frac{\mu \cdot L \cdot Q}{A})_{\text{inf}}$ |
|       | [Pa]                     | [Pa.m <sup>2</sup> ]              |                          | [Pa.m <sup>2</sup> ]              | [Pa.m <sup>2</sup> ]                           | [Pa.m <sup>2</sup> ]                           |
| No. 1 | $2.5504 \times 10^3$     | $1.3596 \times 10^{-8}$           | $5.3415 \times 10^{-12}$ | $1.3574 \times 10^{-8}$           | $1.3667 \times 10^{-8}$                        | $1.3481 \times 10^{-8}$                        |
|       | $2.1228 \times 10^3$     | $1.1263 \times 10^{-8}$           |                          | $1.1290 \times 10^{-8}$           | $1.1354 \times 10^{-8}$                        | $1.1225 \times 10^{-8}$                        |
|       | $1.5720 \times 10^3$     | $8.3402 \times 10^{-9}$           |                          | $8.3474 \times 10^{-9}$           | $8.4096 \times 10^{-9}$                        | $8.2852 \times 10^{-9}$                        |
|       | $1.0313 \times 10^3$     | $5.4716 \times 10^{-9}$           |                          | $5.4593 \times 10^{-9}$           | $5.5566 \times 10^{-9}$                        | $5.3621 \times 10^{-9}$                        |
| No. 2 | $3.0872 \times 10^3$     | $8.7045 \times 10^{-9}$           | $2.8328 \times 10^{-12}$ | $8.7069 \times 10^{-9}$           | $8.7256 \times 10^{-9}$                        | $8.6882 \times 10^{-9}$                        |
|       | $2.4362 \times 10^3$     | $6.8689 \times 10^{-9}$           |                          | $6.8627 \times 10^{-9}$           | $6.8854 \times 10^{-9}$                        | $6.8400 \times 10^{-9}$                        |
|       | $1.5364 \times 10^3$     | $4.3057 \times 10^{-9}$           |                          | $4.3138 \times 10^{-9}$           | $4.3388 \times 10^{-9}$                        | $4.2888 \times 10^{-9}$                        |
|       | $1.1283 \times 10^3$     | $3.1620 \times 10^{-9}$           |                          | $3.1576 \times 10^{-9}$           | $3.2013 \times 10^{-9}$                        | $3.1140 \times 10^{-9}$                        |
| No. 3 | $4.5427 \times 10^3$     | $6.1182 \times 10^{-9}$           | $1.3505 \times 10^{-12}$ | $6.1068 \times 10^{-9}$           | $6.1449 \times 10^{-9}$                        | $6.0686 \times 10^{-9}$                        |
|       | $3.4647 \times 10^3$     | $4.6355 \times 10^{-9}$           |                          | $4.6510 \times 10^{-9}$           | $4.6932 \times 10^{-9}$                        | $4.6088 \times 10^{-9}$                        |
|       | $2.5497 \times 10^3$     | $3.4106 \times 10^{-9}$           |                          | $3.4152 \times 10^{-9}$           | $3.4718 \times 10^{-9}$                        | $3.3587 \times 10^{-9}$                        |
|       | $1.5326 \times 10^3$     | $2.0503 \times 10^{-9}$           |                          | $2.0417 \times 10^{-9}$           | $2.0912 \times 10^{-9}$                        | $1.9922 \times 10^{-9}$                        |

Table D.6: Data from permeability tests for felt sample No. 249031-12 (similar to Figure 4.8, Chapter 4).

| Trial | Experimental data        |                                   | Model                    | Estimate                          | Confidence interval                            |                                                |
|-------|--------------------------|-----------------------------------|--------------------------|-----------------------------------|------------------------------------------------|------------------------------------------------|
|       | $\Delta P_{\text{Felt}}$ | $(\frac{\mu \cdot L \cdot Q}{A})$ |                          | $(\frac{\mu \cdot L \cdot Q}{A})$ | $(\frac{\mu \cdot L \cdot Q}{A})_{\text{sup}}$ | $(\frac{\mu \cdot L \cdot Q}{A})_{\text{inf}}$ |
|       | [Pa]                     | [Pa.m <sup>2</sup> ]              |                          | [Pa.m <sup>2</sup> ]              | [Pa.m <sup>2</sup> ]                           | [Pa.m <sup>2</sup> ]                           |
| No. 1 | $1.3616 \times 10^3$     | $1.2021 \times 10^{-8}$           | $8.8478 \times 10^{-12}$ | $1.2025 \times 10^{-8}$           | $1.2049 \times 10^{-8}$                        | $1.2001 \times 10^{-8}$                        |
|       | $1.0882 \times 10^3$     | $9.6077 \times 10^{-9}$           |                          | $9.6061 \times 10^{-9}$           | $9.6226 \times 10^{-9}$                        | $9.5896 \times 10^{-9}$                        |
|       | $7.8720 \times 10^2$     | $6.9501 \times 10^{-9}$           |                          | $6.9428 \times 10^{-9}$           | $6.9590 \times 10^{-9}$                        | $6.9267 \times 10^{-9}$                        |
|       | $4.7400 \times 10^2$     | $4.1665 \times 10^{-9}$           |                          | $4.1717 \times 10^{-9}$           | $4.1968 \times 10^{-9}$                        | $4.1465 \times 10^{-9}$                        |
| No. 2 | $4.9125 \times 10^3$     | $7.2373 \times 10^{-9}$           | $1.4754 \times 10^{-12}$ | $7.2242 \times 10^{-9}$           | $7.2627 \times 10^{-9}$                        | $7.1857 \times 10^{-9}$                        |
|       | $3.9240 \times 10^3$     | $5.7501 \times 10^{-9}$           |                          | $5.7658 \times 10^{-9}$           | $5.8006 \times 10^{-9}$                        | $5.7310 \times 10^{-9}$                        |
|       | $2.8839 \times 10^3$     | $4.2259 \times 10^{-9}$           |                          | $4.2311 \times 10^{-9}$           | $4.2656 \times 10^{-9}$                        | $4.1966 \times 10^{-9}$                        |
|       | $1.5879 \times 10^3$     | $2.3268 \times 10^{-9}$           |                          | $2.3189 \times 10^{-9}$           | $2.3583 \times 10^{-9}$                        | $2.2796 \times 10^{-9}$                        |
| No. 3 | $5.9470 \times 10^3$     | $5.0014 \times 10^{-9}$           | $8.4376 \times 10^{-13}$ | $5.0014 \times 10^{-9}$           | $5.0234 \times 10^{-9}$                        | $4.9794 \times 10^{-9}$                        |
|       | $4.7047 \times 10^3$     | $3.9566 \times 10^{-9}$           |                          | $3.9532 \times 10^{-9}$           | $3.9684 \times 10^{-9}$                        | $3.9380 \times 10^{-9}$                        |
|       | $3.1015 \times 10^3$     | $2.5933 \times 10^{-9}$           |                          | $2.6005 \times 10^{-9}$           | $2.6153 \times 10^{-9}$                        | $2.5857 \times 10^{-9}$                        |
|       | $1.6596 \times 10^3$     | $1.3876 \times 10^{-9}$           |                          | $1.3838 \times 10^{-9}$           | $1.4065 \times 10^{-9}$                        | $1.3612 \times 10^{-9}$                        |

# Appendix E

## Moisture ratio evaluation

The following tables (Tables E.1 to E.24) refer to moisture ratio levels of felt samples pressed at different operating temperatures, *i.e.* from 25 to 350 °C, and for all the paper samples tested in the present study. The results obtained before ( $MR_{in}$  = ingoing moisture ratio) and after ( $MR_{out}$  = outgoing moisture ratio) the pressing event are presented according to the grammage, refining level and type of pulp that constitute the paper samples used to evaluate the water uptake capacity of felts as well as the amount of water transferred from the paper sample into the felt by the influence of the applied pressure and operating temperatures.

Table E.1: Moisture ratio of the felt samples prior and after the impulse drying event performed at 25 and 80 °C. 60 g/m<sup>2</sup>, 25 °SR, Eucalyptus globulus paper samples were used.

| $T = 25\text{ }^{\circ}\text{C}$ |                               |                               | $T = 80\text{ }^{\circ}\text{C}$ |                               |                               |
|----------------------------------|-------------------------------|-------------------------------|----------------------------------|-------------------------------|-------------------------------|
| Felt No.                         | $MR_{in}$                     | $MR_{out}$                    | Felt No.                         | $MR_{in}$                     | $MR_{out}$                    |
|                                  | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                  | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                         | 0.13774                       | 0.13928                       | 249031-1                         | 0.13774                       | 0.16251                       |
| 249031-2                         | 0.16820                       | 0.16896                       | 249031-2                         | 0.16818                       | 0.18569                       |
| 249031-3                         | 0.12930                       | 0.13089                       | 249031-3                         | 0.12936                       | 0.14605                       |
| 249031-4                         | 0.16454                       | 0.16645                       | 249031-4                         | 0.16451                       | 0.17731                       |
| 249031-5                         | 0.14823                       | 0.15355                       | 249031-5                         | 0.14829                       | 0.16055                       |
| 249031-6                         | 0.14712                       | 0.15440                       | 249031-6                         | 0.14720                       | 0.15533                       |

Table E.2: Moisture ratio of the felt samples prior and after the impulse drying event performed at 150 and 200 °C. 60 g/m<sup>2</sup>, 25 oSR, Eucalyptus globulus paper samples were used.

| $T = 150 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 200 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                           | 0.13774                       | 0.15551                       | 249031-7                           | 0.13459                       | 0.15189                       |
| 249031-2                           | 0.16820                       | 0.17901                       | 249031-8                           | 0.15485                       | 0.17087                       |
| 249031-3                           | 0.12931                       | 0.14154                       | 249031-9                           | 0.14968                       | 0.16776                       |
| 249031-4                           | 0.16451                       | 0.17235                       | 249031-10                          | 0.14096                       | 0.15722                       |
| 249031-5                           | 0.14824                       | 0.15530                       | 249031-11                          | 0.13376                       | 0.15995                       |
| 249031-6                           | 0.14712                       | 0.15287                       | 249031-12                          | 0.12821                       | 0.15197                       |

Table E.3: Moisture ratio of the felt samples prior and after the impulse drying event performed at 250 and 350 °C. 60 g/m<sup>2</sup>, 25 oSR, Eucalyptus globulus paper samples were used.

| $T = 250 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 350 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                           | 0.13440                       | 0.16094                       | 249031-1                           | 0.13771                       | 0.17727                       |
| 249031-8                           | 0.15528                       | 0.18216                       | 249031-2                           | 0.16820                       | 0.20965                       |
| 249031-9                           | 0.14983                       | 0.16959                       | 249031-3                           | 0.12933                       | 0.16870                       |
| 249031-10                          | 0.14102                       | 0.15834                       | 249031-4                           | 0.16443                       | 0.20075                       |
| 249031-11                          | 0.13362                       | 0.14984                       | 249031-5                           | 0.14827                       | 0.18558                       |
| 249031-12                          | 0.12808                       | 0.16492                       | 249031-6                           | 0.14722                       | 0.16402                       |



Table E.4: Moisture ratio of the felt samples prior and after the impulse drying event performed at 25 and 80 °C. 60 g/m<sup>2</sup>, 40 oSR, Eucalyptus globulus paper samples were used.

| $T = 25 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 80 \text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                          | 0.13774                       | 0.14699                       | 249031-7                          | 0.13775                       | 0.14625                       |
| 249031-8                          | 0.16820                       | 0.17749                       | 249031-8                          | 0.16820                       | 0.17808                       |
| 249031-9                          | 0.12930                       | 0.13647                       | 249031-9                          | 0.12930                       | 0.13607                       |
| 249031-10                         | -                             | -                             | 249031-10                         | 0.16454                       | 0.17261                       |
| 249031-11                         | 0.14823                       | 0.15204                       | 249031-11                         | 0.14825                       | 0.16138                       |
| 249031-12                         | 0.14712                       | 0.15762                       | 249031-12                         | 0.14712                       | 0.15643                       |

Table E.5: Moisture ratio of the felt samples prior and after the impulse drying event performed at 150 and 200 °C. 60 g/m<sup>2</sup>, 40 oSR, Eucalyptus globulus paper samples were used.

| $T = 150 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 200 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                           | 0.13791                       | 0.15653                       | 249031-7                           | 0.13775                       | 0.16373                       |
| 249031-8                           | 0.16820                       | 0.18838                       | 249031-8                           | 0.16818                       | 0.19725                       |
| 249031-9                           | 0.12933                       | 0.15187                       | 249031-9                           | 0.12931                       | 0.14942                       |
| 249031-10                          | 0.16454                       | 0.18878                       | 249031-10                          | 0.16451                       | 0.18476                       |
| 249031-11                          | 0.14824                       | 0.16517                       | 249031-11                          | 0.14824                       | 0.17077                       |
| 249031-12                          | 0.14713                       | 0.16517                       | 249031-12                          | 0.14713                       | 0.16896                       |

Table E.6: Moisture ratio of the felt samples prior and after the impulse drying event performed at 250 and 350 °C. 60 g/m<sup>2</sup>, 40 oSR, Eucalyptus globulus paper samples were used.

| $T = 250\text{ }^{\circ}\text{C}$ |                               |                               | $T = 350\text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                          | 0.13781                       | 0.17495                       | 249031-7                          | 0.13773                       | 0.18192                       |
| 249031-8                          | 0.16750                       | 0.21077                       | 249031-8                          | 0.16801                       | 0.21417                       |
| 249031-9                          | 0.12974                       | 0.16938                       | 249031-9                          | 0.12927                       | 0.17642                       |
| 249031-10                         | 0.16466                       | 0.20725                       | 249031-10                         | 0.16453                       | 0.21551                       |
| 249031-11                         | 0.14805                       | 0.19218                       | 249031-11                         | 0.14823                       | 0.19637                       |
| 249031-12                         | 0.14715                       | 0.19373                       | 249031-12                         | 0.14666                       | 0.19471                       |

Table E.7: Moisture ratio of the felt samples prior and after the impulse drying event performed at 25 and 80 °C. 80 g/m<sup>2</sup>, 25 oSR, Eucalyptus globulus paper samples were used.

| $T = 25\text{ }^{\circ}\text{C}$ |                               |                               | $T = 80\text{ }^{\circ}\text{C}$ |                               |                               |
|----------------------------------|-------------------------------|-------------------------------|----------------------------------|-------------------------------|-------------------------------|
| Felt No.                         | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                         | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                  | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                  | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                         | 0.14499                       | 0.16238                       | 249031-1                         | 0.13774                       | 0.16251                       |
| 249031-8                         | 0.16907                       | 0.19751                       | 249031-2                         | 0.16818                       | 0.18569                       |
| 249031-9                         | 0.16329                       | 0.18882                       | 249031-3                         | 0.12936                       | 0.14605                       |
| 249031-10                        | 0.16485                       | 0.19009                       | 249031-4                         | 0.16451                       | 0.17731                       |
| 249031-11                        | 0.15719                       | 0.18010                       | 249031-5                         | 0.14829                       | 0.16055                       |
| 249031-12                        | 0.14591                       | 0.17285                       | 249031-6                         | 0.14720                       | 0.15533                       |

Table E.8: Moisture ratio of the felt samples prior and after the impulse drying event performed at 150 and 200 °C. 80 g/m<sup>2</sup>, 25 oSR, Eucalyptus globulus paper samples were used.

| $T = 150\text{ }^{\circ}\text{C}$ |                               |                               | $T = 200\text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                          | 0.14507                       | 0.15936                       | 249031-1                          | 0.13773                       | 0.16914                       |
| 249031-8                          | 0.16930                       | 0.19297                       | 249031-2                          | 0.16843                       | 0.20245                       |
| 249031-9                          | 0.16327                       | 0.18763                       | 249031-3                          | 0.12934                       | 0.15153                       |
| 249031-10                         | 0.16492                       | 0.18831                       | 249031-4                          | 0.16451                       | 0.18919                       |
| 249031-11                         | 0.15719                       | 0.18530                       | 249031-5                          | 0.14827                       | 0.19185                       |
| 249031-12                         | 0.14592                       | 0.16460                       | 249031-6                          | 0.14712                       | 0.18725                       |

Table E.9: Moisture ratio of the felt samples prior and after the impulse drying event performed at 250 and 350 °C. 80 g/m<sup>2</sup>, 25 oSR, Eucalyptus globulus paper samples were used.

| $T = 250\text{ }^{\circ}\text{C}$ |                               |                               | $T = 350\text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                          | 0.13775                       | 0.16737                       | 249031-7                          | 0.14505                       | 0.19645                       |
| 249031-2                          | 0.16820                       | 0.23669                       | 249031-8                          | 0.16914                       | 0.23924                       |
| 249031-3                          | 0.12931                       | 0.18665                       | 249031-9                          | 0.16332                       | 0.22874                       |
| 249031-4                          | 0.16453                       | 0.19016                       | 249031-10                         | 0.16483                       | 0.22978                       |
| 249031-5                          | 0.14820                       | 0.17396                       | 249031-11                         | 0.15714                       | 0.21389                       |
| 249031-6                          | 0.14712                       | 0.18885                       | 249031-12                         | 0.14588                       | 0.19230                       |

Table E.10: Moisture ratio of the felt samples prior and after the impulse drying event performed at 25 and 80 °C. 80 g/m<sup>2</sup>, 40 oSR, Eucalyptus globulus paper samples were used.

| $T = 25 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 80 \text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                          | 0.14505                       | 0.17177                       | 249031-7                          | 0.14488                       | 0.16225                       |
| 249031-8                          | 0.16907                       | 0.19727                       | 249031-8                          | 0.16905                       | 0.18658                       |
| 249031-9                          | 0.16331                       | 0.19357                       | 249031-9                          | 0.16356                       | 0.22061                       |
| 249031-10                         | 0.16485                       | 0.19571                       | 249031-10                         | 0.16486                       | 0.21563                       |
| 249031-11                         | 0.15720                       | 0.15876                       | 249031-11                         |                               |                               |
| 249031-12                         | 0.14592                       | 0.14791                       | 249031-12                         | 0.14595                       | 0.15419                       |

Table E.11: Moisture ratio of the felt samples prior and after the impulse drying event performed at 150 and 200 °C. 80 g/m<sup>2</sup>, 40 oSR, Eucalyptus globulus paper samples were used.

| $T = 150 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 200 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                           | 0.14510                       | 0.18553                       | 249031-7                           | 0.14505                       | 0.19989                       |
| 249031-8                           | 0.16916                       | 0.21257                       | 249031-8                           | 0.16914                       | 0.22871                       |
| 249031-9                           | 0.16332                       | 0.19173                       | 249031-9                           | 0.16330                       | 0.21126                       |
| 249031-10                          | 0.16486                       | 0.19016                       | 249031-10                          | 0.16481                       | 0.21011                       |
| 249031-11                          | 0.15718                       | 0.20770                       | 249031-11                          | 0.15720                       | 0.21406                       |
| 249031-12                          | 0.14592                       | 0.19432                       | 249031-12                          | 0.14591                       | 0.20833                       |

Table E.12: Moisture ratio of the felt samples prior and after the impulse drying event performed at 250 and 350 °C. 80 g/m<sup>2</sup>, 40 oSR, Eucalyptus globulus paper samples were used.

| $T = 250 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 350 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                           | 0.14503                       | 0.20732                       | 249031-7                           | 0.14523                       | 0.23097                       |
| 249031-8                           | 0.16912                       | 0.25943                       | 249031-8                           | 0.16912                       | 0.26141                       |
| 249031-9                           | 0.16331                       | 0.24738                       | 249031-9                           | 0.16330                       | 0.25795                       |
| 249031-10                          | 0.16483                       | 0.21280                       | 249031-10                          | 0.16462                       | 0.25228                       |
| 249031-11                          | 0.15740                       | 0.20596                       | 249031-11                          | 0.15719                       | 0.24842                       |
| 249031-12                          | 0.14593                       | 0.20676                       | 249031-12                          | 0.14592                       | 0.21007                       |

Table E.13: Moisture ratio of the felt samples prior and after the impulse drying event performed at 25 and 80 °C. 60 g/m<sup>2</sup>, 25 oSR, Pinus pinaster paper samples were used.

| $T = 25 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 80 \text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                          | 0.13775                       | 0.15507                       | 249031-1                          | 0.13776                       | 0.15575                       |
| 249031-2                          | 0.16817                       | 0.18796                       | 249031-2                          | 0.16821                       | 0.19079                       |
| 249031-3                          | 0.12931                       | 0.14131                       | 249031-3                          | 0.12931                       | 0.13832                       |
| 249031-4                          | 0.16451                       | 0.17753                       | 249031-4                          | 0.16454                       | 0.17265                       |
| 249031-5                          | 0.14827                       | 0.16507                       | 249031-5                          | 0.14828                       | 0.16510                       |
| 249031-6                          | 0.14724                       | 0.16174                       | 249031-6                          | 0.14720                       | 0.16771                       |

Table E.14: Moisture ratio of the felt samples prior and after the impulse drying event performed at 150 and 200 °C. 60 g/m<sup>2</sup>, 25 °SR, Pinus pinaster paper samples were used.

| $T = 150 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 200 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                           | 0.13775                       | 0.15176                       | 249031-1                           | 0.13774                       | 0.16831                       |
| 249031-2                           | 0.16820                       | 0.18314                       | 249031-2                           | 0.16820                       | 0.19873                       |
| 249031-3                           | 0.12930                       | 0.14173                       | 249031-3                           | 0.12930                       | 0.13995                       |
| 249031-4                           | 0.16453                       | 0.18322                       | 249031-4                           | 0.16450                       | 0.17622                       |
| 249031-5                           | 0.14824                       | 0.16785                       | 249031-5                           | 0.14830                       | 0.18204                       |
| 249031-6                           | 0.14712                       | 0.16768                       | 249031-6                           | 0.14712                       | 0.18252                       |

Table E.15: Moisture ratio of the felt samples prior and after the impulse drying event performed at 250 and 350 °C. 60 g/m<sup>2</sup>, 25 °SR, Pinus pinaster paper samples were used.

| $T = 250 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 350 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                           | 0.13774                       | 0.16348                       | 249031-1                           | 0.13775                       | 0.17660                       |
| 249031-2                           | 0.16819                       | 0.19621                       | 249031-2                           | 0.16820                       | 0.20827                       |
| 249031-3                           | 0.12936                       | 0.14989                       | 249031-3                           | 0.12932                       | 0.17290                       |
| 249031-4                           | 0.16449                       | 0.18555                       | 249031-4                           | 0.16454                       | 0.20848                       |
| 249031-5                           | 0.14827                       | 0.16777                       | 249031-5                           | 0.14823                       | 0.20051                       |
| 249031-6                           | 0.14714                       | 0.16488                       | 249031-6                           | 0.14712                       | 0.19760                       |

Table E.16: Moisture ratio of the felt samples prior and after the impulse drying event performed at 25 and 80 °C. 60 g/m<sup>2</sup>, 40 °SR, Pinus pinaster paper samples were used.

| $T = 25 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 80 \text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                          | 0.13774                       | 0.16086                       | 249031-7                          | 0.14504                       | 0.17897                       |
| 249031-2                          | 0.16819                       | 0.19962                       | 249031-8                          | 0.16912                       | 0.20545                       |
| 249031-3                          | 0.12938                       | 0.15702                       | 249031-9                          | 0.16328                       | 0.18821                       |
| 249031-4                          | 0.16454                       | 0.19277                       | 249031-10                         | 0.16483                       | 0.18659                       |
| 249031-5                          | 0.14825                       | 0.17914                       | 249031-11                         | 0.15719                       | 0.17839                       |
| 249031-6                          | 0.14712                       | 0.17864                       | 249031-12                         | 0.14590                       | 0.16513                       |

Table E.17: Moisture ratio of the felt samples prior and after the impulse drying event performed at 150 and 200 °C. 60 g/m<sup>2</sup>, 40 °SR, Pinus pinaster paper samples were used.

| $T = 150 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 200 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                           | 0.13775                       | 0.14270                       | 249031-7                           | 0.14507                       | 0.18898                       |
| 249031-2                           | 0.16820                       | 0.17439                       | 249031-8                           | 0.16914                       | 0.21165                       |
| 249031-3                           | 0.12930                       | 0.13674                       | 249031-9                           | 0.16330                       | 0.21393                       |
| 249031-4                           | 0.16452                       | 0.17371                       | 249031-10                          | 0.16482                       | 0.20650                       |
| 249031-5                           | 0.14824                       | 0.15668                       | 249031-11                          | 0.15718                       | 0.20471                       |
| 249031-6                           | 0.14712                       | 0.15718                       | 249031-12                          | 0.14593                       | 0.19118                       |

Table E.18: Moisture ratio of the felt samples prior and after the impulse drying event performed at 250 and 350 °C. 60 g/m<sup>2</sup>, 40 °SR, Pinus pinaster paper samples were used.

| $T = 250\text{ }^{\circ}\text{C}$ |                               |                               | $T = 350\text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                          | 0.13758                       | 0.17922                       | 249031-7                          | 0.14509                       | 0.18454                       |
| 249031-2                          | 0.16813                       | 0.21039                       | 249031-8                          | 0.16891                       | 0.21183                       |
| 249031-3                          | 0.12936                       | 0.16946                       | 249031-9                          | 0.16333                       | 0.19339                       |
| 249031-4                          | 0.16449                       | 0.20609                       | 249031-10                         | 0.16492                       | 0.18978                       |
| 249031-5                          | 0.14825                       | 0.19308                       | 249031-11                         | 0.15719                       | 0.18124                       |
| 249031-6                          | 0.14712                       | 0.19274                       | 249031-12                         | 0.14592                       | 0.17506                       |

Table E.19: Moisture ratio of the felt samples prior and after the impulse drying event performed at 25 and 80 °C. 80 g/m<sup>2</sup>, 25 °SR, Pinus pinaster paper samples were used.

| $T = 25\text{ }^{\circ}\text{C}$ |                               |                               | $T = 80\text{ }^{\circ}\text{C}$ |                               |                               |
|----------------------------------|-------------------------------|-------------------------------|----------------------------------|-------------------------------|-------------------------------|
| Felt No.                         | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                         | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                  | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                  | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                         | 0.14505                       | 0.15252                       | 249031-7                         | 0.14505                       | 0.18076                       |
| 249031-8                         | 0.16898                       | 0.17575                       | 249031-8                         | 0.16914                       | 0.20439                       |
| 249031-9                         | 0.16332                       | 0.19970                       | 249031-9                         | 0.16331                       | 0.22361                       |
| 249031-10                        | 0.16487                       | 0.19687                       | 249031-10                        | 0.16483                       | 0.21848                       |
| 249031-11                        | 0.15719                       | 0.17823                       | 249031-11                        | 0.15719                       | 0.22057                       |
| 249031-12                        | 0.14575                       | 0.16848                       | 249031-12                        | 0.14592                       | 0.20757                       |



Table E.20: Moisture ratio of the felt samples prior and after the impulse drying event performed at 150 and 200 °C. 80 g/m<sup>2</sup>, 25 °SR, Pinus pinaster paper samples were used.

| $T = 150\text{ }^{\circ}\text{C}$ |                               |                               | $T = 200\text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                          | 0.14506                       | 0.19669                       | 249031-7                          | 0.14506                       | 0.20234                       |
| 249031-8                          | 0.16916                       | 0.22810                       | 249031-8                          | 0.16900                       | 0.22690                       |
| 249031-9                          | 0.16328                       | 0.20138                       | 249031-9                          | 0.16331                       | 0.21604                       |
| 249031-10                         | 0.16483                       | 0.19883                       | 249031-10                         | 0.16487                       | 0.27629                       |
| 249031-11                         | 0.15720                       | 0.19761                       | 249031-11                         | 0.15719                       | 0.18792                       |
| 249031-12                         | 0.14593                       | 0.18705                       | 249031-12                         | 0.14593                       | 0.20996                       |

Table E.21: Moisture ratio of the felt samples prior and after the impulse drying event performed at 250 and 350 °C. 80 g/m<sup>2</sup>, 25 °SR, Pinus pinaster paper samples were used.

| $T = 250\text{ }^{\circ}\text{C}$ |                               |                               | $T = 350\text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                          | 0.13773                       | 0.16816                       | 249031-7                          | 0.13774                       | 0.20069                       |
| 249031-8                          | 0.16817                       | 0.19871                       | 249031-8                          | 0.16819                       | 0.23644                       |
| 249031-9                          | 0.12934                       | 0.16266                       | 249031-9                          | 0.12929                       | 0.18641                       |
| 249031-10                         | 0.16449                       | 0.20376                       | 249031-10                         | 0.16455                       | 0.22906                       |
| 249031-11                         | 0.14829                       | 0.19152                       | 249031-11                         | 0.14824                       | 0.21955                       |
| 249031-12                         | 0.14716                       | 0.19539                       | 249031-12                         | 0.14712                       | 0.22057                       |

Table E.22: Moisture ratio of the felt samples prior and after the impulse drying event performed at 25 and 80 °C. 80 g/m<sup>2</sup>, 40 °SR, Pinus pinaster paper samples were used.

| $T = 25 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 80 \text{ }^{\circ}\text{C}$ |                               |                               |
|-----------------------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------|-------------------------------|
| Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                          | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                   | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-7                          | 0.14505                       | 0.17439                       | 249031-1                          | 0.13774                       | 0.16916                       |
| 249031-8                          | 0.16914                       | 0.19981                       | 249031-2                          | 0.16820                       | 0.20595                       |
| 249031-9                          | 0.16328                       | 0.19073                       | 249031-3                          | 0.12930                       | 0.16268                       |
| 249031-10                         | 0.16491                       | 0.18311                       | 249031-4                          | 0.16451                       | 0.19813                       |
| 249031-11                         | 0.15720                       | 0.18386                       | 249031-5                          | 0.14824                       | 0.19336                       |
| 249031-12                         | 0.14592                       | 0.16862                       | 249031-6                          | 0.14712                       | 0.19312                       |

Table E.23: Moisture ratio of the felt samples prior and after the impulse drying event performed at 150 and 200 °C. 80 g/m<sup>2</sup>, 40 °SR, Pinus pinaster paper samples were used.

| $T = 150 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 200 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                           | 0.13773                       | 0.17141                       | 249031-7                           | 0.14503                       | 0.21776                       |
| 249031-2                           | 0.16816                       | 0.20514                       | 249031-8                           | 0.16912                       | 0.24700                       |
| 249031-3                           | 0.12930                       | 0.18782                       | 249031-9                           | 0.16331                       | 0.21516                       |
| 249031-4                           | 0.16436                       | 0.22591                       | 249031-10                          | 0.16482                       | 0.21485                       |
| 249031-5                           | 0.14824                       | 0.19870                       | 249031-11                          | 0.15718                       | 0.22027                       |
| 249031-6                           | 0.14712                       | 0.19709                       | 249031-12                          | 0.14593                       | 0.20619                       |

Table E.24: Moisture ratio of the felt samples prior and after the impulse drying event performed at 250 and 350 °C. 80 g/m<sup>2</sup>, 40 °SR, Pinus pinaster paper samples were used.

| $T = 250 \text{ }^{\circ}\text{C}$ |                               |                               | $T = 350 \text{ }^{\circ}\text{C}$ |                               |                               |
|------------------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------|-------------------------------|
| Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             | Felt No.                           | MR <sub>in</sub>              | MR <sub>out</sub>             |
|                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |                                    | [kg H <sub>2</sub> O / kg ds] | [kg H <sub>2</sub> O / kg ds] |
| 249031-1                           | 0.13772                       | 0.18669                       | 249031-7                           | 0.14505                       | 0.22266                       |
| 249031-2                           | 0.16820                       | 0.21937                       | 249031-8                           | 0.16898                       | 0.24806                       |
| 249031-3                           | 0.12937                       | 0.19722                       | 249031-9                           | 0.16332                       | 0.24817                       |
| 249031-4                           | 0.16453                       | 0.23943                       | 249031-10                          | 0.16482                       | 0.25038                       |
| 249031-5                           | 0.14824                       | 0.21703                       | 249031-11                          | 0.15719                       | 0.23615                       |
| 249031-6                           | 0.14712                       | 0.22046                       | 249031-12                          | 0.14593                       | 0.22423                       |



# Appendix F

## C<sup>++</sup>-based subroutines used in the computer simulations

This section includes the C<sup>++</sup>-based subroutines developed to simulate the mechanical behavior of both paper and felt when submitted to different load and temperature conditions. Due to the extension of the subroutines they are given in separate external .PDF format files.

### F.1 Mechanical model for paper

#### F.1.1 Main program “mecmain1paper.c”

See file “mecmain1paper.pdf”.

#### F.1.2 Subroutine “papervisiscoelastoplastic.c”

See file “papervisiscoelastoplastic.pdf”.

### F.2 Mechanical model for felt

#### F.2.1 Main program “mecmain1felt.c”

See file “mecmain1felt.pdf”.

**F.2.2 Subroutine “feltviscoelastoplastic.c”**

See file “feltviscoelastoplastic.pdf”.

```

                                mecmain1paper.txt
/* EXEMPL01.F -- translated by f2c (version 20000121).
   You must link the resulting object file with the libraries:
       -lf2c -lm      (in that order) */

#ifdef __cplusplus
extern "C" {
#endif
#include "paperviscoelastoplastic.c"

/* ***** */
/*                               MAIN PROGRAM                               */
/* ***** */

void MAIN__()
{
    static doublereal atol;
    static integer itol, iopt;
    static doublereal rtol;
    static doublereal tcrit,tout, t;
    static doublereal y[1101];
    static doublereal yt[1101];
    static integer itask, iwork[Ni*Nj*Nk+1+Ni*Nj+31];
    static doublereal rwork[1222132];
    static integer mf, istate;
    extern /* Subroutine */ integer dlsodes_(U_fp, integer *,
        doublereal *, doublereal *, doublereal *, integer *,
        doublereal *, doublereal *, integer *, integer *,
        integer *, doublereal *, integer *, integer *,
        integer *, U_fp, integer *);

    static FILE *ficheiro;
    static char nomedoficheiro[30];

    integer fex();
    static integer neq;
    integer jex();
    static integer liw, lrw;

    printf("Introduza o nome do ficheiro de resultados\t");
    scanf("%s",nomedoficheiro);
    printf("\nOs resultados serão guardados em : %s\n",nomedoficheiro);

    neq = Ni*Nj*Nk+1+Ni*Nj; // the number of ODE's to be solved
    itol = 1; // scalar RTOL and scalar ATOL
    rtol = (doublereal)0.125e-3; /* local relative error tolerance
        parameter for the solution */
    atol = (doublereal)0.125e-5; /* local absolute error tolerance
        parameter for the solution */
    itask = 4; /* compute output values of Y(t) at t=tout without
        overshooting */
    istate = 1; /* state of the calculation; this is the first call
        for the problem */
    iopt = 1; /* values have been specified for one or more
        optional input parameters */
    lrw = 22+neq*(5+1)+3*neq+neq*neq; /* length of the RWORK array;
        = 22 + NYH * (MAXORD + 1) + 3*NEQ +(NEQ)**2 */
    liw = 31+neq; /* length of the IWORK array; = 31 + NEQ
    mf = 22; /* indicates both the integration method (backward
        differentiation method (2)-BDF) and corrector
        iteration technique to be used(Newton-Raphson(2)) */

    /* istate = 2 returned by LSODES means that the integration
        was performed successfully */

    /* ----- INICIALIZACAO DAS VARIAVEIS ----- */

```

```

LZ=1.0;
LZT=0.0;

for (int i=1; i<=Ni; i++) {
    for (int j=1; j<=Nj; j++) {
        SIJ[i][j]=0.0;
        SIJT[i][j]=0.0;
        //printf("ij %ld %ld \n SIJin %lf SIJTin
%lf\n",i,j,SIJ[i][j],SIJT[i][j]);
        for (int k=1; k<=Nk; k++) {
            /* Z's iniciais */
            Z[i][j][k]=((DOUBLE)k -0.5)*(1./((DOUBLE)Nk));
            ZT[i][j][k]=0.0;
            //printf("ijk %ld %ld %ld\n zin %lf ztin
%lf\n",i,j,k,Z[i][j][k],ZT[i][j][k]);
        }
    }
}

int L=0;
y[L]=(double) LZ;
yt[L]=(double) LZT;
L=L+1;

for (int i=1; i<=Ni; i++)
    for (int j=1; j<=Nj; j++) {
        y[L]=(double) SIJ[i][j];
        yt[L]=(double) SIJT[i][j];
        L=L+1;
        for (int k=1; k<=Nk; k++) {
            y[L]=(double) Z[i][j][k];
            yt[L]=(double) ZT[i][j][k];
            L=L+1;
            //printf("L %ld\t ijk %ld %ld %ld\n",L,i,j,k);
        }
    }

}

/* ----- */
str=6318.2e3;
H=er/str;
V=tau*str/visr;
/* ----- */

/* ***** */
/*                      LSODES                      */
/* ***** */

long siout=(int)(1000000);
t=0.0;
tout = 1e-10; /* The next value of the independent variable at
which the solution is required, if ITASK=1,
3, or 4; LSODES uses TOUT on the first call to
determine the direction of integration */

tcrit=2.;
tp=0.0;
for (long iout = 1; iout <= siout+1; iout++) {
    //rwork[0]=tout;
    rwork[0]=tcrit;
    rwork[5]=0.01;
    iwork[5]=10000000;

    dlsodes_((U_fp)fex, (integer *) &neq, (double *) y,
(double) &t, (double) &tout, (integer *) &itol,
(double) &rtol, (double) &atol,
(integer *) &itask, (integer *) &istate, (integer *) &iopt,
(double) rwork, (integer *) &lrw, (integer *) iwork,
2

```



```

                                mecmain1paper.txt
(integer *) &liw, (U_fp) jex, (integer *) &mf);

/* ----- */
/*                               OUTPUT                               */
/* ----- */
if (((iout % (siout/1000))==(iout / (siout/1000))) || (iout==1) ||
(iout==siout+1)) {

    rosecoaparente=mseco/((DOUBLE)AZ*(DOUBLE)lzo*(double)y[0]);
    POR=1.-rosecoaparente/roseco;

    static doublereal dzsoma1;
    dzsoma1=0.;
    for (int k=1; k<=Nk; k++) {
        DZ[1][1][k]=2.*(y[k+1]-(double)dzsoma1);
        dzsoma1=(double)dzsoma1+DZ[1][1][k];
        dz[1][1][k]=(double)lzo*y[0]*DZ[1][1][k];
    }

    static doublereal dzsoma2;
    dzsoma2=0.;
    for (int k=1; k<=Nk; k++) {
        DZ[5][5][k]=2.*(y[k+1]-(double)dzsoma2);
        dzsoma2=(double)dzsoma2+DZ[5][5][k];
        dz[5][5][k]=(double)lzo*y[0]*DZ[5][5][k];
    }

    static doublereal dzsoma3;
    dzsoma3=0.;
    for (int k=1; k<=Nk; k++) {
        DZ[10][10][k]=2.*(y[k+1]-(double)dzsoma3);
        dzsoma3=(double)dzsoma3+DZ[10][10][k];
        dz[10][10][k]=(double)lzo*y[0]*DZ[10][10][k];
    }

    static doublereal dzsoma4;
    dzsoma4=0.;
    for (int k=1; k<=Nk; k++) {
        DZ[1][5][k]=2.*(y[k+1]-(double)dzsoma4);
        dzsoma4=(double)dzsoma4+DZ[1][5][k];
        dz[1][5][k]=(double)lzo*y[0]*DZ[1][5][k];
    }

    static doublereal dzsoma5;
    dzsoma5=0.;
    for (int k=1; k<=Nk; k++) {
        DZ[1][10][k]=2.*(y[k+1]-(double)dzsoma5);
        dzsoma5=(double)dzsoma5+DZ[1][10][k];
        dz[1][10][k]=(double)lzo*y[0]*DZ[1][10][k];
    }

    static doublereal dztsoma1;
    dztsoma1=0.;
    for (int k=1; k<=Nk; k++) {
        DZ[1][1][k]=2.*(y[k+1]-(double)dztsoma1);
        dztsoma1=(double)dztsoma1+DZ[1][1][k];
    }

    static doublereal dztsoma2;
    dztsoma2=0.;
    for (int k=1; k<=Nk; k++) {
        DZ[5][5][k]=2.*(y[k+1]-(double)dztsoma2);

```

```

        mecmain1paper.txt
    dztsoma2=(double)dztsoma2+DZ[5][5][k];
}

static doublereal dztsoma3;
dztsoma3=0.;
for (int k=1; k<=Nk; k++) {
    DZ[10][10][k]=2.*(y[k+1]-(double)dztsoma3);
    dztsoma3=(double)dztsoma3+DZ[10][10][k];
}

static doublereal dztsoma4;
dztsoma4=0.;
for (int k=1; k<=Nk; k++) {
    DZ[1][5][k]=2.*(y[k+1]-(double)dztsoma4);
    dztsoma4=(double)dztsoma4+DZ[1][5][k];
}

static doublereal dztsoma5;
dztsoma5=0.;
for (int k=1; k<=Nk; k++) {
    DZ[1][10][k]=2.*(y[k+1]-(double)dztsoma5);
    dztsoma5=(double)dztsoma5+DZ[1][10][k];
}

    for (int k=1; k<=Nk; k++) {
        RO[1][1][k]=(ror*dzo+mb(1,1,k)/AZijk)/(lzo*y[0]*DZ[1][1][k]);
    ROS[1][1][k]=(1.+ya+yb(1,1,k))/(1./rocwreal+ya/roa+yb(1,1,k)/rob(1,1,k));
        ROEL[1][1][k]=RO[1][1][k]/ROS[1][1][k];
    }
    for (int k=1; k<=Nk; k++) {
        RO[5][5][k]=(ror*dzo+mb(5,5,k)/AZijk)/(lzo*y[0]*DZ[5][5][k]);
    ROS[5][5][k]=(1.+ya+yb(5,5,k))/(1./rocwreal+ya/roa+yb(5,5,k)/rob(5,5,k));
        ROEL[5][5][k]=RO[5][5][k]/ROS[5][5][k];
    }
    for (int k=1; k<=Nk; k++) {
        RO[10][10][k]=(ror*dzo+mb(10,10,k)/AZijk)/(lzo*y[0]*DZ[10][10][k]);
    ROS[10][10][k]=(1.+ya+yb(10,10,k))/(1./rocwreal+ya/roa+yb(10,10,k)/rob(10,10,k));
        ;
        ROEL[10][10][k]=RO[10][10][k]/ROS[10][10][k];
    }
    for (int k=1; k<=Nk; k++) {
        RO[1][5][k]=(ror*dzo+mb(1,5,k)/AZijk)/(lzo*y[0]*DZ[1][5][k]);
    ROS[1][5][k]=(1.+ya+yb(1,5,k))/(1./rocwreal+ya/roa+yb(1,5,k)/rob(1,5,k));
        ROEL[1][5][k]=RO[1][5][k]/ROS[1][5][k];
    }
    for (int k=1; k<=Nk; k++) {
        RO[1][10][k]=(ror*dzo+mb(1,10,k)/AZijk)/(lzo*y[0]*DZ[1][10][k]);
    ROS[1][10][k]=(1.+ya+yb(1,10,k))/(1./rocwreal+ya/roa+yb(1,10,k)/rob(1,10,k));
        ROEL[1][10][k]=RO[1][10][k]/ROS[1][10][k];
    }

    ficheiro=fopen(nomedoficheiro,"aw+");
    // GLOBAL
    fprintf(ficheiro,"t %le LZ %le POR %le ST %le rosecoaparente
%le\n", (double)t, (double)y[0], (double)POR, (double)ST, (double)rosecoaparente);
    printf("t %le LZ %le POR %le ST %le rosecoaparente
%le\n", (double)t, (double)y[0], (double)POR, (double)ST, (double)rosecoaparente);
        4ágina p

```

```

// IJ - Stress (-)
//fprintf(ficheiro,"t %le s11 %le s110 %le s15 %le s1010 %le s55
%le\n", (double)t, (double)y[1], (double)y[100], (double)y[45], (double)y[1090], (double)y[485]);
//printf("t %le s11 %le s110 %le s15 %le s1010 %le s55
%le\n", (double)t, (double)y[1], (double)y[100], (double)y[45], (double)y[1090], (double)y[485]);

/*
//IJK - thickness column i=1 j=1 (m)
fprintf(ficheiro,"t %le dz111 %le dz113 %le dz115 %le dz117 %le dz1110
%le\n", (double)t, (double)dz[1][1][1], (double)dz[1][1][3], (double)dz[1][1][5], (double)dz[1][1][7], (double)dz[1][1][10]);
printf("t %le dz111 %le dz113 %le dz115 %le dz117 %le dz1110
%le\n", (double)t, (double)dz[1][1][1], (double)dz[1][1][3], (double)dz[1][1][5], (double)dz[1][1][7], (double)dz[1][1][10]);

//IJK - thickness column i=1 j=10 (m)
fprintf(ficheiro,"t %le dz1101 %le dz1103 %le dz1105 %le dz1107 %le
dz11010
%le\n", (double)t, (double)dz[1][10][1], (double)dz[1][10][3], (double)dz[1][10][5], (double)dz[1][10][7], (double)dz[1][10][10]);
printf("t %le dz1101 %le dz1103 %le dz1105 %le dz1107 %le dz11010
%le\n", (double)t, (double)dz[1][10][1], (double)dz[1][10][3], (double)dz[1][10][5], (double)dz[1][10][7], (double)dz[1][10][10]);

//IJK - thickness column i=1 j=5 (m)
fprintf(ficheiro,"t %le dz151 %le dz153 %le dz155 %le dz157 %le dz1510
%le\n", (double)t, (double)dz[1][5][1], (double)dz[1][5][3], (double)dz[1][5][5], (double)dz[1][5][7], (double)dz[1][5][10]);
printf("t %le dz151 %le dz153 %le dz155 %le dz157 %le dz1510
%le\n", (double)t, (double)dz[1][5][1], (double)dz[1][5][3], (double)dz[1][5][5], (double)dz[1][5][7], (double)dz[1][5][10]);

//IJK - thickness column i=10 j=10 (m)
fprintf(ficheiro,"t %le dz10101 %le dz10103 %le dz10105 %le dz10107
%le dz101010
%le\n", (double)t, (double)dz[10][10][1], (double)dz[10][10][3], (double)dz[10][10][5], (double)dz[10][10][7], (double)dz[10][10][10]);
printf("t %le dz111 %le dz113 %le dz115 %le dz117 %le dz1110
%le\n", (double)t, (double)dz[10][10][1], (double)dz[10][10][3], (double)dz[10][10][5], (double)dz[10][10][7], (double)dz[10][10][10]);

//IJK - thickness column i=5 j=5 (m)
fprintf(ficheiro,"t %le dz551 %le dz553 %le dz555 %le dz557 %le dz5510
%le\n", (double)t, (double)dz[5][5][1], (double)dz[5][5][3], (double)dz[5][5][5], (double)dz[5][5][7], (double)dz[5][5][10]);
printf("t %le dz551 %le dz553 %le dz555 %le dz557 %le dz5510
%le\n", (double)t, (double)dz[5][5][1], (double)dz[5][5][3], (double)dz[5][5][5], (double)dz[5][5][7], (double)dz[5][5][10]);
*/
/*
// IJK
for (int i=1; i<=1; i++) {
    for (int j=1; j<=1; j++) {
        for (int k=1; k<=1; k++) {
            fprintf(ficheiro,"t111a %le i %ld j %ld k %ld Egijk %le Esijk %le
xLijk %le vgijk %le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)xl(i, j, k), (double)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));
            printf("t %le i %ld j %ld k %ld Egijk %le Esijk %le xLijk %le vgijk
%le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)xl(i, j, k), (double)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));

            fprintf(ficheiro,"t111 %le i %ld j %ld k %ld EIJK %le dzijk %le
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```

```

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ROIjk %le Sijk %le RORELIjk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
    printf("t %le i %ld j %ld k %ld EIJK %le dzijk %le ROIjk %le Sijk
%le RORELIjk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
    }
}
for (int i=1; i<=1; i++) {
    for (int j=1; j<=1; j++) {
        for (int k=5; k<=5; k++) {
            fprintf(ficheiro, "t115a %le i %ld j %ld k %ld Egijk %le Esijk %le
XLijk %le vgijk %le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)x1(i, j, k), (do
uble)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));
            printf("t %le i %ld j %ld k %ld Egijk %le Esijk %le XLijk %le vgijk
%le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)x1(i, j, k), (do
uble)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));

            fprintf(ficheiro, "t115 %le i %ld j %ld k %ld EIJK %le dzijk %le
ROIjk %le Sijk %le RORELIjk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
            printf("t %le i %ld j %ld k %ld EIJK %le dzijk %le ROIjk %le Sijk
%le RORELIjk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
        }
    }
}
for (int i=1; i<=1; i++) {
    for (int j=1; j<=1; j++) {
        for (int k=10; k<=10; k++) {
            fprintf(ficheiro, "t1110a %le i %ld j %ld k %ld Egijk %le Esijk %le
XLijk %le vgijk %le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)x1(i, j, k), (do
uble)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));
            printf("t %le i %ld j %ld k %ld Egijk %le Esijk %le XLijk %le vgijk
%le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)x1(i, j, k), (do
uble)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));

            fprintf(ficheiro, "t1110 %le i %ld j %ld k %ld EIJK %le dzijk %le
ROIjk %le Sijk %le RORELIjk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
            printf("t %le i %ld j %ld k %ld EIJK %le dzijk %le ROIjk %le Sijk
%le RORELIjk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
        }
    }
}
}

*/
fclose(ficheiro);
//printf("t %le LZ %le POR %le ST
%le\n", (double)t, (double)y[0], (double)POR, (double)ST);
}

if (iout==0) tout=0.0;
tout += 1.0/(double)real(sout);

}

```

```

} //END of MAIN

/* ***** */
/*                               FEX                               */
/* ***** */

integer fex(integer *neq, doublereal *t, doublereal *y,
            doublereal *yt)
{
    int L=0;
    LZ=(DOUBLE)y[L];
    LZT=(DOUBLE)yt[L];
    L=L+1;

    for (int i=1; i<=Ni; i++) {
        for (int j=1; j<=Nj; j++) {
            SIJ[i][j]=(DOUBLE)y[L];
            SIJT[i][j]=(DOUBLE)yt[L];
            L=L+1;
            for (int k=1; k<=Nk; k++) {
                Z[i][j][k]=(DOUBLE)y[L];
                ZT[i][j][k]=(DOUBLE)yt[L];
                L=L+1;
            }
        }
    }

    //tp=((double)
    *t)*(DOUBLE)tau*(DOUBLE)1000.0-(DOUBLE)tpo)/(DOUBLE)alfa+(DOUBLE)0.5;
    // printf("#t %le\n", (double)*t);
    //printf("#tp %le\n", (DOUBLE)tp);

    /* ----- Call UPDATE ----- */

    UPDATE((double) *t);

    L=0;
    y[L]=(doublereal)LZ;
    yt[L]=(doublereal)LZT;
    L=L+1;

    for (int i=1; i<=Ni; i++) {
        for (int j=1; j<=Nj; j++) {
            y[L]=(doublereal)SIJ[i][j];
            yt[L]=(doublereal)SIJT[i][j];
            L=L+1;
            for (int k=1; k<=Nk; k++) {
                y[L]=(doublereal)Z[i][j][k];
                yt[L]=(doublereal)ZT[i][j][k];
                L=L+1;
            }
        }
    }

    // stotal/=(DOUBLE)Ni*Nj;
    // printf("out %le\n", *t);
    // printf("out %le %le %le %le %le %le\n", *t, y[0], y[1]*str, stotal*str, STF(*t));
} // END of FEX

```

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```
/* ***** */
/*                JEX                */
/* ***** */

integer jex(integer *neq, doublereal *t, doublereal *y, integer
            *ml, integer *mu, doublereal *pd, integer *nrpd)
{
    /* System generated locals */
    integer pd_dim1, pd_offset;

    /* Parameter adjustments */
    --y;
    pd_dim1 = *nrpd;
    pd_offset = 1 + pd_dim1 * 1;
    pd -= pd_offset;

    /* Function Body */
    return 0;
} // END of JEX

#ifdef __cplusplus
}
#endif

//getchar();
```

```

                                paperviscoelastoplastic.txt
/*****
*                               Modelo mecanico de prensagem do papel                               *
*****/

*****
*                               Definicao de variaveis                                           *
*****

    As variaveis a letra maiuscula referem-se a valores
    adimensionais, EXCEPTO PARA T e K!

*****/

#include <stdio.h>
#include <math.h>
#include <f2c.h>

/* ----- PARAMETROS GLOBAIS ----- */

#define DOUBLE double

#define Ni (10)
#define Nj (10)
#define Nk (10)
#define Nij (100)
#define Nijk (1000)

/* ----- VARIAVEIS GLOBAIS ----- */

#define lxo (DOUBLE) (0.0375)
#define lyo (DOUBLE) (0.0375)
#define lzo (DOUBLE) (2.129609e-3) // lzo= valor experimental! papel
#define AZ (DOUBLE) (1.40625e-3) // área de 1/4 da folha de papel
#define AZijk (DOUBLE) (14.0625e-6)

#define tau (DOUBLE) (0.0825667)
#define Tprato (DOUBLE) (25.0)
#define A (DOUBLE) (1.414213562)
#define B (DOUBLE) (-216.349)
#define C (DOUBLE) (-0.4190262407)
#define tpm (DOUBLE) (0.9428090413)
#define tpr (DOUBLE) (71.9333)
#define tpo (DOUBLE) (35.2)

#define alfa1 (DOUBLE) (73.4666)
#define beta1 (DOUBLE) (1.5333)

/* ----- OUTRAS VARIAVEIS ----- */
DOUBLE LZ;
DOUBLE LZT;
DOUBLE SIJ[Ni+2][Nj+2];      DOUBLE SIJT[Ni+2][Nj+2];
DOUBLE Z[Ni+2][Nj+2][Nk+2];  DOUBLE ZT[Ni+2][Nj+2][Nk+2];

DOUBLE DZ[Ni+2][Nj+2][Nk+2];  DOUBLE DZT[Ni+2][Nj+2][Nk+2];
DOUBLE dz[Ni+2][Nj+2][Nk+2];
DOUBLE DEF[Ni+2][Nj+2][Nk+2];  DOUBLE DEFT[Ni+2][Nj+2][Nk+2];

DOUBLE FI[Ni+2][Nj+2][Nk+2];
DOUBLE FIT[Ni+2][Nj+2][Nk+2];
DOUBLE rorel[Ni+2][Nj+2][Nk+2];

DOUBLE RO[Ni+2][Nj+2][Nk+2];
DOUBLE ROS[Ni+2][Nj+2][Nk+2];
DOUBLE ROREL[Ni+2][Nj+2][Nk+2];
DOUBLE Fi[Ni+2][Nj+2][Nk+2];

```

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```

DOUBLE t;
DOUBLE tp;

DOUBLE lx,ly;
DOUBLE POR,roap, rosecoaparente;
DOUBLE st,stt,sij;
DOUBLE ST,STT;

/* ----- PROPRIEDADES FISICAS ----- */

static DOUBLE LX=1.0;           // considerado constante = lx/lx0 ;
lx0=0.075 m
static DOUBLE LY=1.0;           // considerado constante = ly/ly0 ;
ly0=0.075 m

static DOUBLE DX=LX;            // =1
static DOUBLE DY=LY;            // =1

static DOUBLE dxo=(DOUBLE)lxo/(DOUBLE)Ni;
static DOUBLE dyo=(DOUBLE)lyo/(DOUBLE)Nj;
static DOUBLE dzo=(DOUBLE)lzo/(DOUBLE)Nk;

static DOUBLE str;              /* str= valor maximo da tensao aplicada a
1/4                             do volume de controlo */
                                //valor minimo para a fibra de celulose a
static DOUBLE er=3.4e6;         //valor para a fibra a 25 °C
25°C e HR=1 (fibra saturada)   // Pa
static DOUBLE visr=3.7e6;       // em kelvin (25 °C)
static DOUBLE ego=101325.;
static DOUBLE To=298.15;
static DOUBLE Po=101325.;
static DOUBLE egas1;

static DOUBLE C1=1.;
static DOUBLE C2=0.5;
static DOUBLE C3=0.015; // limite de elasticidade

DOUBLE E;
DOUBLE VIS;//ES,EG,EL;

static DOUBLE rocwreal=1550.; // kg/m3
static DOUBLE roa=1100.;
static DOUBLE mcw=0.3616e-3*4./4.; // kg (massa de 4 folhas/4)
static DOUBLE ya=0.15/100.;
static DOUBLE ma=mcw*ya;
static DOUBLE mseco=mcw+ma;
static DOUBLE roseco=(1.+ya)/(1./rocwreal+ya/roa);
static DOUBLE ror=(mseco/(DOUBLE)Nijk)/((DOUBLE)AZijk*(DOUBLE)lzo);
static DOUBLE Mar=(0.21*32.+0.79*28.)/1000.;
static DOUBLE magua=(70./30.)*(mseco/(DOUBLE)Nijk);
/* ----- Numeros adimensionais ----- */
DOUBLE H;
DOUBLE V;

/* ----- PROTOTIPOS DAS FUNCOES ----- */

void DZF();
void DZTF();
void FIF();
void FITF();
void rorelF();
/* ----- */
DOUBLE Kz (int i,int j,int k);
DOUBLE kr1 (int i,int j,int k);
DOUBLE krg (int i,int j,int k);

```



```

DOUBLE Klz (int i,int j,int k);
DOUBLE Kgz (int i,int j,int k);

DOUBLE S (int i,int j,int k);
DOUBLE Sg (int i,int j,int k);
DOUBLE Sb (int i,int j,int k);
DOUBLE Se (int i,int j,int k);

DOUBLE PORIJK (int i,int j,int k);
DOUBLE gama (int i,int j,int k);

DOUBLE el (int i,int j,int k);
DOUBLE eg (int i,int j,int k);
DOUBLE ef (int i,int j,int k);
DOUBLE ef1 (int i,int j,int k);
DOUBLE ea (int i,int j,int k);
DOUBLE es (int i,int j,int k);
DOUBLE EIJK (int i, int j,int k);
DOUBLE EIJKO (int i, int j,int k);
DOUBLE EIJ (int i, int j);
DOUBLE rol (int i,int j,int k);
DOUBLE rog (int i,int j,int k);
DOUBLE ro (int i,int j,int k);
DOUBLE ros (int i,int j,int k);
DOUBLE rob (int i,int j,int k);
//DOUBLE rorel (int i,int j,int k);
DOUBLE mb (int i,int j,int k);
DOUBLE xl (int i,int j,int k);

DOUBLE Vgo (int i,int j,int k);
DOUBLE Vg (int i,int j,int k);
DOUBLE PORIJKO (int i,int j,int k);
DOUBLE Sbo (int i,int j,int k);
DOUBLE xlo (int i,int j,int k);

DOUBLE VISIJ (int i,int j);
DOUBLE VISIJK (int i,int j,int k);
DOUBLE ycw (int i,int j,int k);
DOUBLE yagua (int i,int j,int k);
DOUBLE yg (int i,int j,int k);

DOUBLE dev (int i,int j,int k);
DOUBLE Pg (int i,int j,int k);
DOUBLE EGT (int i,int j,int k);
DOUBLE ELT (int i,int j,int k);
DOUBLE EIJKT (int i,int j,int k);
DOUBLE RORELT (int i,int j,int k);

DOUBLE BETAT (int i,int j,int k);
DOUBLE EST (int i,int j,int k);
DOUBLE DT (int i,int j,int k);
DOUBLE XLT (int i,int j,int k);
DOUBLE EFT (int i,int j,int k);
DOUBLE PgT (int i,int j,int k);
DOUBLE VgT (int i,int j,int k);
DOUBLE AT (int i,int j,int k);
DOUBLE PORIJKT (int i,int j,int k);
DOUBLE Sbt (int i,int j,int k);
DOUBLE GAMAT (int i,int j,int k);
DOUBLE Q4T (int i,int j,int k);
DOUBLE BT (int i,int j,int k);

DOUBLE T (int i,int j,int k);
DOUBLE alfa (int i,int j,int k);
DOUBLE beta (int i,int j,int k);

```

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```

DOUBLE visl (int i,int j,int k);
DOUBLE visg (int i,int j,int k);
DOUBLE sigmagas (int i,int j,int k);
DOUBLE sigma1iq (int i,int j,int k);

DOUBLE STF(DOUBLE teta);
DOUBLE STTF(DOUBLE teta);
DOUBLE UPDATE(DOUBLE teta);

/* ***** */
/*                               FUNCAO UPDATE                               */
/* ***** */
DOUBLE UPDATE(DOUBLE teta)
{
/* ----- */
/*                               Input experimental                               */
/* ----- */
//getchar();

ST=STF(teta);
STT=STTF(teta);
DZF();
DZTF();
rorelF();
FIF();
FITF();

/* ----- */
/*   Calculo do modulo de Young medio e do parametro viscoso medio   */
/* ----- */
E=0.0; VIS=0.0;

for (int i=1; i<=Ni; i++) {
    for (int j=1; j<=Nj; j++) {
        E=E+EIJ(i,j);
        VIS=VIS+VISIJ(i,j);
    }
}

E=E/(DOUBLE)Ni*j;
VIS=VIS/(DOUBLE)Ni*j;

/* ----- */
/*                               Equacoes a integrar                               */
/* ----- */

DOUBLE soma4;
DOUBLE deftemp;

LZT=STT/(E*H)+V*ST/VIS;

for (int i=1; i<=Ni; i++) {
    for (int j=1; j<=Nj; j++) {
        soma4=0.0;

        SIJT[i][j]=H*EIJ(i,j)*LZT-H*V*EIJ(i,j)*SIJ[i][j]/VISIJ(i,j);

        for (int k=1; k<=Nk; k++) {

```

```

                                paperviscoelastoplastic.txt
deflttemp=SIJT[i][j]/(H*EIJKO(i,j,k))+V*SIJ[i][j]/VISIJK(i,j,k);

ZT[i][j][k]=(1./(2.*(DOUBLE)Nk*LZ))*(deflttemp+2.*soma4)-Z[i][j][k]*LZT/LZ;
    soma4=soma4+deflttemp;
}
}
}

/* ----- */
/* calculo da porosidade global e da densidade aparente do papel */
/* ----- */
rosecaparente=mseco/((DOUBLE)AZ*(DOUBLE)lzo*LZ);
POR=1.-rosecaparente/rosec;

} // Fim da UPDATE

/* ***** */
/* FUNCOES e PROPRIEDADES */
/* ***** */
DOUBLE mb(int i,int j,int k)
{
    DOUBLE MB;
    MB=(43.60605-0.05284*(T(i,j,k)-273.15))*(mcw/(DOUBLE)Nijk)/100.;

    return MB;
}
/* ----- */
/* Temperatura */
/* ----- */
DOUBLE T(int i,int j,int k)
{
    return Tprato+273.15;
}

/* ----- */
/* Permeabilidades */
/* ----- */
DOUBLE Kz (int i, int j, int k)
{
    return (4.4164e-14)*exp(13.4208*PORIJK(i,j,k));
}

DOUBLE krg (int i, int j, int k)
{
    return (1.+3.*Se(i,j,k))*pow((1.-Se(i,j,k)),3.); // segundo Michaels
}

DOUBLE kr1 (int i, int j, int k)
{
    //return pow(Se(i,j,k),3.4); // segundo Jewett
    return pow(Se(i,j,k),4.); // segundo Michaels
}

DOUBLE Klz (int i, int j, int k) { return kr1(i,j,k)*Kz(i,j,k); }
DOUBLE Kgz (int i, int j, int k) { return krg(i,j,k)*Kz(i,j,k); }

/* ----- */
/* Saturacao */
/* ----- */
DOUBLE S (int i, int j, int k) {
    DOUBLE sat;

    sat=(magua/rol(i,j,k))/(PORIJK(i,j,k)*(DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]);
    return sat;
}

```

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```

}
DOUBLE Sg (int i, int j, int k) { return 1.-S(i,j,k); }
DOUBLE Sb (int i,int j,int k)
{
    DOUBLE sbound;

    sbound=(mb(i,j,k)/ro1(i,j,k))/((DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]*PORIJK(i,j,k));

    return sbound;
}
DOUBLE Se (int i, int j, int k) { return (S(i,j,k)-Sb(i,j,k))/(1.-Sb(i,j,k)); }

/* ----- */
/* Porosidades do papel */
/* ----- */
DOUBLE PORIJK (int i,int j,int k) { return
1.-(mseco/(DOUBLE)Nijk)/(roseco*(DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]); }
DOUBLE PORIJKEF (int i,int j,int k) { return PORIJK(i,j,k)*(1.-Sb(i,j,k)); }

/* ----- */
/* Viscosidades */
/* ----- */
DOUBLE visl (int i,int j,int k)
{
    DOUBLE miu,indice0;
    if (T(i,j,k)>373.15) {
        indice0=(-1.37272*(100.-20.0)-0.001053*(100.-20.0)*(100.-20.0))/(100.+105.0);
    }
    else {
        indice0=(-1.37272*(T(i,j,k)-273.15-20.0)-0.001053*(T(i,j,k)-273.15-20.0)*(T(i,j,k)-273.15-20.0))/(T(i,j,k)-273.15+105.0);
    }
    miu=1.002e-3*pow(10.0,indice0);

    return miu;
}

DOUBLE visg (int i,int j,int k)
{
    return 3.8e-8*T(i,j,k)-1.57e-6;
}
DOUBLE viscw(int i, int j, int k)
{
    DOUBLE VISCW;

    VISCW=1e6*exp(3241./(8.314*T(i,j,k)));

    return VISCW;
}

/* ----- */
/* Módulos de elasticidade */
/* ----- */
DOUBLE gama (int i,int j,int k)
{
    DOUBLE GAMA;

    GAMA=1.-((ma/(DOUBLE)Nijk)/roa)/(rorel[i][j][k]*(DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]*LZ);

    return GAMA;
}
DOUBLE yb (int i,int j, int k) { return mb(i,j,k)/(mcw/(DOUBLE)Nijk); }
DOUBLE ef1(int i,int j,int k) {return

```

```
562E2*exp(2024./(T(i,j,k)-273.15+468.)+0.0016/(yb(i,j,k)-0.2029)));}
```

```
DOUBLE ef (int i,int j,int k)
```

```
{
    DOUBLE EF;
    EF=ef1(i,j,k)*gama(i,j,k)+(1.-gama(i,j,k))*ea(i,j,k);

    return EF;
}
```

```
DOUBLE es (int i,int j,int k)
```

```
{
    DOUBLE ES;

    ES=C2*ef(i,j,k)*rorel[i][j][k]*rorel[i][j][k];
    return ES;
}
```

```
DOUBLE ea (int i,int j,int k)
```

```
{
    DOUBLE EA;
    EA=1e5;
    return EA;
}
```

```
DOUBLE sigmaliq (int i,int j,int k)
```

```
{
    DOUBLE Sigma2;

    Sigma2=0.0;
    return Sigma2;
}
```

```
DOUBLE el (int i,int j,int k)
```

```
{
    DOUBLE EL;
    EL=0.5*1.034e8;

    return EL;
}
```

```
DOUBLE sigmagas (int i,int j,int k)
```

```
{
    DOUBLE Sigma;

    Sigma=(DOUBLE)Nijk*visg(i,j,k)*((DOUBLE)lzo*DZ[i][j][k]*LZ)*((DOUBLE)lzo*DZ[i][j][k]*LZ)*(LZ*DZT[i][j][k]+DZ[i][j][k]*LZT)/Kgz(i,j,k)/(DOUBLE)tau;

    return Sigma;
}
```

```
DOUBLE eg (int i,int j,int k)
```

```
{
    DOUBLE EG;

    EG=(Pg(i,j,k)-(DOUBLE)Po)/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.);
    return EG;
}
```

```
DOUBLE EIJK (int i,int j,int k)
```

```
{
    DOUBLE eijk;

    eijk=es(i,j,k)*FI[i][j][k]+(1.-rorel[i][j][k])*(1.-beta(i,j,k))*eg(i,j,k)+(1.-rorel[i][j][k])*beta(i,j,k)*el(i,j,k);
}
```

```

    return eijk;
}

DOUBLE EIJKO(int i, int j, int k)
{
    DOUBLE eijk;
    eijk=EIJK(i,j,k)+((DOUBLE)Nk*LZ*DZ[i][j][k]-1.)*EIJKT(i,j,k);
    return eijk/er;
}

DOUBLE EIJ(int i,int j)
{
    DOUBLE soma1=0.0,valor=0.0;
    for (int k=1;k<=Nk;k++) {
        soma1=soma1+1./(EIJKO(i,j,k)*er);
    }
    valor=soma1;
    return (DOUBLE)Nk/valor/er;
}

DOUBLE VISIJK(int i,int j,int k)
{
    DOUBLE visijk;
    visijk=ycw(i,j,k)*viscw(i,j,k)+yagua(i,j,k)*visl(i,j,k);
    return visijk/visr;
}

DOUBLE VISIJ(int i,int j)
{
    DOUBLE soma3=0.0,valor2=0.0;
    for (int k=1;k<=Nk;k++){
        soma3=soma3+1./VISIJK(i,j,k);
    }
    valor2=soma3;
    return (DOUBLE)Nk/soma3;
}

DOUBLE yagua1 (int i,int j,int k) { return magua/(mcw/(DOUBLE)Nijk); }
DOUBLE yagua (int i,int j,int k) { return
yagua1(i,j,k)/(1.+ya+yagua1(i,j,k)+yg(i,j,k)); }
DOUBLE yg (int i,int j,int k) { return
(Vg(i,j,k)/rog(i,j,k))/(mcw/(DOUBLE)Nijk); }
DOUBLE ycw (int i,int j,int k) {return 1./(1.+ya+yagua1(i,j,k)+yg(i,j,k)); }

/* ----- */
/*                               Densidades                               */
/* ----- */

DOUBLE rol (int i,int j,int k) { return 1157.8-0.5361*T(i,j,k); }
DOUBLE rog (int i,int j,int k) { return Mar*Pg(i,j,k)/(8.314*T(i,j,k)); }
DOUBLE rob (int i,int j,int k) { return rol(i,j,k); }
DOUBLE ros (int i,int j,int k) { return
(1.+ya+yb(i,j,k))/(1./rocreal+ya/roa+yb(i,j,k)/rob(i,j,k)); }

DOUBLE ro (int i,int j,int k) { return
(ror*dzo+mb(i,j,k)/(DOUBLE)AZijk)/((DOUBLE)lzo*LZ*DZ[i][j][k]); }

/* ----- */
/*                               alfa e beta                               */
/* ----- */
DOUBLE xl (int i,int j,int k) {

```

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```

DOUBLE XL;

XL=(S(i,j,k)-Sb(i,j,k))*PORIJK(i,j,k);

return XL;
}
DOUBLE alfa (int i,int j,int k) { return rorel[i][j][k]; }
DOUBLE beta (int i,int j,int k) { return xl(i,j,k)/(1.-alfa(i,j,k)); }

DOUBLE Vgo (int i,int j,int k) { return
(DOUBLE)AZijk*(DOUBLE)lzo*(PORIJKo(i,j,k)*(1.-Sbo(i,j,k))-xlo(i,j,k))/(DOUBLE)Nk
; }
DOUBLE PORIJKo (int i,int j,int k) { return
1.-(mseco/(DOUBLE)Nijk)/(roseco*(DOUBLE)AZijk*(DOUBLE)lzo/(DOUBLE)Nk); }
DOUBLE Sbo (int i,int j,int k) { return
(mb(i,j,k)/rol(i,j,k))/((DOUBLE)AZijk*(DOUBLE)lzo/(DOUBLE)Nk-(mseco/(DOUBLE)Nijk
)/roseco); }
DOUBLE xlo (int i,int j,int k) { return
(magua-mb(i,j,k))/(rol(i,j,k)*(DOUBLE)AZijk*(DOUBLE)lzo/(DOUBLE)Nk); }

DOUBLE Vg(int i,int j,int k)
{
    DOUBLE vg;

vg=(DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]*(PORIJK(i,j,k)*(1.-Sb(i,j,k))-xl(i,j
,k));

    return vg;
}

/* ----- */
/*          MC, SC e Porosidade          */
/* ----- */
DOUBLE scijk (int i,int j,int k)
{

    return (mseco/(DOUBLE)Nijk)/(mseco/(DOUBLE)Nijk+magua);
}

DOUBLE mcijk (int i,int j,int k) { return 1.-scijk(i,j,k); }

/* ----- */
/*          Derivada de eijk em ordem à deformação          */
/* ----- */
DOUBLE EIJKT(int i,int j,int k)
{
    DOUBLE eijkt,A1,B1,C11;

        A1=FI[i][j][k]*EST(i,j,k)+es(i,j,k)*FIT[i][j][k];

B1=(1.-rorel[i][j][k])*((1.-beta(i,j,k))*EGT(i,j,k)+beta(i,j,k)*ELT(i,j,k)+(el(i
,j,k)-eg(i,j,k))*BETAT(i,j,k));
    C11=((beta(i,j,k)-1.)*eg(i,j,k)-beta(i,j,k)*el(i,j,k))*RORELT(i,j,k);

        eijkt=A1+B1+C11;
        return eijkt;
}

/* ----- */
/*          Função não-linear e derivada          */
/* ----- */
void rorelF()
{

```

```

DOUBLE rorela;
for (int i=1; i<=Ni;i++)
  for (int j=1; j<=Nj;j++)
    for (int k=1; k<=Nk;k++) {
      rorela=ro(i,j,k)/ros(i,j,k);
      rorel[i][j][k]=rorela;
    }
}

void FIF()
{
  DOUBLE difo,fi,Q1,Q2;
  for (int i=1; i<=Ni;i++)
    for (int j=1; j<=Nj;j++)
      for (int k=1; k<=Nk;k++) {
        difo=DEF[i][j][k]-C3;

        if (abs(DEF[i][j][k])<=C3) {
          fi=1.0;
        }
        else {
          Q2=rorel[i][j][k]/(1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.))+C3);

          Q1=(1.-pow(rorel[i][j][k],(1./3.)))/(1.-pow(Q2,(1./3.)));
          fi=(C3/C2)*Q1*Q1/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.);

        }

        FI[i][j][k]=fi;
      }
}

void FITF()          //derivada em ordem à deformação!
{
  DOUBLE dif0,fit,Q3,Q4;
  for (int i=1; i<=Ni;i++)
    for (int j=1; j<=Nj;j++)
      for (int k=1; k<=Nk;k++) {
        dif0=DEF[i][j][k]-C3;
        if (abs(DEF[i][j][k])<=C3) {
          fit=0.0;
        }
        else {
          Q3=rorel[i][j][k]/(1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.))+C3);

          Q4=(1.-pow(rorel[i][j][k],(1./3.)))/(1.-pow(Q3,(1./3.)));

          fit=(C3/C2)*(-(Q4/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.))*(Q4/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.))+2.*Q4*Q4T(i,j,k)/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.));

        }
        FIT[i][j][k]=fit;
      }
}

DOUBLE Q4T(int i,int j,int k)
{
  DOUBLE quatro,Q5,Q6;
  Q5=rorel[i][j][k]/(1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.))+C3);

  Q6=pow((1.-pow(Q5,(1./3.))),2.);

  quatro=((1./3.)*(1.-pow(rorel[i][j][k],(1./3.)))*BT(i,j,k)*pow(Q5,(-2./3.))-(1./3.)*pow(rorel[i][j][k],(-2./3.))*RORELT(i,j,k)*(1.-pow(Q5,(1./3.)))/Q6;
}

```



```

    return quatro;
}

DOUBLE BT(int i,int j,int k)
{
    DOUBLE bt;

    bt=((1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.))+C3)*RORELT(i,j,k)+rorel[i][j][k])/pow(
    (1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.))+C3),2.);

    return bt;
}

DOUBLE RORELT(int i,int j,int k)          // derivada de rorel em ordem à
deformação
{
    DOUBLE rorelt;

    rorelt=-(1./ros(i,j,k))*(ror+mb(i,j,k)/((DOUBLE)AZijk*dzo))/pow(((DOUBLE)Nk*LZ*D
    Z[i][j][k]),2.);
    return rorelt;
}

DOUBLE BETAT(int i,int j,int k)          // derivada de beta em ordem à
deformação
{
    DOUBLE betat;

    betat=((1.-rorel[i][j][k])*XLT(i,j,k)+xl(i,j,k)*RORELT(i,j,k))/pow((1.-rorel[i][
    j][k]),2.);
    return betat;
}

DOUBLE XLT(int i,int j,int k)          // derivada de xl em ordem à deformação
{
    DOUBLE xlt;

    xlt=-(magua-mb(i,j,k))/((DOUBLE)Nk*(DOUBLE)lzo*(DOUBLE)AZijk*ro1(i,j,k)*LZ*LZ*DZ
    [i][j][k]*DZ[i][j][k]);

    return xlt;
}

/* ----- */
/*          Derivada de EG em ordem à deformação          */
/* ----- */
DOUBLE EGT(int i,int j,int k)
{
    DOUBLE egt,B7;          // derivada de eg em ordem à deformação
    B7=abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.)*abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.);
    egt=(abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.0)*PgT(i,j,k)-Pg(i,j,k)+Po)/B7;
    return egt;
}

DOUBLE dev(int i,int j,int k)
{
    DOUBLE de;
    de=0.0;

```

```

        return de;
    }

    DOUBLE ELT(int i,int j,int k)
    {
        DOUBLE elt,B8;           // derivada de el em ordem à deformação
        elt=0.;
        return elt;
    }

    DOUBLE PgT(int i,int j,int k) // derivada de Pg em ordem à deformação
    {
        DOUBLE pgt;
        pgt=-Po*Vgo(i,j,k)*VgT(i,j,k)/pow(Vg(i,j,k),2.);
        return pgt;
    }

    DOUBLE VgT(int i,int j,int k) //derivada do volume de gas em ordem à deformação
    {
        DOUBLE vgt;
        vgt=((DOUBLE)AZijk*(DOUBLE)lzo/(DOUBLE)Nk)*(PORIJK(i,j,k)*(1.-Sb(i,j,k))-xl(i,j,k)+(DOUBLE)Nk*LZ*DZ[i][j][k]*AT(i,j,k));
        return vgt;
    }

    DOUBLE AT(int i,int j,int k)
    {
        DOUBLE at;
        at=(1.-Sb(i,j,k))*PORIJKT(i,j,k)-PORIJK(i,j,k)*SbT(i,j,k)-XLT(i,j,k);
        return at;
    }

    DOUBLE PORIJKT(int i,int j,int k)
    {
        DOUBLE porijkt,B9;
        B9=(mseco*(DOUBLE)dzo)/((DOUBLE)Nijk*roseco)/(DOUBLE)AZijk;
        porijkt=B9/pow(((DOUBLE)lzo*LZ*DZ[i][j][k]),2.);
        return porijkt;
    }

    DOUBLE SbT(int i,int j,int k)
    {
        DOUBLE sbt,A9;
        A9=((DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]-(mseco/(DOUBLE)Nijk)/roseco)*((DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]-(mseco/(DOUBLE)Nijk)/roseco);
        sbt=-(mb(i,j,k)/rol(i,j,k))*(DOUBLE)AZijk*(DOUBLE)dzo/A9;
        return sbt;
    }

    /* ----- */
    /*          Derivada de ES em ordem à deformação          */
    /* ----- */
    DOUBLE EST(int i,int j,int k)
    {
        DOUBLE est;

        est=2.*C2*ef(i,j,k)*rorel[i][j][k]*RORELT(i,j,k)+C2*EFT(i,j,k)*rorel[i][j][k]*rorel[i][j][k];
        return est;
    }

```

```

}

DOUBLE EFT(int i,int j,int k)
{
    DOUBLE eft;
    eft=(ef1(i,j,k)-ea(i,j,k))*GAMAT(i,j,k);
    return eft;
}

DOUBLE GAMAT(int i,int j,int k)
{
    DOUBLE gamat,A7,A77,A8;

A7=((ma/(DOUBLE)Nijk)/roa)*(rorel[i][j][k]+(DOUBLE)Nk*LZ*DZ[i][j][k]*RORELT(i,j,
k));
    A77=rorel[i][j][k]*DZ[i][j][k]*DZ[i][j][k]*LZ*LZ;
    A8=(DOUBLE)lzo*(DOUBLE)AZijk*(DOUBLE)Nk*A77;
    gamat=A7/A8;
    return gamat;
}

DOUBLE DT(int i,int j,int k) // derivada de T em ordem ao tempo
{
    DOUBLE dt;
    dt=0.0;
    return dt;
}

DOUBLE Pg(int i,int j,int k)
{
    DOUBLE pg;
    pg=Po*Vgo(i,j,k)/Vg(i,j,k);

    return pg;
}

/* ----- */
/* Funcao que calcula os DZ a partir dos Z */
/* ----- */
void DZF()
{
    DOUBLE dzsoma;

    for (int i=1; i<=Ni; i++)
        for (int j=1; j<=Nj; j++) {
            dzsoma=0.0;
            for (int k=1; k<=Nk; k++) {
                DZ[i][j][k]= 2.0*(Z[i][j][k]-dzsoma);
                dzsoma=dzsoma+DZ[i][j][k];
                DEF[i][j][k]=((DOUBLE)Nk*LZ*DZ[i][j][k]-1.0);
            }
        }
}

/* ----- */
/* Funcao que calcula as derivadas de DZ */
/* ----- */

void DZTF()
{
    DOUBLE dztsoma;

    for (int i=1; i<=Ni; i++)
        for (int j=1; j<=Nj; j++) {

```

```

                                paperviscoelastoplastic.txt
dztsoma=0.0;
for (int k=1; k<=Nk; k++) {
    DZT[i][j][k]=2.*(ZT[i][j][k]-dztsoma);
    dztsoma=dztsoma+DZT[i][j][k];
    DEFT[i][j][k]=(DOUBLE)Nk*(LZ*DZT[i][j][k]+DZ[i][j][k]*LZT);
}
}

/* ----- */
/*          Funcao que calcula a tensao aplicada          */
/* ----- */
DOUBLE STF(DOUBLE teta)
{
    DOUBLE st;

    tp=(teta*tau*1000.0-tpo)/alfa1+0.5;

    if (tp<tpm) {
        st=(-tp*tp*tp+A*tp*tp)/C;
    }else {
        st=-(1.+B*(tp-tpm)*(tp-tpm)*(tp-tpm));
    }

    return st;
}

/* ----- */
/*          Funcao que calcula a derivada da tensao aplicada          */
/* ----- */
DOUBLE STTF(DOUBLE teta)
{
    DOUBLE stt;

    if (tp<tpm){
        stt=-((3.*tp*tp-2.*A*tp)/C);
    }else {
        stt=-(3.*B*(tp-tpm)*(tp-tpm));
    }

    return stt*tau*1000.0/alfa1;
}

// Fim do programa secundario

```

```

                                mecmain1felt.txt
/* EXEMPL01.F -- translated by f2c (version 20000121).
   You must link the resulting object file with the libraries:
      -lf2c -lm   (in that order) */

#ifdef __cplusplus
extern "C" {
#endif
#include "feltviscoelastoplastic.c"

/* ***** */
/*                               MAIN PROGRAM                               */
/* ***** */

void MAIN__()
{
    static doublereal atol;
    static integer itol, iopt;
    static doublereal rtol;
    static doublereal tcrit,tout, t;
    static doublereal y[1101];
    static doublereal yt[1101];
    static integer itask, iwork[Ni*Nj*Nk+1+Ni*Nj+31];
    static doublereal rwork[1222132];
    static integer mf, istate;
    extern /* Subroutine */ integer dlsodes_(U_fp, integer *,
        doublereal *, doublereal *, doublereal *, integer *,
        doublereal *, doublereal *, integer *, integer *,
        integer *, doublereal *, integer *, integer *,
        integer *, U_fp, integer *);

    static FILE *ficheiro;
    static char nomedoficheiro[30];

    integer fex();
    static integer neq;
    integer jex();
    static integer liw, lrw;

    printf("Introduza o nome do ficheiro de resultados\t");
    scanf("%s",nomedoficheiro);
    printf("\nOs resultados serão guardados em : %s\n",nomedoficheiro);

    neq = Ni*Nj*Nk+1+Ni*Nj; // the number of ODE's to be solved
    itol = 1; // scalar RTOL and scalar ATOL
    rtol = (doublereal)0.125e-6; /* local relative error tolerance
        parameter for the solution */
    atol = (doublereal)0.125e-8; /* local absolute error tolerance
        parameter for the solution */
    itask = 4; /* compute output values of Y(t) at t=tout without
        overshooting */
    istate = 1; /* state of the calculation; this is the first call
        for the problem */
    iopt = 1; /* values have been specified for one or more
        optional input parameters */
    lrw = 22+neq*(5+1)+3*neq+neq*neq; /* length of the RWORK array;
        = 22 + NYH * (MAXORD + 1) + 3*NEQ +(NEQ)**2 */
    liw = 31+neq; /* length of the IWORK array; = 31 + NEQ
    mf = 22; /* indicates both the integration method (backward
        differentiation method (2)-BDF) and corrector
        iteration technique to be used(Newton-Raphson(2)) */

    /* istate = 2 returned by LSODES means that the integration
        was performed successfully */

    /* ----- INICIALIZACAO DAS VARIAVEIS ----- */

    LZ=1.0;

```

```

LZT=0.0;

for (int i=1; i<=Ni; i++) {
    for (int j=1; j<=Nj; j++) {
        SIJ[i][j]=0.0;
        SIJT[i][j]=0.0;
        //printf("ij %ld %ld \n SIJin %lf SIJTin
%lf\n",i,j,SIJ[i][j],SIJT[i][j]);
        for (int k=1; k<=Nk; k++) {
            /* Z's iniciais */
            Z[i][j][k]=((DOUBLE)k -0.5)*(1./(DOUBLE)Nk);
            ZT[i][j][k]=0.0;
            //printf("ijk %ld %ld %ld\n zin %lf ZTin
%lf\n",i,j,k,Z[i][j][k],ZT[i][j][k]);
        }
    }
}

int L=0;
y[L]=(double) LZ;
yt[L]=(double) LZT;
L=L+1;

for (int i=1; i<=Ni; i++)
    for (int j=1; j<=Nj; j++) {
        y[L]=(double) SIJ[i][j];
        yt[L]=(double) SIJT[i][j];
        L=L+1;
        for (int k=1; k<=Nk; k++) {
            y[L]=(double) Z[i][j][k];
            yt[L]=(double) ZT[i][j][k];
            L=L+1;
            //printf("L %ld\t ijk %ld %ld %ld\n",L,i,j,k);
        }
    }

}

/* ----- */
str=6.2094e6;
H=er/str;
V=tau*str/visr;
/* ----- */

/* ***** */
/* LSODES */
/* ***** */

long siout=(int)(1000000);
t=0.0;
tout = 1e-10; /* The next value of the independent variable at
which the solution is required, if ITASK=1,
3, or 4; LSODES uses TOUT on the first call to
determine the direction of integration */

tcrit=2.;
tp=0.0;
for (long iout = 1; iout <= siout+1; iout++) {
    //rwork[0]=tout;
    rwork[0]=tcrit;
    rwork[5]=0.0001;
    iwork[5]=10000000;

    dlsodes_((U_fp)fex, (integer *) &neq, (double) y,
(double) &t, (double) &tout, (integer *) &itol,
(double) &rto1, (double) &ato1,
(integer *) &itask, (integer *) &istate, (integer *) &iopt,
(double) rwork, (integer *) &lrw, (integer *) iwork,
(integer *) &liw, (U_fp) jex, (integer *) &mf);
}

```

# mecmain1felt.txt

```

/* ----- */
/*                               OUTPUT                               */
/* ----- */
if (((iout % (siout/1000))==(iout / (siout/1000))) || (iout==1) ||
(iout==siout+1)) {

```

```

rosecoaparente=mseco/((DOUBLE)AZ*(DOUBLE)lzo*(double)y[0]);
POR=1.-rosecoaparente/roseco;

```

```

static doublereal dzsoma1;
dzsoma1=0.;
for (int k=1; k<=Nk; k++) {
    dz[1][1][k]=2.*(y[k+1]-(double)dzsoma1);
    dzsoma1=(double)dzsoma1+DZ[1][1][k];
    dz[1][1][k]=(double)lzo*y[0]*DZ[1][1][k];
}

static doublereal dzsoma2;
dzsoma2=0.;
for (int k=1; k<=Nk; k++) {
    dz[5][5][k]=2.*(y[k+1]-(double)dzsoma2);
    dzsoma2=(double)dzsoma2+DZ[5][5][k];
    dz[5][5][k]=(double)lzo*y[0]*DZ[5][5][k];
}

static doublereal dzsoma3;
dzsoma3=0.;
for (int k=1; k<=Nk; k++) {
    dz[10][10][k]=2.*(y[k+1]-(double)dzsoma3);
    dzsoma3=(double)dzsoma3+DZ[10][10][k];
    dz[10][10][k]=(double)lzo*y[0]*DZ[10][10][k];
}

static doublereal dzsoma4;
dzsoma4=0.;
for (int k=1; k<=Nk; k++) {
    dz[1][5][k]=2.*(y[k+1]-(double)dzsoma4);
    dzsoma4=(double)dzsoma4+DZ[1][5][k];
    dz[1][5][k]=(double)lzo*y[0]*DZ[1][5][k];
}

static doublereal dzsoma5;
dzsoma5=0.;
for (int k=1; k<=Nk; k++) {
    dz[1][10][k]=2.*(y[k+1]-(double)dzsoma5);
    dzsoma5=(double)dzsoma5+DZ[1][10][k];
    dz[1][10][k]=(double)lzo*y[0]*DZ[1][10][k];
}

```

```

static doublereal dztsoma1;
dztsoma1=0.;
for (int k=1; k<=Nk; k++) {
    dz[1][1][k]=2.*(y[k+1]-(double)dztsoma1);
    dztsoma1=(double)dztsoma1+DZ[1][1][k];
}

```

```

static doublereal dztsoma2;
dztsoma2=0.;
for (int k=1; k<=Nk; k++) {
    dz[5][5][k]=2.*(y[k+1]-(double)dztsoma2);
    dztsoma2=(double)dztsoma2+DZ[5][5][k];
}

```

```

}

static doublereal dztsoma3;
dztsoma3=0.;
for (int k=1; k<=Nk; k++) {
    dz[10][10][k]=2.*(y[k+1]-(double)dztsoma3);
    dztsoma3=(double)dztsoma3+DZ[10][10][k];
}

static doublereal dztsoma4;
dztsoma4=0.;
for (int k=1; k<=Nk; k++) {
    dz[1][5][k]=2.*(y[k+1]-(double)dztsoma4);
    dztsoma4=(double)dztsoma4+DZ[1][5][k];
}

static doublereal dztsoma5;
dztsoma5=0.;
for (int k=1; k<=Nk; k++) {
    dz[1][10][k]=2.*(y[k+1]-(double)dztsoma5);
    dztsoma5=(double)dztsoma5+DZ[1][10][k];
}

for (int k=1; k<=Nk; k++) {
    RO[1][1][k]=(ror*dzo+mb(1,1,k)/AZijk)/(lzo*y[0]*DZ[1][1][k]);
    ROS[1][1][k]=(1.+ya+yb(1,1,k))/(1./rocwreal+ya/roa+yb(1,1,k)/rob(1,1,k));
    ROEL[1][1][k]=RO[1][1][k]/ROS[1][1][k];
}
for (int k=1; k<=Nk; k++) {
    RO[5][5][k]=(ror*dzo+mb(5,5,k)/AZijk)/(lzo*y[0]*DZ[5][5][k]);
    ROS[5][5][k]=(1.+ya+yb(5,5,k))/(1./rocwreal+ya/roa+yb(5,5,k)/rob(5,5,k));
    ROEL[5][5][k]=RO[5][5][k]/ROS[5][5][k];
}
for (int k=1; k<=Nk; k++) {
    RO[10][10][k]=(ror*dzo+mb(10,10,k)/AZijk)/(lzo*y[0]*DZ[10][10][k]);
    ROS[10][10][k]=(1.+ya+yb(10,10,k))/(1./rocwreal+ya/roa+yb(10,10,k)/rob(10,10,k));
    ;
    ROEL[10][10][k]=RO[10][10][k]/ROS[10][10][k];
}
for (int k=1; k<=Nk; k++) {
    RO[1][5][k]=(ror*dzo+mb(1,5,k)/AZijk)/(lzo*y[0]*DZ[1][5][k]);
    ROS[1][5][k]=(1.+ya+yb(1,5,k))/(1./rocwreal+ya/roa+yb(1,5,k)/rob(1,5,k));
    ROEL[1][5][k]=RO[1][5][k]/ROS[1][5][k];
}
for (int k=1; k<=Nk; k++) {
    RO[1][10][k]=(ror*dzo+mb(1,10,k)/AZijk)/(lzo*y[0]*DZ[1][10][k]);
    ROS[1][10][k]=(1.+ya+yb(1,10,k))/(1./rocwreal+ya/roa+yb(1,10,k)/rob(1,10,k));
    ROEL[1][10][k]=RO[1][10][k]/ROS[1][10][k];
}

ficheiro=fopen(nomedoficheiro,"aw+");
// GLOBAL
// fprintf(ficheiro,"t %le LZ %le POR %le ST %le rosecoaparente
%le\n",(double)t,(double)y[0],(double)POR,(double)ST,(double)rosecoaparente);
//printf("t %le LZ %le POR %le ST %le rosecoaparente
%le\n",(double)t,(double)y[0],(double)POR,(double)ST,(double)rosecoaparente);

```



# mecmain1felt.txt

```
// IJ - Stress (-)
//      fprintf(ficheiro,"t %le s11 %le s110 %le s15 %le s1010 %le s55
%le\n", (double)t, (double)y[1], (double)y[100], (double)y[45], (double)y[1090], (double)y[485]);
//      printf("t %le s11 %le s110 %le s15 %le s1010 %le s55
%le\n", (double)t, (double)y[1], (double)y[100], (double)y[45], (double)y[1090], (double)y[485]);

/*
//IJK - thickness column i=1 j=1 (m)
      fprintf(ficheiro,"t %le dz111 %le dz113 %le dz115 %le dz117 %le dz1110
%le\n", (double)t, (double)dz[1][1][1], (double)dz[1][1][3], (double)dz[1][1][5], (double)dz[1][1][7], (double)dz[1][1][10]);
      printf("t %le dz111 %le dz113 %le dz115 %le dz117 %le dz1110
%le\n", (double)t, (double)dz[1][1][1], (double)dz[1][1][3], (double)dz[1][1][5], (double)dz[1][1][7], (double)dz[1][1][10]);

//IJK - thickness column i=1 j=10 (m)
      fprintf(ficheiro,"t %le dz1101 %le dz1103 %le dz1105 %le dz1107 %le
dz11010
%le\n", (double)t, (double)dz[1][10][1], (double)dz[1][10][3], (double)dz[1][10][5], (double)dz[1][10][7], (double)dz[1][10][10]);
      printf("t %le dz1101 %le dz1103 %le dz1105 %le dz1107 %le dz11010
%le\n", (double)t, (double)dz[1][10][1], (double)dz[1][10][3], (double)dz[1][10][5], (double)dz[1][10][7], (double)dz[1][10][10]);

//IJK - thickness column i=1 j=5 (m)
      fprintf(ficheiro,"t %le dz151 %le dz153 %le dz155 %le dz157 %le dz1510
%le\n", (double)t, (double)dz[1][5][1], (double)dz[1][5][3], (double)dz[1][5][5], (double)dz[1][5][7], (double)dz[1][5][10]);
      printf("t %le dz151 %le dz153 %le dz155 %le dz157 %le dz1510
%le\n", (double)t, (double)dz[1][5][1], (double)dz[1][5][3], (double)dz[1][5][5], (double)dz[1][5][7], (double)dz[1][5][10]);

//IJK - thickness column i=10 j=10 (m)
      fprintf(ficheiro,"t %le dz10101 %le dz10103 %le dz10105 %le dz10107
%le dz101010
%le\n", (double)t, (double)dz[10][10][1], (double)dz[10][10][3], (double)dz[10][10][5], (double)dz[10][10][7], (double)dz[10][10][10]);
      printf("t %le dz111 %le dz113 %le dz115 %le dz117 %le dz1110
%le\n", (double)t, (double)dz[10][10][1], (double)dz[10][10][3], (double)dz[10][10][5], (double)dz[10][10][7], (double)dz[10][10][10]);

//IJK - thickness column i=5 j=5 (m)
      fprintf(ficheiro,"t %le dz551 %le dz553 %le dz555 %le dz557 %le dz5510
%le\n", (double)t, (double)dz[5][5][1], (double)dz[5][5][3], (double)dz[5][5][5], (double)dz[5][5][7], (double)dz[5][5][10]);
      printf("t %le dz551 %le dz553 %le dz555 %le dz557 %le dz5510
%le\n", (double)t, (double)dz[5][5][1], (double)dz[5][5][3], (double)dz[5][5][5], (double)dz[5][5][7], (double)dz[5][5][10]);
*/

// IJK
      for (int i=1; i<=1; i++) {
          for (int j=1; j<=1; j++) {
              for (int k=1; k<=1; k++) {
                  //fprintf(ficheiro,"t111 %le i %ld j %ld k %ld Egijk %le Esijk %le
xLijk %le vgijk %le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)xl(i, j, k), (double)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));
                  //printf("t %le i %ld j %ld k %ld Egijk %le Esijk %le xLijk %le
vgijk %le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)xl(i, j, k), (double)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));

                  fprintf(ficheiro,"t111 %le i %ld j %ld k %ld EIJK %le dzijk %le
Roijk %le Sijk %le RORELijk %le ROSijk
5ágina p
```

```

                                mecmain1felt.txt
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
    printf("t %le i %ld j %ld k %ld EIJK %le dzijk %le Roijk %le Sijk
%le RORELijk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
    }
}
for (int i=1; i<=1; i++) {
    for (int j=1; j<=1; j++) {
        for (int k=5; k<=5; k++) {
            //fprintf(ficheiro, "t115 %le i %ld j %ld k %ld Egijk %le Esijk %le
XLijk %le Vgijk %le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)x1(i, j, k), (do
uble)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));
            //printf("t %le i %ld j %ld k %ld Egijk %le Esijk %le XLijk %le
vgijk %le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)x1(i, j, k), (do
uble)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));

            fprintf(ficheiro, "t115 %le i %ld j %ld k %ld EIJK %le dzijk %le
Roijk %le Sijk %le RORELijk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
            printf("t %le i %ld j %ld k %ld EIJK %le dzijk %le Roijk %le Sijk
%le RORELijk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
        }
    }
}

for (int i=1; i<=1; i++) {
    for (int j=1; j<=1; j++) {
        for (int k=10; k<=10; k++) {
            //fprintf(ficheiro, "t1110 %le i %ld j %ld k %ld Egijk %le Esijk %le
XLijk %le Vgijk %le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)x1(i, j, k), (do
uble)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));
            // printf("t %le i %ld j %ld k %ld Egijk %le Esijk %le XLijk %le
vgijk %le FI %le Pgijk
%le\n", (double)t, i, j, k, (double)eg(i, j, k), (double)es(i, j, k), (double)x1(i, j, k), (do
uble)vg(i, j, k), (double)FI[i][j][k], (double)Pg(i, j, k));

            fprintf(ficheiro, "t1110 %le i %ld j %ld k %ld EIJK %le dzijk %le
Roijk %le Sijk %le RORELijk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
            printf("t %le i %ld j %ld k %ld EIJK %le dzijk %le Roijk %le Sijk
%le RORELijk %le ROSijk
%le\n", (double)t, i, j, k, (double)EIJK(i, j, k), (double)dz[i][j][k], (double)RO[i][j][
k], (double)S(i, j, k), (double)ROREL[i][j][k], (double)ROS[i][j][k]);
        }
    }
}

fclose(ficheiro);
//printf("t %le LZ %le POR %le ST
%le\n", (double)t, (double)y[0], (double)POR, (double)ST);
}

if (iout==0) tout=0.0;
tout += 1.0/(double)real(siout);

}

```

```
} //END of MAIN
```

```
/* ***** */
/*                      FEX                      */
/* ***** */
```

```
integer fex(integer *neq, doublereal *t, doublereal *y,
           doublereal *yt)
{
```

```
    int L=0;
    LZ=(DOUBLE)y[L];
    LZT=(DOUBLE)yt[L];
    L=L+1;
```

```
    for (int i=1; i<=Ni; i++) {
        for (int j=1; j<=Nj; j++) {
            SIJ[i][j]=(DOUBLE)y[L];
            SIJT[i][j]=(DOUBLE)yt[L];
            L=L+1;
            for (int k=1; k<=Nk; k++) {
                Z[i][j][k]=(DOUBLE)y[L];
                ZT[i][j][k]=(DOUBLE)yt[L];
                L=L+1;
            }
        }
    }
```

```
//tp=((double)
*t)*(DOUBLE)tau*(DOUBLE)1000.0-(DOUBLE)tpo)/(DOUBLE)alfa+(DOUBLE)0.5;
// printf("#t %le\n", (double)*t);
//printf("#tp %le\n", (DOUBLE)tp);
```

```
/* ----- Call UPDATE ----- */
```

```
    UPDATE((double) *t);
```

```
    L=0;
    y[L]=(doublereal)LZ;
    yt[L]=(doublereal)LZT;
    L=L+1;
```

```
    for (int i=1; i<=Ni; i++) {
        for (int j=1; j<=Nj; j++) {
            y[L]=(doublereal)SIJ[i][j];
            yt[L]=(doublereal)SIJT[i][j];
            L=L+1;
            for (int k=1; k<=Nk; k++) {
                y[L]=(doublereal)Z[i][j][k];
                yt[L]=(doublereal)ZT[i][j][k];
                L=L+1;
            }
        }
    }
```

```
//    stotal/=(DOUBLE)Ni*Nj;
//    printf("out %le\n", *t);
//    printf("out %le %le %le %le %le\n", *t, y[0], y[1]*str, stotal*str, STF(*t));
```

```
} // End of FEX
```

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```
/* ***** */
/*               JEX               */
/* ***** */

integer jex(integer *neq, doublereal *t, doublereal *y, integer
            *m1, integer *mu, doublereal *pd, integer *nrpd)
{
    /* System generated locals */
    integer pd_dim1, pd_offset;

    /* Parameter adjustments */
    --y;
    pd_dim1 = *nrpd;
    pd_offset = 1 + pd_dim1 * 1;
    pd -= pd_offset;

    /* Function Body */
    return 0;
} // End of JEX

#ifdef __cplusplus
}
#endif

//getchar();
```

```

                                feltviscoelastoplastic.txt
/*****
*                               Modelo mecanico de prensagem do feltro
*****/

*****
*                               Definicao de variaveis
*****

    As variaveis a letra maiuscula referem-se a valores
    adimensionais, EXCEPTO PARA T e K!

*****/

#include <stdio.h>
#include <math.h>
#include <f2c.h>

/* ----- PARAMETROS GLOBAIS ----- */

#define DOUBLE double

#define Ni (10)
#define Nj (10)
#define Nk (10)
#define Nij (100)
#define Nijk (1000)

/* ----- VARIAVEIS GLOBAIS ----- */

#define lxo (DOUBLE) (0.0375)
#define lyo (DOUBLE) (0.0375)
#define lzo (DOUBLE) (3.660e-3) // lzo= valor experimental!      feltro 3
#define AZ (DOUBLE) (1.40625e-3)
#define AZijk (DOUBLE) (14.0625e-6)
// #define lzo (DOUBLE) (2.389119e-3) // lzo= valor experimental!

#define tau (DOUBLE) (0.0279667)
#define Tprato (DOUBLE) (25.0)
#define A (DOUBLE) (1.414213562)
#define B (DOUBLE) (-216.349)
#define C (DOUBLE) (-0.4190262407)
#define tpm (DOUBLE) (0.9428090413)
#define tpr (DOUBLE) (71.9333)
#define tpo (DOUBLE) (35.2)

#define alfa1 (DOUBLE) (73.4666)
#define beta1 (DOUBLE) (1.5333)

/* ----- OUTRAS VARIAVEIS ----- */
DOUBLE LZ;
DOUBLE LZT;
DOUBLE SIJ[Ni+2][Nj+2];      DOUBLE SIJT[Ni+2][Nj+2];
DOUBLE Z[Ni+2][Nj+2][Nk+2];  DOUBLE ZT[Ni+2][Nj+2][Nk+2];

DOUBLE DZ[Ni+2][Nj+2][Nk+2];  DOUBLE DZT[Ni+2][Nj+2][Nk+2];
DOUBLE dz[Ni+2][Nj+2][Nk+2];
DOUBLE DEF[Ni+2][Nj+2][Nk+2];  DOUBLE DEFT[Ni+2][Nj+2][Nk+2];

DOUBLE FI[Ni+2][Nj+2][Nk+2];
DOUBLE FIT[Ni+2][Nj+2][Nk+2];
DOUBLE rorel[Ni+2][Nj+2][Nk+2];
DOUBLE Fi[Ni+2][Nj+2][Nk+2];

```

# feltviscoelastoplastic.txt

```

DOUBLE t;
DOUBLE tp;

DOUBLE lx,ly;
DOUBLE POR,roap, rosecoaparente;
DOUBLE st,stt,sij;
DOUBLE ST,STT;

/* ----- PROPRIEDADES FISICAS ----- */

static DOUBLE LX=1.0;           // considerado constante = lx/lx0 ;
lx0=0.075 m
static DOUBLE LY=1.0;           // considerado constante = ly/ly0 ;
ly0=0.075 m

static DOUBLE DX=LX;            // =1
static DOUBLE DY=LY;            // =1

static DOUBLE dxo=(DOUBLE)lxo/(DOUBLE)Ni;
static DOUBLE dyo=(DOUBLE)lyo/(DOUBLE)Nj;
static DOUBLE dzo=(DOUBLE)lzo/(DOUBLE)Nk;

static DOUBLE str;               /* str= valor maximo da tensao aplicada a
1/4                               do volume de controlo */
                                //valor minimo para a fibra de nylon

static DOUBLE er=6.66e6;         // Pa
static DOUBLE visr= 2.5e6;       // em kelvin (25 °C)
static DOUBLE ego=101325.;
static DOUBLE To=298.15;
static DOUBLE Po=101325.;
static DOUBLE egas1;

static DOUBLE C1=1.;
static DOUBLE C2=1.; //0.5;
static DOUBLE C3=0.015; // limite de elasticidade

DOUBLE E;
DOUBLE VIS;//ES,EG,EL;

static DOUBLE rocwreal=1140.; // kg/m3
static DOUBLE roa=1100.;
static DOUBLE mcw=8.4795e-3/4.; // kg (mnylon/4)

static DOUBLE ya=0.0;
static DOUBLE ma=mcw*ya;
static DOUBLE mseco=mcw+ma;
static DOUBLE roseco=(1.+ya)/(1./rocwreal+ya/roa);
static DOUBLE ror=(mseco/(DOUBLE)Nijk)/((DOUBLE)AZijk*(DOUBLE)lzo);
static DOUBLE Mar=(0.21*32.+0.79*28.)/1000.;
static DOUBLE magua=(0.15*(mseco/(DOUBLE)Nijk)/0.85);
/* ----- Numeros adimensionais ----- */
DOUBLE H;
DOUBLE V;

/* ----- PROTOTIPOS DAS FUNCOES ----- */

void DZF();
void DZTF();
void FIF();
void FITF();
void rorelF();
/* ----- */
DOUBLE Kz (int i,int j,int k);
DOUBLE kr1 (int i,int j,int k);
DOUBLE krg (int i,int j,int k);

```

feltviscoelastoplastic.txt

```

DOUBLE Klz (int i,int j,int k);
DOUBLE Kgz (int i,int j,int k);

DOUBLE S (int i,int j,int k);
DOUBLE Sg (int i,int j,int k);
DOUBLE Sb (int i,int j,int k);
DOUBLE Se (int i,int j,int k);

DOUBLE PORIJK (int i,int j,int k);
DOUBLE gama (int i,int j,int k);

DOUBLE el (int i,int j,int k);
DOUBLE eg (int i,int j,int k);
DOUBLE ef (int i,int j,int k);
DOUBLE ea (int i,int j,int k);
DOUBLE es (int i,int j,int k);
DOUBLE EIJK (int i, int j,int k);
DOUBLE EIJKO (int i, int j,int k);
DOUBLE EIJ (int i, int j);
DOUBLE rol (int i,int j,int k);
DOUBLE rog (int i,int j,int k);
DOUBLE ro (int i,int j,int k);
DOUBLE ros (int i,int j,int k);
DOUBLE rob (int i,int j,int k);

DOUBLE mb (int i,int j,int k);
DOUBLE xl (int i,int j,int k);

DOUBLE Vgo (int i,int j,int k);
DOUBLE Vg (int i,int j,int k);
DOUBLE PORIJKo (int i,int j,int k);
DOUBLE Sbo (int i,int j,int k);
DOUBLE xlo (int i,int j,int k);

DOUBLE VISIJ (int i,int j);
DOUBLE VISIJK (int i,int j,int k);
DOUBLE ycw (int i,int j,int k);
DOUBLE yagua (int i,int j,int k);
DOUBLE yg (int i,int j,int k);

DOUBLE dev (int i,int j,int k);
DOUBLE Pg (int i,int j,int k);
DOUBLE EGT (int i,int j,int k);
DOUBLE ELT (int i,int j,int k);
DOUBLE EIJKT (int i,int j,int k);
DOUBLE RORELT (int i,int j,int k);

DOUBLE BETAT (int i,int j,int k);
DOUBLE EST (int i,int j,int k);
DOUBLE DT (int i,int j,int k);
DOUBLE XLT (int i,int j,int k);
DOUBLE EFT (int i,int j,int k);
DOUBLE PgT (int i,int j,int k);
DOUBLE VgT (int i,int j,int k);
DOUBLE AT (int i,int j,int k);
DOUBLE PORIJKT (int i,int j,int k);
DOUBLE SbT (int i,int j,int k);
DOUBLE GAMAT (int i,int j,int k);
DOUBLE Q4T (int i,int j,int k);
DOUBLE BT (int i,int j,int k);

DOUBLE T (int i,int j,int k);
DOUBLE alfa (int i,int j,int k);
DOUBLE beta (int i,int j,int k);

```

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```

DOUBLE visl (int i,int j,int k);
DOUBLE visg (int i,int j,int k);
DOUBLE sigmagas (int i,int j,int k);
DOUBLE sigmaliq (int i,int j,int k);

DOUBLE STF(DOUBLE teta);
DOUBLE STTF(DOUBLE teta);
DOUBLE UPDATE(DOUBLE teta);

/* ***** */
/*          FUNCAO UPDATE          */
/* ***** */
DOUBLE UPDATE(DOUBLE teta)
{
/* ----- */
/*          Input experimental          */
/* ----- */
//getchar();

ST=STF(teta);
STT=STTF(teta);
DZF();
DZTF();
rorelF();
FIF();
FITF();

/* ----- */
/*  Calculo do modulo de Young medio e do parametro viscoso medio  */
/* ----- */
E=0.0; VIS=0.0;
for (int i=1; i<=Ni; i++) {
    for (int j=1; j<=Nj; j++) {
        E=E+EIJ(i,j);
        VIS=VIS+VISIJ(i,j);
    }
}

E=E/(DOUBLE)Nij;
VIS=VIS/(DOUBLE)Nij;

/* ----- */
/*          Equacoes a integrar          */
/* ----- */

DOUBLE soma4;
DOUBLE deftttemp;

LZT=STT/(E*H)+V*ST/VIS;

for (int i=1; i<=Ni; i++) {
    for (int j=1; j<=Nj; j++) {
        soma4=0.0;
        SIJT[i][j]=H*EIJ(i,j)*LZT-H*V*EIJ(i,j)*SIJ[i][j]/VISIJ(i,j);

        for (int k=1; k<=Nk; k++) {
            deftttemp=SIJT[i][j]/(H*EIJKO(i,j,k))+V*SIJ[i][j]/VISIJK(i,j,k);
        }
    }
}

```



```

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ZT[i][j][k]=(1./(2.*(DOUBLE)Nk*LZ))*(defttemp+2.*soma4)-Z[i][j][k]*LZT/LZ;
    soma4=soma4+defttemp;

    }
}

/* ----- */
/*  Calculo da porosidade global e da densidade aparente do papel */
/* ----- */
rosecoaparente=mseco/((DOUBLE)AZ*(DOUBLE)lzo*LZ);
POR=1.-rosecoaparente/roseco;
//POREF=POR*(1.-Swo);

} // Fim da UPDATE

/* ***** */
/*          FUNCOES e PROPRIEDADES */
/* ***** */
DOUBLE mb(int i,int j,int k)
{
    DOUBLE MB;
    MB=0.05*mcw/(DOUBLE)Nijk;
    return MB;
}
/* ----- */
/*          Temperatura */
/* ----- */
DOUBLE T(int i,int j,int k)
{
    return Tprato+273.15;
}

/* ----- */
/*          Permeabilidades */
/* ----- */
DOUBLE Kz (int i, int j, int k)
{
    return (4.4164e-14)*exp(13.4208*PORIJK(i,j,k));
}

DOUBLE krg (int i, int j, int k)
{
    return (1.+3.*Se(i,j,k))*pow((1.-Se(i,j,k)),3.); // segundo Michaels
}

DOUBLE krl (int i, int j, int k)
{
    //return pow(Se(i,j,k),3.4); // segundo Jewett
    return pow(Se(i,j,k),4.); // segundo Michaels
}

DOUBLE Klz (int i, int j, int k) { return krl(i,j,k)*Kz(i,j,k); }
DOUBLE Kgz (int i, int j, int k) { return krg(i,j,k)*Kz(i,j,k); }

/* ----- */
/*          Saturacao */
/* ----- */
DOUBLE S (int i, int j, int k) {
    DOUBLE sat;

    sat=(magua/rol(i,j,k))/(PORIJK(i,j,k)*(DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]);
    return sat;
}
DOUBLE Sg (int i, int j, int k) { return 1.-S(i,j,k); }
DOUBLE Sb (int i,int j,int k)

```

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```

{
    DOUBLE sbound;

    sbound=(mb(i,j,k)/ro1(i,j,k))/((DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]*PORIJK(i,j,k));
    //printf("mb %le Nijk %le ro1 %le lzo %le LZ %le DZ %le mseco %le roseco %le sbound\n", (double)mb(i,j,k), (double)Nijk, (double)ro1(i,j,k), (double)lzo, (double)LZ, (double)DZ[i][j][k], (double)mseco, (double)roseco, (double)sbound);
    return sbound;
}
DOUBLE Se (int i, int j, int k) { return (S(i,j,k)-Sb(i,j,k))/(1.-Sb(i,j,k)); }

/* ----- */
/* Porosidades do papel */
/* ----- */
DOUBLE PORIJK (int i,int j,int k) { return 1.-(mseco/(DOUBLE)Nijk)/(roseco*(DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]); }
DOUBLE PORIJKEF (int i,int j,int k) { return PORIJK(i,j,k)*(1.-Sb(i,j,k)); }

/* ----- */
/* Viscosidades */
/* ----- */
DOUBLE visl (int i,int j,int k)
{
    DOUBLE miu,indice0;

    indice0=(-1.37272*(T(i,j,k)-273.15-20.0)-0.001053*(T(i,j,k)-273.15-20.0)*(T(i,j,k)-273.15-20.0))/(T(i,j,k)-273.15+105.0);
    miu=1.002e-3*pow(10.0,indice0);
    return miu;
}

DOUBLE visg (int i,int j,int k)
{
    return 3.8e-8*T(i,j,k)-1.57e-6;
}
DOUBLE viscw(int i, int j, int k)
{
    DOUBLE VISCW;
    VISCW=2.5e6;
    return VISCW;
}

/* ----- */
/* Módulos de elasticidade */
/* ----- */
DOUBLE gama (int i,int j,int k)
{
    DOUBLE GAMA;

    GAMA=1.-(mb(i,j,k)/ro1(i,j,k))/(rorel[i][j][k]*(DOUBLE)AZijk*(DOUBLE)lzo*LZ);
    return GAMA;
}

DOUBLE ef (int i,int j,int k)
{
    DOUBLE EF;
    EF=6.66e6*gama(i,j,k)+(1.-gama(i,j,k))*el(i,j,k); //valor de G1 (Pa)
    return EF;
}

DOUBLE es (int i,int j,int k)
{
    DOUBLE ES;

```

```

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    ES=C2*ef(i,j,k)*rorel[i][j][k]*rorel[i][j][k];
    return ES;
}

DOUBLE ea (int i,int j,int k)
{
    DOUBLE EA;
    EA=1e5;
    return EA;
}

DOUBLE sigmaliq (int i,int j,int k)
{
    DOUBLE Sigma2;
    Sigma2=0.0;
    return Sigma2;
}

DOUBLE el (int i,int j,int k)
{
    DOUBLE EL;
    EL=2.*1.034e8;
    return EL;
}

DOUBLE sigmagas (int i,int j,int k)
{
    DOUBLE Sigma;

    Sigma=(DOUBLE)Nijk*visg(i,j,k)*((DOUBLE)lzo*DZ[i][j][k]*LZ)*((DOUBLE)lzo*DZ[i][j][k]*LZ)*(LZ*DZT[i][j][k]+DZ[i][j][k]*LZT)/KgZ(i,j,k)/(DOUBLE)tau;
    return Sigma;
}

DOUBLE eg (int i,int j,int k)
{
    DOUBLE EG;
    EG=(Pg(i,j,k)-(DOUBLE)Po)/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.);
    return EG;
}

DOUBLE EIJK (int i,int j,int k)
{
    DOUBLE eijk;

    eijk=es(i,j,k)*FI[i][j][k]+(1.-rorel[i][j][k])*(1.-beta(i,j,k))*eg(i,j,k)+(1.-rorel[i][j][k])*beta(i,j,k)*el(i,j,k);
    return eijk;
}

DOUBLE EIJKO(int i, int j, int k)
{
    DOUBLE eijko;
    eijko=EIJK(i,j,k)+((DOUBLE)Nk*LZ*DZ[i][j][k]-1.)*EIJKT(i,j,k);
    return eijko/er;
}

DOUBLE EIJ(int i,int j)
{
    DOUBLE soma1=0.0,valor=0.0;
    for (int k=1;k<=Nk;k++) {
        soma1=soma1+1./(EIJKO(i,j,k)*er);
    }
    valor=soma1;
}

```

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```

    return (DOUBLE)Nk/valor/er;
}
DOUBLE VISIJK(int i,int j,int k)
{
    DOUBLE visijk;
    visijk=ycw(i,j,k)*viscw(i,j,k)+yagua(i,j,k)*visl(i,j,k);

    return visijk/visr;
}

DOUBLE VISIJ(int i,int j)
{
    DOUBLE soma3=0.0,valor2=0.0;

    for (int k=1;k<=Nk;k++){
        soma3=soma3+1./VISIJK(i,j,k);
    }
    valor2=soma3;

    return (DOUBLE)Nk/soma3;
}

DOUBLE yagua1 (int i,int j,int k) { return magua/(mcw/(DOUBLE)Nijk); }
DOUBLE yagua (int i,int j,int k) { return
yagua1(i,j,k)/(1.+ya+yagua1(i,j,k)+yg(i,j,k)); }
DOUBLE yg (int i,int j,int k) { return
(Vg(i,j,k)/rog(i,j,k))/(mcw/(DOUBLE)Nijk); }
DOUBLE ycw (int i,int j,int k) {return 1./(1.+ya+yagua1(i,j,k)+yg(i,j,k)); }

/* ----- */
/*                               Densidades                               */
/* ----- */
DOUBLE yb (int i,int j, int k) { return mb(i,j,k)/(mcw/(DOUBLE)Nijk); }
DOUBLE rol (int i,int j,int k) { return 1157.8-0.5361*T(i,j,k); }
DOUBLE rog (int i,int j,int k) { return Mar*Pg(i,j,k)/(8.314*T(i,j,k)); }
DOUBLE rob (int i,int j,int k) { return rol(i,j,k); }
DOUBLE ros (int i,int j,int k) { return
(1.+ya+yb(i,j,k))/(1./rocwreal+ya/roa+yb(i,j,k)/rob(i,j,k)); }

DOUBLE ro (int i,int j,int k) { return
(ror*dzo+mb(i,j,k)/(DOUBLE)AZijk)/((DOUBLE)lzo*LZ*DZ[i][j][k]); }

/* ----- */
/*                               alfa e beta                               */
/* ----- */
DOUBLE xl (int i,int j,int k) {
    DOUBLE XL;

    XL=(S(i,j,k)-Sb(i,j,k))*PORIJK(i,j,k);

    return XL;
}
DOUBLE alfa (int i,int j,int k) { return rorel[i][j][k]; }
DOUBLE beta (int i,int j,int k) { return xl(i,j,k)/(1.-alfa(i,j,k)); }

DOUBLE Vgo (int i,int j,int k) { return
(DOUBLE)AZijk*(DOUBLE)lzo*(PORIJKo(i,j,k)*(1.-Sbo(i,j,k))-xlo(i,j,k))/(DOUBLE)Nk
; }
DOUBLE PORIJKo (int i,int j,int k) { return
1.-(mseco/(DOUBLE)Nijk)/(roseco*(DOUBLE)AZijk*(DOUBLE)lzo/(DOUBLE)Nk); }
DOUBLE Sbo (int i,int j,int k) { return
(mb(i,j,k)/rol(i,j,k))/((DOUBLE)AZijk*(DOUBLE)lzo/(DOUBLE)Nk-(mseco/(DOUBLE)Nijk
)/roseco); }
DOUBLE xlo (int i,int j,int k) { return

```

```

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(magua-mb(i,j,k))/(ro1(i,j,k)*(DOUBLE)AZijk*(DOUBLE)lzo/(DOUBLE)Nk); }

DOUBLE Vg(int i,int j,int k)
{
    DOUBLE vg;

vg=(DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]*(PORIJK(i,j,k)*(1.-Sb(i,j,k))-xl(i,j,k));

    return vg;
}

/* ----- */
/*                               MC, SC e Porosidade                               */
/* ----- */
/*DOUBLE scijk (int i,int j,int k)
{
    return 1./(1.+rocwreal*(lzo*LZ/BW-1./rocwreal));
}

DOUBLE mcijk (int i,int j,int k) { return 1.-scijk(i,j,k); }

/* ----- */
/*                               Derivada de eijk em ordem à deformação                               */
/* ----- */
DOUBLE EIJKT(int i,int j,int k)
{
    DOUBLE eijkt,A1,B1,C11;

        A1=FI[i][j][k]*EST(i,j,k)+es(i,j,k)*FIT[i][j][k];
B1=(1.-rorel[i][j][k])*((1.-beta(i,j,k))*EGT(i,j,k)+beta(i,j,k)*ELT(i,j,k)+(el(i,j,k)-eg(i,j,k))*BETAT(i,j,k));
        C11=((beta(i,j,k)-1.)*eg(i,j,k)-beta(i,j,k)*el(i,j,k))*RORELT(i,j,k);

        eijkt=A1+B1+C11;
    return eijkt;
}

/* ----- */
/*                               Função não-linear e derivada                               */
/* ----- */
void rorelF()
{
    DOUBLE rorela;
    for (int i=1; i<=Ni;i++)
        for (int j=1; j<=Nj;j++)
            for (int k=1; k<=Nk;k++) {

                rorela=ro(i,j,k)/ros(i,j,k);
                rorel[i][j][k]=rorela;
            }
}

void FIF()
{
    DOUBLE difo,fi,Q1,Q2;
    for (int i=1; i<=Ni;i++)
        for (int j=1; j<=Nj;j++)
            for (int k=1; k<=Nk;k++) {
                difo=DEF[i][j][k]-C3;

                if (abs(DEF[i][j][k])<=C3) {
                    fi=1.0;

```

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```

    }
    else {
        Q2=rorel[i][j][k]/(1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.)+C3);

        Q1=(1.-pow(rorel[i][j][k],(1./3.)))/(1.-pow(Q2,(1./3.)));
        fi=(C3/C2)*Q1*Q1/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.);

    }

    FI[i][j][k]=fi;
}
}

void FITF()          //derivada em ordem à deformação!
{
    DOUBLE dif0,fit,Q3,Q4;
    for (int i=1; i<=Ni;i++)
        for (int j=1; j<=Nj;j++)
            for (int k=1; k<=Nk;k++) {
                dif0=DEF[i][j][k]-C3;
                if (abs(DEF[i][j][k])<=C3) {
                    fit=0.0;
                }
                else {
                    Q3=rorel[i][j][k]/(1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.)+C3);

                    Q4=(1.-pow(rorel[i][j][k],(1./3.)))/(1.-pow(Q3,(1./3.)));

                    fit=(C3/C2)*(-(Q4/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.))*(Q4/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.))+2.*Q4*Q4T(i,j,k)/abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.));
                }
                FIT[i][j][k]=fit;
            }
}

DOUBLE Q4T(int i,int j,int k)
{
    DOUBLE quatro,Q5,Q6;
    Q5=rorel[i][j][k]/(1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.)+C3);

    Q6=pow((1.-pow(Q5,(1./3.))),2.);

    quatro=((1./3.)*(1.-pow(rorel[i][j][k],(1./3.)))*BT(i,j,k)*pow(Q5,(-2./3.))-(1./3.)*pow(rorel[i][j][k],(-2./3.))*RORELT(i,j,k)*(1.-pow(Q5,(1./3.)))/Q6;

    return quatro;
}

DOUBLE BT(int i,int j,int k)
{
    DOUBLE bt;

    bt=((1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.)+C3)*RORELT(i,j,k)+rorel[i][j][k])/pow(
    (1.-abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.)+C3),2.);

    return bt;
}

DOUBLE RORELT(int i,int j,int k)          // derivada de rorel em ordem à
deformação
{

```

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```

DOUBLE rorelt;

rorelt=-(1./ros(i,j,k))*(ror+mb(i,j,k)/((DOUBLE)AZijk*dzo))/pow(((DOUBLE)Nk*LZ*D
Z[i][j][k]),2.);
    return rorelt;
}

DOUBLE BETAT(int i,int j,int k)          // derivada de beta em ordem à
deformação
{
    DOUBLE betat;

    betat=((1.-rorel[i][j][k])*XLT(i,j,k)+xl(i,j,k)*ROREL(i,j,k))/pow((1.-rorel[i][
j][k]),2.);
    return betat;
}

DOUBLE XLT(int i,int j,int k)    // derivada de xl em ordem à deformação
{
    DOUBLE xlt;

    xlt=-(magua-mb(i,j,k))/((DOUBLE)Nk*(DOUBLE)lzo*(DOUBLE)AZijk*rol(i,j,k)*LZ*LZ*DZ
[i][j][k]*DZ[i][j][k]);

    return xlt;
}

/* ----- */
/*          Derivada de EG em ordem à deformação          */
/* ----- */
DOUBLE EGT(int i,int j,int k)
{
    DOUBLE egt,B7;          // derivada de eg em ordem à deformação

    B7=abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.)*abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.);
    egt=(abs((DOUBLE)Nk*LZ*DZ[i][j][k]-1.0)*PgT(i,j,k)-Pg(i,j,k)+Po)/B7;

    return egt;
}

DOUBLE dev(int i,int j,int k)
{
    DOUBLE de;
    de=0.0;
    return de;
}

DOUBLE ELT(int i,int j,int k)
{
    DOUBLE elt,B8;          // derivada de el em ordem à deformação

    elt=0.;
    return elt;
}

DOUBLE PgT(int i,int j,int k)    // derivada de Pg em ordem à deformação
{
    DOUBLE pgt;
    pgt=-Po*Vgo(i,j,k)*VgT(i,j,k)/pow(Vg(i,j,k),2.);

```

```

    return pgt;
}

DOUBLE VgT(int i,int j,int k) //derivada do volume de gas em ordem à deformação
{
    DOUBLE vgt;

    vgt=((DOUBLE)AZijk*(DOUBLE)lzo/(DOUBLE)Nk)*(PORIJK(i,j,k)*(1.-Sb(i,j,k))-xl(i,j,
    k)+(DOUBLE)Nk*LZ*DZ[i][j][k]*AT(i,j,k));
    return vgt;
}

DOUBLE AT(int i,int j,int k)
{
    DOUBLE at;
    at=(1.-Sb(i,j,k))*PORIJKT(i,j,k)-PORIJK(i,j,k)*SbT(i,j,k)-XLT(i,j,k);
    return at;
}

DOUBLE PORIJKT(int i,int j,int k)
{
    DOUBLE porijkt,B9;
    B9=(mseco*(DOUBLE)dzo)/((DOUBLE)Nijk*roseco)/(DOUBLE)AZijk;
    porijkt=B9/pow(((DOUBLE)lzo*LZ*DZ[i][j][k]),2.);
    return porijkt;
}

DOUBLE SbT(int i,int j,int k)
{
    DOUBLE sbt,A9;

    A9=((DOUBLE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]-(mseco/(DOUBLE)Nijk)/roseco)*((DOUB
    LE)AZijk*(DOUBLE)lzo*LZ*DZ[i][j][k]-(mseco/(DOUBLE)Nijk)/roseco);
    sbt=-(mb(i,j,k)/rol(i,j,k))*(DOUBLE)AZijk*(DOUBLE)dzo/A9;
    return sbt;
}

/* ----- */
/*           Derivada de ES em ordem à deformação           */
/* ----- */
DOUBLE EST(int i,int j,int k)
{
    DOUBLE est;
    //est=-el(i,j,k)*GAMAT(i,j,k);

    //est=C2*(ef(i,j,k)+(1.-gama(i,j,k))*el(i,j,k))*2.*rorel[i][j][k]*RORELT(i,j,k)-
    C2*rorel[i][j][k]*rorel[i][j][k]*el(i,j,k)*GAMAT(i,j,k);

    est=2.*C2*ef(i,j,k)*rorel[i][j][k]*RORELT(i,j,k)+C2*EFT(i,j,k)*rorel[i][j][k]*ro
    rel[i][j][k];
    return est;
}

DOUBLE EFT(int i,int j,int k)
{
    DOUBLE eft;
    eft=(ef(i,j,k)-el(i,j,k))*GAMAT(i,j,k);
    return eft;
}

DOUBLE GAMAT(int i,int j,int k)
{
    DOUBLE gamat,A7,A77,A8;

    A7=(mb(i,j,k)/rol(i,j,k))*(rorel[i][j][k]+(DOUBLE)Nk*LZ*DZ[i][j][k]*RORELT(i,j,k
    ));

```



# feltviscoelastoplastic.txt

```

A77=(DOUBLE)dzo*(DOUBLE)AZijk*(DOUBLE)Nk*LZ*DZ[i][j][k]*rorel[i][j][k]*(DOUBLE)d
zo*(DOUBLE)AZijk*(DOUBLE)Nk*LZ*DZ[i][j][k]*rorel[i][j][k];
    A8=(DOUBLE)dzo*(DOUBLE)AZijk*A77;
    gamat=A7/A8;
    return gamat;
}

```

```

DOUBLE DT(int i,int j,int k) // derivada de T em ordem ao tempo
{
    DOUBLE dt;
    dt=0.0;
    return dt;
}

```

```

DOUBLE Pg(int i,int j,int k)
{
    DOUBLE pg;
    pg=Po*Vgo(i,j,k)/Vg(i,j,k);

    return pg;
}

```

```

/* ----- */
/*          Funcao que calcula os DZ a partir dos Z          */
/* ----- */
void DZF()
{
    DOUBLE dzsoma;

    for (int i=1; i<=Ni; i++)
        for (int j=1; j<=Nj; j++) {
            dzsoma=0.0;
            for (int k=1; k<=Nk; k++) {
                DZ[i][j][k]= 2.0*(Z[i][j][k]-dzsoma);
                dzsoma=dzsoma+DZ[i][j][k];
                DEF[i][j][k]=((DOUBLE)Nk*LZ*DZ[i][j][k]-1.0);
            }
        }
}

```

```

/* ----- */
/*          Funcao que calcula as derivadas de DZ          */
/* ----- */
void DZTF()
{
    DOUBLE dztsoma;

    for (int i=1; i<=Ni; i++)
        for (int j=1; j<=Nj; j++) {
            dztsoma=0.0;
            for (int k=1; k<=Nk; k++) {
                DZT[i][j][k]=2.0*(ZT[i][j][k]-dztsoma);
                dztsoma=dztsoma+DZT[i][j][k];
                DEFT[i][j][k]=(DOUBLE)Nk*(LZ*DZT[i][j][k]+DZ[i][j][k]*LZT);
            }
        }
}

```

```

/* ----- */
/*          Funcao que calcula a tensao aplicada          */
/* ----- */

```

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```

DOUBLE STF(DOUBLE teta)
{
    DOUBLE st,m0,m1,m2,m3,m4,m5,m6;

    tp=teta;

    if (tp<=0.585192163) {
        m0=0.0; m1=0.182921; m2=1.267666; m3=28.139506; m4=-88.460746;
        m5=111.906331; m6=-61.962560;
    }
    else {
        m0=651.602095; m1=-5202.952054; m2=17088.374554; m3=-29497.289576;
        m4=28237.901987; m5=-14232.784514; m6=2955.153220;
    }

    st=-(m0+m1*tp+m2*pow(tp,2.)+m3*pow(tp,3.)+m4*pow(tp,4.)+m5*pow(tp,5.)+m6*pow(tp,
6.));

    return st;
}
/* ----- */
/*          Funcao que calcula a derivada da tensao aplicada          */
/* ----- */
DOUBLE STTF(DOUBLE teta)
{
    DOUBLE stt,m0,m1,m2,m3,m4,m5,m6;
    tp=teta;

    if (tp<=0.585192163) {
        m0=0.0; m1=0.182921; m2=1.267666; m3=28.139506; m4=-88.460746;
        m5=111.906331; m6=-61.962560;
    }
    else {
        m0=651.602095; m1=-5202.952054; m2=17088.374554; m3=-29497.289576;
        m4=28237.901987; m5=-14232.784514; m6=2955.153220;
    }

    stt=-(m1+2.*m2*tp+3.*m3*pow(tp,2.)+4.*m4*pow(tp,3.)+5.*m5*pow(tp,4.)+6.*m6*pow(t
p,5.));

    return stt;
}

// Fim do programa secundario

```