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THERMAL AND ENERGETIC ANALYSIS OF A NATURALLY VENTILATED REVERSIBLE WINDOW

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ABSTRACT

The SOLVENT window is a new concept, with the goal of improving the balance between energy efficiency and visual comfort for glazing systems. It consists of double clear glazing and an absorptive glazing, separated by an air gap open at the bottom and at the top. The window frame is reversible, so that the absorptive glazing is at the indoor side in Winter mode and at the outdoor side in Summer mode.

This work describes the thermal and aerodynamic behaviour of the SOLVENT window, studies its energetic balance and its implications upon visual comfort and energy consumption for heating, cooling and lighting when integrated in real buildings.

In the thermal and aerodynamic analysis, a special attention was devoted to the characterization of the heat convection at the buoyancy-induced flow in the open air channel, which proved to be a critical aspect to characterize the system behaviour. An integrated thermal and air flow model for the entire system was developed and validated with experimental data obtained from a prototype installed at a PASSYS test cell in Porto.

The resulting model was then applied to characterize the energy balance of the window and to obtain its solar factor in Winter mode and in Summer mode.

The model was also integrated in a whole building simulation ESP-r scheme, to evaluate the energetic consequences of the SOLVENT window when used in realistic buildings. The dynamics of controlling the shading devices and the electric lighting received a special attention.

In the two case-studies analysed, an office and a school, both with a South orientation of the windows, the SOLVENT window generally produced energy savings when compared to either a double clear glazing window or a double glazing solar control window. The magnitude of the savings depends significantly on the particular characteristics of the building, such as internal loads, climate and orientation.

A more general conclusion was the confirmation of the large potential for energy savings by using efficient and integrated controls for window shadings and space electric lighting, sometimes close to 50% of the primary energy needed for heating, cooling and lighting.

RESUMO

A janela SOLVENT corresponde a um conceito inovador, desenvolvido com o objectivo de tornar mais favorável o comportamento das superfícies envidraçadas em termos de equilíbrio entre o seu desempenho energético e o seu impacto sobre o conforto visual dos ocupantes dos espaços. Consiste num vidro duplo claro e num vidro absorvente, separados por um canal de ar aberto nas extremidades inferior e superior. A caixilharia de suporte é reversível, de modo a que o vidro absorvente se localize no interior em modo de Inverno e no exterior em modo de Verão.

Este trabalho descreve a modelação do comportamento térmico e aerodinâmico da janela SOLVENT, e estuda o seu balanço energético, assim como as suas implicações sobre o conforto visual e as necessidades energéticas para aquecimento, arrefecimento e iluminação, quando integrada em edifícios reais.

Aquando da modelação, dedica-se particular atenção à caracterização da convecção de calor entre os vidros e o escoamento de ar que circula no canal por efeito da diferença de temperatura entre ambos. Este aspecto revelou-se crítico em termos de desempenho do modelo. Considerando ainda outras componentes da modelação, foi desenvolvido um modelo global para caracterização integrada do sistema. Este modelo foi calibrado e validado com dados experimentais obtidos numa das células de teste PASSYS existente no Porto, na qual foi instalado um protótipo da janela SOLVENT.

O modelo resultante foi depois aplicado à caracterização do balanço energético da janela e à obtenção do seu factor solar, quer em modo de Inverno quer em modo de Verão.

O modelo foi também integrado no software de simulação térmica global de edifícios ESP-r, de modo a estimar as consequências energéticas da janela SOLVENT quando integrada em edifícios reais. Nesta fase dedicou-se especial atenção à dinâmica do controlo dos dispositivos de sombreamento e da iluminação artificial, por parte dos ocupantes ou de sistemas automáticos.

Nos dois casos de estudo analisados, um gabinete tipo escritório e uma escola, verifica-se que de uma forma geral a janela SOLVENT propicia poupanças energéticas, quer quando comparada com uma janela de vidro duplo claro, quer quando comparada com uma janela de vidro duplo de controlo solar. A extensão dessas poupanças depende significativamente das características particulares do edifício, tais como ganhos internos, clima e orientação das fachadas envidraçadas.

Uma conclusão mais genérica foi a confirmação do grande potencial de poupança energética que se poderá obter através do controlo eficiente e integrado dos sistemas de sombreamento e iluminação eléctrica. Este potencial de poupança poderá, em certos casos, ser próximo de 50% do consumo de energia primária para aquecimento, arrefecimento e iluminação.

RESUME

La fenêtre SOLVENT est un nouveau concept, qui a pour objectif d' améliorer l'équilibre entre l'efficacité énergétique et le confort visuel des systèmes de l'enveloppe transparente des bâtiments. Elle consiste en un double vitrage clair et en un verre absorbant, séparés par un espace d'air (un canal), ouvert à ses extrémités supérieure et inférieure. L'armature de la fenêtre est réversible, de telle façon que le verre absorbant est à l'intérieur du bâtiment en mode hiver, et à l'extérieur en mode été.

Ce travail rapporte l'analyse du comportement thermique et aérodynamique de la fenêtre SOLVENT, et ses implications sur le confort visuel et la demande énergétique pour le chauffage, le refroidissement et l'éclairage intégrés aux bâtiments.

En ce qui concerne les analyses thermique et aérodynamique, une attention spéciale a été apportée à la caractérisation de la convection naturelle de chaleur entre l'air et les murs du canal, ceci étant un aspect critique pour obtenir une caractérisation satisfaisante du comportement du système. Un modèle intégré des phénomènes thermiques et de l'écoulement d'air a été développé et validé avec les données expérimentales obtenues à partir d'un prototype installé à une cellule PASSYS située à Porto.

Le modèle résultant a ensuite été appliqué pour caractériser le bilan énergétique de la fenêtre et pour obtenir son facteur solaire en mode hiver et en mode été. Le modèle a été également intégré dans un logiciel de simulation thermique de bâtiments, l'ESP-r, de façon à estimer les conséquences énergétiques de la fenêtre SOLVENT, une fois utilisée dans bâtiments réels. La dynamique de commande des dispositifs d'ombrage et de l'éclairage électrique a reçu une attention particulière.

Dans les deux cas d'étude analysés, un bureau et une école, tous les deux avec une orientation des fenêtres vers le sud, la fenêtre SOLVENT a engendré une réelle économie d'énergie, que ce soit en comparaison avec une fenêtre de double vitrage clair, ou en comparaison avec une fenêtre de double vitrage à contrôle solaire. La magnitude de cette économie dépend cependant de manière significative des caractéristiques spécifiques du bâtiment, telles que les charges internes, le climat et l'orientation des façades.

Une conclusion plus générale de la thèse a été la confirmation du grand potentiel d'épargne d'énergie en employant un commande efficace et intégrée pour les dispositifs d'ombrage des fenêtres et pour l'éclairage électrique de l'espace intérieur. Ce potentiel peut, en certains cas, être environ le 50% des besoins d'énergie primaire pour le chauffage, le refroidissement et l'éclairage.

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LIST OF SYMBOLS

α	Heat diffusivity (m^2/s)
$\alpha_{gx,dif}$	Fraction of diffuse solar radiation that is absorbed by glazing x
$\alpha_{gx,dir}$	Fraction of direct solar radiation that is absorbed by glazing x
β	Gas expansion coefficient (K^{-1})
Bi	Biot number
c_p	Specific heat at constant pressure (J/kg.K)
C	Blending constant (-)
δ_{WM}	Function whose value is 0 if the air gap is open and 1 if it is closed
δ_{SM}	Function whose value is 1 if the air gap is open and 0 if it is closed
D_h	Hydraulic diameter (-)
ε_{gx}	Emissivity of the glazing x (-)
e	Inflation rate for the energy price
f	Darcy friction factor (-)
F_a	Acceleration force (N)
F_f	Friction force (N)
g	Gravity acceleration constant (m/s^2)
G_h	Global solar radiation incident at the horizontal plane (W/m^2)
h	Heat convection coefficient ($\text{W/m}^2\text{K}$)
h_{ext}	Heat convection coefficient at the external surface ($\text{W/m}^2\text{K}$)
$h_{ext,c+r}$	Heat exchange coefficient at the external surface due to combined convection and long wavelength radiation ($\text{W/m}^2\text{K}$)
H	Window height (m)
I	Buoyant force (N)
$I_{lw,out}$	Long wavelength radiation arriving at an external surface from outdoors (W/m^2)
I_{dirn}	Direct normal solar radiation (W/m^2)
I_{difv}	Diffuse solar radiation incident at the vertical plane (sky-component, W/m^2)
j	Interest rate of the for the investment capital
k	Thermal conductivity (W/m.K)
K	Local pressure loss coefficient (-)
$\dot{m}$	Mass air flow (kg/s)
μ	Dynamic viscosity (N.s/m^2)
Nu	Nusselt number (-)
P	Local air pressure (Pa)
Pr	Prandtl number (-)
Q	Heat flow (W)
ρ	Density (kg/m^3)

r_g	Ground reflectivity (-)
Ra	Rayleigh number (-)
Re	Reynolds number (-)
σ	Stefan-Boltzmann constant ($W/m^2.K^4$)
S	Channel width (m)
S_0	Economic saving in a typical year with current energy prices
S_N	Accumulated economic savings after N years, at current value
τ_w	Shear stress at the channel wall (N/m^2)
t	Time (s)
T_{ext}	Outdoor air temperature ($^{\circ}C$)
T_{gx}	Temperature of the glazing x ($^{\circ}C$)
$T_{airAB,mean}$	Average air temperature in the air gap A-B ($^{\circ}C$)
T_{int}	Indoor air temperature ($^{\circ}C$)
T_S	Equivalent channel wall temperature ($^{\circ}C$)
T_{in}	Air temperature at the channel entry ($^{\circ}C$)
u	Local longitudinal air velocity (m/s)
U	Air velocity in the open air gap – cross section average (m/s)
U_{AB}	Heat transfer coefficient due to conduction and convection through a closed air gap between glazings A and B ($W/m^2.K$)
ν	Kinematic viscosity (m^2/s)
ν	Local transversal air velocity (m/s)
V	Wind velocity (m/s)
V_f	Free-stream air velocity (m/s)
W	Window width (m)

1 INTRODUCTION

1.1 WINDOWS, ENERGY AND VISUAL COMFORT

Windows play a fundamental role in the relationship between the indoor and the outdoor environment. In different shapes, sizes and concepts, they have been used since the most primitive constructions known, and in nearly all buildings throughout the ages.

To the building occupant, windows provide a view towards outdoors, daylighting, solar radiation and often fresh air. They are therefore a special “bridge” in the building envelope, linking the indoor and the outdoor environment. For the external observer, windows have an important aesthetical role too. Windows or glazed façades usually make the building appear lighter than the equivalent volume in opaque materials such as concrete or metal. Due to a combination of technological evolution of the glazings and frames, as well as for cultural and the already mentioned aesthetical reasons, the use of glazed elements in the building envelope – windows, double skin façades, etc. – has been growing. Carefully designed and selected glazed elements are also a common feature of the so called “bio-climatic” buildings.

From the perspective of thermal engineering, windows are a special gate in the building envelope too. Their global heat transfer coefficient is typically 3 to 10 times higher than the equivalent for the opaque envelope. Therefore, they let the heat flow more easily between the indoor and the outdoor. In buildings located in climates with cold winters, the heat loss through windows can be quite significant. However, windows are also permeable to the penetration of solar radiation. Thus, if properly orientated, they can also contribute with a “free heating energy” in winter time. In the summer time, however, the penetration of solar radiation may be a concern and contribute to overheating or increased energy demand for cooling. In the opposite trend, windows can contribute to cool the building through ventilation free-cooling, including night ventilation.

A more subtle influence of the windows in the thermal and energetic performance of the building comes through the interaction between daylighting and electric lighting. On the one hand, windows allow daylighting to enter the building and therefore may contribute to decrease the need for electric lighting. However, if not properly shaded, they may also cause glare to the building occupants, which, in response, tend to activate internal blinds and/or turn on the electric lighting.

It is clear that windows play a fundamental role in the luminous and visual comfort of the occupants too. Over millions of years, the human eye has adapted to the sunlight spectrum. Daylighting is therefore more likely to provide a better visual environment than other lighting sources. Care must be taken, however, to avoid excessive contrasts in the visual field, incidence of strong direct solar radiation in the working areas, etc.

It thus becomes clear that windows are on the cross-roads of many influence factors and that its study and design requires the integration of several fields of expertise. This presents a general challenge which has often been difficult to overcome in the past. For instance, the direct thermal implications of windows, in terms of heat transmission and solar radiation, are integrated in all reliable thermal design tools and in most building thermal regulations currently in force in many European countries. However, the interaction between windows, daylighting and electric lighting is still not usually considered in many of these tools, although it has been widely reported that it can impact the primary energy needs for heating, cooling and lighting of many buildings up to about 50%. Probably because of the complexity of the problem and of the expertise required, most buildings are still designed for fully artificial lighting operation. Independent electric lighting and external shading or internal blinds allow a response to all conditions.

The importance of energy efficiency in buildings is clearly stated in the fact that, in the European Union (EU) in 2002, buildings were responsible for about 55% of the electricity consumption, and for about 36% of the primary energy – more than the industry or the transport sectors (IEA, 2005). In the same year, about 78% of the energy supply in the EU was obtained from fossil fuels, from which another 78% were imported.

One of the most emphasised drawbacks of burning fossil fuels is the impact upon the environment, in particular the effect upon global warming (Houghton, 2004). This concern, along with the compromises assumed at the Kyoto agreement, is day by day becoming complemented in equal foot by the growing economic cost of importing energy resources and by the uncertainties about the future of oil supply, as some specialists forecast that the oil “production” will reach a peak (Hubert peak) sometime before 2020 and then start to decline (Laherrere, 1999). Similar concerns apply for gas and, even if to a minor extent and to a much later date, to coal.

On the other hand, the production of electricity through nuclear fission keeps presenting some risks during its operation and producing residues that remain dangerous for several thousands of years. A great hope and investment is concentrated upon the development of nuclear fusion, but the time horizon for the practical use of this technology remains far away. Furthermore, there is no objective guarantee that the technological problems remaining will in fact be all overcome.

Therefore, through a mix of environmental, economical, cultural and political reasons, the civilization attitude towards energy may be at a turning point.

In line with these concerns, and moving towards a concept of sustainable development, public awareness and building regulations are increasingly becoming more demanding about the efficient use of energy and environmental resources. A major move in this direction was the adoption, in the European Union, of the Energy Performance of Buildings Directive (European Parliament, 2003), which is expected to promote energy efficiency in buildings and therefore stimulate the development and dissemination of better design tools and innovative building components.

1.2 DRAWBACKS OF CONVENTIONAL WINDOWS

The most conventional window currently used, in Europe and in many other parts of the world, is a window with two panes of clear glazing separated by a layer of air – the double clear glazing window. Some variants of this solution include applying a low-e film at one of

the gap-oriented surfaces (low-e glazing), or filling the gap between the two layers with inert gases like Argon.

In climates where the outdoor temperature is low during a significant part of the year, the incorporation of clear glazing in the façades may be one of the most effective ways of collecting solar radiation to the interior spaces and thus improving the thermal comfort and/or decreasing the energy demand for heating. However, the penetration of direct solar radiation to the indoor environment is often also a cause of problems of thermal and visual comfort, e.g., overheating and excessive contrast in the vision field (glare). External or internal shading devices may be used to block the solar radiation, but this decreases the collected solar energy and the available daylighting. It often leads to the need to use electric lighting, thus contributing to increase, instead of decrease, the overall energy demand.

For buildings located in climates with a hot summer, or even in mild or cold climates but with high internal loads, there is also a cooling season, when the penetration of solar radiation is unwanted. In principle, the best way to cope with this is external shading. However, for architectural reasons, it is not always “possible” to use external shading. A solution often found is the use of solar control glazing, which is similar to double clear glazing but in which the external pane of glazing reflects or absorbs a significant part of the solar radiation. However, this kind of glazing has lower solar factors, and thus will also penalise the energy performance of the building during the heating season. Furthermore, the effectiveness of the solar control glazing for these purposes is inversely proportional to its transmissivity, and this means that solar control glazing may also lead to increased demand of electric lighting.

The “ideal window” or glazing system would be one which would allow the entrance of enough daylighting while simultaneously preventing glare, together with maximising the collection of solar energy in the heating season, and rejecting the incident solar energy in the cooling season. All this while allowing a direct and clear view towards outdoors.

1.3 INNOVATIVE WINDOWS

Several innovative windows or glazing systems have been developed over time, in an attempt to achieve a better compromise between visual comfort, daylighting and global energetic performance. The most significant ones appear to be prismatic glazing, selective glazing, electrochromic glazing, thermochromic glazing and ventilated windows.

Prismatic glazing uses the basic laws of light reflection and refraction to try to differentiate the entrance of the solar rays as function of their incident angle. In the most basic configuration, for a south-oriented vertical window, the rays incident from a high solar altitude (typical of summer) are reflected towards outdoors, while the rays incident from a low solar altitude (typical of winter) are transmitted towards indoors. More elaborated versions have been developed, to allow multiple orientations and inclinations, as well as reflecting part of the rays towards the ceiling, to achieve better daylight uniformity in the room (Lorenz, 2001). While the objective of the differentiated transmittance can be globally met, some drawbacks remain. A major one is the fact that in many buildings there is a significant time lag between the solar position and the ambient temperature. For instance, at the end of the afternoon the sun is already low but the air temperature is often still high. Other disadvantages are a significantly increased economic cost, the loss of a clear and

undisturbed view towards outside and the need to carefully design the prismatic geometric properties of the glazing as function of the latitude of the building site.

Another product that aims to deliver daylight while cutting the passage of solar radiation is the selective glazing. The concept consists on applying a thin chemical coating to the glazing, making it transparent to visible radiation and opaque to solar radiation (Lee, Hopkins et al., 1994). However, since the wavelengths of visible radiation are inside the band of the solar radiation, and in fact account for nearly 50% of it, this goal can only be met in part. This means that, below a certain value, a reduction of 10% in the solar transmissivity necessarily implies a reduction of about 5% in the visible transmissivity. In practice, due to the non-optimal behaviour of the chemical films, the reductions in the visible transmissivity are sometimes even more noticeable. Another aspect that sometimes becomes a disadvantage is the fact that the most effective coatings make the glazing have a coloured appearance, which is not always appreciated by designers. Nevertheless, this kind of product has a good acceptance in the market and is widely used in glazed façades that are exposed to direct solar radiation. Figure 1-1 shows the relations between visible transmissivity and solar transmissivity, obtained from data of a number of double solar control glazings incorporating selective glazing, available at the European market (Saint-Gobain-Glass, 2000).

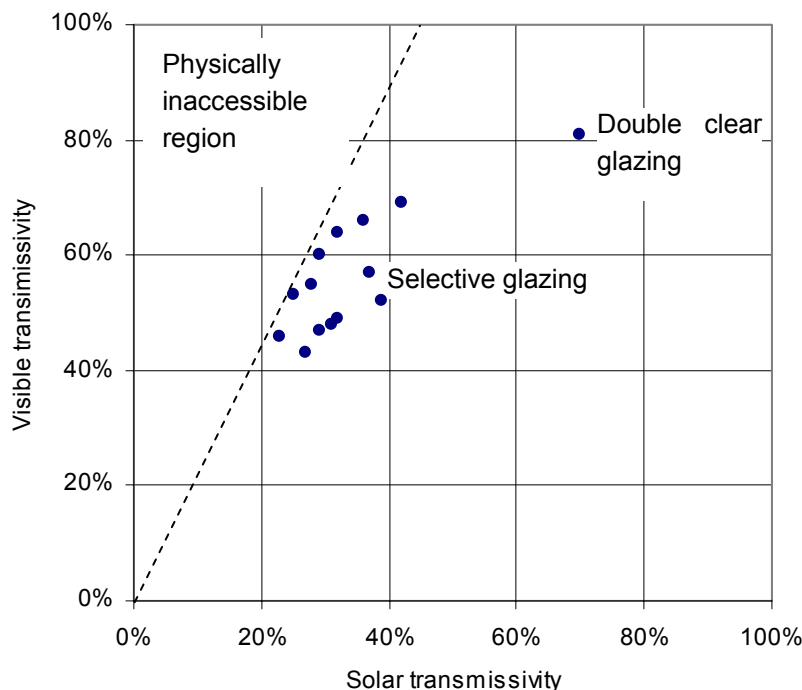


Figure 1-1: Relation between visible and solar transmissivity for a number of double glazings available at the European market.

Electrochromic glazing is characterised by having its optical properties, in particular the colour, transmissivity and reflectivity, variable as function of an electric field applied at its boundaries (Svensson and Granqvist, 1984; Lampert, 1998). When integrated in building façades, it presents an opportunity for energy savings. In overcast or low-luminance days, during the heating season, the transmissivity is set at high values (bleached state) to maximise daylighting in the room. In sunny days during the cooling season, the glazing can

be set to the coloured state, which has a lower transmissivity, and thus allow to decrease the cooling load and potential glare sensation for the building occupants. The transmissivity of the system can also be easily varied at any time to almost any value between the minimum and the maximum, to control the daylighting level or glare. The potentialities of the system seem to be such that it is often, abusively, used as synonymous of “smart window”. However, the system also has some drawbacks. One of them is the economic cost, considerably higher than that of common glazing. Others, of more technical nature, are the question of durability if frequently switched (Nagai, McMeeking et al., 1999), the difficulty in manufacturing glazings with areas above about 1 m², the conflict between glare control and collection of solar energy during sunny days in winter (Sullivan, Rubin et al., 1997) and the fact that the system consumes electric energy.

A more passive system but, which also with changing optical properties, is the thermochromic or thermotropic glazing (Wilson, Ferber et al., 1994; Inoue, 2003). This system incorporates a polymer gel and changes its transmissivity as function of its temperature. At low temperatures the system is transparent, with a transmissivity close to 70%. At higher temperatures, the system approaches the translucent state, which has a transmissivity of only 15 to 20%. Compared to electrochromic glazing, the system has the advantage of not requiring sensors for measuring the environmental variables neither a control system. However, it maintains the potential conflict between glare control and collection of solar energy in the sunny days of the heating season. An additional disadvantage is that, in the translucent state, it does not allow a clear view through the system.

Another approach towards energy-efficient glazing systems are the ventilated windows. There are mainly two versions of the concept: single-sided ventilated windows, and ventilated supply-air windows. The first are essentially used in buildings where cooling is the main concern. They consist of a double glazing which has the air gap opened to the outdoor environment at the bottom and at the top. The movement of the air in the air gap can be imposed by mechanical means, or it can be obtained by natural buoyancy induced by the heat absorbed at the glass and transmitted to the channel air. These systems often incorporate controllable venetian blinds in the air gap (Tanimoto and Kimura, 1997). Their main disadvantages are the economic cost, the fact that they retain solar energy also during the heating season, and the consumption of electric energy in the mechanically ventilated version.

Ventilated supply-air windows aim to supply rooms with outdoor air for ventilation purposes, while at the same time collecting solar energy for decreasing the apparent U-value of the windows (Aitken, 1981; Brandle and Boehm, 1983; McEvoy, Southall et al., 2003). While they succeed in this purpose, the decrease in the apparent U-value is essentially due to a reduction in the solar factor, which is not desirable in the heating season. Furthermore, these systems fail in blocking the entrance of solar energy during the cooling season.

1.4 THE “SOLVENT WINDOW” CONCEPT

The SOLVENT window is an innovative window system (Etzion and Erell, 2000), which has the objective of tackling the energetic and visual comfort performance in an integrated way. Figure 1-2 shows a representation of the window concept. The window basically consists of double clear glazing and a layer of absorptive glazing. Between the double clear

and the absorptive glazing there is an air channel, which is left open at the bottom and at the top. The window requires a frame capable of allowing two different configurations, one for Winter mode and another for Summer mode. It can thus be seen as a reversible ventilated window.

In Winter mode, the absorptive glazing is at the indoor side, and the channel is opened to the indoor air. When the absorptive glazing is hit by solar radiation, it will warm-up and eventually create a buoyancy-induced flow in the open air channel. The amount of solar radiation passing through the window will thus be decreased, but most of the radiation that is cut is still expected to be a heat gain to the indoor environment, in the forms of convective flow of warm air from the channel and long wavelength radiation to the indoor surfaces.

In Summer mode, the absorptive glazing is at the outdoor side and the air channel is open to the outdoor air as well. A part of the incident solar radiation is thus retained at the absorptive glazing, not reaching the interior of the building.

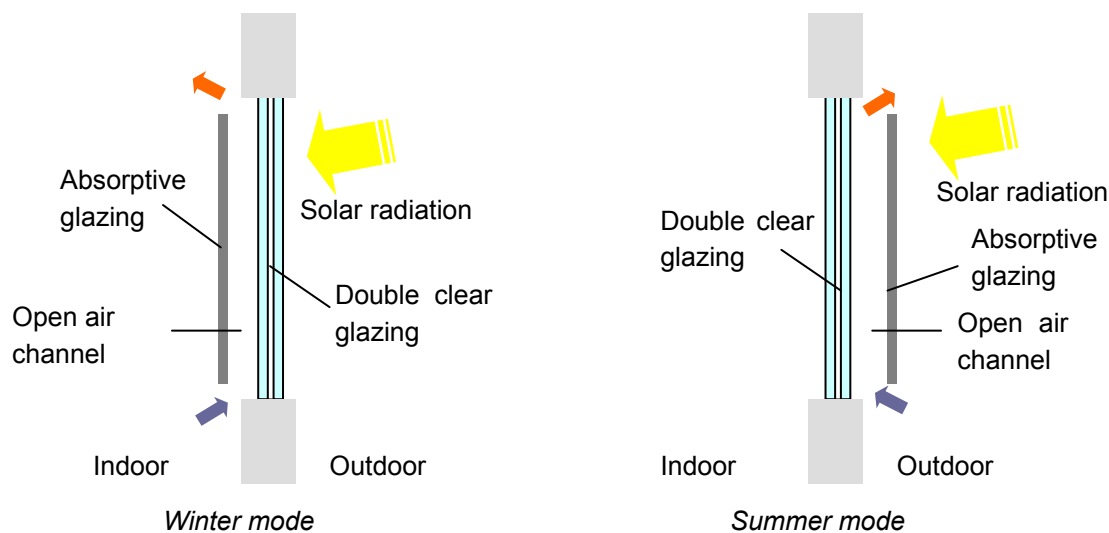


Figure 1-2: Concept of the SOLVENT glazing system

1.5 OBJECTIVES AND STRUCTURE OF THE WORK

The qualitative concept of the SOLVENT window raises a number of questions that require an in-depth study in several specific areas, as well as its integration to obtain a global assessment of the window performance in terms of energy and visual comfort. In particular, the following questions seem to be pertinent:

- How to quantify the buoyancy-induced air flow in the open air channel ? Can down-flow occur as well, e.g., during the night ?
- What is the influence of the open air gap width ? Is it beneficial to be large, to increase the volume of available air, or is it better to have a narrower air gap, to increase the heat convection coefficient at the channel walls ?
- What is the solar factor of the system, for some “typical” configurations ?
- How can the glazing properties be optimally selected, depending on the climate and building type ?

- How to estimate the energy demand of a building equipped with this window ?
- How does the energy demand with the SOLVENT window compare, for some set of buildings and climates, with other window alternatives ?
- What are the quantified advantages of the SOLVENT window in terms of visual comfort ?

The answer to these questions was achieved through a predominantly phased process, which is roughly in correspondence with the main chapters of this work:

- Setting up a heat transfer and air flow model of the window system (chapter 2);
- Mounting a prototype of the window at a PASSYS test cell (chapter 3);
- Implementation of the heat transfer and air flow models in a software simulation program. Comparison of the simulation results with experimental results obtained from the prototype, and model optimization (chapter 4);
- Analysis of the energy fluxes and solar factor of the window, under reference conditions (chapter 5);
- Integration of the window simulation models into a whole building simulation (WBS) software (chapter 6)
- Application of WBS to exemplify the process of optimisation of the glazing choice, and to assess the energy and visual comfort performance of the SOLVENT window, for some case studies (chapter 7).

The described sequence of chapters is preceded by this introductory chapter (chapter 1) and followed by a chapter with conclusions and opportunities for further developments (chapter 8).

The sequence of chapters 2 and 3 is quite conventional, suggesting that the experimental setup was mounted after the model was completed and only to serve for its validation. In practice, however, the experimental campaigns had a more active role than what a simple look at sequence of the chapters could suggest. The experimental campaign started nearly at the same time as the modelling process, and contributed to some initial decisions for the model, such as the predominance of laminar flow or the assumption that the temperature of each glazing is uniform. Later, after first results from the model, it was decided to refine it and to measure additional variables, such as the exchange of long wavelength radiation between the window and the outdoor environment. The new measurements contributed to validate the developments and final version of the model.

2 HEAT TRANSFER AND AIR FLOW MODEL

The heat transfer and fluid flow in the open air channel are linked phenomena which mutually affect each other. Calculation of glazing temperatures, convective heat transfer coefficients and air velocity must be done simultaneously in an integrated way.

In order to simplify the analysis, the first section presents the energy balance equations for each glazing layer, along with the energy balance of the air flowing in the open channel and some accessory parameters. The air flow model and an initial study on the heat convection at the open air gap are presented in sections 2.2 and 2.3 respectively.

Figure 2-1 shows a representation of the SOLVENT window for modelling purposes. In short, it consists of a set of three glazings separated by two air gaps. The difference between Winter and Summer is the type of the air gaps (open or closed) and the optical properties of the glazings. In Winter mode, channel 1-2 is closed (a typical air gap in a double-clear glazing window) and channel 2-3 is open. Glazings 1 and 2 are clear and glazing 3 is the absorptive glazing. In Summer mode, channel 1-2 is open and channel 2-3 is closed. Glazings 2 and 3 are clear and glazing 1 is the absorptive glazing.

In order to obtain a general model for both Winter and Summer mode operation, for each air gap, the terms specific of open air gap and the terms specific of closed air gap are both considered. They are then multiplied by a “flag” that is either 1 or 0 according to the channel type (open or closed).

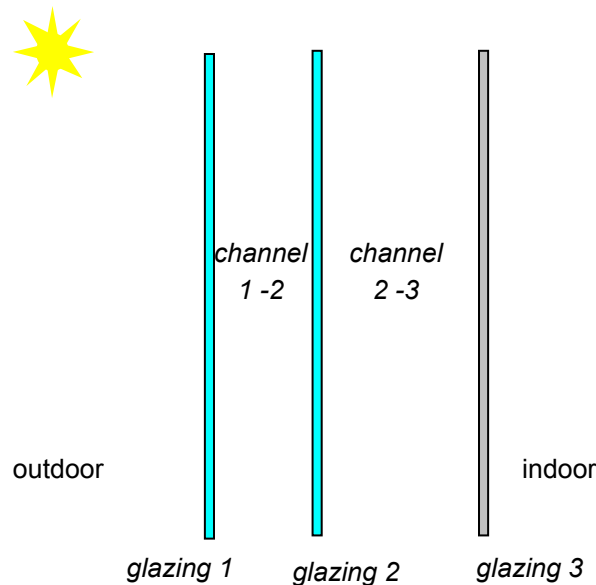


Figure 2-1: SOLVENT window scheme for modelling purposes

2.1 HEAT TRANSFER MODEL

This section presents a heat transfer model for each part of the glazing system. It establishes the equations that, together with the air flow model equations, will later allow the calculation of glazing temperatures and all energy fluxes in the system.

The basic assumption in the model is that each of the glazings is at uniform temperature. For a glazing with thickness $e=5$ mm, typical thermal conductivity $k=1$ W/m.K and convection coefficient $h=5$ W/m².K at each side, the Biot number in the horizontal direction becomes

$$Bi = \frac{h(e/2)}{k} = 0.0125 \quad \text{eq. 2-1}$$

This very low value justifies the assumption of neglecting horizontal temperature gradients within each glazing. Figure 2-2 shows the evolution of the measured glazing temperature at both sides of the absorptive glazing, on the 2nd and 3rd April 2003, showing indeed very small differences. During the sunny day, the temperature, as expected, is slightly higher at the channel side due to the circulation of warm air.

In the vertical direction, for a length of 1.15 m, the Biot number becomes 2.9. This value, higher than 0.1, indicates that some vertical temperature gradient is likely to exist if the boundary conditions to which the glazing is exposed also vary significantly in the vertical direction. The boundary conditions likely to vary vertically are the temperature of the air and the local heat convection coefficient in the open gap and in the face of the glazing system facing indoors (free convection along a vertical plate). Experimental observation via an IR camera, and via spot measurements on the glass, during a sunny day, has shown that the temperature in the lower part of the glazing (first 20% of the length), was a few degrees (about 2 °C) lower than at the upper part. For the upper 80% of the window the temperature was quite uniform (Etzion and Erell, 2002).

As this temperature difference is small (lower than 2°C), the glazing temperature will be treated here as an average over its entire surface.

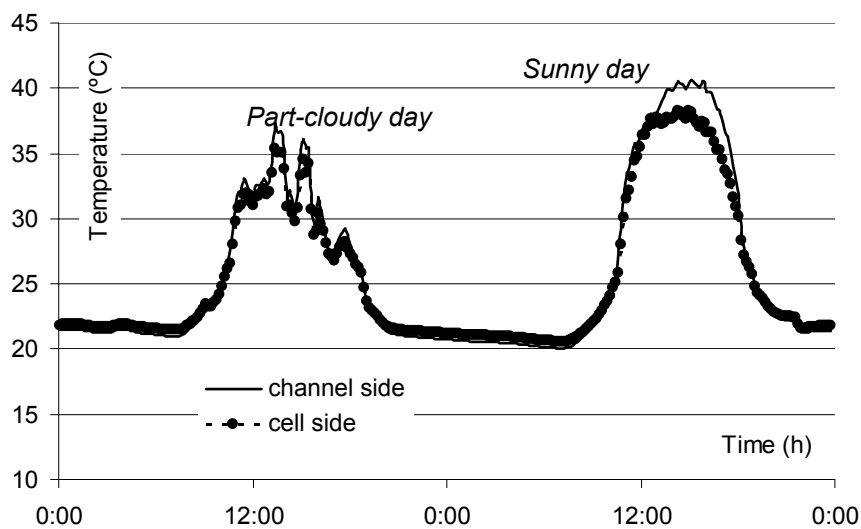


Figure 2-2: Dark glazing temperature at channel side and cell side for two consecutive days (2-3 April 2003), measured at centre mid-height.

2.1.1 Heat balance for the outer glazing (glazing 1)

The glazing facing the exterior environment (glazing 1) can exchange energy with the surroundings by the following modes: Convection with outdoor air, exchange of long wavelength radiation with landscape surfaces and with the sky, absorption of solar radiation (direct, sky-diffuse and ground reflected), exchange of long wavelength radiation with the middle glazing (glazing 2), convection with glazing 2 if gap 1-2 is closed, convection with air circulating in the gap 1-2 if gap 1-2 is open and, finally, it can store or release heat due to its thermal capacity. The quantification of each of these terms is as follows:

- Convection with outdoor air: $h_{ext}(T_{ext} - T_{g1})$
- Long wavelength radiation exchange with outdoor landscape surfaces and with sky:
 $\varepsilon_{g1}(I_{lw,out} - \sigma T_{g1}^4)$
- Absorbed solar radiation: $\alpha_{g1,dir} I_{dirn} + \alpha_{g1,dif}(I_{difv} + 0.5r_g G_h)$
- Long wavelength exchange with glazing 2: $\frac{\sigma(T_{g2}^4 - T_{g1}^4)}{\frac{1}{\varepsilon_{g1}} + \frac{1}{\varepsilon_{g2}} - 1}$
- Convection with glazing 2 if gap 1-2 is closed (δ_{WM} is a function whose value is 0 if the air gap is open and 1 if it is closed): $U_{12}(T_{g2} - T_{g1}) \cdot \delta_{WM}$
- Convection with air circulating in the gap 1-2 if gap 1-2 is open (δ_{SM} is a function whose value is 1 if the air gap is open and 0 if it is closed): $h_{g1}(T_{air12,mean} - T_{g1}) \cdot \delta_{SM}$
- Heat storage: $e_{g1}\rho c \frac{\partial T_{g1}}{\partial t}$

The optical properties of the glazings are assumed to be angle-dependent and already including the inter-reflection effects. For example, $\alpha_{g1,dir}$ is the fraction of incident direct solar radiation that ends up absorbed at glazing 1. Therefore, the optical properties of each layer of glazing are determined simultaneously for each glazing of the system. Proper software programs can be used for this purpose, such as Window 5 (Huizenga, Arasteh et al., 2003) or WIS (Dijk, 2003). When the optical properties of one glazing change, this will also cause a change in the values of the other glazings (due to the effects of mutual reflections).

The equation of heat balance for glazing 1 thus becomes:

$$\begin{aligned}
 &h_{ext}(T_{ext} - T_{g1}) + \varepsilon_{g1}(I_{lw,out} - \sigma T_{g1}^4) + \alpha_{g1,dir} I_{dirn} + \alpha_{g1,dif}(I_{difv} + 0.5r_g G_h) + \\
 &+ \frac{\sigma(T_{g2}^4 - T_{g1}^4)}{\frac{1}{\varepsilon_{g1}} + \frac{1}{\varepsilon_{g2}} - 1} + U_{12}(T_{g2} - T_{g1}) \cdot \delta_{WM} + h_{g1}(T_{air12,mean} - T_{g1}) \cdot \delta_{SM} = \\
 &= e_{g1}\rho c \frac{\partial T_{g1}}{\partial t} \quad \text{eq. 2-2}
 \end{aligned}$$

2.1.2 Heat balance for middle glazing (glazing 2)

The middle glazing has the following possibilities for exchanging heat with its surroundings: absorption of solar radiation, exchange of long wavelength radiation with the exterior glazing (glazing 1), exchange of long wavelength radiation with the internal glazing (glazing 3), convection with glazing 1 if gap 1-2 is closed, convection with air circulating in the gap 1-2 if gap 1-2 is open, convection with glazing 3 if gap 2-3 is closed, and convection with air circulating in the gap 2-3 if gap 2-3 is open. It can also store or release heat. The quantification of each of these terms is as follows:

- Solar radiation absorbed: $\alpha_{g2,dir} I_{dirn} + \alpha_{g2,dif} (I_{difv} + 0.5r_g G_h)$
- Long wavelength radiation exchange with glazing 1: $\frac{\sigma(T_{g1}^4 - T_{g2}^4)}{\frac{1}{\epsilon_{g1}} + \frac{1}{\epsilon_{g2}} - 1}$
- Long wavelength radiation exchange with glazing 3: $\frac{\sigma(T_{g3}^4 - T_{g2}^4)}{\frac{1}{\epsilon_{g3}} + \frac{1}{\epsilon_{g2}} - 1}$
- Convection with glazing 1 if gap 1-2 is closed: $U_{12}(T_{g1} - T_{g2}) \cdot \delta_{WM}$
- Convection with glazing 3 if gap 2-3 is closed: $U_{23}(T_{g3} - T_{g2}) \cdot \delta_{SM}$
- Convection with air circulating in the gap 1-2 if gap 1-2 is open: $h_{g2}(T_{air12,mean} - T_{g2}) \cdot \delta_{SM}$
- Convection with air circulating in the gap 2-3 if gap 2-3 is open: $h_{g2}(T_{air23,mean} - T_{g2}) \cdot \delta_{WM}$
- Heat storage: $e_{g2} \rho c \frac{\partial T_{g2}}{\partial t}$

The terms described above combine to form the following balance equation for glazing 2:

$$\begin{aligned} & \alpha_{g2,dir} I_{dirn} + \alpha_{g2,dif} (I_{difv} + 0.5r_g G_h) + \frac{\sigma(T_{g1}^4 - T_{g2}^4)}{\frac{1}{\epsilon_{g1}} + \frac{1}{\epsilon_{g2}} - 1} + \frac{\sigma(T_{g3}^4 - T_{g2}^4)}{\frac{1}{\epsilon_{g3}} + \frac{1}{\epsilon_{g2}} - 1} + \\ & U_{12}(T_{g1} - T_{g2}) \cdot \delta_{WM} + U_{23}(T_{g3} - T_{g2}) \cdot \delta_{SM} + h_{g2}(T_{air12,mean} - T_{g2}) \cdot \delta_{SM} + \\ & h_{g2}(T_{air23,mean} - T_{g2}) \cdot \delta_{WM} = e_{g2} \rho c \frac{\partial T_{g2}}{\partial t} \end{aligned} \quad \text{eq. 2-3}$$

2.1.3 Heat balance for the interior glazing (glazing 3)

The glazing facing the interior of the room can exchange heat via the following modes: absorption of solar radiation, exchange of long wavelength radiation with the middle glazing

(glazing 2), exchange of long wavelength radiation with the walls, floor and ceiling of the room, convection with the air in the room, convection with air circulating in channel 2-3 if channel 2-3 is open, convection with glazing 2 if gap 2-3 is closed. It can also store or release previously stored heat. The quantification of the terms formerly described is as follows:

- Solar radiation absorbed: $\alpha_{g3,dir} I_{dirn} + \alpha_{g3,dif} (I_{difv} + 0.5r_g G_h)$
- Long wavelength radiation exchange with glazing clear 2: $\frac{\sigma(T_{g2}^4 - T_{g3}^4)}{\frac{1}{\epsilon_{g3}} + \frac{1}{\epsilon_{g2}} - 1}$
- LW exchange with room interior surfaces: $\sigma\epsilon_{g3}(T_{int}^4 - T_{g3}^4)$
- Convection with room indoor air: $h_{int}(T_{int} - T_{g3})$
- Convection with air circulating in channel 2-3 if channel 2-3 is open: $h_{g3}(T_{air,mean} - T_{g3}) \cdot \delta_{WM}$
- Convection with glazing 2 if gap 2-3 is closed: $U_{23}(T_{g2} - T_{g3}) \cdot \delta_{SM}$
- Heat storage: $e_{g3}\rho c \frac{\partial T_{g3}}{\partial t}$

The temperature of the room internal surfaces, T_{int} , can be assumed as nearly uniform or, if the individual values are known and expected to be significantly different, calculated as an average, weighted by the area and view shape factors. The first approach was used for the stand-alone study of the window (chapters 4 and 5), while the second approach was used for the detailed simulation with ESP-r (chapters 6 and 7).

The heat balance equation for this glazing thus becomes:

$$\alpha_{g3,dir} I_{dirn} + \alpha_{g3,dif} (I_{difv} + 0.5r_g G_h) + \frac{\sigma(T_{g2}^4 - T_{g3}^4)}{\frac{1}{\epsilon_{g3}} + \frac{1}{\epsilon_{g2}} - 1} + \sigma\epsilon_{g3}(T_{int}^4 - T_{g3}^4) + h_{int}(T_{int} - T_{g3}) + h_{g3}(T_{air,mean} - T_{g3}) \cdot \delta_{WM} + U_{23}(T_{g2} - T_{g3}) \cdot \delta_{SM} = e_{g3}\rho c \frac{\partial T_{g3}}{\partial t} \quad \text{eq. 2-4}$$

2.1.4 Heat balance for the air flowing in the open channel

When the temperature of the glazings bounding an open air channel is higher than the air temperature, buoyancy induces an upward airflow in the channel. In a similar manner, if the temperature of the channel walls (glazings) is lower than the air temperature, a downward flow is induced. The characterization of the air flow induced at an open air channel, in particular the air velocity, will be studied in detail in section 2.2. Meanwhile, it is important to establish the heat balance for the air flowing in the channel.

A local heat balance equation to the air at a certain area with an infinitesimal length dy , located at a height y above the channel entry, relates the local air temperature variation, dT , with the heat exchange by convection with each of the adjacent glazing panes (A and B in figure 2-3 yields:

$$\dot{m}c_p dT_{air}(y) = (q_A'' + q_B'')Wdy \quad \text{eq. 2-5}$$

$$dT_{air}(y) = \frac{h_A W dy [T_A - T_{air}(y)] + h_B W dy [T_B - T_{air}(y)]}{\rho W H S U c_p} \quad \text{eq. 2-6}$$

For now, it is assumed that the average values of the convection coefficients, h_A and h_B , and the cross-section average velocity, U , are known. The problem of their determination will be analysed later.

Integrating between 0 and y , the result is the expression for the temperature at height y :

$$T_{air}(y) = \frac{h_A T_A + h_B T_B}{h_A + h_B} - \frac{h_A (T_A - T_{in}) + h_B (T_B - T_{in})}{h_A + h_B} e^{-\frac{h_A + h_B}{\rho U S c_p} y} \quad \text{eq. 2-7}$$

The previous equation suggests that the equivalent temperature of the channel walls be defined as:

$$T_S = \frac{h_A T_A + h_B T_B}{h_A + h_B} \quad (\text{eq. 2-8})$$

With this definition, the form of eq. 2-7 may be simplified to:

$$T_{air}(y) = T_S - (T_S - T_{in}) e^{-\frac{h_A + h_B}{\rho U S c_p} y} \quad \text{eq. 2-9}$$

which is analogous to the typical expression for the evolution of the fluid temperature in internal pipe flow.

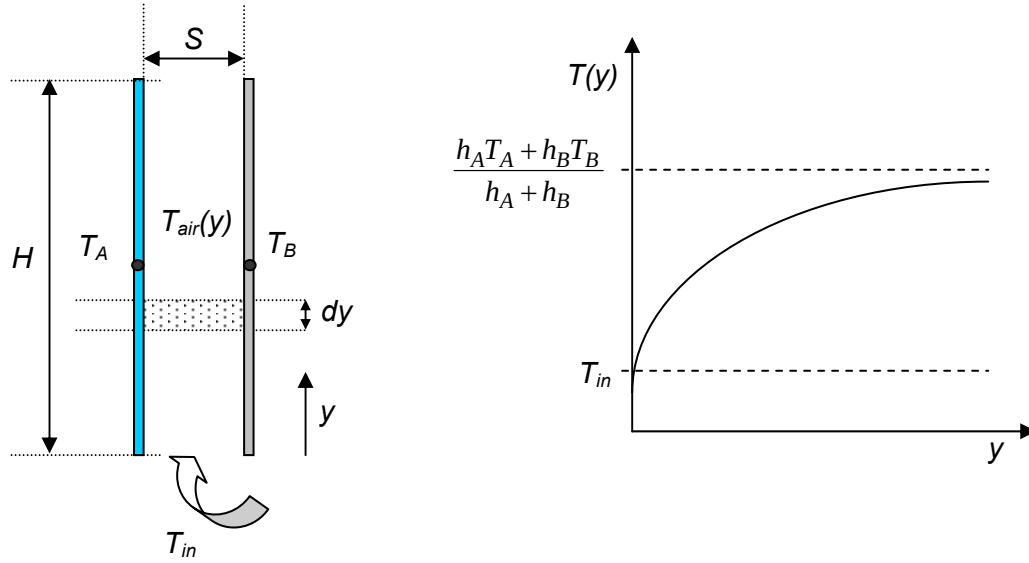


Figure 2-3: Evolution of the air temperature in the vertical air channel

2.1.5 Convection between the external surface and the outdoor air

Some variables in the heat balance equations, presented in section 2.1.4, need to be parameterized in terms of known boundary conditions, such as wind speed or temperature, or in terms of the glazing temperatures. That is the case of the convection coefficient with the outdoor air at the external surface, convection coefficient between the two clear glazings across the closed air gap, convection coefficients at the open air gap and the albedo for the ground-reflected solar radiation.

The convection coefficient between the exterior glazing and the outdoor air, h_{ext} , is, theoretically, the result of a mix of natural convection due to the temperature differences, and of forced convection due to the effect of wind. It is thus expected to depend on conditions such as the temperatures of the glazing and of the air, the local wind speed and direction and wind turbulence. The local wind speed, direction and turbulence are deeply influenced by the local geometry of the window and of the surroundings. In practice, it is almost impossible to predict dynamically through theoretical models. CFD analysis could, in principle, provide reliable results. However, it would be nearly impossible to perform CFD analysis for all wind conditions that may occur throughout all the year.

A simple solution often found to overcome the problem is to assume a constant value for the external convection coefficient. This approach seems adequate only for problems involving long-term estimations or when the available climatic data does not contain information about the wind.

A second, more realistic approach relies on experiments to take into account the effect of wind velocity. A first study by McAdams, with parallel flow in a wind tunnel, proposed that the convection coefficient would be given by (McAdams, 1954) :

$$h_{ext} = 5.678 \left[a + b \left(\frac{V}{0.3048} \right)^n \right] \quad \text{eq. 2-10}$$

where a , b and n are empirical constants depending on the wind velocity range and on the surface roughness (table 2-1). Although not usually made explicit in the bibliography, the resulting convection coefficient has the units of $\text{W/m}^2\cdot^\circ\text{C}$, and the constants have the units needed to assure dimensional coherence.

Table 2-1: Empirical coefficients for eq. 2-10

Type of surface	$V < 4.88 \text{ m/s}$			$V > 4.88 \text{ m/s}$		
	a	b	n	a	b	n
Smooth	0.99	0.21	1	0	0.50	0.78
Rough	1.09	1.23	1	0	0.53	0.78

McAdams formula has often been used disregarding the assumptions that the flow is parallel to the window, and that the wind velocity in the formula is the wind velocity near the window, whereas the wind velocity in climatic weather files is typically measured in a tower, without nearby obstacles, at 10 m height.

Widely-used software for building simulation DOE-2 (LBL, 1981) adopted another correlation dependent on wind velocity. The formula is based on the ASHRAE adaptation of early work by Rowley and Eckley (1931), and combines the convective exchange with the long wavelength radiative exchange. This is a more or less common procedure, although in fact the equivalent temperature for LW exchange is often different from the outdoor air temperature, e.g. due to clear sky cooling. The convection coefficient adopted in DOE-2 is:

$$h_{ext,c+r} = 8.23 + 3.83V - 0.047V^2 \quad \text{eq. 2-11}$$

A very similar correlation is proposed in some technical manuals for glazing professionals (Saint-Gobain-Glass, 2000):

$$h_{ext,c+r} = 8.23 + 3.33V - 0.036V^2 \quad \text{eq. 2-12}$$

For surface temperatures between 10°C and 30°C , and exterior temperatures between 5 and 25°C , the exchange coefficient for long wavelength radiation is comprised between 4.5 and $5.5 \text{ W/m}^2\cdot^\circ\text{C}$ (a detailed analysis will be presented in section 5.3). At the average value of $5.0 \text{ W/m}^2\cdot^\circ\text{C}$, the Rowley/DOE-2 model for pure convection at exterior smooth surfaces, such as windows, is thus given by:

$$h_{ext} = 3.23 + 3.83V - 0.047V^2 \quad \text{eq. 2-13}$$

Ito et al. correlated the wind velocity close to the window, V , with the free stream air velocity typically measured in meteorological stations, V_f . The correlation depends on whether the window is exposed windward or leeward, and also on the wind speed range (Ito, Kimura et al., 1972):

- For windward wind:
$$V = \begin{cases} 0.25V_f & \Leftarrow V_f > 2 \text{ m.s}^{-1} \\ 0.5 & \Leftarrow V_f \leq 2 \text{ m.s}^{-1} \end{cases} \quad \text{eq. 2-14}$$

- For leeward wind:
$$V = 0.3 + 0.05V_f \quad \text{eq. 2-15}$$

Based on measurements performed at the 4th floor of a medium-rise building, Kimura (1977) also proposed different formulas for the windward and leeward hemispheres:

- For windward wind:
$$h_{ext} = 6.22 + 1.824V \quad \text{eq. 2-16}$$

- For leeward wind:
$$h_{ext} = 6.22 + 0.4864V \quad \text{eq. 2-17}$$

The main concern regarding the use of Kimura model is whether a correlation based on measurements at the 4th floor of a building is adequate to predict the convection coefficient for low-rise buildings, as is the case of the PASSYS test cell, where the SOLVENT window prototype was mounted (chapter 3).

In conditions closer to those of the PASSYS test cell, Yazdanian and Klems (1994) performed measurements in a low-rise test cell and suggested a correlation that considers the influence of wind as well as natural convection due to surface-to-air temperature differences:

$$h_{ext} = \left\{ \left[0.84(T_s - T_{ext})^{1/3} \right]^2 + (2.38V^{0.89})^2 \right\}^{1/2} \Leftarrow \text{windward wind} \quad \text{eq. 2-18}$$

$$h_{ext} = \left\{ \left[0.84(T_s - T_{ext})^{1/3} \right]^2 + (2.86V^{0.617})^2 \right\}^{1/2} \Leftarrow \text{leeward wind} \quad \text{eq. 2-19}$$

Figure 2-4 shows the how significantly the prediction of the outdoor convection coefficient varies with the correlation chosen.

For this study, the first approach will be to use the correlation proposed by Yazdanian and Klems, since it is specific for low-rise buildings such as the PASSYS test cell. Later, if the comparison between experimental and simulation results suggests so, other alternatives may be adopted.

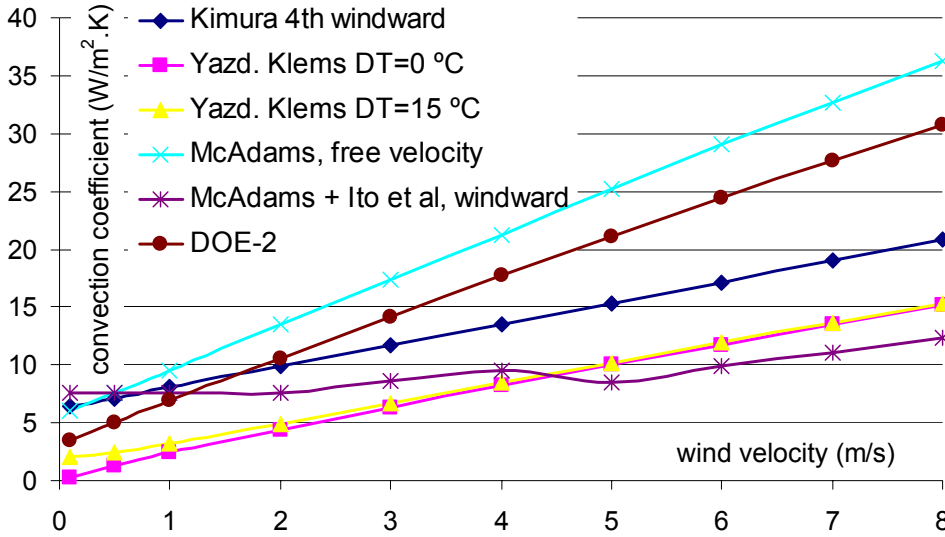


Figure 2-4: Outdoor convection coefficient vs wind speed for different correlations

2.1.6 Convection in the closed air gap

The heat exchange between the two clear glazings due to conduction and/or convection in the closed air gap was accounted through the heat transfer coefficient U_{A-B} . According to (Wright, 1996), the Nusselt number is given by:

$$Nu_s = \begin{cases} 0.0673838 \cdot Ra^{\frac{1}{3}} & \Leftarrow Ra > 5 \times 10^4 \\ 0.028154 \cdot Ra^{0.4134} & \Leftarrow 10^4 < Ra \leq 5 \times 10^4 \\ 1 + 1.75967 \times 10^{-10} \cdot Ra^{2.2984755} & \Leftarrow Ra < 10^4 \end{cases} \quad \text{eq. 2-20}$$

Both the Nusselt and the Rayleigh numbers are based on the closed channel width. The exchange coefficient between the two glazings, U_{A-B} , is given by:

$$U_{A-B} = \frac{Nu_{s_{A-B}} k}{S_{A-B}} \quad \text{eq. 2-21}$$

2.2 AIR FLOW MODEL

A balance of forces acting upon the air flowing through the air gap yields the following equation (Sandberg and Moshfegh, 2002):

Buoyant force = Force to accelerate the fluid from rest to the velocity in the air gap + Friction force against surfaces + Entrance losses + Exit losses

In practice, this equation is equivalent to applying the principle of conservation of linear momentum, between a “free point”, far from the channel entry, and the channel exit.

The exact description of each of these terms would require the detailed knowledge of the velocity and temperature fields in the air channels as well as in the regions close to the entry and the exit. Such detailed knowledge is not possible, and thus simplified modelling techniques are required. These are presented in the following sub-sections.

2.2.1 Buoyant force

The buoyant force is computed from Archimedes principle as:

$$I = g(WS) \int_0^H [\rho_\infty - \rho(y)] dy \quad \text{eq. 2-22}$$

Combining this with Boussinesq approximation

$$\rho \cong \rho_\infty [1 - \beta(T - T_\infty)] \quad \text{eq. 2-23}$$

and taking into account that, for ideal gases, $\beta = \frac{1}{T_\infty}$, it results that

$$I = \rho_\infty g(WS) \int_0^H \frac{T(y) - T_\infty}{T_\infty} dy \quad \text{eq. 2-24}$$

2.2.2 Fluid acceleration

The force needed to accelerate the fluid from rest in the room to a certain air velocity in the air channel is given by the dynamic pressure $\frac{1}{2} \rho U^2$ multiplied by the section area (WS):

$$F_a = \frac{1}{2} \rho (WS) U^2 \quad \text{eq. 2-25}$$

2.2.3 Friction force

The friction force is obtained multiplying the shear stress at the channel walls by the area of the walls:

$$F_f = 2HW\tau_w \quad \text{eq. 2-26}$$

Using the Darcy friction factor $f = \frac{8\tau_w}{\rho U^2}$, it results that

$$F_f = \frac{f}{4} HW \rho U^2 \quad \text{eq. 2-27}$$

For laminar flow in ducts with rectangular section, the value of the friction coefficient may be computed from eq. 2-28 :

$$f = \frac{C}{\text{Re}_{D_h}} \quad \text{eq. 2-28}$$

D_h is the hydraulic diameter given by eq. 2-29, and C is a constant depending on the aspect ratio a/b , (figure 2-5) whose value can be found in table 2-2 (Munson, Young et al., 1998).

$$D_h = \frac{2ab}{a+b} \quad \text{eq. 2-29}$$

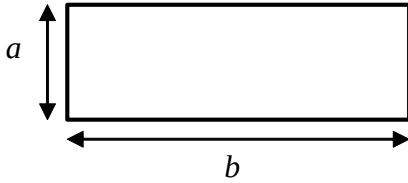


Table 2-2: C values for eq. 2-28

a/b	
0	96.0
0.5	89.9
0.10	84.7

Figure 2-5: Channel section

Interpolating for a channel with $a=0.04$ and $b=1.13$ m, as in the studied prototype, it becomes:

$$f = \frac{91.4}{\text{Re}_{D_h}} \quad \text{eq. 2-30}$$

This formula thus yields values slightly higher than those predicted by the formula for laminar flow in smooth round ducts ($f = \frac{64}{\text{Re}_{D_h}}$).

Under certain conditions, the flow may become turbulent. Similarly to what is common in forced flow, it will be assumed that the transition from laminar for turbulent flow occurs when the Reynolds number reaches a value around 2300.

A formula commonly used for determining the friction coefficient of turbulent flow in round pipes, for $\text{Re} < 10^5$, is the Blasius formula (Munson, Young et al., 1998):

$$f = \frac{0.316}{\text{Re}_{D_h}^{0.25}} \quad \text{eq. 2-31}$$

As in the case of laminar flow, it must be accounted that the channel has a rectangular section, rather than a round section. As specific data for rectangular pipes is not available, a possible approximation to account for this effect is to apply the correction factor obtained from laminar flow (91.4/64). The result is, therefore,

$$f = \frac{0.316}{\text{Re}_{D_h}^{0.25}} \cdot \frac{91.4}{64} \quad \text{eq. 2-32}$$

2.2.4 Entry and exit losses

In engineering applications, the localised losses are typically accounted for through a local loss coefficient K , defined as:

$$K = \frac{\Delta P}{\frac{1}{2} \rho U^2} \quad \text{eq. 2-33}$$

Values of K were derived from experimental data, for many geometries, and are reported in the classical bibliography of fluid dynamics. It is common to assume that the K values are independent of the Reynolds numbers. However, it is reminded that such assumption is valid only for flows where the inertial forces are clearly dominant over viscous forces (Munson, Young et al., 1998). This will not always be the case of the natural convection flow, especially at low Reynolds numbers. Therefore, it is possible that the effective K values may depend upon the flow regime. This must be taken into consideration when analysing the results with low air velocities.

Typical values for entry (sudden contraction) and exit (sudden expansion) loss coefficients are, respectively, $K_{in} = 0.5$ and $K_{out} = 1.0$ (Munson, Young et al., 1998).

2.2.5 Force balance – implicit velocity equation

The force balance equation for the air flowing in the open air gap, stated qualitatively at the beginning of this section, can now be quantitatively written as

$$\rho g \int_0^H \frac{T(y) - T_{in}}{T_{in}} dy = \rho \frac{U^2}{2} (1 + f \frac{H}{2S} + k_{in} + k_{out}) \quad \text{eq. 2-34}$$

The temperature profile along the air gap $T(y)$ is given by eq. 1-7, which in turn also depends on the air velocity. Additionally, the heat transfer coefficients present in eq. 1-7 also depend on the velocity U . This means the calculation of glazing temperatures, air velocity and temperature and heat transfer coefficients must be performed together through an iterative procedure, solving successively the convection coefficients, glazing temperatures and the air velocity until all the values converge.

2.2.6 Implicit equation for air velocity

The integral on the left side of eq. 2-34 can be evaluated from eq. 2-9, yielding:

$$\rho g \int_0^H \frac{T(y) - T_{in}}{T_{in}} dy = \rho g \frac{\rho U W S c_p \left(e^{\frac{W H (h_A + h_B)}{\rho U W S c_p}} - 1 \right) + W H (h_A + h_B)}{W (h_A + h_B)} \frac{(T_S - T_{in})}{T_{in}} \quad \text{eq. 2-35}$$

And thus, going back to eq. 2-34, the following implicit equation for the mean air velocity in the open channel is obtained:

$$U = \left\{ \frac{2g \left[\rho U W S c_p \left(e^{\frac{W H (h_A + h_B)}{\rho U W S c_p}} - 1 \right) + W H (h_A + h_B) \right] \frac{(T_S - T_{in})}{T_{in}}}{W (h_A + h_B) \left(1 + f \frac{H}{2S} + k_{in} + k_{out} \right)} \right\}^{\frac{1}{2}} \quad \text{eq. 2-36}$$

Since the surface and inlet temperatures are known, the velocity will only be a function of the friction coefficient f , local loss coefficients k_{in} and k_{out} and channel convection coefficient correlation chosen. Assuming f , k_{in} and k_{out} treated as described in sections 2.2.3 and 2.2.4, the only dependence not yet covered is the heat convection at the channel walls (h_A and h_B). This is precisely the subject of the next section.

2.3 CONVECTION IN THE OPEN AIR GAP

The heat transfer by convection between the glazings and the air flowing in the air gap is strongly coupled with the air velocity in the channel. Contrarily to forced flow, where the air velocity (or at least the volumetric air flow rate) is imposed and independent of the convection coefficients at the channel walls, in the case of natural convection the heat transfer coefficients and the air velocity / flow are mutually dependent parameters.

2.3.1 Fundamental equations

The fundamental equations characterizing the fluid motion in the air gap are the mass, momentum and energy conservation equations. In the coordinates defined by figure 2-6 and in the differential form, for nearly steady and incompressible flow, they are:

- Mass conservation:

$$\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} = 0 \quad \text{eq. 2-37}$$

- Momentum conservation in the x direction:

$$\rho \left(v \frac{\partial v}{\partial x} + u \frac{\partial v}{\partial y} \right) = - \frac{\partial P}{\partial x} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad \text{eq. 2-38}$$

- Momentum conservation in the y direction:

$$\rho \left(v \frac{\partial u}{\partial x} + u \frac{\partial u}{\partial y} \right) = - \frac{\partial P}{\partial y} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \rho g \quad \text{eq. 2-39}$$

- Energy conservation:

$$v \frac{\partial T}{\partial x} + u \frac{\partial T}{\partial y} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad \text{eq. 2-40}$$

The above set of equations strongly couples horizontal and vertical velocities, pressure and temperatures. Analytical solutions have only been found for some special conditions under which reasonable degrees of decoupling (or similarity analysis) can be obtained.

The general natural convection channel flow can be seen as bounded between two limiting cases: the natural convection flow along a single vertical plate and the fully developed channel. These two limiting cases are the subject of study of the next two subsections.

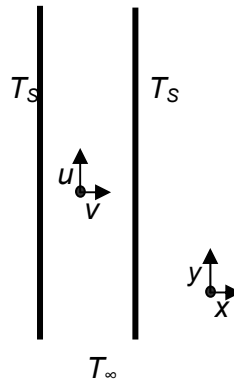


Figure 2-6: Velocity coordinates at a generic point in the channel air

2.3.2 The free vertical plate

It can be expected that, if the distance between the two channel walls is large compared with the channel height, or when the air velocity is low, there will be some similarities with that of the flow developing along a free vertical surface. Approximate analytical solutions have been found for this “limiting case” (Ostrach, 1953; Holman, 2002).

One basic assumption of these solutions is that the fluid velocity at the edge of the boundary layer is zero. In the general case under study here, the mass conservation in the channel demands that the fluid velocity is not zero, even outside the thermal boundary layer. Such assumption is only approximately valid if the aspect ratio H/S is small (which is not the case here), or if the flow rates are very low. The later condition may sometimes be met, so the natural convection along a vertical free surface may be a limiting case of this problem. For this case, the following correlation based on experimental data, which holds for the entire range of Rayleigh numbers, has been extensively used in engineering applications (Churchill and Chu, 1975):

$$Nu_L = \left\{ 0.825 + \frac{0.387 Ra_L^{1/6}}{\left[1 + \left(\frac{0.492}{Pr} \right)^{9/16} \right]^{8/27}} \right\}^2 \quad \text{eq. 2-41}$$

2.3.3 The fully developed flow

For the fully developed zone, an approximate analytical solution may be derived from the basic equations seen in section 2.3.1 (Bejan, 1984). Noting that, for fully developed flow $v = 0$ and $\frac{\partial u}{\partial y} = 0$, eq 2.39 becomes:

$$0 = -\frac{\partial P}{\partial y} + \mu \frac{\partial^2 u}{\partial x^2} - \rho g \quad \text{eq. 2-42}$$

The pressure gradient $\frac{\partial P}{\partial y}$ can be estimated by applying Stevin law of hydrostatics to the air adjacent to the channel by the exterior side:

$$\frac{\partial P}{\partial y} = -\rho_\infty g \quad \text{eq. 2-43}$$

The last term of the equation can be treated using the Boussinesq approximation. The local and free fluid densities ρ and ρ_∞ are related through the thermal expansion coefficient β through:

$$\rho \cong \rho_\infty [1 - \beta(T - T_\infty)] \quad \text{eq. 2-44}$$

Eq. 2-42 may now be rewritten as

$$\mu \frac{\partial^2 u}{\partial x^2} = \frac{-\beta(T - T_\infty)}{1 - \beta(T - T_\infty)} g \quad \text{eq. 2-45}$$

and noting that, if the wall temperatures are moderate, then $\beta(T - T_\infty) \ll 1$, it finally becomes

$$\frac{\partial^2 u}{\partial x^2} = -\frac{g\beta}{\nu}(T - T_\infty) \quad \text{eq. 2-46}$$

In order to find an approximate analytical solution, at this point Bejan proposes that, in the fully developed region,

$$(T - T_\infty) \cong (T_S - T_\infty) \quad \text{eq. 2-47}$$

This assumption, together with the boundary condition that at the channel walls $u=0$ allows easily solving eq. 2-46 and obtaining the velocity profile in the fully developed region:

$$u(x) = \frac{g\beta(T_S - T_\infty)S^3}{8\nu} \left[1 - \left(\frac{x}{S/2} \right)^2 \right] \quad \text{eq. 2-48}$$

The mass flow per unit of width is now obtained by integration:

$$\frac{\dot{m}}{W} = \int_0^S \rho u(x) dx = \frac{\rho g \beta (T_S - T_\infty) S^3}{12\nu} \quad \text{eq. 2-49}$$

An energy balance to the fluid between entry and exit yields

$$\frac{Q}{W} = \frac{\dot{m}}{W} c_p (T_S - T_\infty) \quad \text{eq. 2-50}$$

On another perspective, the heat transferred to the air in the gap can also be written as

$$\frac{Q}{W} = 2Hh(T_S - T_\infty) \quad \text{eq. 2-51}$$

Combining equations 2-50 and 2-51 and noting that $h = \frac{Nu_S k}{S}$, it is possible to obtain

$$Nu_S = \frac{Ra_S}{24} \frac{S}{H} \quad \text{eq. 2-52}$$

where Ra_S is the Rayleigh number based on the channel width S

$$Ra_S = \frac{g\beta(T_s - T_\infty)S^3}{\nu\alpha} \quad \text{eq. 2-53}$$

2.3.4 Blending correlations.

In the previous sections there were presented two correlations for the heat transfer between the open air channel walls and the air. They can be seen as representing two limiting cases of the channel flow: the single plate and the fully developed channel flow.

In fact, the flow conditions in the channel are expected to lay in between the two limiting cases. For low flow rates or aspect ratios H/S , it is expected that the convection heat transfer behaves closer to the single plate, while for high flow rates or aspect ratios H/S it is expected that it may display a behaviour closer to fully developed flow.

Churchill and Usagi (1972) proposed a general methodology to combine limiting cases in heat transfer, which applied to this case of natural convection between the single plate and the fully developed limit has the following form:

$$Nu = \left[\left(\frac{1}{Nu_{sp}} \right)^n + \left(\frac{1}{Nu_{fd}} \right)^n \right]^{-\frac{1}{n}} \quad \text{eq. 2-54}$$

Churchill and Usagi proposed a blending constant $n=1.5$. This methodology was also applied to the investigation of the cooling of electronic devices and the optimal spacing of vertical plates, with a blending constant $n=2$ (Bar-Cohen and Rohsenow, 1984). The result is now adopted in some general heat transfer handbooks. For an open vertical channel with isothermal walls, the correlation is (Incropera and DeWitt, 1996) :

$$Nu_S = \left[576 \left(Ra_S \frac{S}{H} \right)^{-2} + 2.87 \left(Ra_S \frac{S}{H} \right)^{-\frac{1}{2}} \right]^{-\frac{1}{2}} \quad (\text{eq. 2-55})$$

The same methodology was applied to a vertical channel with only one heated wall (Sparrow and Azevedo, 1985).

2.3.5 Comparison of correlations.

Figure 2-7 shows the Nusselt number as function of the Rayleigh number, for the correlation options seen in the previous sections. The Rayleigh number appears multiplied by an aspect ratio S/H , becoming a parameter sometimes called the modified Rayleigh number.

The results predicted by the blending with $n=1.5$ (Churchill and Usagi) and $n=2$ (Bar-Cohen and Rohsenow) are quite similar. As expected, both correlations yield the single plate result when $\frac{S}{H} \rightarrow \infty$, and the fully developed flow result when $\frac{S}{H} \rightarrow 0$.

In terms of flow intensity, the correlations yield the fully developed flow limit at low Rayleigh numbers, and the single plate limit at high Rayleigh numbers. It is not clear that this behaviour is expectable, since the low Rayleigh numbers are associated with low temperature gradients and therefore with thin boundary-layers. If the boundary-layer developing from an extremity of a wall is thin, and the air velocity is low, even outside the boundary-layer, then this suggests that the effect of the other wall will be small. This resembles a similarity with single plate flow rather than with fully-developed flow. Conversely, high Rayleigh numbers are associated with higher temperature differences between the walls and the air, which may lead to thicker thermal boundary-layers and to a quicker merging of the two boundary-layers. This would result in fully developed flow rather than in single plate flow.

Another important observation is that the blending correlations presented always yield Nusselt numbers, and therefore heat convection coefficients, that are lower than the minimum of the two limiting cases. This seems to be contradictory with results from other authors when performing experimental studies in channel-type geometries (Nelson and Wood, 1989; James, El-Genk et al., 2002), which reported that the measured heat convection coefficient was often between the two limiting cases.

This issue will receive a special attention ahead in sections 4.2 and 4.3, when studying the initial model results.

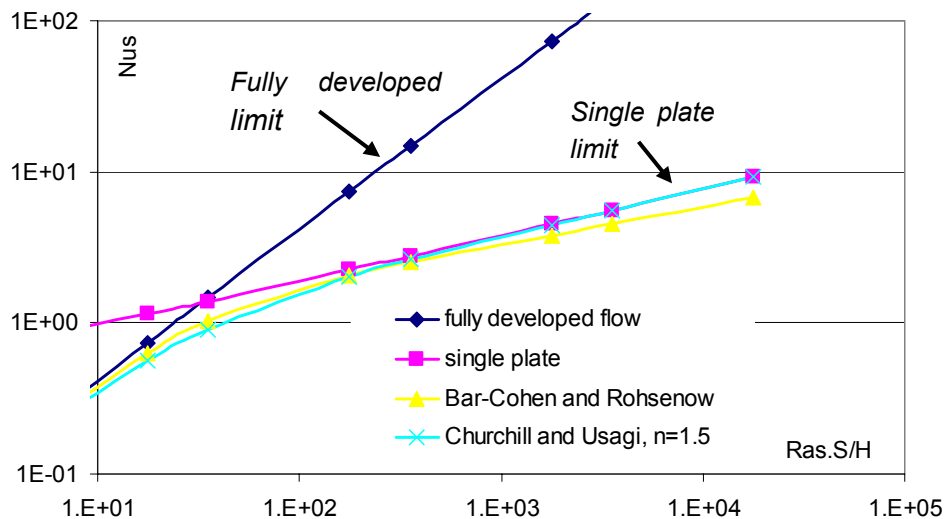


Figure 2-7: Nusselt number vs modified Rayleigh number, as function of the heat transfer correlation, for a channel with 4 cm width and 1.13 m height.

3 EXPERIMENTAL SETUP

The experimental part of this study was developed using a prototype of the SOLVENT window installed in a PASSYS test cell. In a first phase, the experimental tests served to monitor how the system behaved qualitatively and to gain sensitivity to the system behaviour, such as the degree of magnitude of the temperatures and air velocities achieved, effects of wind, nature of the channel air flow, occurrence of downward flow at night, etc. At a second stage, the experimental results were mainly used to validate the simulation models that were developed for the energy balances, air flow and daylight transmission.

There was a first measuring campaign between September and November 2001, as part of the SOLVENT project (Erell, Etzion et al., 2004). Besides playing a role in the development of the prototype, this campaign also allowed an identification of some points where more specific measurement would be desirable or useful to validate more elaborated modelling hypothesis. This resulted in a second measurement campaign, that took place between February and May 2003, specifically for this work. The data presented and used for validation in this work was taken almost exclusively from this second measuring campaign.

3.1 THE PASSYS TEST CELL

A prototype model of the SOLVENT window was installed in an existing PASSYS test cell (Vandaele and Wouters, 1994), located in the Laboratory for Evaluation of Thermal Components of Buildings¹, Porto, Portugal. Figure 3-1 shows a representation of the structure and construction of the original PASSYS test cell, and figure 3-2 shows an external view of the South wall, where the test components are installed. The test cell originally had heavily insulated walls and was later upgraded with the pseudo-adiabatic shell (PAS) system (Borges, 1999). This system uses electric resistances to compensate any temperature gradient across a part of the wall, thus guaranteeing a nearly adiabatic envelope (figure 3-3). The exception is the South wall, where the components being studied are mounted.

The PASSYS test cells work basically as calorimeters. They allow the measurement of the heat flow from the components mounted in the south wall, due to the combined effects of conduction, convection and thermal radiation exchange at its surfaces, and of solar radiation entering through the transparent components.

The test room is very airtight. Usually, average air change rates of infiltration are lower than 0.01 ach⁻¹. Therefore, the contribution of the air change to the energy balance is very

¹ The official designation is in Portuguese: “LECTE – Laboratório de Ensaio de Componentes Térmicos de Edifícios”.

low. A precise characterization of the airtightness under the actual testing conditions is made through a pressurization test at the beginning and at the end of each test.

The temperature in the interior of the test room can be controlled through a conditioning system that adds or removes heat as required. The heat added or removed by the system is also closely monitored. Thus, if the test room temperature is maintained at a nearly constant value, the quantity of heat added or removed from the room will be nearly equal to the energy balance at the internal face of the test component.

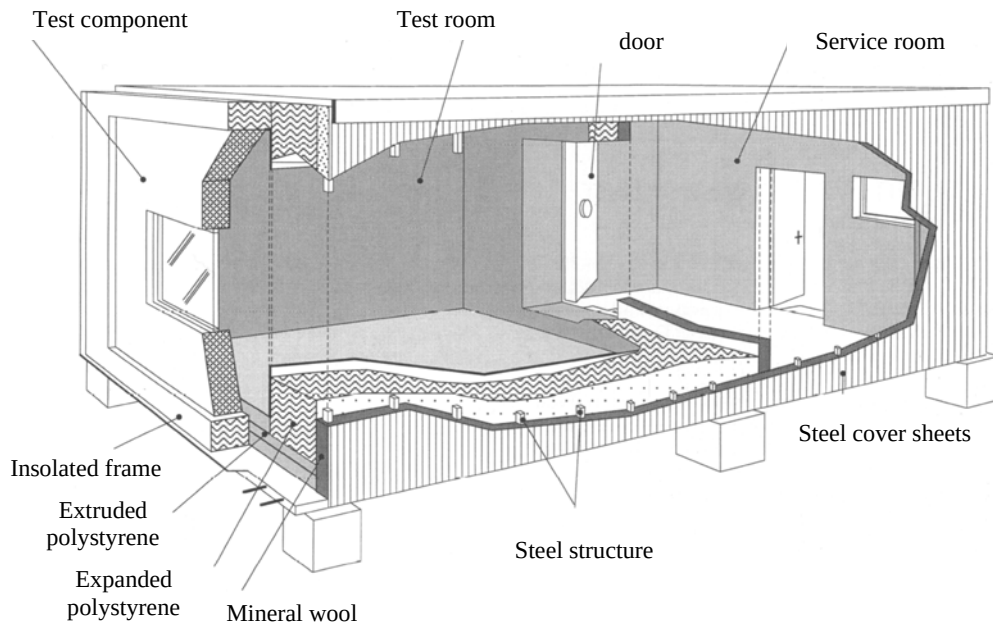


Figure 3-1: A representation of the original PASSYS test cell (Vandaele and Wouters, 1994) .



Figure 3-2: A view of the PASSYS test cell with the aperture for the test component in the South façade.

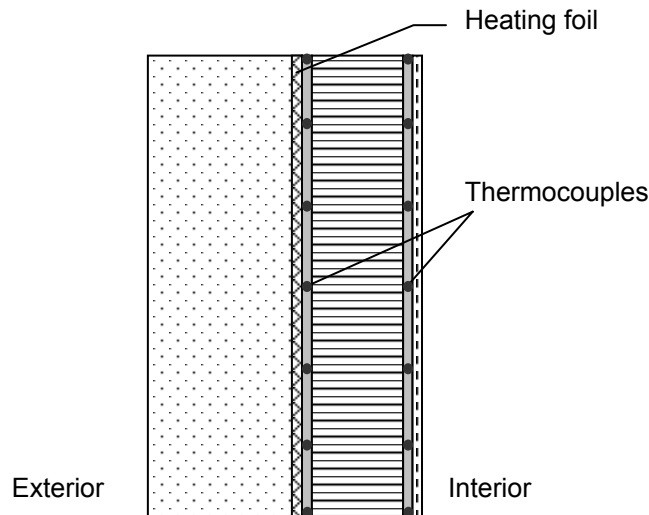


Figure 3-3: A representation of the pseudo-adiabatic shell (PAS): a set of thermocouples measures the temperature difference across a section of the wall, and a heating foil is activated if the temperature at the interior of the wall is lower than at the internal surface.

3.2 THE SOLVENT WINDOW SETUP

3.2.1 Structure

Figure 3-4 shows a representation of the SOLVENT window prototype installed in the PASSYS test cell. This prototype was developed in the context of the SOLVENT project. The main parts are a frame of timber, a fixed pane of double glazing and a pane of absorptive glazing fixed to the timber frame through hinges. The hinges are screwed to the frame, thus allowing the absorptive glazing to be moved, either to vary the distance to the double glazing or to commute between Summer mode and Winter mode. Figure 3-5 shows a close view of the SOLVENT window prototype mounted in Summer mode, thus with the absorptive glazing at the external side and with the air channel opened to the exterior.

The sill and head of the frame were complemented with a separate piece of timber, chamfered at an angle of 45 degrees, to reduce the aerodynamic resistance and thus allow a smoother flow of air into and out of the channel. The heights of the air gap entry and exit could also be adjusted by adding or removing horizontal layers of timber.

The absorptive glazing was divided in two equal parts, one attached to each side of the frame. At the middle, there was a gap of 15 mm between the two parts. This gap was covered with grey tape.

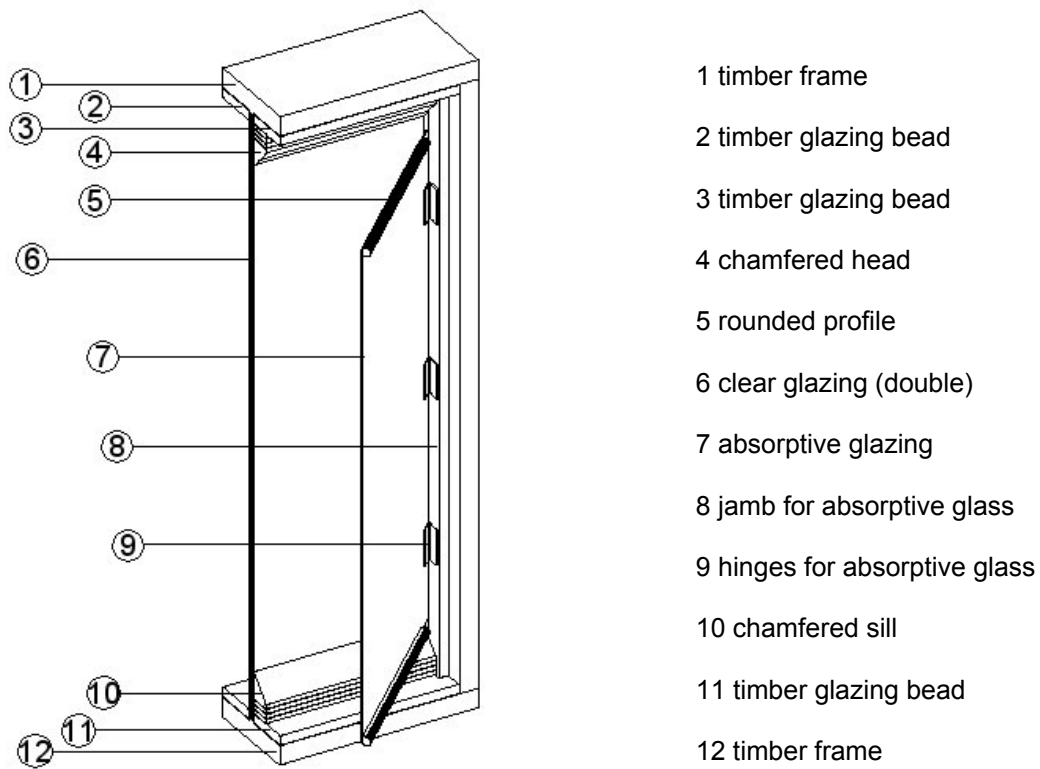


Figure 3-4: Drawing of the SOLVENT window prototype used in the experimental tests (Erell and Etzion, 2000) .



Figure 3-5: A view of the Solvent window prototype mounted in Summer mode.

3.2.2 Glazing

The SOLVENT window tested comprised a double clear glazing plus an absorptive glazing that is located outside of the double clear glazing in Summer mode and indoor of the double clear glazing in Winter mode. All used glazings were easily available in the local market. The optical and thermal characteristics of the glazings published by the manufacturer are as shown in table 3-1.

Table 3-1: Optical and solar properties of the glazings used in the prototype (Saint-Gobain-Glass, 2000).

	Clear (1 pane)	Double clear (assembly)	Absorptive glazing
Width (mm)	4	4 + 6 (air) +4	5
Luminous Transmissivity (%)	90	81	47
Luminous Reflectivity (%)	8	14	5
Solar Transmissivity (%)	83	70	50
Solar Reflectivity (%)	8	13	6
Solar Absorptivity (%)	9	7	44
Solar factor (EN410)	0.85	0.75	0.61

3.2.3 Instrumentation

The instrumentation mounted on the window prototype and test room in the cell was aimed at monitoring the following variables:

- Glazing temperature at each glazing surface;
- Air temperature in the open air channel at different heights.;
- Velocity of the air in the air gap;
- Illumination levels at different points inside the test cell;
- Air temperature inside the test cell.

3.2.3.1 Temperature Sensors

The temperatures of every glazing surface and of the air circulating in the open channel were measured using Type-T thermocouples with a wire diameter of 0.5 mm. The thermocouple head had a diameter of approx. 1.0 mm. The thermocouples were calibrated in a bath of fusing water/ice, to a standard deviation < 0.1K. Figure 3-6 shows the location of the temperature sensors at the test window.

The thermocouples were shaded from the incidence of direct solar radiation, to minimise its effect in their energy balance and thus the resulting error in the measured temperature. For thermocouples attached to surfaces, a layer of reflective tape was glued at the outside of the attachment tape (figure 3-7).

For thermocouples measuring the temperature of air, these were located at the middle of a small cylinder which had the external surface covered with reflective tape (figure 3-8). A later study showed that, in fact, for the thermocouples measuring air temperature, the effect

of the shields is limited, and that it would have been more effective to use thermocouples with lower diameter. The estimated error induced by an area averaged solar radiation flux of 300 W/m^2 , at an air speed of 0.5 m/s , is about $1.1 \text{ }^\circ\text{C}$ for a thermocouple with a head diameter of 1 mm , but only $0.2 \text{ }^\circ\text{C}$ for a thermocouple with a head diameter of 0.2 mm (Erell, Leal et al., 2005).

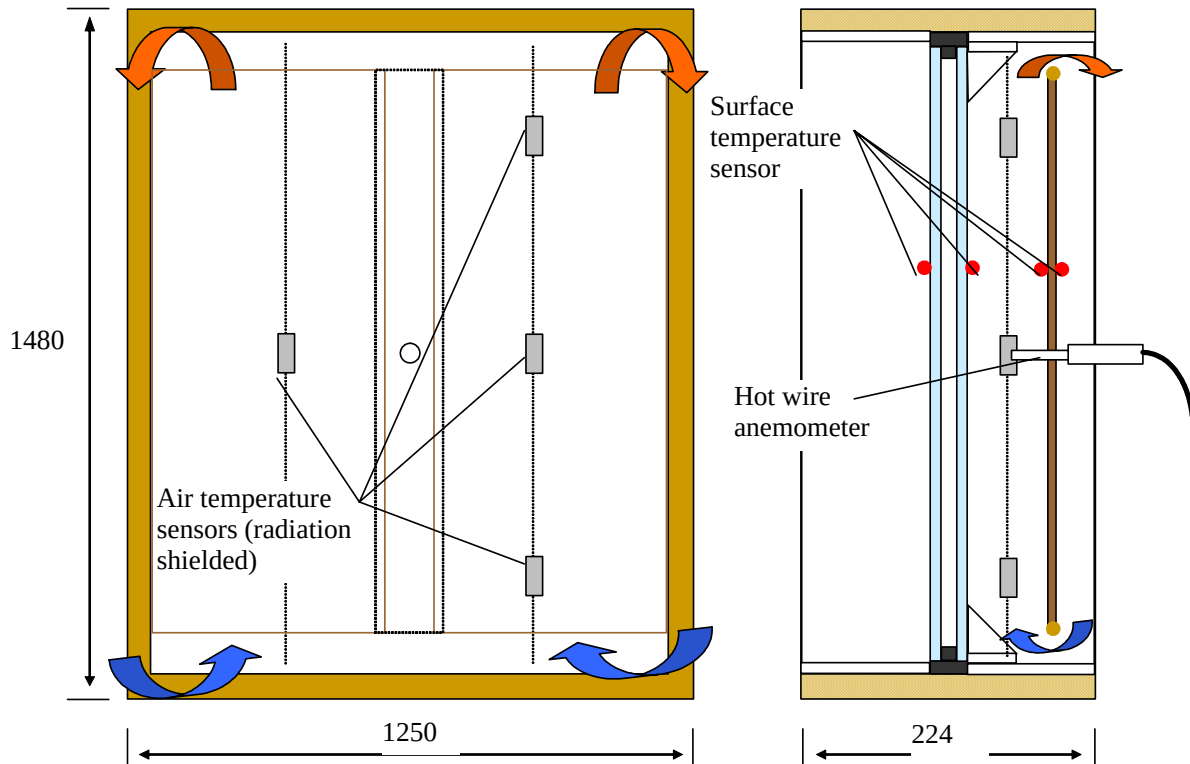


Figure 3-6: Location of the main instrumentation at the window



Figure 3-7: Tape protecting glazing temperature sensors from direct radiation.



Figure 3-8: Cylinders protecting air temperature sensors from direct radiation.

3.2.3.2 Illuminance Sensors

The illuminance inside the test room was measured at five different points, according to the plan shown in figure 3-9. The luxmeters were mounted on small horizontal platforms at a height of 85 centimetres above the floor. Two types of luxmeters were used:

- i) Type A luxmeters with accuracy better than 1%, capable of measuring in the range 1-100 000 Lux and response time lower than 0.1 s (figure 3-10)
- ii) Type B luxmeters with accuracy better than 5%, measuring in one of the ranges: 0-2000 Lux, 2000-20000 Lux or 20000-50000 Lux (figure 3-11).

A type A luxmeter was installed in point (1), whereas type B luxmeters were installed in points (2), (3), (4) and (5). Besides the difference in accuracy, experience also showed that the type B luxmeters required periodic shutdown and restart in order to measure correctly. A second type A luxmeter was installed outdoors to measure the outdoor global illuminance (figure 3-10).

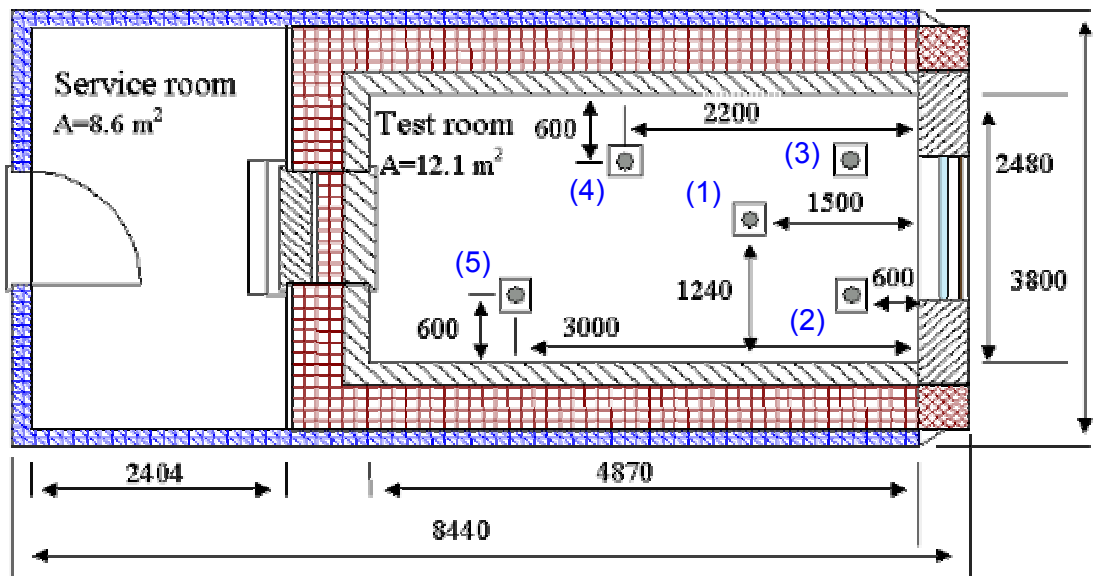


Figure 3-9: Cell plan showing the placement of the luxmeters.



Figure 3-10: Type A luxmeter measuring outdoor illuminance.



Figure 3-11: Type B luxmeter mounted in the platform.

3.2.3.3 Air Velocity Sensor

The velocity of the air in the open channel was monitored with a hot-wire anemometer. The model used can measure in the range 0.01-1 m/s with an accuracy of $\pm 2\%$ of full scale at the temperature of 20°C. It can operate in the range from -20 to +80°C.

The anemometer was mounted on a platform that was specifically designed for this purpose. The insertion of the anemometer in the air channel was performed through a hole in the tape that connects the two half-glazings (absorptive layer) at the centre of the window (figure 3-12). A small piece of tape was placed in front of the anemometer sensor in order to minimise any hypothetical influence of the solar radiation upon the measurement.

3.2.3.4 General view of the test room

Besides the specific instrumentation for monitoring the SOLVENT window, described in the previous sections, the test cell also has standard instrumentation for measuring wall and air temperature. Two long textile sleeves help diffusing the air, coming from the fan coils with a very low velocity, in a more uniform way. The inner layer of the cell walls, floor and ceiling is made of polished steel. Figure 3-13 and figure 3-14 show a forward and a backward-looking view of the test room.



Figure 3-12: Hot-wire anemometer insertion in the air gap during the first measuring campaign, here in Winter mode.



Figure 3-13: View of the cell and window from the back of the test room



Figure 3-14: The back of the test cell viewed from the test window.

3.3 METEOROLOGICAL DATA MEASUREMENT

A major objective of this work is the characterization of how the new window responds to the exterior environment. The characterization of the outdoor climate during the tests is therefore of outmost importance.

The PASSYS network has selected a set of standard environmental variables to be measured:

- Temperature of the outdoor air;
- Relative humidity of the outdoor air;
- Global solar radiation impinging on a horizontal surface;
- Direct solar radiation impinging on a horizontal surface;
- Global solar radiation impinging on the South façade.
- Wind velocity;
- Wind direction.

For the SOLVENT project, a luxmeter was placed outdoors to measure the global horizontal illuminance. A second luxmeter was added at a later stage to measure the diffuse outdoor illuminance as well.

3.4 UPGRADE FOR THE SECOND MEASURING CAMPAIGN

The experience gathered during the first experimental campaign and the analysis of the experimental data suggested that some changes to the original setup would be beneficial. The upgrade covered four aspects:

- i) Measurement of the air channel velocity;
- ii) Measurement of outdoor illuminance;
- iii) Measurement of environmental LW radiation.
- iv) Measurement of the cooling load;

3.4.1 Insertion of the hot-wire anemometer in the air channel

The first change concerned the method for measuring the velocity of the air in the open air gap. In the original configuration, the air velocity was being measured at an “atypical” region, due to the perturbation caused by the tape (figure 3-12 in section 3.2.3.3). It was then decided to make 5 small holes at one of the halves of the absorptive glazing, each with a diameter of 10 mm, where the anemometer could be tightly inserted. The space between the two halves at the junction was also reduced to only approximately 1 mm. Figure 3-15 shows the positioning of the holes in the left half of the window. Figure 3-16 and figure 3-17 show a view of the anemometer inserted according to this method.

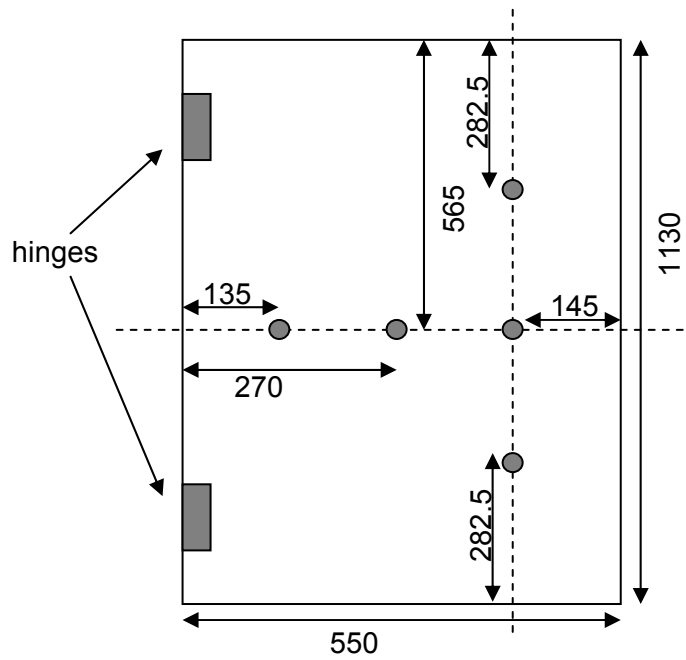


Figure 3-15: Location of the holes in the glazing (left half of the window) for inserting the hot-wire anemometer



Figure 3-16: A view of the new method for the anemometer insertion



Figure 3-17: View of the new method for the anemometer insertion from the inside of the test-cell.

3.4.2 Outdoor illuminance

In the first setup, only the global outdoor illuminance was measured, through a type A luxmeter located horizontally near the window. It was later recognised that, in order to perform accurate simulations of daylighting, it is important to separate the direct and the

diffuse components of outdoor daylighting available. In order to perform this task, two type A luxmeters were placed on the roof of a PASSYS test cell, at the same platform that is used for the measurement of solar radiation. One luxmeter was placed near the global radiation pyranometer, thus measuring global outdoor illuminance (figure 3-18), while the second luxmeter was attached at the side of the diffuse radiation pyranometer, subjected to the same shadow band, thus measuring the diffuse illuminance only (figure 3-19). The difference between the two measurements is the direct illuminance.



Figure 3-18: Luxmeter for measuring outdoor global illuminance



Figure 3-19: Luxmeter attached to pyranometer for measuring outdoor diffuse illuminance

3.4.3 Incoming long wavelength radiation

One of the components of the heat balance at the exterior surfaces of building envelopes is the long wavelength radiative exchange with landscape surfaces, sky and eventually other buildings. For modelling purposes it is often assumed that these surfaces are at the same temperature as the exterior air. However, in reality, the landscape temperature can be significantly affected by the incidence of solar radiation or by radiative loss to the sky. Cloudless sky can also have an apparent temperature several degrees lower than air temperature. For validation purposes, as will be the case in this study, it may therefore be convenient to measure the incoming LW radiative flux. This can be performed by means of a LW radiometer, also known as Pyrgeometer.

A pyrgeometer was thus mounted at the South façade, slightly above the window and very slightly tilted downwards to have nearly the same view field as the centre of the window (figure 3-20). The model used has a response time of 2 s, a linearity better than $\pm 1\%$ up to 700 W/m^2 and a temperature dependence lower than 1% between -20°C and $+40^\circ\text{C}$.



Figure 3-20: Pyrgeometer for measuring the LW radiation impingent at the external surface of the glazing.

3.4.4 Measurement of the cooling load

The measurement of the cooling load at the PASSYS test cells initially was a matter of concern. The error associated with the measurements was often too high to be acceptable, and a number of upgrades allowed obtaining more reliable results (Borges, 1999). In the case of the SOLVENT window tests, there was however a question that required special attention and which is analysed next.

The cooling of the test room is achieved by circulating cold water from the service room to a fan coil heat exchanger at the test room. The circulation is induced by a water pump. The pump is ON when cooling is required, and OFF when cooling is not required. The calculation of the cooling power is based on the precise measurement of the cold water flow to the test room, and of the temperature difference between the water coming out of the test room and that entering the test room. When operating in intermittent mode, a possible source of incertitude arises, due to the period of the temperature measurements.

By default, the temperatures and the flow are measured once per minute. Figure 3-22 shows the characteristic evolution of the temperature of the water at the exit of the cooling coil inside the test cell. When the test room air reaches a certain predefined temperature, the cold water pump is stopped. The water in the cooling coil will slowly increase its temperature towards the room air temperature. If the test room air temperature increases, e.g., due to the effect of solar radiation, cooling may be required again. When this happens, the water pump is turned ON, and the temperature at the exit of the cooling coil drops very quickly. Under these conditions, measuring once per minute was not enough, as the value measured may not be representative of the sampling period. Figure 3-23 shows the evolution of the measured water flow and water in/out temperature difference during one hour in a day with the original 2001 configuration. Figure 3-24 shows the corresponding calculated cooling power. It is clearly seen that when the water starts circulating, the measurement rate is too low to the speed of the phenomena and thus a significant uncertainty may be introduced to the measurement.

In order to decrease the magnitude of this phenomenon, the following measures were taken:

- i) The water flow was decreased from about 5.9 l/min to about 2.4 l/min;
- ii) The measurement of the inlet-outlet temperature difference was raised from 1 to 9 times per measurement cycle of the data acquisition system;
- iii) The interval of the data acquisition system measurement cycle was decreased from 60 to 50 seconds.

The results of these changes are observed in figure 3-25 and figure 3-26, which show the water flow, water in/out temperature difference and cooling power for a day in 2003, with the upgraded configuration. The following of the curve is much tighter, and no sudden unmonitored variations are observed.

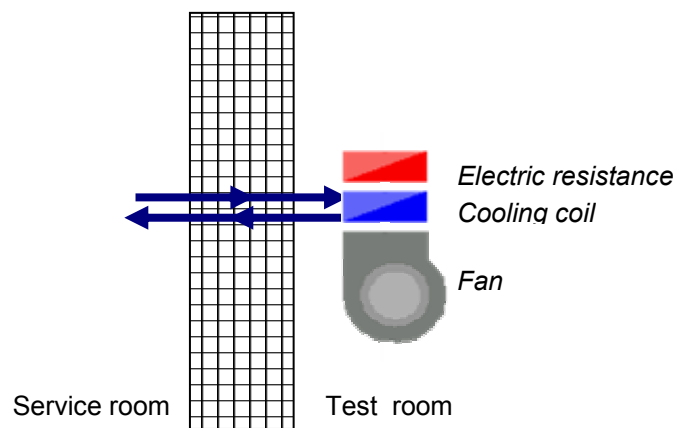


Figure 3-21: Test cell conditioning system

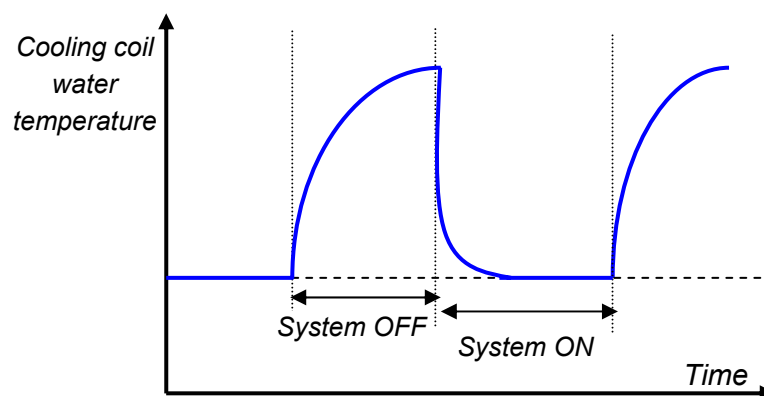


Figure 3-22: Characteristic evolution of the water temperature at the exit of the cooling coil inside the test cell.

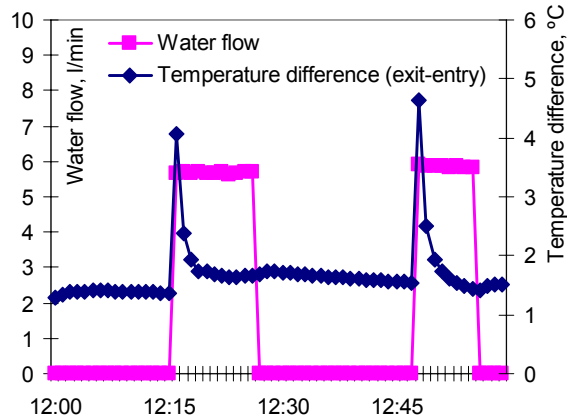


Figure 3-23: Water flow and temperature difference between cooling coil exit and entry, 2001 configuration.

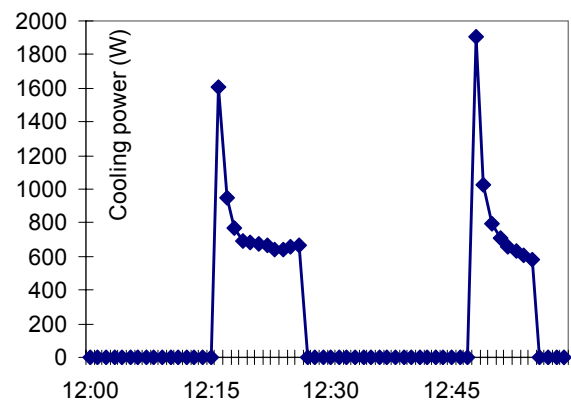


Figure 3-24: Calculated cooling power, 2001 configuration.

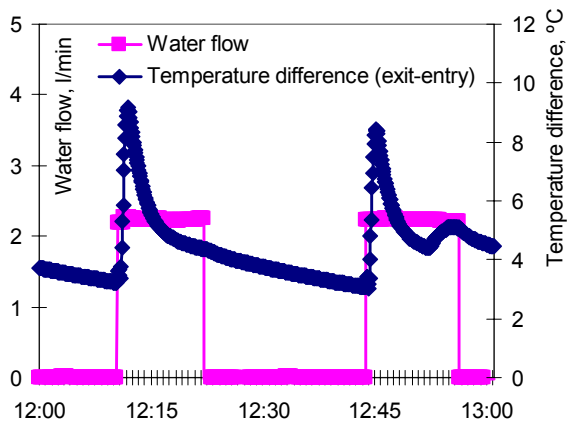


Figure 3-25: Water flow and temperature difference between cooling coil exit and entry, 2003 configuration.

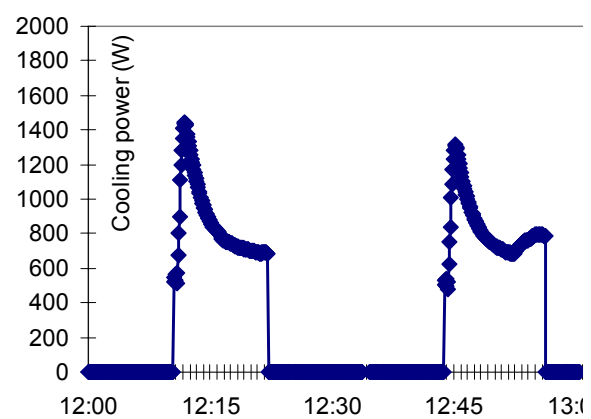


Figure 3-26: Calculated cooling power, 2003 configuration.

3.5 TEST CELL AIRTIGHTNESS

A quantitative evaluation of the airtightness of the test room with the SOLVENT window mounted was performed. This was achieved through a pressurization test, using a fan and a precision rotameter. Figure 3-27 shows the results in terms of air changes per hour (ach^{-1}). The value measured at 50 Pa was 0.006 ach^{-1} , a value already very low. Applying the rule of thumb that the average air change is about the value at 50 Pa divided by 20 (Sherman, 1987), the average air change rate during the window tests is estimated to be about $3 \times 10^{-4} \text{ ach}^{-1}$.

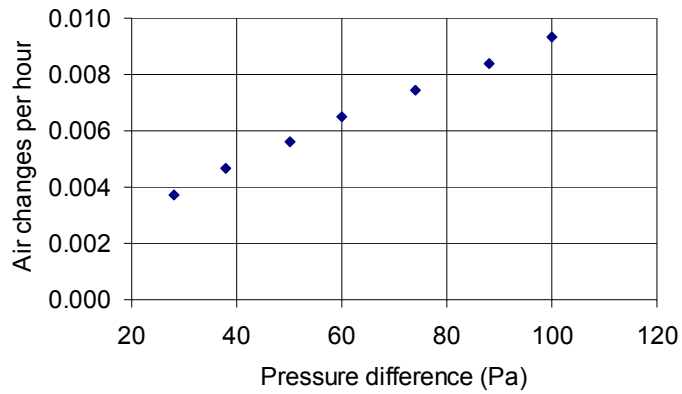


Figure 3-27: Results of the pressurization test for determining the airtightness of the test room.

3.6 MEASUREMENT SETS

The window prototype was tested in four different configurations, two in Winter mode and two in Summer mode. Concerning the air gap widths, it was considered that:

- i) For architectural and economical reasons, the total window thickness shall not be very large.
- ii) Increasing the air gap width after a certain value may decrease the convective flow.
- iii) A limited number of tests shall be enough to develop and validate a theoretical model. Once it exists, any channel geometry can be studied.

Taking into account these factors, it was decided to test the window with open air gaps of about 4 cm and 2 cm, both in Winter mode and in Summer mode. After mounting, the glass-to-glass distances were measured at each of the 4 corners (figure 3-28) and the average values taken as the effective air gap widths (table 2-2). The actual mean air gap widths achieved after mounting were 4.1 cm and 2.1 cm in Winter mode, and 4.0 and 2.0 cm in Summer mode.

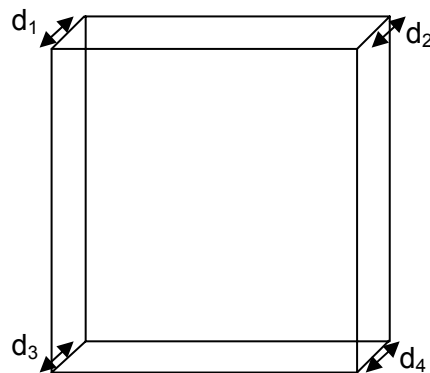


Figure 3-28: The glass to glass distance was measured at each of the corners of the channel to calculate the open air gap width.

Table 3-2: Open air gap glass-to glass distances at each of the corners and average values (cm)

	d_1	d_2	d_3	d_4	average
WM 2cm	2.0	2.1	1.9	2.1	2.0
WM 4cm	4.1	4.0	4.1	4.1	4.1
SM 2cm	2.0	2.0	2.0	2.0	2.0
SM 4cm	4.0	4.0	4.1	3.9	4.0

Each of the configurations was tested during periods not shorter than a week, sometimes longer due to cloudy or rainy meteorological conditions. In the former cases, a reference week including at least two consecutive sunny days was chosen. The diagrams from figure 3-29 to figure 3-32 show the meteorological conditions during each of the test reference weeks. Detailed quantitative characterization will be given later in chapter 4 when using the information for validating the simulation models.

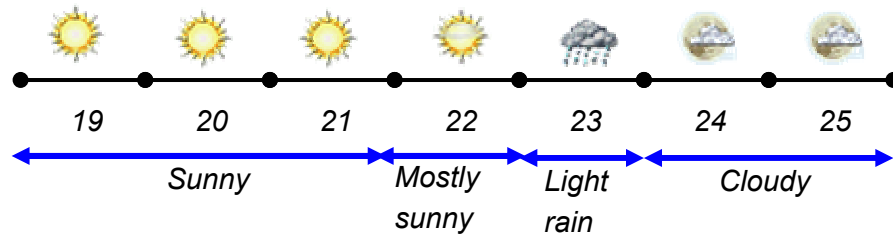


Figure 3-29: Meteorological conditions during the test reference week for winter mode configuration, 2 cm air gap (19-25th March 2003).

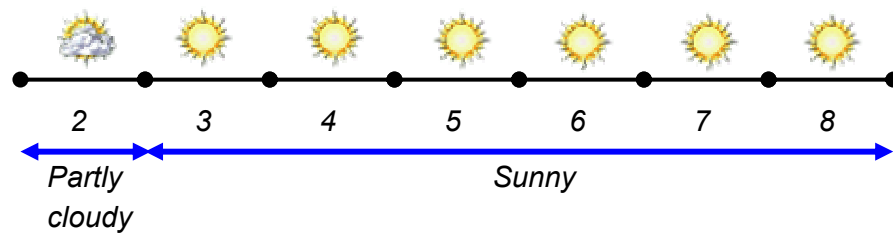


Figure 3-30: Meteorological conditions during the test reference week for winter mode configuration, 4 cm air gap (2-8th April 2003).

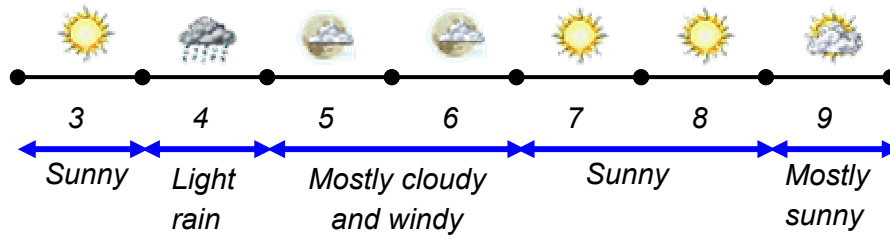


Figure 3-31: Meteorological conditions during the test reference week for summer mode configuration, 2 cm air gap (3-9th May 2003).

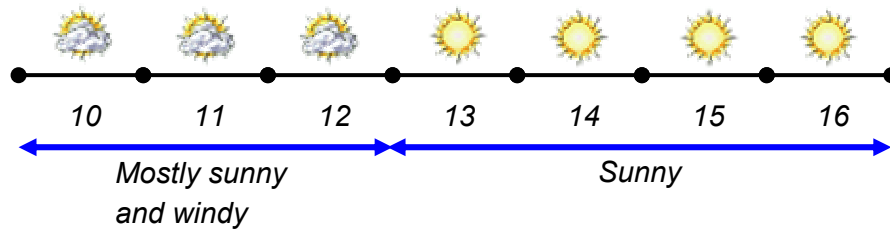


Figure 3-32: Meteorological conditions during the test reference week for summer mode configuration, 4 cm air gap (10-16th May 2003).

4 WINDOW SIMULATION MODEL

4.1 THE “SIMSOLWIN” SIMULATION PROGRAM

The combined heat transfer, channel convection and air flow models presented in chapter 2 were implemented in a computer simulation program, here called “SIMSOLWIN”, standing for “SIMulation of the SOLar WINdow”.

The program was written to account for both Winter and Summer operating modes. The basic input information is the window geometry (height, width, glazing thickness, air gap type and widths), outdoor and indoor test cell temperatures, solar radiation on the horizontal plane and long wavelength radiation arriving to the window. It was implemented in the MAPLE language and software pack (Maplesoft, 2001). Figure 4-1 shows the program flowchart, whereas the complete listing is presented in Annex 1.

The main strategy for solving the heat transfer and fluid dynamics equations at each time step was to start with the temperatures of the glazings and with the air velocity at the end of the previous time-step, then compute the convection coefficients, solve the heat balance equations for each of the glazings simultaneously, and then compute an updated air velocity. These latest values of glazing temperatures and air velocities are used as initial values for a second iteration within the same time-step, and the iteration continues until a criterion of convergence is met. The criterion of convergence that was adopted states that the sum of the differences between the temperatures of the three glazings at consecutive iterations (variable *Residual*), in absolute value, must be less than a certain value defined by the user (variable *Maxerror*). For reasons of maximising accuracy, the value of *Maxerror* was typically set to 0.3 (an average of 0.1 °C per glazing).

4.1.1 Calculation of the solar position

The model implements routines for calculating the solar position and incidence angles. The models for these calculations are the same used by the software ESP-r, described in (Clarke, 2001). Besides influencing the value of the solar radiation impinging on the window, the solar position also affects the choice of the optical properties of each glazing, which are considered angle-dependent. The angular optical properties of the glazings were computed using the software Window 5.2 (Huizenga, Arasteh et al., 2003).

4.1.2 Albedo and diffuse radiation

Weather stations usually only measure the diffuse and the global solar radiation on the horizontal plane. Calculating the solar radiation impinging on a window, typically in a vertical position, requires modelling the spatial distribution of the diffuse radiation and knowing the local albedo (ground reflectivity).

SIMSOLWIN program flux diagram

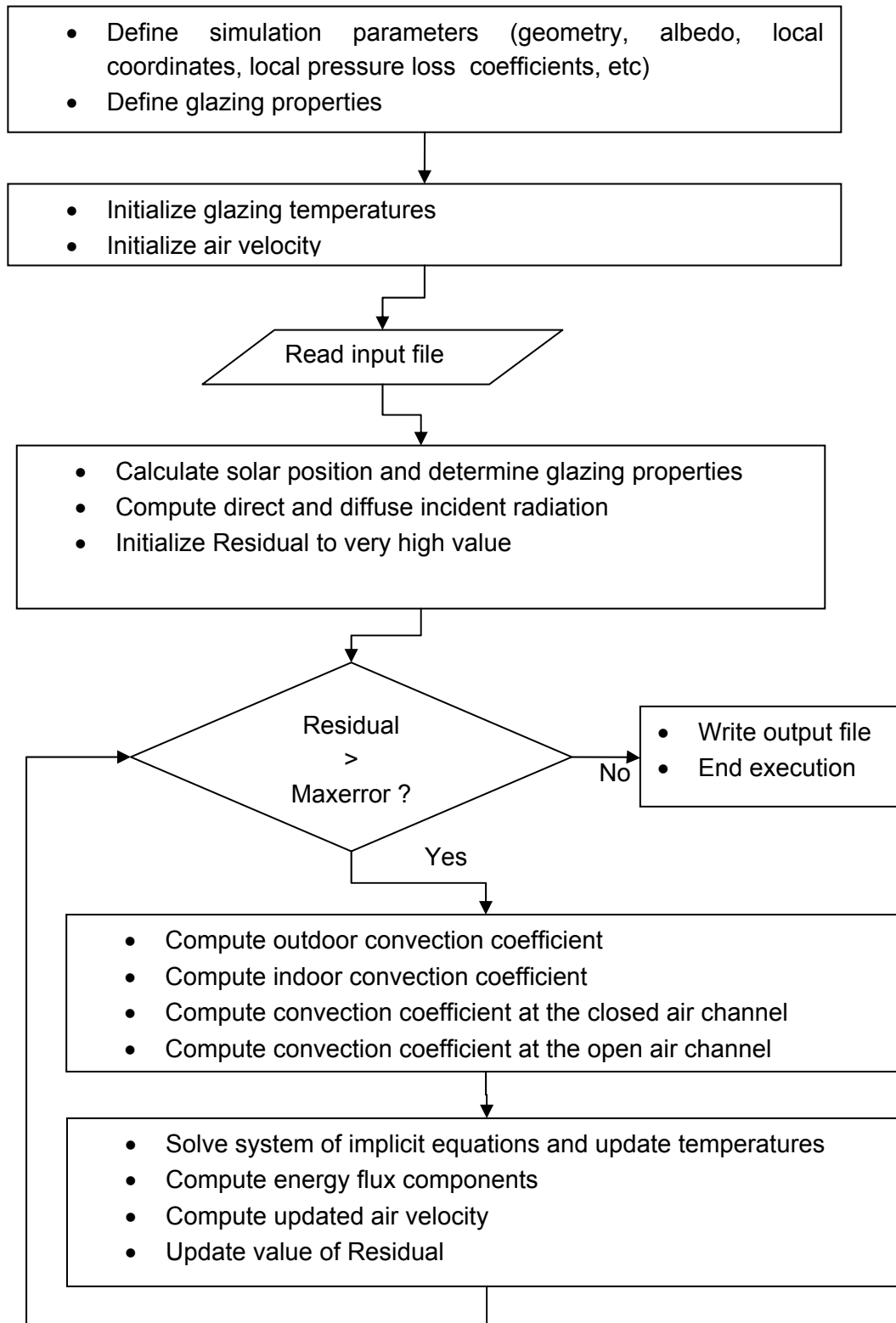


Figure 4-1: SIMSOLWIN program flowchart.

The global vertical radiation impinging on a surface is the sum of three components: direct, diffuse and radiation reflected by the ground and other outdoor surfaces. Assuming that the radiation reflected by the ground is isotropic, and given that the view factor from a vertical surface is 0.5 to the sky and 0.5 to the ground, the global vertical radiation thus becomes:

$$I_{gv} = I_{dirv} + I_{difv} + 0.5\rho I_{gh} \quad \text{eq. 4-1}$$

Since the global radiation at the south-oriented vertical plane was measured at the test site, the equation can be inverted to calculate the albedo:

$$\rho = \frac{I_{gv} - (I_{dirv} + I_{difv})}{0.5I_{gh}} \quad \text{eq. 4-2}$$

The global radiation on the vertical surface, I_{gv} , and the global radiation on the horizontal, I_{gh} , were both measured, and the direct radiation impinging on the south-vertical plane, I_{dirv} , is easily computed from geometric considerations. Concerning the sky diffuse radiation on the vertical surface, I_{difv} , it depends on its spatial distribution. There are several models trying to account for the effect of sky cloudiness on this distribution, such as those proposed by Hay (1979) and by Perez et al (1990). A simple treatment often used is to assume that the sky diffuse radiation is isotropic too. In this case it becomes simply:

$$I_{difv} = 0.5I_{difh} \quad \text{eq. 4-3}$$

The results for the calculated albedo as a function of the solar azimuth, computed with the data measured in the experimental facility between the 2nd and the 9th April 2003, are shown in the graphs of figure 4-2 (isotropic method). The result is compatible with the typical assumption in building simulation that, if not measured on site, a constant value of 0.20 is used.

Overall, comparing the radiation in the vertical surface facing South, as measured and as calculated from the global and diffuse radiation measured in the horizontal plane, the agreement is rather good, as shown in figure 4-3. The method described in this section for computing the radiation on the South-oriented vertical plane from the components measured at the horizontal plane thus becomes validated.

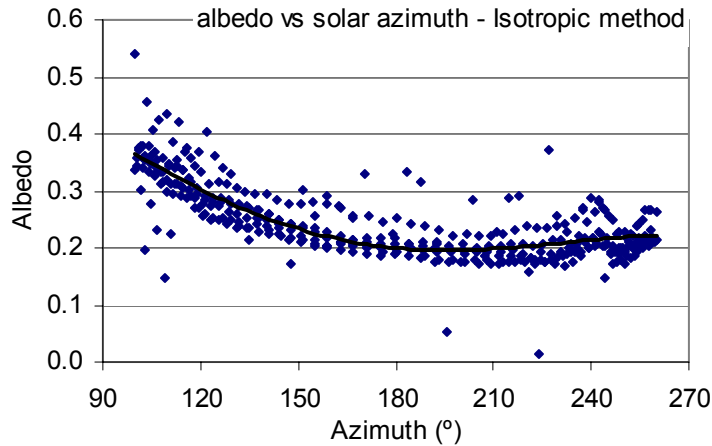


Figure 4-2: Measured albedo treating the sky diffuse radiation as isotropic.

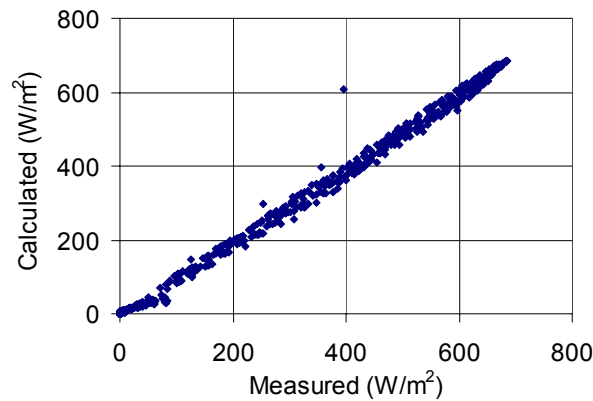


Figure 4-3: Radiation in the vertical surface facing South, as measured and as calculated from the global and diffuse radiation measured in the horizontal plane.

4.2 FIRST RESULTS

The first assessment of the SIMSOLWIN program and models was performed for the window in Winter configuration, with an open air gap of 4.1 cm. The choice of starting with Winter mode is due to the fact that it does not have a direct influence of the environmental wind upon the open channel flow. As will be seen later in section 4.7, wind introduces additional complexity, which is not desirable for the first approach. The local pressure drop coefficients were set to 0.5 at the entry and 1.0 at the exit, as seen in section 2.2.4. The outdoor heat convection coefficient was computed with the correlation specific for low-rise buildings (eq. 2-18 and eq. 2-19).

The meteorological data measured during the test with this configuration are shown in figure 4-4.

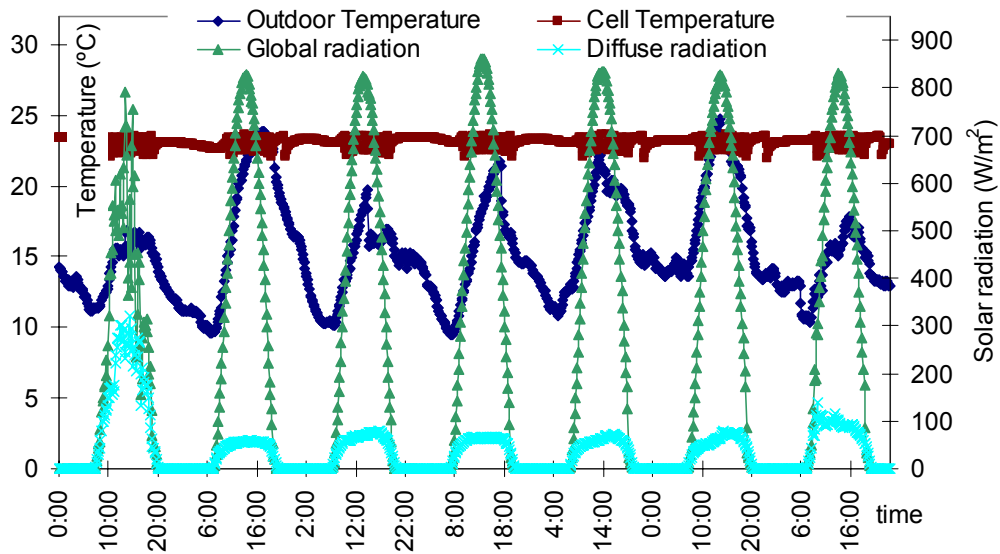


Figure 4-4: Outdoor temperature, cell temperature, global radiation on the horizontal plane and diffuse radiation on the horizontal plane during the period 2-8 April 2003.

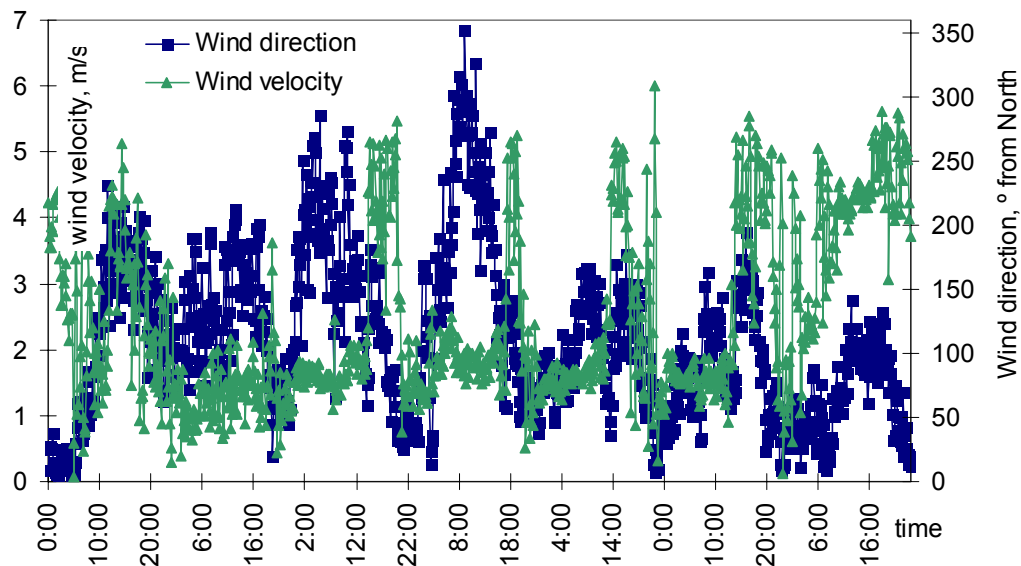


Figure 4-5: Wind velocity and direction during the period 2-8 April 2003.

The starting points in terms of heat convection at the open air channel are the limiting cases seen in section 2.3: the natural convection along a single vertical plate and the convection in natural fully developed channel flow. Figure 4-6 shows the temperature of the external glazing, as measured and as simulated with the two limiting cases. Figure 4-7 shows the equivalent results for the middle glazing, while figure 4-8 shows the results for the inner (absorptive) glazing.

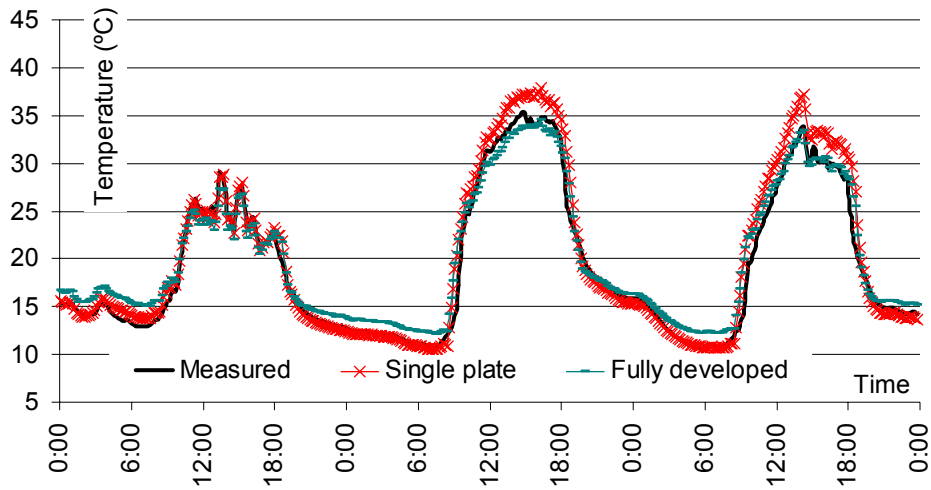


Figure 4-6: Temperature of the external glazing as measured and as simulated with different channel convection options.

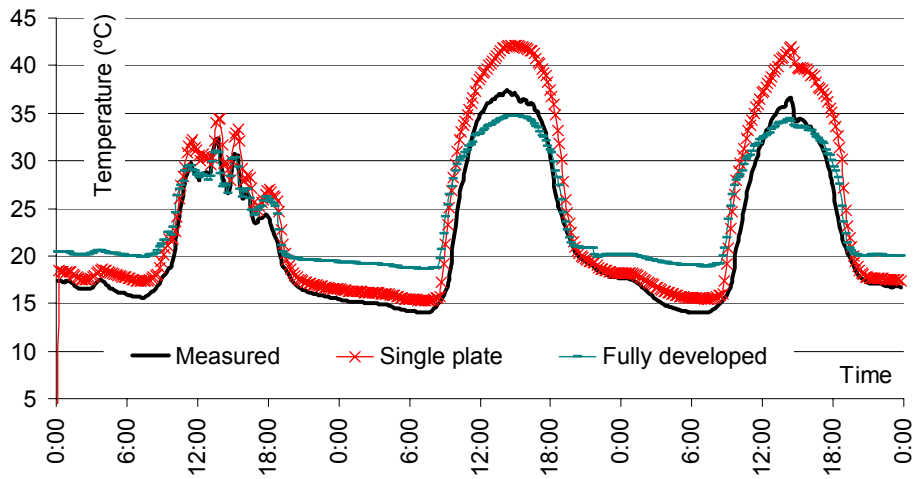


Figure 4-7: Temperature of the glazing 2 as measured and as simulated with different channel convection options.

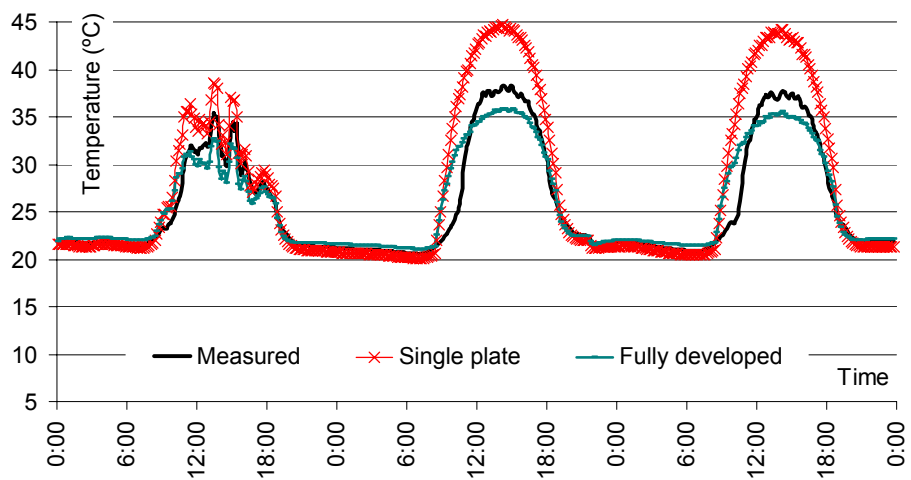


Figure 4-8: Temperature of the glazing 3 as measured and as simulated with different channel convection options.

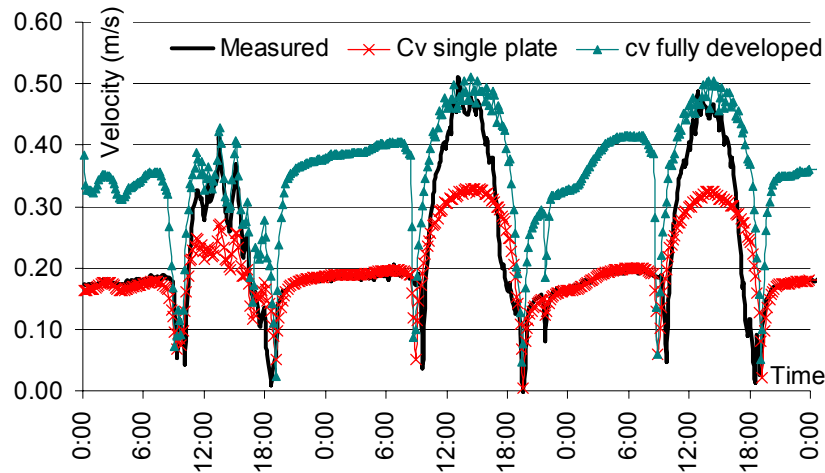


Figure 4-9: Velocity of the air in the open channel as measured and as simulated with different channel convection options.

The first conclusion from these results is that the model captures the main features of the system behaviour. The general trends of the glazing temperatures and air flow velocity are reproduced by the simulation model.

The second main conclusion is that the option taken for treating the convective heat transfer in the air gap has a significant importance, both on the glazing temperatures and on the predicted air gap velocity.

The correlation for natural convection along a single vertical plate yields very good results during the night. During this period, the glazings are colder than the indoor air, and the air flows downwards. Although the anemometer was only capable of measuring the velocity in absolute value, the graph shows two moments, at the beginning of the morning and at the end of the day, when the velocity is nearly zero. These moments correspond to the flow reversion. Because the temperature gradients are lower, the air velocities during night time are typically lower than during daytime. The correlation for single plate flow seems to work well precisely when the flow is slow. During the day, when the temperature gradients are higher, the correlation for single plate convection yields poor results, with a considerable underestimation of the flow.

Analysing the results produced by the correlation for natural convection with fully developed flow, the behaviour seems quite opposite. During the night, when the air velocity is low, there is a large overprediction of the air velocity. But during the day, when the temperature gradients and the air velocity are higher, the results obtained with this correlation approach the measurements.

It is also interesting to note that the deviations observed in the flow prediction and those observed in the temperature prediction during the day are coherent. By underestimating the air flow, single plate convection also underestimates the cooling effect in the glazings, and thus it leads to an overestimation of the glazing temperatures.

In summary, it seems that the system behaviour tends to single plate convection when the buoyancy force is low, and then tends to fully developed flow as the buoyancy force increases. Figure 4-10 shows the air gap velocity, as measured and as simulated with the two convection options, which seems to confirm this conclusion. For Rayleigh numbers up to $Ra_S \approx 3 \times 10^4$ the measured air velocity is quite correlated with the values predicted using

single plate convection. For Ra_S between aprox. 3×10^4 and 8×10^4 , the measured velocity is generally between those predicted with single plate convection and those predicted with fully developed flow convection. Finally, for Ra_S higher than about 8×10^4 , the measured velocity agrees quite well with the velocity predicted using fully developed convection.

The discussion in the previous paragraph suggests that the channel heat convection may be regarded as a blend of single plate and fully developed channel flow, with asymptotic behaviour. This was also the main concept behind the correlations of Churchill and of Bar-Cohen and Rohsenow described in section 2.3.4 but, as first mentioned in section 2.3.5, they fail to capture the trends with the Rayleigh numbers observed with the SOLVENT window. The results shown in figure 4-11 confirm that the Bar-Cohen and Rohsenow correlation does not lead to satisfying results – it actually leads to about the same results as the correlation for single plate flow.

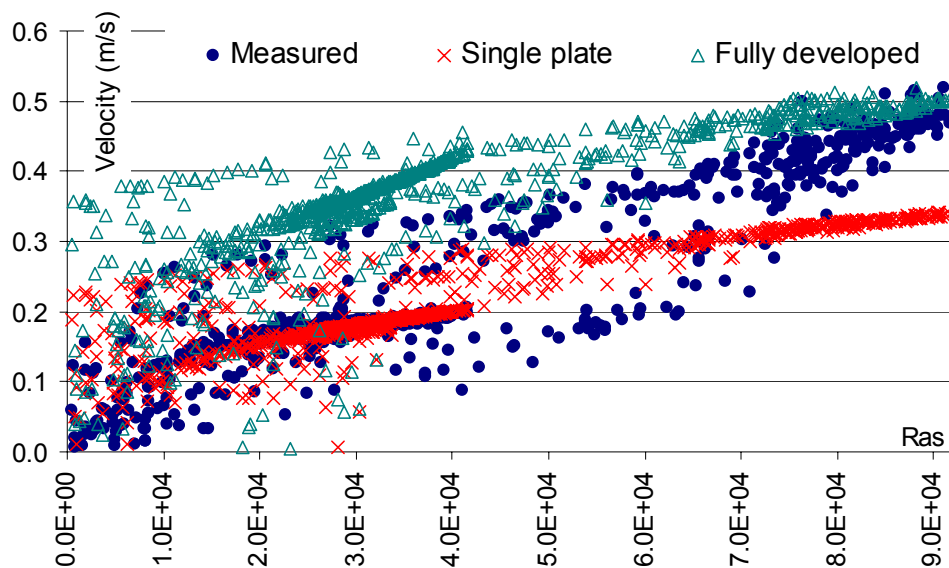


Figure 4-10: Velocity of the air gap as function of the Rayleigh number (based on the average wall temperature).

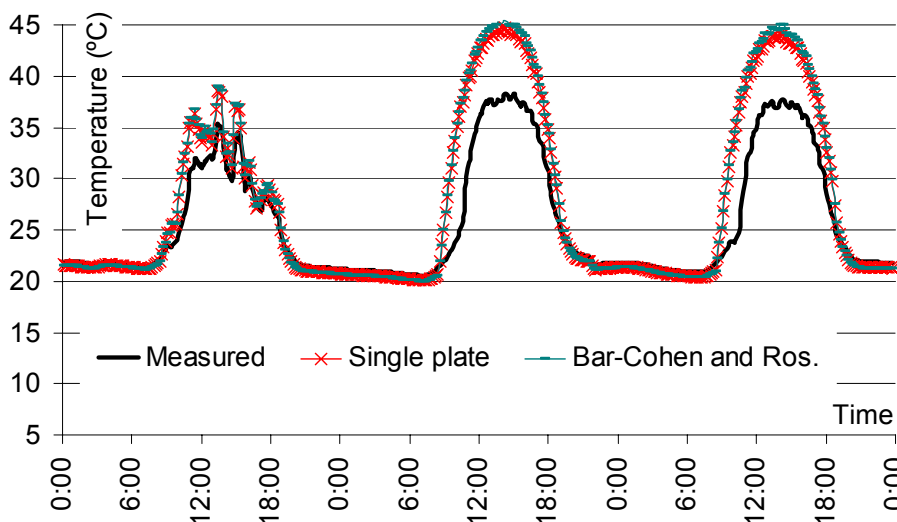


Figure 4-11: Temperature of the middle (absorptive) glazing, as measured and as predicted by single plate and by Bar-Cohen and Rohsenow correlations.

4.3 A NEW CORRELATION FOR OPEN CHANNEL NATURAL HEAT CONVECTION

As seen in the previous section, the experimental results for the air gap velocity generally lay between those predicted with the correlations for single plate convection, and those predicted with the correlations for the fully developed flow convection. Furthermore, the system behaviour seems to converge with the single plate convection limit at low Rayleigh numbers and with fully developed channel convection at high Rayleigh numbers. The existing blending correlations, such as the Churchill or the Bar-Cohen and Rohsenow correlations, do not seem to produce good predictions for the whole range of Rayleigh numbers and aspect ratios that occur with this window. A new blending approach must therefore be attempted.

A detailed experimental study of the channel convection would be far beyond the scope of this work. It should be performed at an indoor laboratory to avoid the potential disturbance in temperature readings due to solar radiation, and it would require precise and complete instrumentation, such as the ability to measure the velocity cross-section profile, etc. It would certainly constitute an independent in-depth work on its own. Therefore, while trying to preserve a basic coherence with heat convection principles and dimensional analysis, it must be stressed that the main effort shall be placed upon the search of a useful, practical way of combining the two limiting cases to obtain a good agreement with the measurements.

The goal is to obtain an expression that combines the limiting cases of single plate convection and fully developed natural channel convection, respecting the following conditions:

- i) It must tend to single plate behaviour as Ra_S approaches zero, and to fully developed flow as Ra_S approaches infinite;
- ii) It must be a continuous function that yields smooth intermediate results between the two limiting cases in the transition region.

A simple way of achieving these goals may be built in terms of the Nusselt number as a function of the following form:

$$Nu_S = e^{-\frac{Ra_S}{C}} Nu_{sp} + \left(1 - e^{-\frac{Ra_S}{C}}\right) Nu_{fd} \quad \text{eq. 4-4}$$

C is a constant controlling the blend, which must be determined by experimental fitting. Figure 4-12 shows the Nusselt number versus Rayleigh number computed with the new blend approach, depending on the blending constant C . As required, the new blend alternatives converge to the single plate limit when the Rayleigh number tends to zero, and to the fully developed limit when it tends to very high values, yielding intermediate values in the intermediate values of Ra_S . From the analysis of figure 4-10, it is known that the constant C should make the function stay with a behaviour close to single plate flow for Rayleigh numbers below approx. 3×10^4 , and then start gradually approaching the fully developed flow behaviour, which should be met at $Ra_S \approx 1 \times 10^5$. Looking again at Figure 4-12, it appears that a C value around 1×10^5 is a good starting point to evaluate the potential of this methodology.

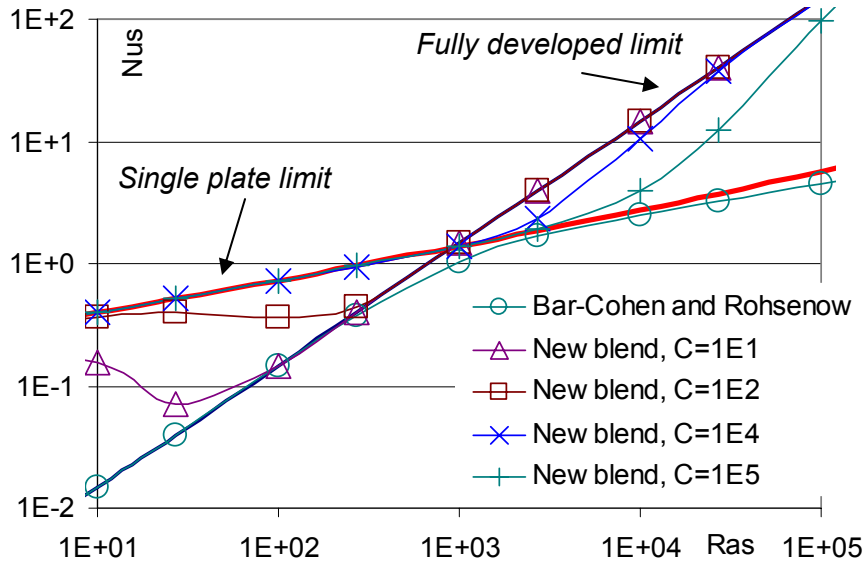


Figure 4-12: Nusselt number versus Rayleigh number computed with the new blend approach, depending on the blending constant C .

The results of simulation using this new methodology for treating the convective heat transfer in the air channel are shown in the graphs from figure 4-13 to figure 4-15. Two alternatives are presented in terms of the blending constant C : $C=1 \times 10^5$ as an initial trying value, and $C=4 \times 10^5$ as a value that returned better adjustment to the experimental results. Compared to both the limiting cases (figure 4-8), or to the Bar-Cohen and Rohsenow correlation (figure 4-11), the improvement seems quite significant.

Figure 4-16 shows the evolution of the Nusselt number with the Rayleigh number for the new blend correlation with the C value of 4×10^5 . As expected, the curve takes off from the single plate limit shortly after $Ra_s \approx 1 \times 10^4$. The convergence with the fully developed limit, though, is slightly slower than anticipated, the full convergence being completed only for $Ra_s \approx 1 \times 10^6$. However, for $Ra_s \geq 1 \times 10^5$ the Nusselt number is already significantly closer to fully developed flow, which seems to be enough to yield good results in terms of prediction of the glazing temperatures.

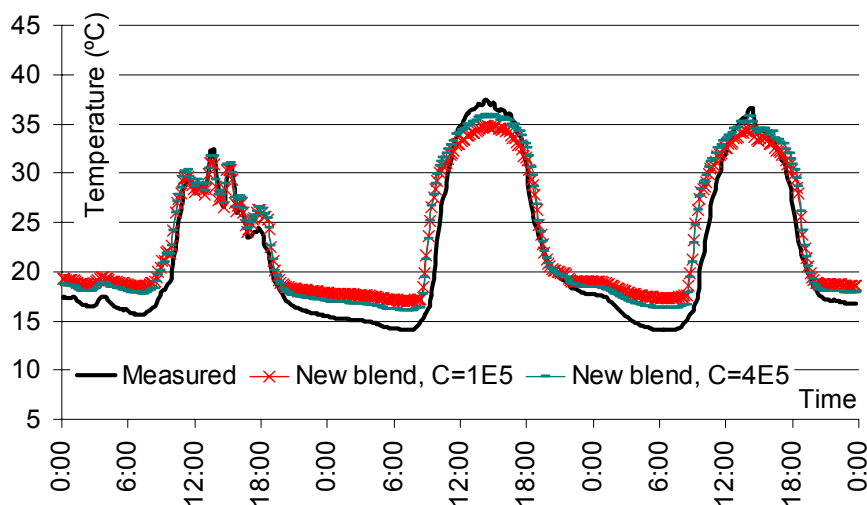


Figure 4-13: Middle (clear) glazing temperature as measured and as simulated with the new correlation

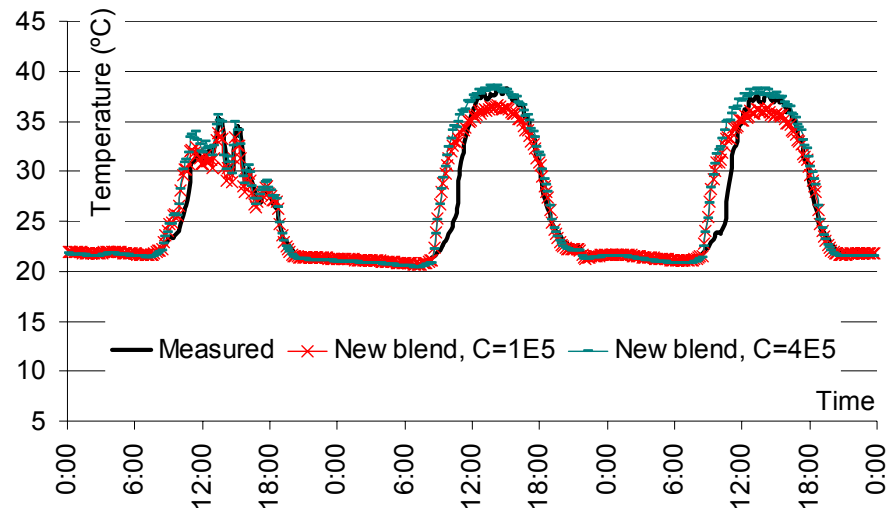


Figure 4-14: Inner (absorptive) glazing temperature as measured and as simulated with new correlation

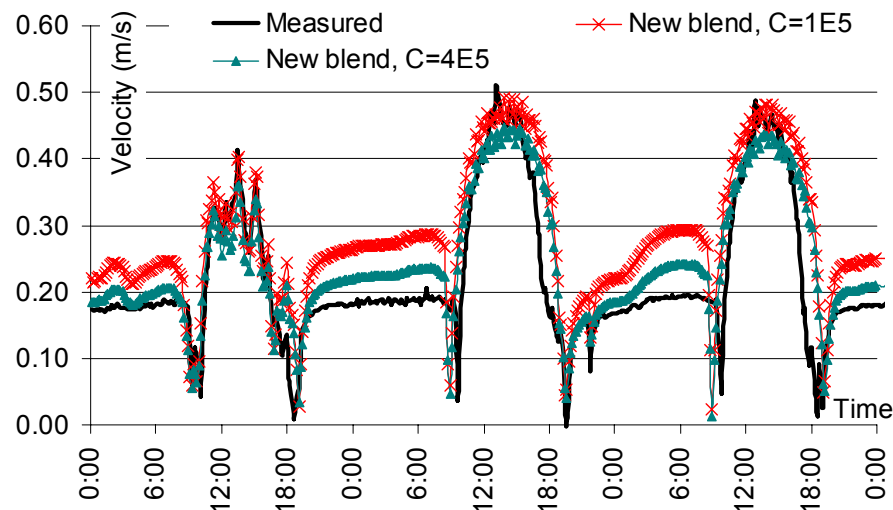


Figure 4-15: Channel air velocity measured and as simulated with the new correlation

A careful analysis shows that the model still reveals a slight overestimation of the temperature of the intermediate glazing, during the night, as well as an equally slight overestimation of the velocity in the air channel, also during the night.

It is possible to show that these deviations are not directly caused by the heat transfer correlation by itself. In fact, it is the slight deviation in the temperature that causes the deviation in the velocity. Figure 4-17 shows the air velocity that is predicted if the glazing temperatures are imposed from the measurements instead of computed by the program. The agreement is rather good. The slight deviation in the temperature of the glazings may be caused by any of the terms in the heat balance equation. As the temperature gradient between the glazings and the air during the night is low, a deviation of only 1 or 2 °C is percentually high and may have a considerable effect on the predicted air velocity.

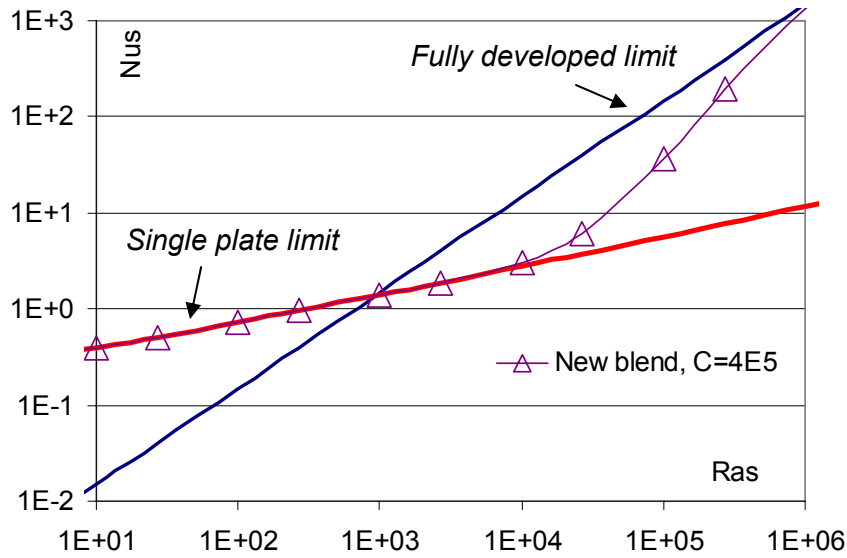


Figure 4-16: Nusselt number versus Rayleigh number computed with the new blend approach, depending on the blending constant C .

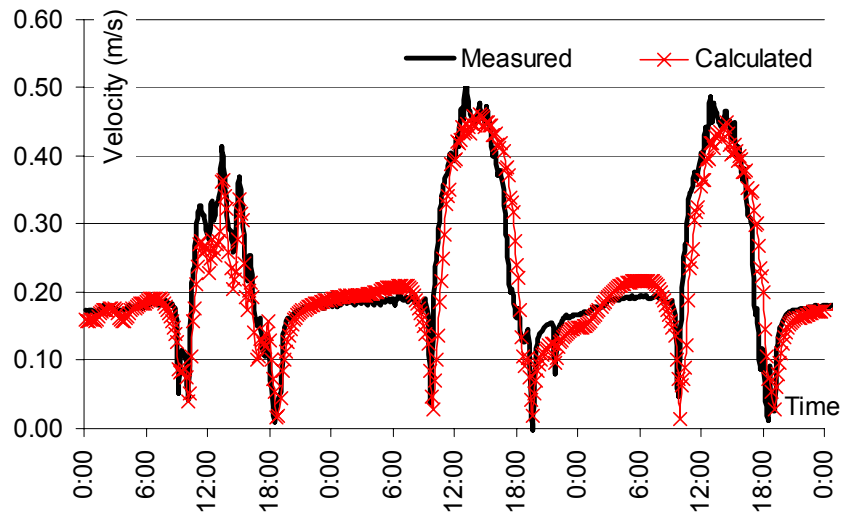


Figure 4-17: Channel air velocity measured and as simulated with new correlation, imposing the measured glazing temperatures

4.4 RESULTS FOR WINTER MODE, OPEN CHANNEL WIDTH 4 cm

The graphs from figure 4-18 to figure 4-21 show the results for the glazing temperatures and air velocity using the correlation of eq. 4-4. Globally the agreement is good. As discussed in the previous section, there are slight deviations between the predictions and the measurements, for the temperature of the middle glazing and for the air velocity, during the night. The most likely explanation for this deviation is an underestimation in the convective losses through the closed air gap, calculated with eq. 2-20.

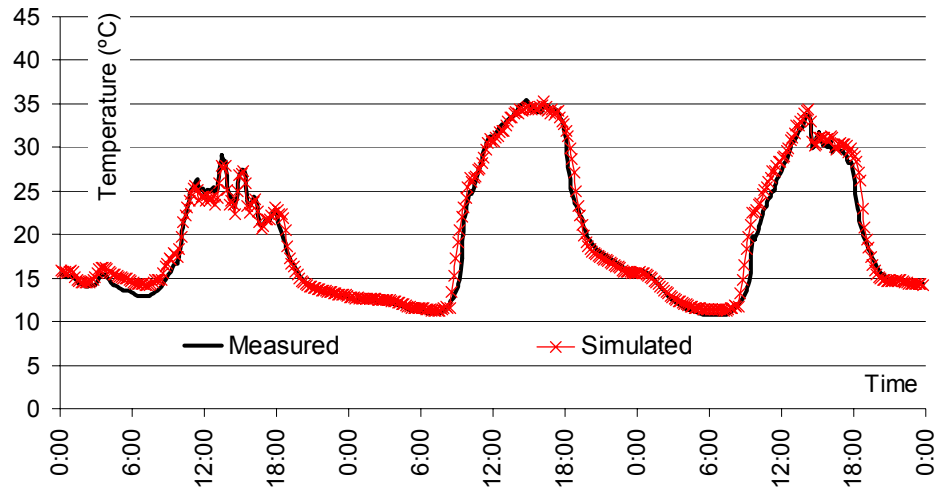


Figure 4-18: Temperature of the external glazing, as measured and as simulated with new correlation.

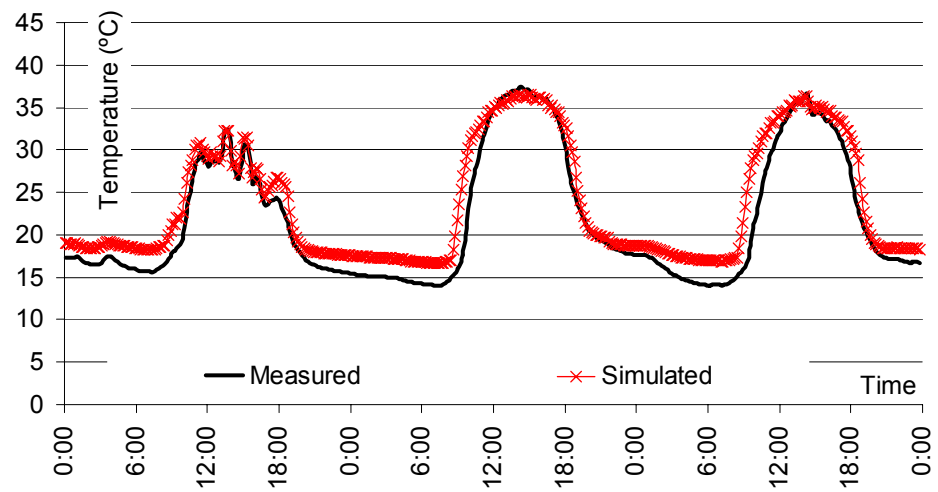


Figure 4-19: Temperature of the middle glazing, as measured and as simulated with new correlation.

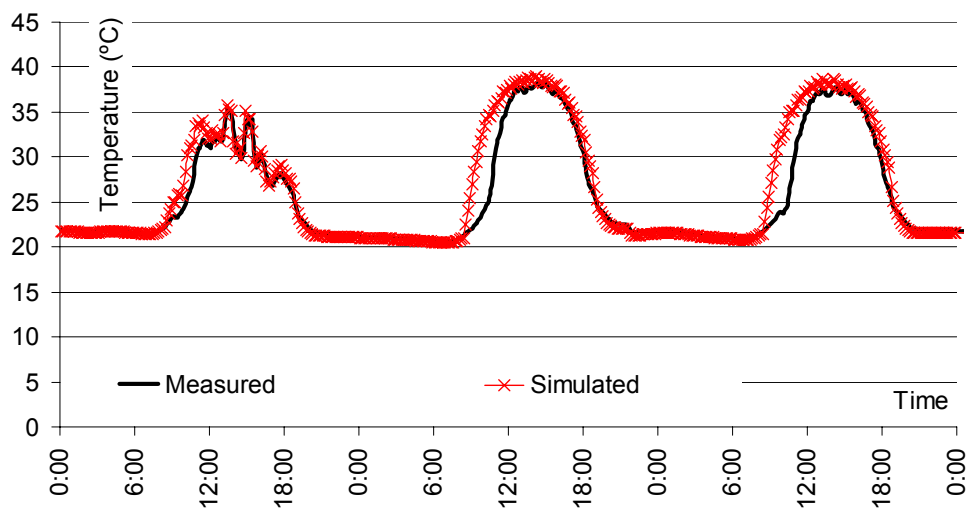


Figure 4-20: Temperature of the absorptive glazing, as measured and as simulated with new correlation.

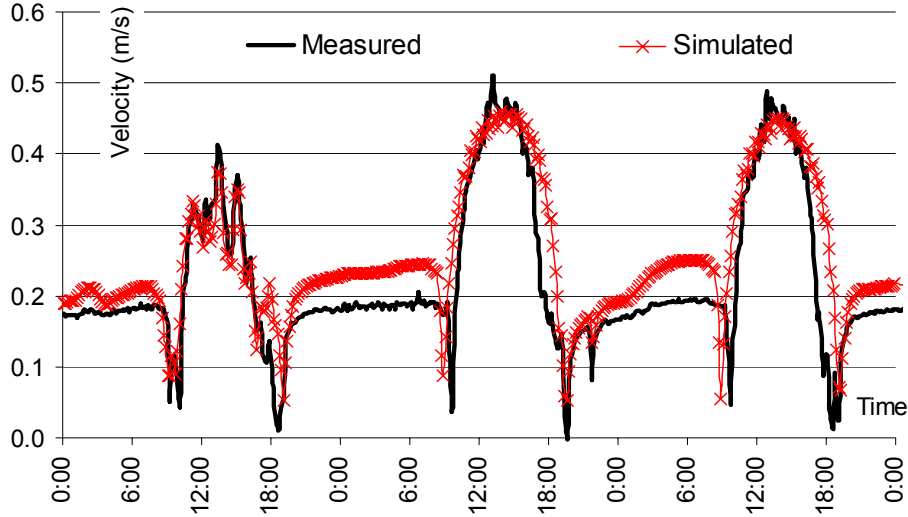


Figure 4-21: Velocity of the air in the open channel as measured and as simulated with new correlation

4.5 STATISTICAL VALIDATION PARAMETERS

A first evaluation on the level of agreement between simulated and experimental or theoretical values is usually achieved by graphical comparison, as presented in the previous section. A more objective evaluation, although less intuitive, is obtained by conducting an analysis of the statistical deviations.

The most used criteria for characterising the quality of the agreement is probably the correlation coefficient between the set of simulated values and the set of experimental or theoretical values. The correlation index between a set of simulated values (y) and a set of measured values (x) is calculated according to eq. 4-5. However, it is questionable if this criterion is the most adequate for this study. On one hand, the meaning of the correlation value is not of easy interpretation. On the other hand, the calculation of the correlation index bases on the assumption that the relation between the two sets of values is linear. This is not necessarily the case between measured and simulated values.

Some authors therefore argue that the correlation index is not the best criteria to characterise the agreement between measured and simulated values (Wilmott, 1981), (Kobayashi and Salam, 2000). The latest argue that the best criterion is the Root Mean Squared Deviation (RMSD), defined in eq. 4-6. Another possibility, suggested here, which yields results with a clear meaning, is to use the Mean Absolute Deviation (MAD) as defined in eq. 4-7.

$$CORR = \frac{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sigma_x \sigma_y} \quad \text{eq. 4-5}$$

$$RMSD = \sqrt{\frac{\sum_{i=1}^N (y_i - x_i)^2}{N}} \quad \text{eq. 4-6}$$

$$MAD = \frac{\sum_{i=1}^N |y_i - x_i|}{N} \quad \text{eq. 4-7}$$

Table 4-1 shows the three statistical parameters of comparison between simulated and experimental values, for the different channel convection options. The values shown are for the whole period 2nd-8th April, with the Winter mode configuration and 4 cm channel studied in the previous section.

It is observable that the options with the best correlation index are not always those with the best RMSD, MAD or graphical fitting. This seems to confirm the reservations in using the correlation index as an indicator of the quality of the agreement between the simulated and the measured values.

The results further confirm that, although not being the best for every indicator, the new blend is clearly the correlation that leads to better global results.

Table 4-1: Statistical parameters of comparison between simulated and experimental values for different channel convection options, configuration Winter mode 4 cm

		Single plate	Fully developed	Bar-Cohen & Rohsenow	New blend
Outer glazing	Corr	0.99	0.99	0.99	0.99
	MAD	1.44	1.18	1.59	0.85
	RMSD	2.09	1.49	2.25	1.35
Middle glazing	Corr	0.99	0.98	0.99	0.98
	MAD	2.94	2.81	3.01	2.06
	RMSD	3.95	3.27	4.25	2.60
Inner glazing	Corr	0.97	0.96	0.97	0.96
	MAD	3.07	0.96	3.33	1.21
	RMSD	4.66	1.71	5.02	2.28
Velocity	Corr	0.88	0.76	0.87	0.90
	MAD	0.04	0.14	0.05	0.05
	RMSD	0.06	0.16	0.07	0.06

4.6 RESULTS FOR WINTER MODE, OPEN CHANNEL WIDTH 2 CM

The simulation model was also applied to Winter mode with a narrow air gap, measuring 2.0 cm. The prototype was mounted and monitored with this configuration in the period between the 20th and the 25th March 2003. Figure 4-22 shows the characterization of temperatures and solar radiation for this period, and figure 4-23 shows the equivalent information for wind velocity and direction.

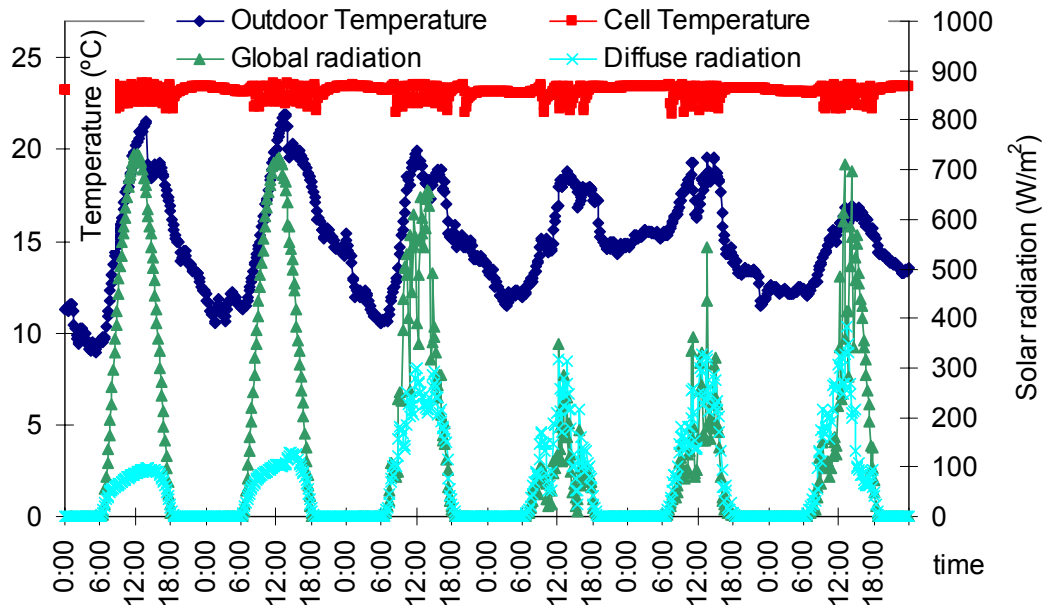


Figure 4-22: Outdoor temperature, cell temperature, global radiation on the horizontal plane and diffuse radiation on the horizontal plane during the period 20th-25th March 2003.

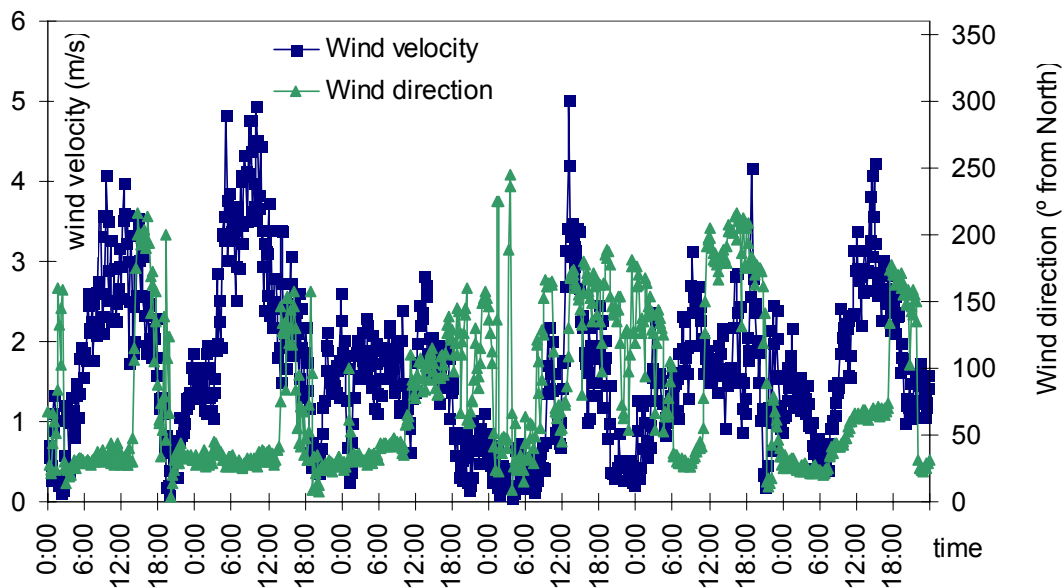


Figure 4-23: Wind velocity and direction during the period 20th-25th March 2003.

As for the 4 cm channel, it is expected that the thermal and aerodynamic behaviour of the window be comprised between that predicted applying single plate natural convection, and that obtained applying fully developed natural convection in a channel. Figure 4-24 shows the temperature of the dark glazing as measured and as simulated with the two convection options, and figure 4-25 shows the equivalent results for the air velocity at the open air channel. The results confirm the trend of the 4 cm channel, in which the correlation for single plate flow behaves better during the night, at low Rayleigh numbers, and the correlation for fully developed flow behaves better during the day, at higher Rayleigh numbers.

The results also show a large difference between the air velocity measured during the day and that computed with any of the conventional convection correlations. In order to explain this evident discrepancy, it now becomes important to recall that the value computed by the model is the average velocity in the air gap, while the experimental value was measured at the centre of the air gap.

For the 4-cm gap, varying the position of the anemometer across the height or the cross-section of the air gap did not reveal any perceptible difference in the air velocity. Therefore, it was assumed that the cross-section velocity profile is nearly uniform, and thus the air velocity at the centre of the air gap is representative of the average air velocity. This assumption was then reinforced by the good agreement between the measured and simulated air velocity.

For the 2-cm gaps, however, the anemometer was too big in size to allow the measurement of the velocity at positions closer to the walls. However, the results of the glazing temperature seem to indicate that during the day the flow is fully developed. This was confirmed by precision measurements performed at an indoor laboratory in the Indoor Climate Division of the KTH in Sweden (Sandberg, 2002). Although these later measurements were conducted in conditions partially different of those in this study, with imposed heat flux and just one wall heated, they have shown that for channels of 3.5 cm and 5.0 cm the velocity profile at mid-height is nearly flat, while for a 2.0 cm air gap the velocity profile tends to parabolic (figure 4-26). Recent CFD results for a channel formed by two walls of clear glass confirm this observation (Ismail and Henriquez, 2005).

If the velocity profile were perfectly parabolic, the average velocity would be about half the velocity measured at the centre. The results presented in figure 4-25 are compatible with this hypothesis, as the velocity measured during the day is in fact about twice the average calculated velocity.

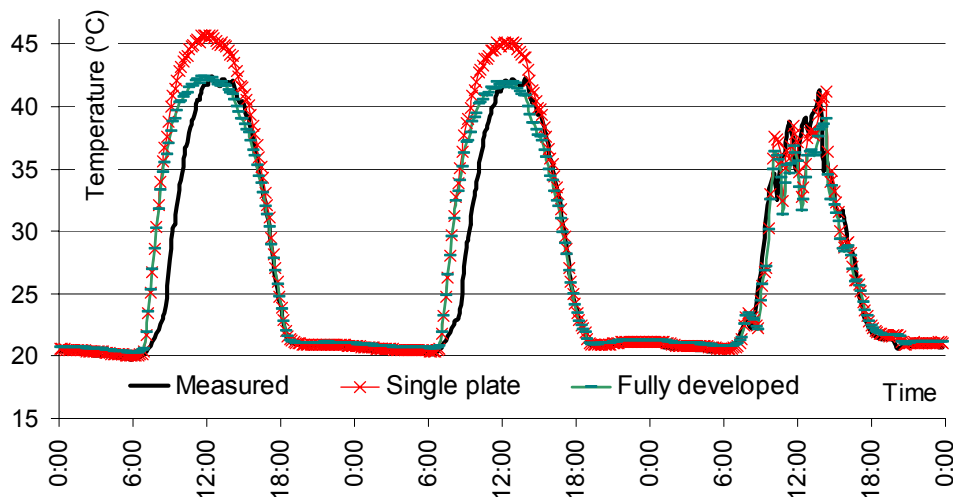


Figure 4-24: Temperature of the dark glazing, in Winter mode with a 2-cm air gap, as measured and as simulated with single plate natural convection and with fully developed natural convection.

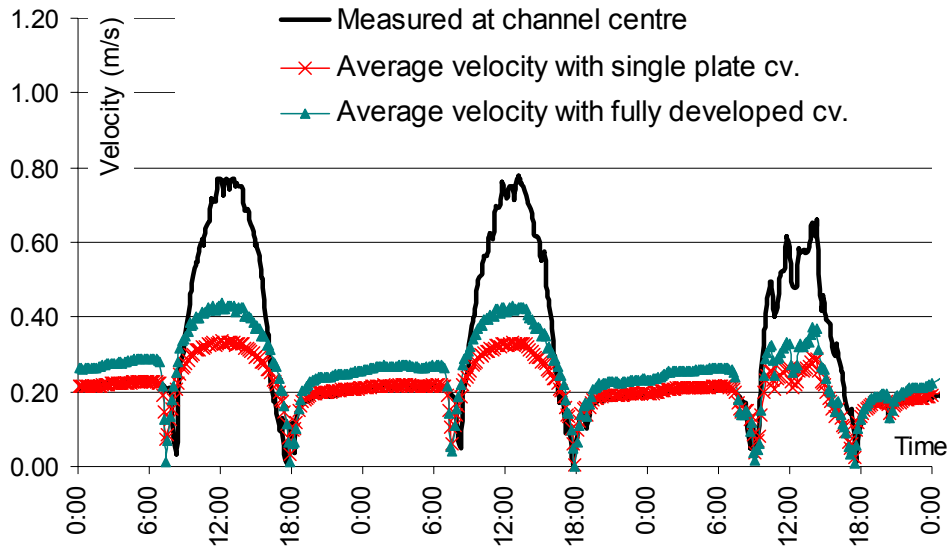


Figure 4-25: Velocity in the air channel, in Winter mode with a 2-cm air gap, as measured at the centre of the air gap, and as simulated with single plate natural convection and with fully developed natural convection.

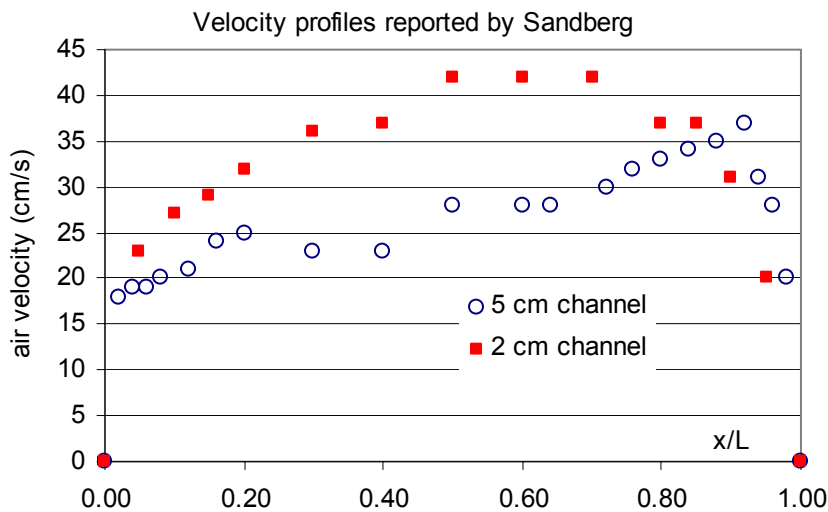


Figure 4-26: Cross-section velocity profile in 2 cm and in 5 cm wide air gaps, as reported in (Sandberg, 2002).

Since the first results indicate that the thermal and aerodynamic behaviour of the window is something between the single plate and the fully developed convection, it is reasonable to try to use the blending correlation developed when studying the 4 cm channel, eq. 4-4, bearing in mind that the constant C needs to be readjusted to the new geometry. A brief trial-and-error procedure reveals that a blending constant of $C=1 \times 10^3$ is adequate (figure 4-27).

The graphs from figure 4-28 to figure 4-30 show the temperatures of the three glazings, as measured and as simulated with the new blend correlation. Table 4-2 shows the statistical parameters of comparison with the measurements, for the glazing temperatures, including also the limiting cases of single plate convection and fully developed flow.

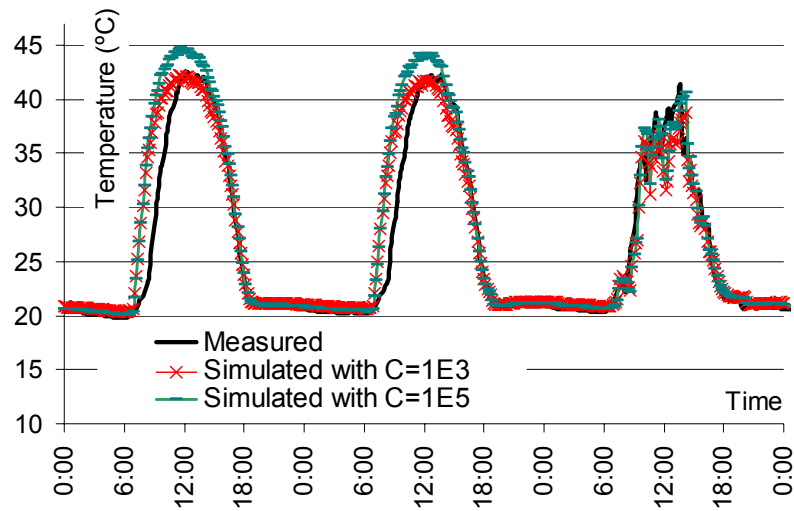


Figure 4-27: Temperature of the dark glazing, as measured and as simulated with the new blend correlation, with two values for the blending constant C .

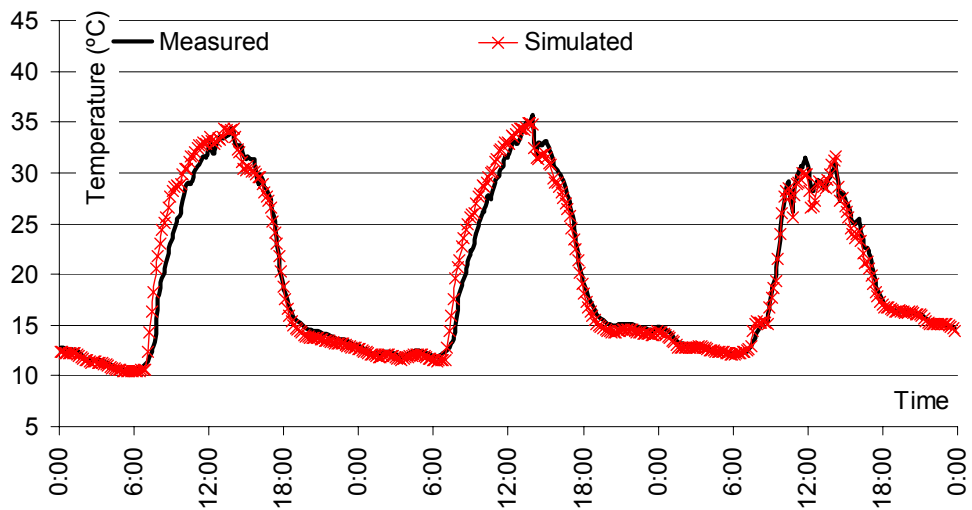


Figure 4-28: Temperature of the external glazing for the 2 cm air gap in Winter mode.

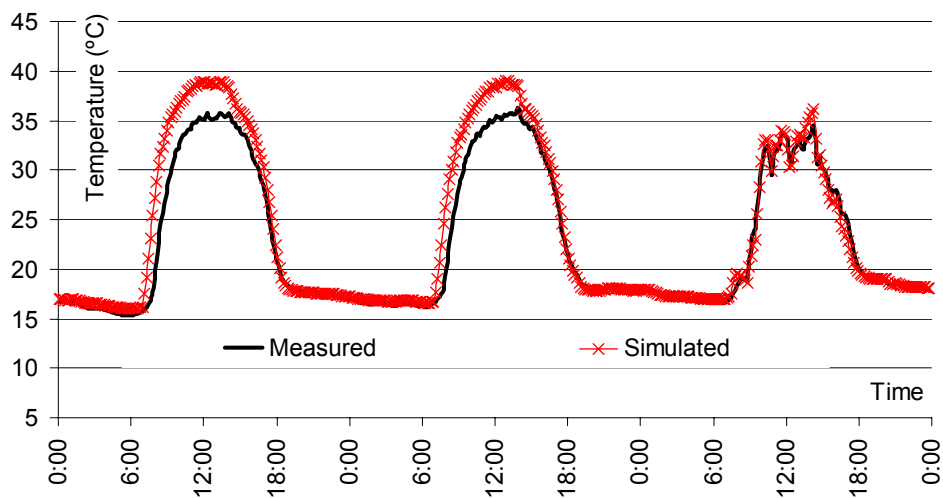


Figure 4-29: Temperature of the middle glazing for the 2 cm air gap in Winter mode.

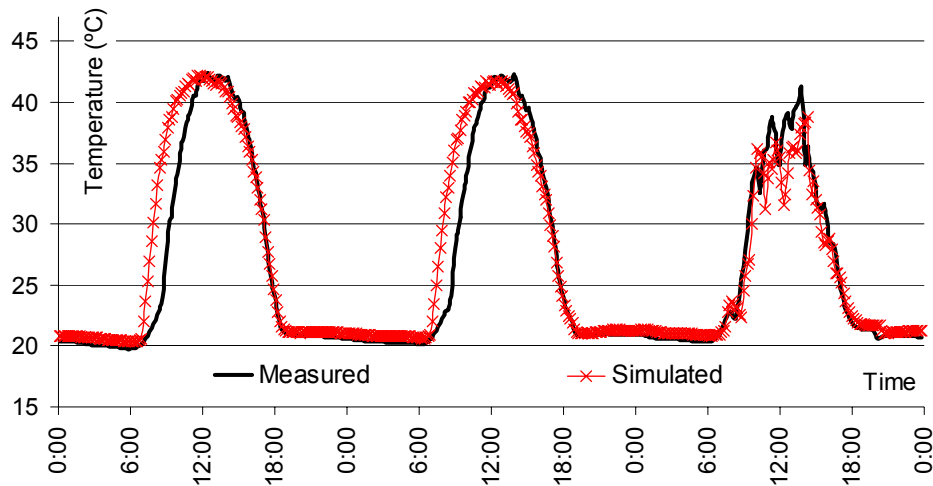


Figure 4-30: Temperature of the indoor side glazing for the 2 cm air gap in Winter mode

The results generally show a good agreement, although there is some overestimation of the middle glazing temperature and a slight advance in the time of the prediction of the absorptive glazing temperature during the morning. This could be due to some of the assumptions inherent to the air flow model developed in section 2.2. In fact, the set of equations in section 2.3 assumes that the flow is nearly steady and therefore disregards the effect of time-variations. The early morning is one of the times of the day when conditions vary quickly and therefore this approximation is more distant from reality. Furthermore, in section 2.2.4 it was assumed that the entry and exit loss factors are constant, but it also stressed that this frequent approximation in engineering applications could be not met for flows characterised by low Reynolds numbers. And, in fact, at the early morning the flow is reversing from downwards to upwards, with very low velocities and Reynolds numbers. In other words, during the early morning the flow has to reorganise itself and to overcome the inertia of the surrounding medium, which may cause a certain delay not foreseen by the model.

The results also show that the new blend correlation is, in this case, nearly behaving as one of its theoretical limits, the fully developed flow natural convection.

Table 4-2: Summary of statistical parameters of comparison with measurements, Winter mode 2 cm

	External glazing			Middle glazing			Inner glazing		
	Corr	MAD	RMSD	Corr	MAD	RMSD	Corr	MAD	RMSD
Single plate	0.97	1.2	1.5	0.96	1.6	2.3	0.92	1.6	2.8
Fully developed	0.97	1.1	1.4	0.96	1.2	1.8	0.92	1.6	2.6
New blend	0.97	1.1	1.4	0.96	1.2	1.8	0.92	1.6	2.6

4.7 RESULTS FOR SUMMER MODE, OPEN CHANNEL WIDTH 4 CM

As described in chapter 2, the SOLVENT window was also tested in Summer mode, with an air channel of 4 cm, during the period from the 10th to the 16th May 2003. Figure 4-31 shows the evolution of the outdoor temperature, cell temperature, global solar radiation and diffuse solar radiation on the horizontal plane during this period. Figure 4-32 shows the evolution of wind speed and direction.

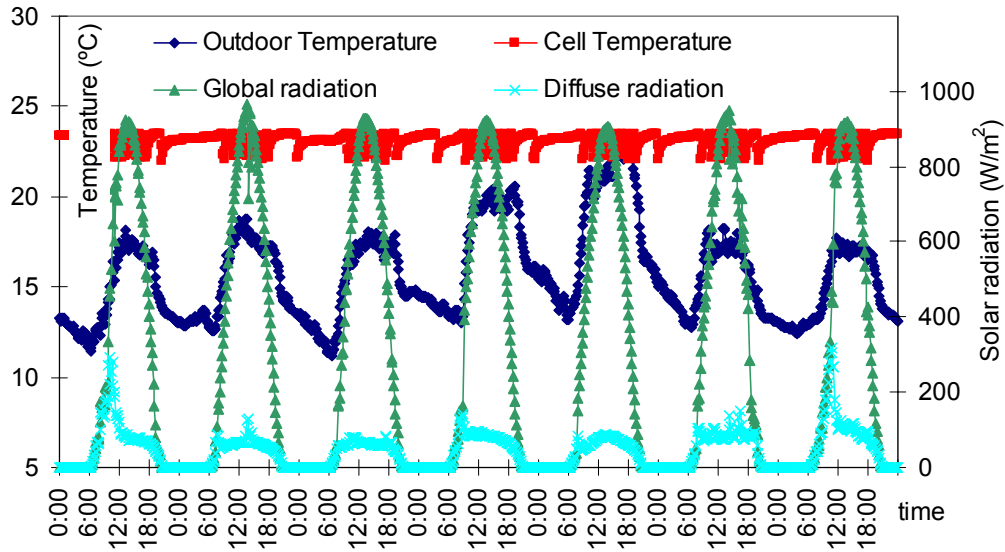


Figure 4-31: Outdoor temperature, cell temperature, global radiation on the horizontal plane and diffuse radiation on the horizontal plane during the period 10th-16th May 2003.

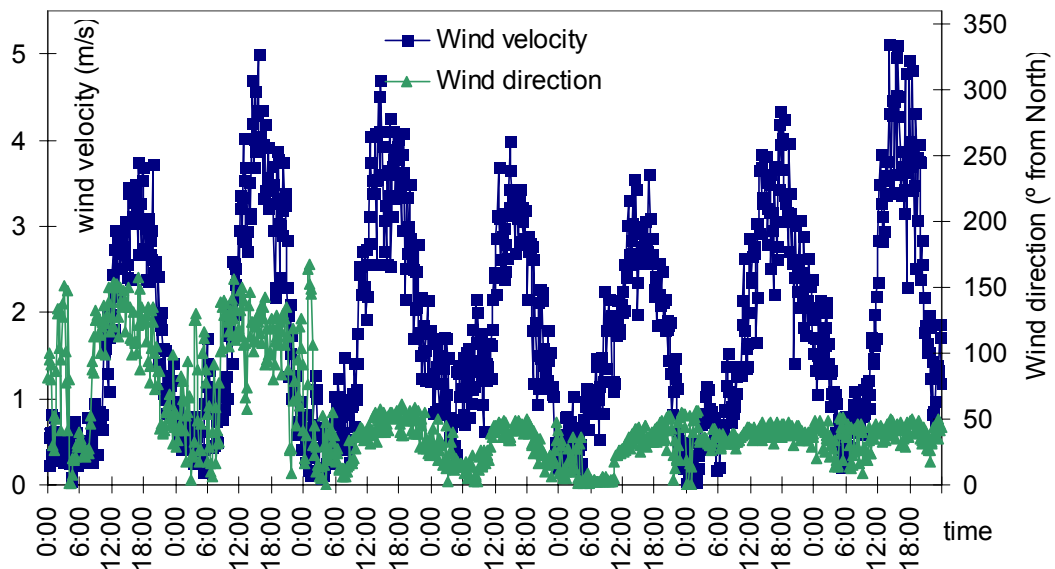


Figure 4-32: Wind velocity and direction during the period 10th-16th May 2003.

Three days were chosen as reference for graphical representation, in order to improve the clarity of the graphical analysis (14th-16th May).

In Summer mode, the absorptive glazing is facing outdoors, and the air channel is open to the outdoor air both at the bottom and at the top. Figure 4-33 shows the temperature of the absorptive glazing, as measured and as simulated with the two limiting cases of heat convection in the air channel: Natural convection along a vertical single plate and natural convection with fully developed flow in a vertical channel.

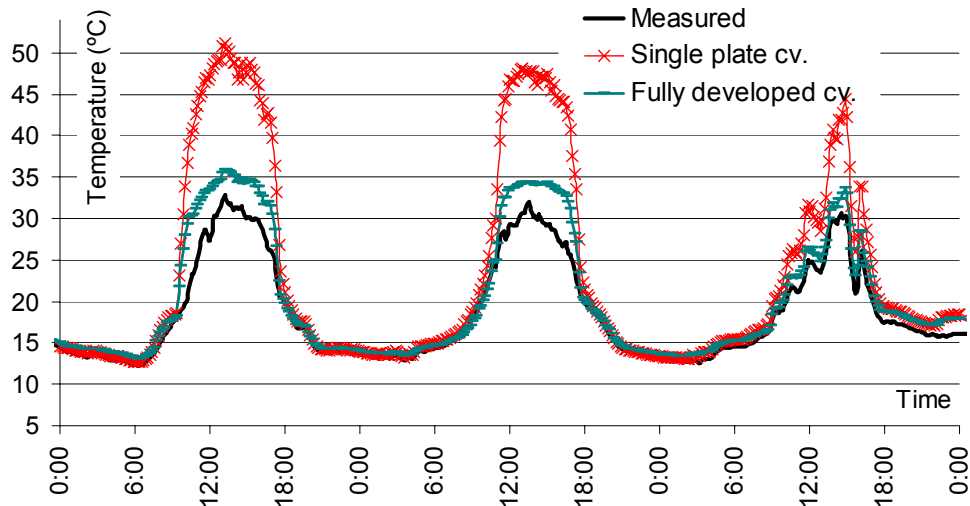


Figure 4-33: Temperature of absorptive glazing, simulated with the single plate natural convection and with fully-developed flow natural convection

As expected, during the day, single plate convection leads to much higher temperatures than fully developed flow convection. This happens because the heat convection coefficients calculated with single plate convection are much lower than those calculated with fully developed convection. However, unlike what happened in Winter mode, even the fully developed convection, which has higher convection coefficients, leads to a temperature prediction that is tangibly higher than the measured temperature. These results mean that there must be some other factor contributing to the heat dissipation in the absorptive glazing, in addition to those that were already analysed.

The key for these discrepancies is, as could be expected, the environmental wind. In fact, it may now be recalled that the absence of influence from the environmental wind upon the air velocity in the open air channel was the main reason for having started the study with the Winter mode configuration. Figure 4-34 shows a sequence of 6 photos of the anemometer display taken with intervals of a few seconds (approx. 30 seconds for the complete sequence). Unlike what happened in Winter mode, in Summer mode the velocity of the air in the open air channel has strong fluctuations with a short time-scale.

The wind has two main effects on the glazing system:

a) The instantaneous air velocity in the open air channel loses the primary dependence on the temperature difference between the channel walls and the entering air (figure 4-35) and becomes primarily dependent on the environmental wind velocity (figure 4-36), at least for wind speeds higher than about 1 m/s.

b) The velocity fluctuations induced in the open air channel cause an in-and-out flux of air at the bottom and at the top openings of the air channel. The net effect is equivalent to increasing the heat transfer coefficient between the external glazing and the outdoor air.

The scientific literature shows that the characterization of the effect of wind upon flows and heat convection is nearly always done by establishing experimental correlations. This method is also used for similar purposes as, for example, finding the pressure coefficients in double-skin façades (Gomes and Silva, 2004). Apart from the very simplest geometries, such as a flat plate, for most cases the complexity involved in trying to obtain an analytical solution is such that it is not possible to solve the equations.

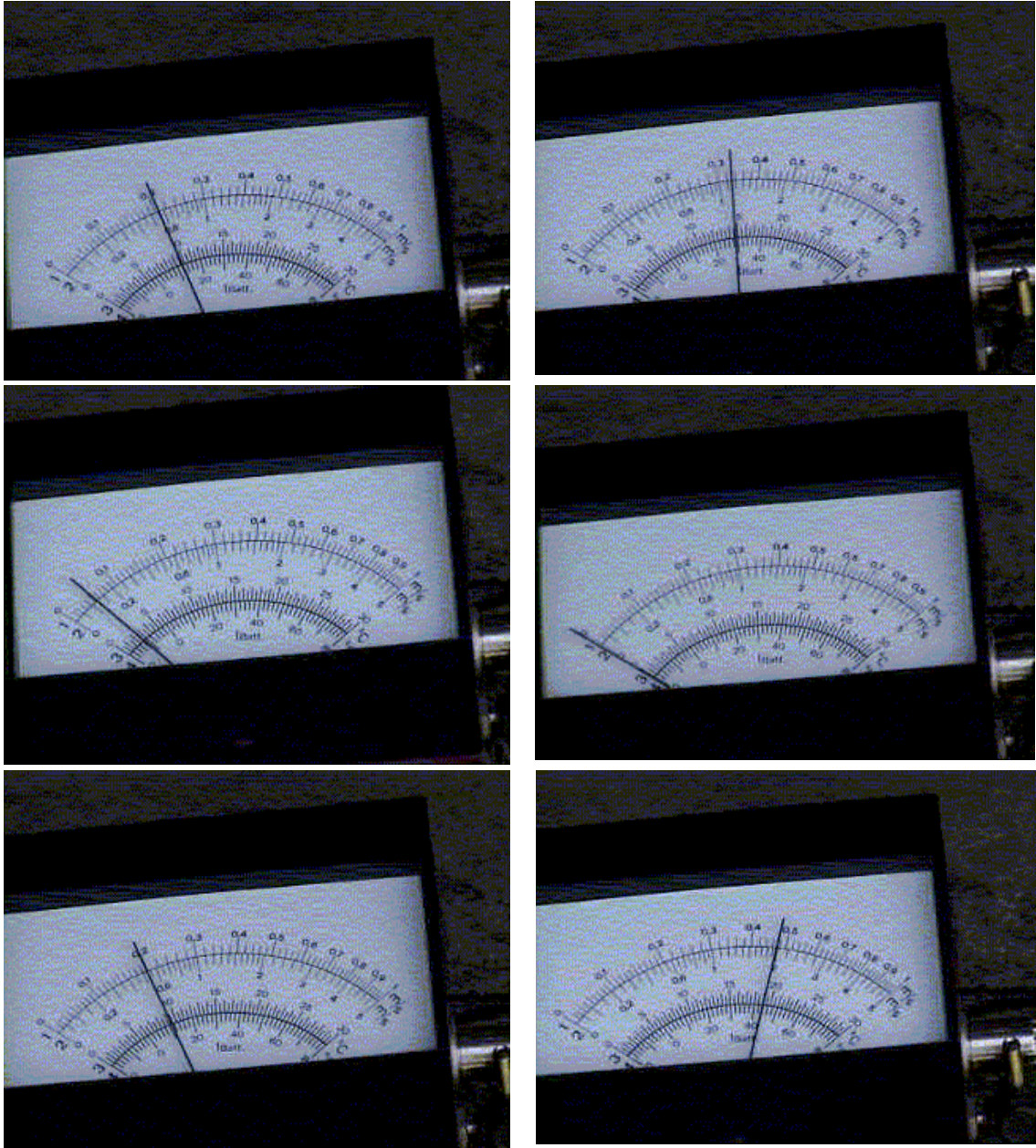


Figure 4-34: Sequence of photos of the anemometer display taken with intervals of a few seconds (approx. 30 seconds for the complete sequence)

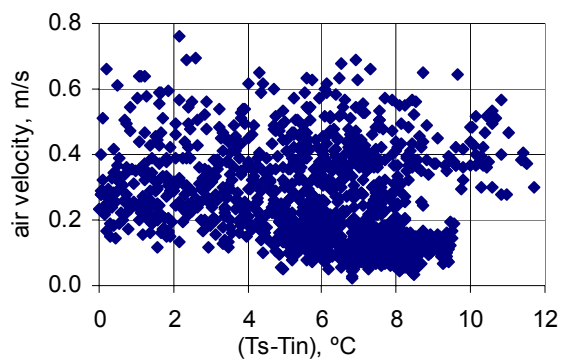


Figure 4-35: Channel air velocity vs. absolute value of temperature difference between channel surfaces and outdoor air.

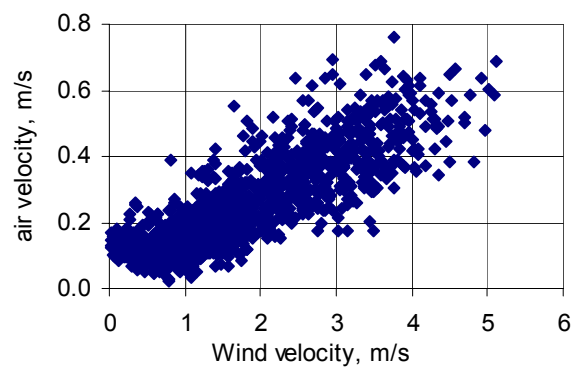


Figure 4-36: Channel air velocity vs. environmental wind speed

Theoretically, CFD simulations have the potential to predict the effect of wind upon the flow. However, they require a high degree of detail in the experimental monitorization, for calibrating and validating the models, which could not be compatible with the experimental setup used. Furthermore, a new detailed study would still be required for each specific geometry. Considering these limitations, inherent to nature of the processes, the procedure adopted to include the effect of wind in the air channel, in Summer mode, consists of two steps based on a practical approach:

- i) Finding and incorporating in the model a correlation representing the influence of environmental wind upon the channel air velocity.
- ii) Including an “augmentation factor” to the heat transfer coefficient between the outer glazing and the outdoor air, due to the air velocity fluctuations.

Figure 4-37 provides a linear correlation between the air velocity in the air channel and the outdoor air. Since figure 4-36 shows that this dependence is only dominant for wind velocities higher than 1 m/s, the correlation was obtained with data that meets this condition and is only applied when this condition is met.

Concerning the heat convection with the outdoor air, after several hypothesis were tested, it was empirically found that the Rowley correlation used in DOE-2 (eq. 2-13), increased by 50% leads to a reasonable agreement.

Given the good results achieved in Winter mode and its strong link to the physics of the phenomena, the base correlation chosen for the heat convection in the air channel was the new blend correlation eq. 4-4. The effect of wind was then added to this base, as described in the previous paragraphs. Table 4-3 summarises the resulting methods for treating the channel heat convection, convection with the outdoor air, and channel air velocity.

The graphs from figure 4-38 to figure 4-41 show the glazing temperatures and the air velocity in the air channel as measured and as simulated with these conditions. Table 4-4 shows the statistical parameters characterizing the agreement between the simulated and the measured values, including several options on the treatment of the channel and of the exterior glazing convection.

The results of the model with the corrections for wind effect are quite satisfactory. The value of the mean average deviation for the glazings is always below 1°C. Table 4-4 also shows that not accounting for the wind effect would lead to strong deviations in the prediction of the external glazing temperature (with an MAD value around 2.5 °C).

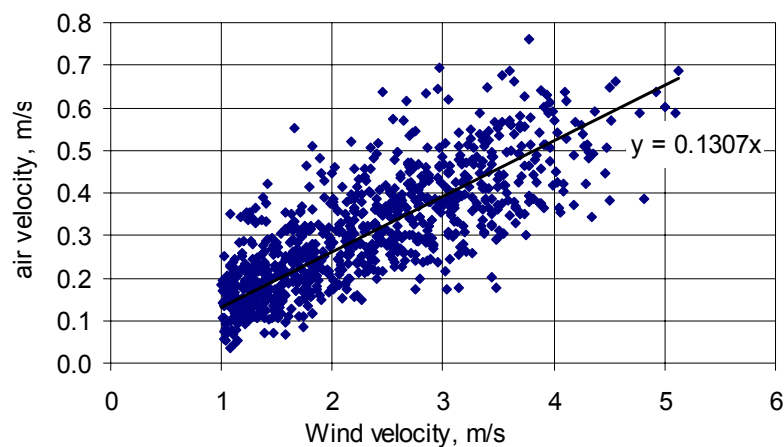


Figure 4-37: Correlation between channel air velocity and environmental wind speed, for wind speed higher than 1 m/s.

Table 4-3: Methods applied in the simulation of the Window in Summer mode (4 cm channel)

<i>Item</i>	<i>Solution adopted</i>
Channel heat convection	New blend correlation, eq. 4-4
External convection	Rowley's correlation increased by 50%
Channel air velocity	- As calculated by eq. 2-36, if wind velocity $\leq$ 1m/s; - Maximum of (eq. 2-36, $0.1307 \cdot \text{wind_speed}$), if wind velocity $>$ 1m/s

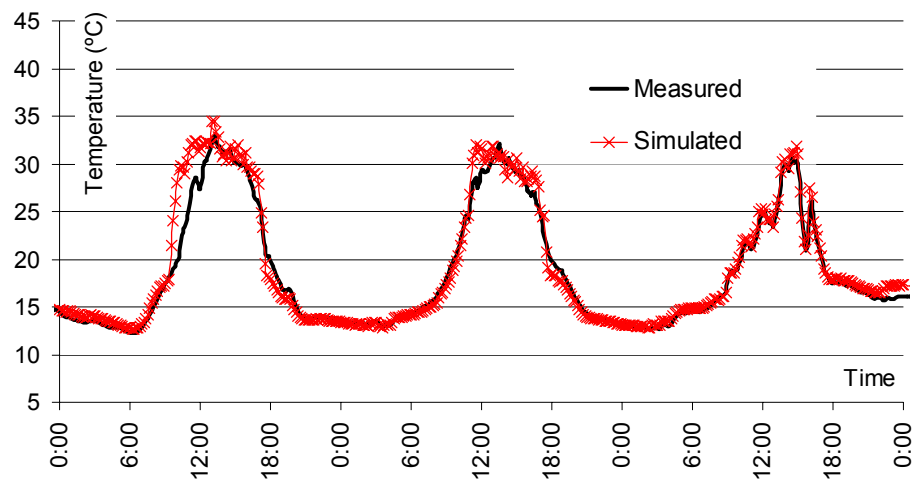


Figure 4-38: Temperature of the external glazing as measured and as simulated after the model adjustment to include the wind effects.

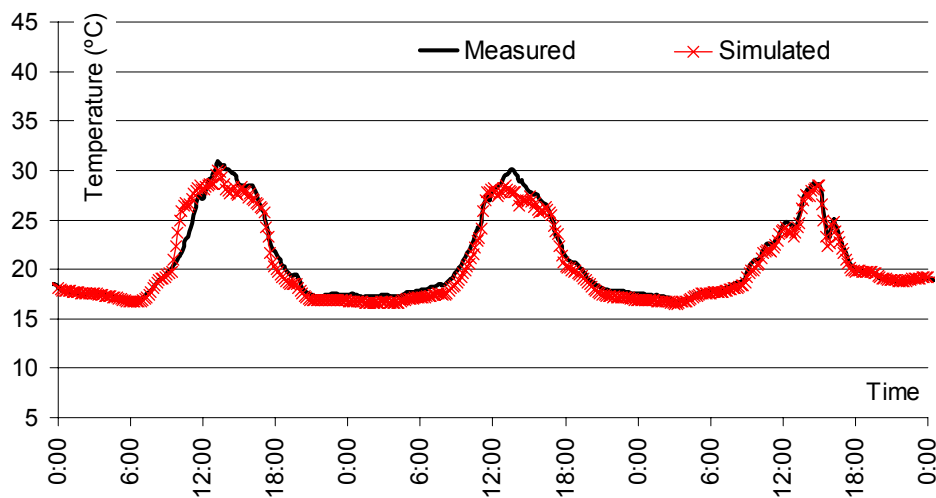


Figure 4-39: Temperature of the middle glazing as measured and as simulated after the model adjustment to include the wind effects.

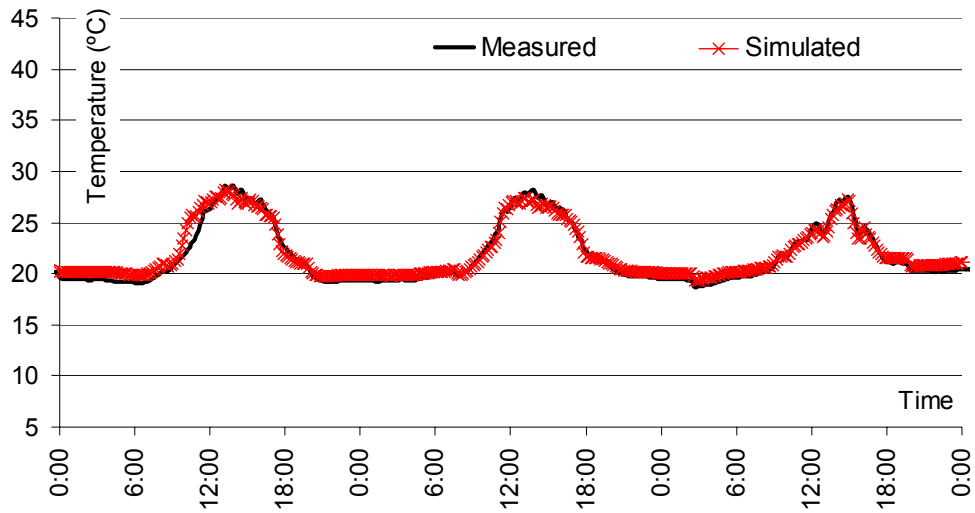


Figure 4-40: Temperature of the inner glazing as measured and as simulated after the model adjustment to include the wind effects.

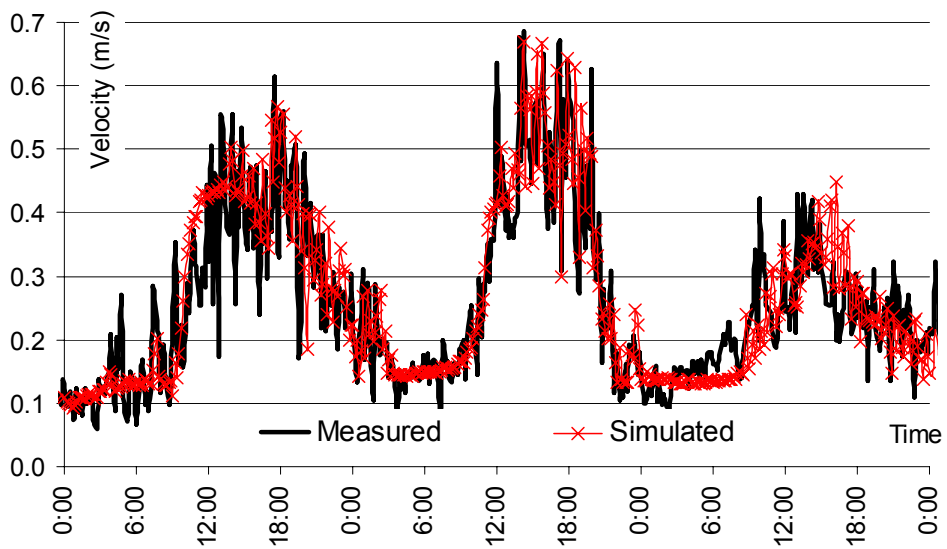


Figure 4-41: Air velocity in the open air channel as measured and as simulated after the model adjustment to include the wind effects.

Table 4-4: Statistical parameters of comparison between simulated and experimental values for different channel convection options, configuration Summer mode 4 cm

	Channel convection	New blend eq. 4-4)	New blend eq. 4-4)	New blend eq. 4-4)
	External convection	Yazdanian & Klems (eq. 3-18)	Yazdanian & Klems (eq. 3-18)	Rowley $\times 1.5$ (eq. 3-13)
	Channel velocity	No wind effect	With wind effect (table 4-3)	With wind effect (table 4-3)
External glazing (absor.)	Corr	0.98	0.98	0.98
	MAD	2.56	2.51	0.94
	RMSD	4.11	4.06	1.59
Middle glazing	Corr	0.99	0.99	0.98
	MAD	1.08	1.08	0.72
	RMSD	1.61	1.61	0.96
Indoor glazing	Corr	0.99	0.99	0.99
	MAD	0.84	0.81	0.53
	RMSD	1.03	1.00	0.66
Channel air velocity	Corr	0.69	0.88	0.89
	MAD	0.09	0.06	0.05
	RMSD	0.12	0.08	0.07

4.8 RESULTS FOR SUMMER MODE, OPEN CHANNEL WIDTH 2 CM

The last configuration setup that will be analysed has an open channel of 2.0 cm operating in Summer mode. This setup was tested and monitored between the 4th and the 8th of May 2003. The climatic boundary conditions during this period are shown in figure 4-42 and in figure 4-43.

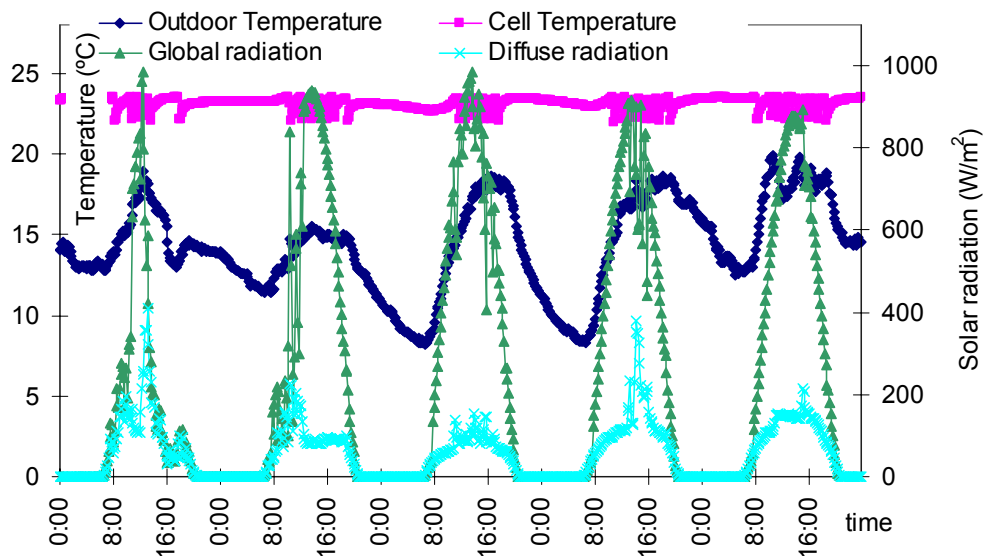


Figure 4-42: Outdoor temperature, solar radiation and test cell temperature during the period 4-8th May 2003

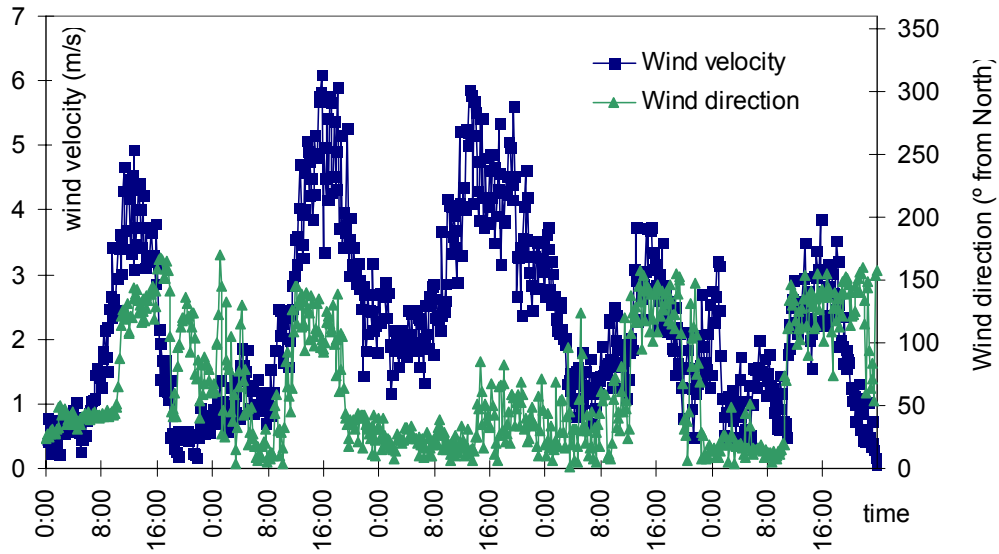
Figure 4-43: Wind speed and direction ($^{\circ}$ from North) during the period 4-8th May 2003

Figure 4-44 shows the correlation between the air velocity measured at the centre of the air channel and the difference between the channel glass walls and the inlet air temperature. Figure 4-45 shows the equivalent plot between air velocity at the centre of the air channel and the environmental wind. As for the 4 cm channel in Summer mode, the air velocity in the channel is essentially correlated with the wind, at least for wind speeds above 1 m/s. Figure 4-46 shows the correlation between the air velocity measured at the channel centre and the environmental wind, for wind speeds higher than 1 m/s. The proportionality constant calculated is 0.1178. Due to the parabolic profile characteristic of fully developed flow, the proportionality coefficient between the average air velocity in the channel and the wind velocity shall be half of this value, hence 0.0589. The air velocity in the air channel is thus computed as the maximum between the value computed by the buoyancy effect alone and the air velocity calculated taking into account the effect of wind ($0.0589 \cdot \text{windv}$).

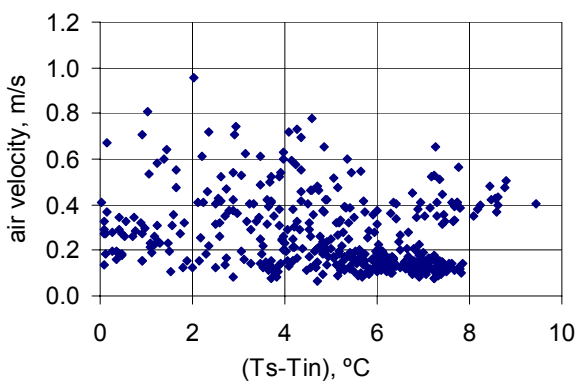


Figure 4-44: Centre air velocity vs. buoyancy temperature difference.

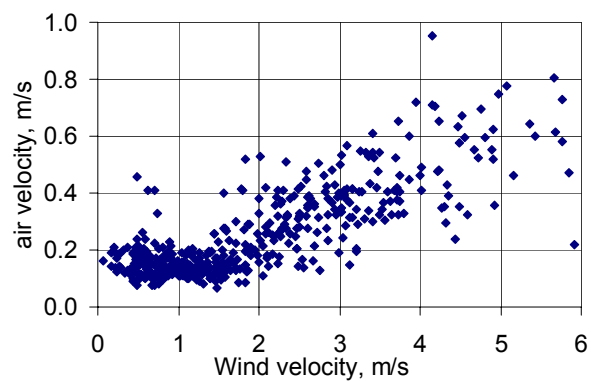


Figure 4-45: Centre channel air velocity vs. environmental wind velocity.

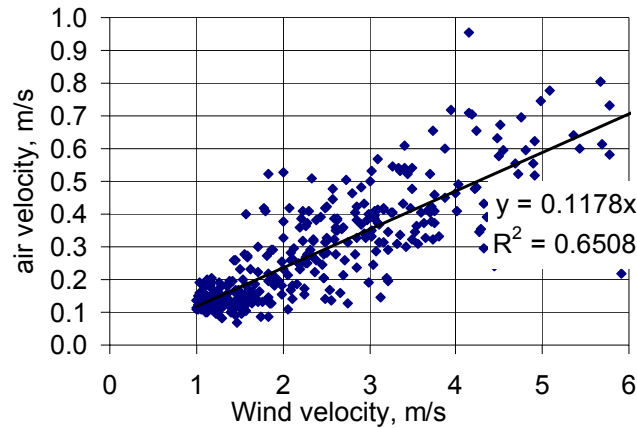


Figure 4-46: Correlation between channel air velocity (at center) and environmental wind speed for wind speed > 1 m/s.

As for all the previous configurations, the convection in the air channel is treated using the new blend correlation eq. 4-4.

For the heat convection with the outdoor air at the external glazing, the same correlation adopted for the window with 4 cm air gap in Summer mode (Rowley correlation increased by 50%) is also valid.

Table 4-5 summarises the resulting methods for treating the channel heat convection, convection with the outdoor air, and channel air velocity.

Table 4-5: Methods applied in the simulation of the Window in Summer mode (4 cm channel)

<i>Item</i>	<i>Solution adopted</i>
Channel heat convection	New blend correlation eq. 4-4)
External convection	Rowley's correlation increased by 50%
Channel air velocity	- As calculated by eq. 3.37, if wind speed $\leq$ 1m/s; - Maximum of (eq. 3.37, $0.0589 \cdot \text{wind_speed}$), if wind speed > 1m/s

The results of the simulation with the options described above are presented in the graphs from figure 4-47 and figure 4-48. The first three days of the period under analysis cover the highest meteorological variety and were therefore selected for graphical representation. During this period, the hotwire anemometer at the air channel was off part of the time, and the thermocouple in glazing 2 was found displaced. Therefore, the results for this glazing are not considered. Table 4-6 shows the statistical parameters characterizing the agreement between simulated and measured values. It also includes the results that are obtained without considering the wind effect, and those obtained treating the channel convection as fully developed. Overall, the results confirm the good agreement achieved with the optimized correlations. It is also clear that not accounting for the influence of wind in the intensification of the channel convection would result in large deviations between the temperature measured at the external glazing and the model predictions.

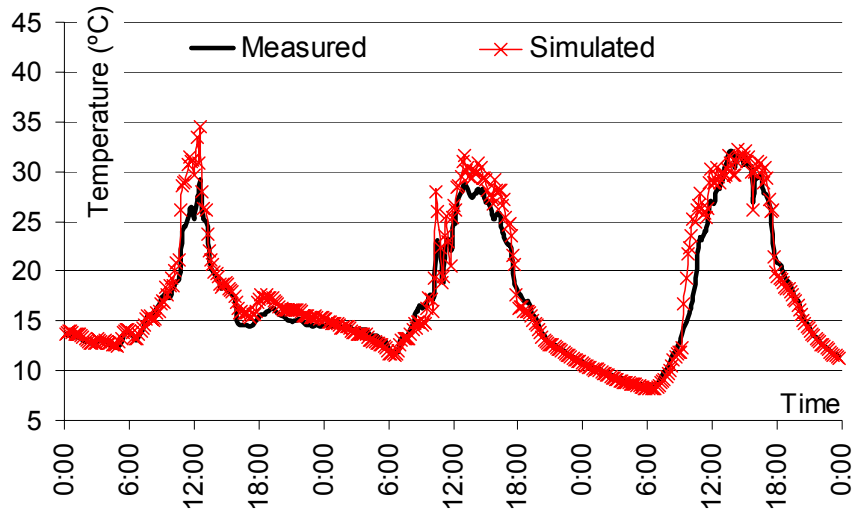


Figure 4-47: Temperature of glazing 1a as measured and as simulated, 2 cm channel in Summer mode.

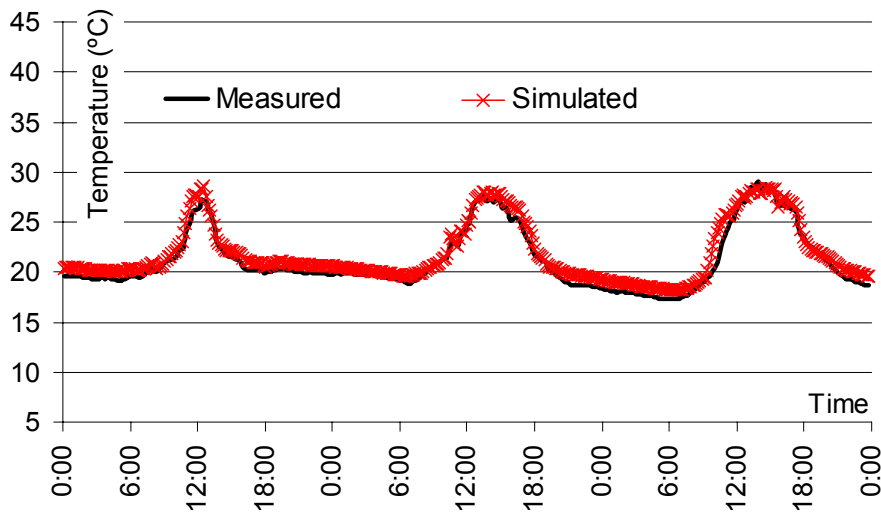


Figure 4-48: Temperature of glazing 3 as measured and as simulated, 2 cm channel in Summer mode.

Table 4-6: Statistical parameters of comparison between simulated and experimental values for different channel convection options, configuration Summer mode 2.0 cm

	Channel convection	New blend		
		Yazdanian & Klems (eq. 3-18 and 3-19)	Yazdanian & Klems (eq. 3-18 and 3-19)	Rowley $\times$ 1.5 (eq. 3-18 and 3-19)
		No wind effect	With wind effect (table 4-5)	With wind effect (table 4-5)
External glazing (absor.)	Corr	0.98	0.98	0.98
	MAD	3.51	3.52	1.14
	RMSD	5.84	5.84	1.92
Indoor glazing	Corr	0.98	0.98	0.99
	MAD	1.26	1.24	0.67
	RMSD	1.58	1.57	0.80

5 ANALYSIS OF THE ENERGY FLOWS

The previous chapter presented the development and calibration of an integrated model for simulating the thermal behaviour of the SOLVENT window. In this chapter, that model will be used to analyse the energy flows at each component of the window and across the window as a whole.

The chapter contains three sections. The first section shows a breakdown of the energy flow components at each glazing. It thus allows an assessment of the relative importance of each of the modes of heat transfer for each glazing. The second section presents the breakdown of the energy flow at the system boundaries, i.e., it assesses the magnitudes of energy flows at the boundary with the outdoor environment and at the boundary with the indoor environment. Finally, the third section deals with the calculation of the solar factor of the window in several configurations and operating modes. The calculated solar factor values are also compared with those of current products such as a double clear glazing window.

The analysis of the first and second sections is performed using the climatic data of two reference days. For the analysis of the solar factor, the reference boundary conditions were taken from the European standard EN 410 (CEN, 1998).

5.1 ENERGY FLOWS AT EACH GLAZING

The analysis of the relative importance of the energy balance components at each glazing was performed using data measured under real meteorological conditions. The selection fell upon the 21st and the 22nd of March 2003, a sunny day and a partially cloudy day, respectively. Table 5-1 shows a summary of the climatic conditions during these two days. A more detailed characterization was previously presented in section 4.6.

The configuration with open air channel of 4-cm will be used as reference for both Winter mode and Summer mode. Figure 5-1 recalls the outline of the window in each mode.

Table 5-1: Summary of the climatic conditions on the days used as reference for sections 5.1 and 5.2

	<i>21st March</i>	<i>22nd March</i>
Minimum outdoor temperature (°C)	10.6	10.5
Maximum outdoor temperature (°C)	22.0	20.0
Average wind speed (m/s)	2.3	1.4
Total daily solar radiation on the horizontal plane (MJ/m ²)	18.7	13.6
Maximum global solar radiation on the horizontal plane (W/m ²)	724	658

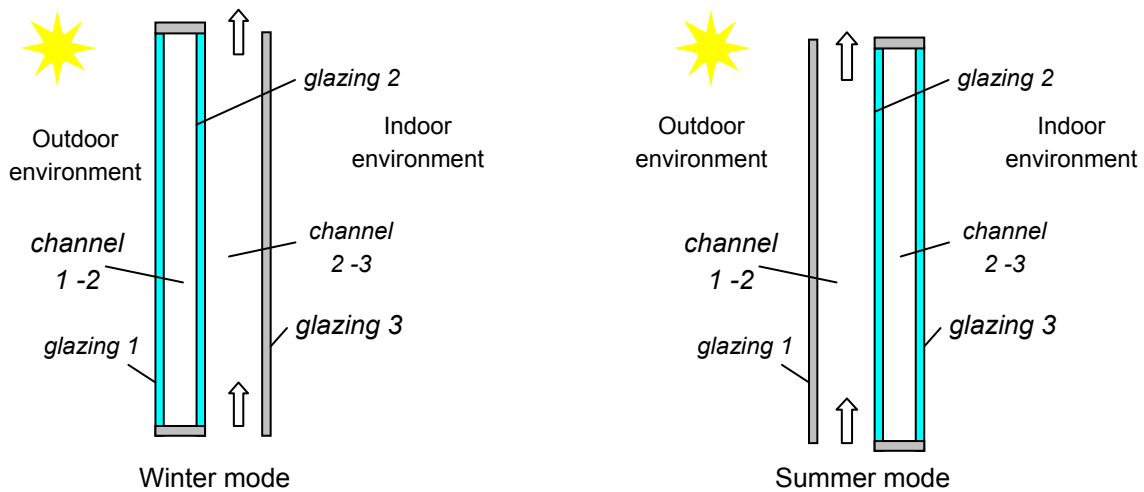


Figure 5-1: Outline of the SOLVENT Window in Winter mode and in Summer mode

5.1.1 Results for Winter mode

Figure 5-2 shows the components of the energy balance for glazing 1 (the exterior glazing), calculated for the sequence of the two reference days. The positive values are energy flows into the glazing, while negative values represent energy leaving the glazing. The values are shown in terms of heat flux per unit of glazing area, thus in W/m^2 .

Even though this is a clear glazing, absorption of solar radiation is the main mode of heat gain during day time. The rest of heat gain is typically arriving from glazing 2 (the middle glazing), both during day time and night time. It arrives by long wavelength radiation and by convection across the closed air gap 1-2. It is interesting to note that the energy transferred by the two modes is nearly equal: the lines for “LW radiation from glazing 2” and for “Convection from glazing 2” practically overlap in the graph of figure 5-2.

The main modes for heat loss are long wavelength radiation and convection to the outdoor environment. During night time, LW radiation exchange with the landscape surfaces and with the sky clearly predominates, thus underlying the importance of measuring the incoming LW radiation when performing calibration or validation studies involving heat balances at external surfaces. As measured by the pyrgeometer, during this reference period, the equivalent radiative outdoor temperature was always lower than the glazing temperature.

Finally, it is observed that the heat flux stored in the glazing is generally low. This observation is in line the often used assumption of neglecting the energy storage in window glazings.

Figure 5-3 shows the energy balance components for glazing 2 (the middle glazing). Alike glazing 1, and despite being a clear glazing too, the main mode of heat gain during day time is absorption of solar energy. The heat incoming by long wavelength radiation from glazing 3 (the absorptive glazing, facing indoors) is also important, and more relevant during night time.

The heat exchange between this glazing and the air circulating in the air channel 2-3 has a mixed behaviour. During daytime, the glazing is warmer than the air circulating upwards in the air channel, and thus the glazing loses heat to the airflow. The heat loss to the air

circulating in the air channel appears clearly as the most important mode of heat release by this glazing during daytime. During night time, the glazing is cooled by energy losses to glazing 1 and thus becomes colder than the air in the channel. The flow changes to the downward direction and the heat flow by convection becomes from the air to the glazing.

Under the climatic conditions tested, glazing1 was always colder than glazing 2 and thus the direction of the heat flow is always from glazing 2 to glazing 1. As it could be expected after the results for glazing 1, the heat fluxes by convection and by long wavelength radiation across the closed air gap have a nearly equal magnitude, which leads again to an almost overlapping of the two lines in figure 5-3.

Heat storage seems to be important at the early hours of the day and whenever the climatic conditions are changing quickly, e.g. in partially cloudy conditions during March 22nd.

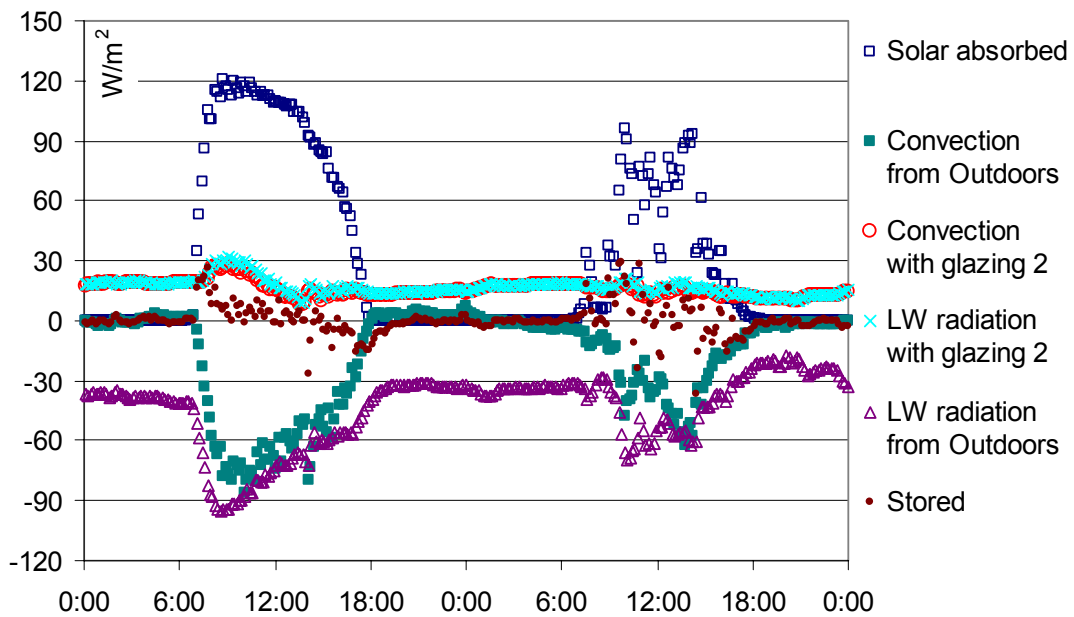


Figure 5-2: Components of the energy balance for the outside glazing in Winter mode.

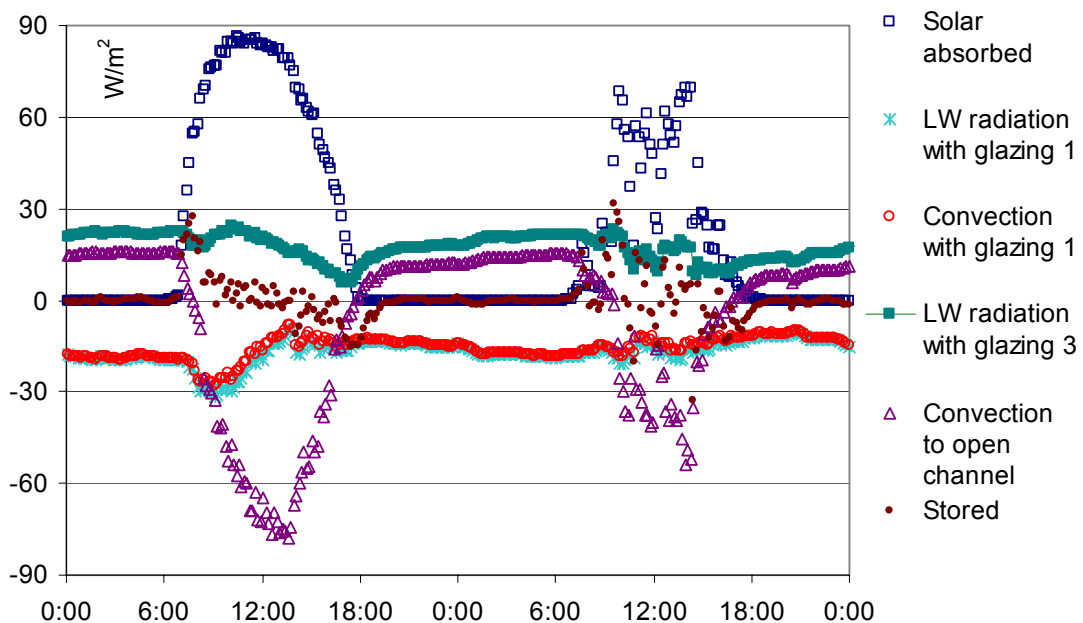


Figure 5-3: Components of the energy balance for the middle glazing in Winter mode.

The components of the heat balance for glazing 3 are displayed in figure 5-4. Glazing 3 is the absorptive glazing that, in Winter mode, is located indoors.

During daytime, the absorption of solar radiation is the only mode of heat gain. The glazing warms up to a temperature that is higher than anywhere in its surroundings. Therefore, all the other balance components are negative – except for the heat storage during the warm-up periods. Similarly to glazing 2, the main mode of heat dissipation during day time is heat convection to the air circulating in the open channel. The losses to the indoor environment, by long wavelength radiation and by heat convection, are also important, and often their sum is higher than the loss to the air channel alone.

Again, as expected, heat storage seems to play a part only when environmental boundary conditions are changing rapidly.

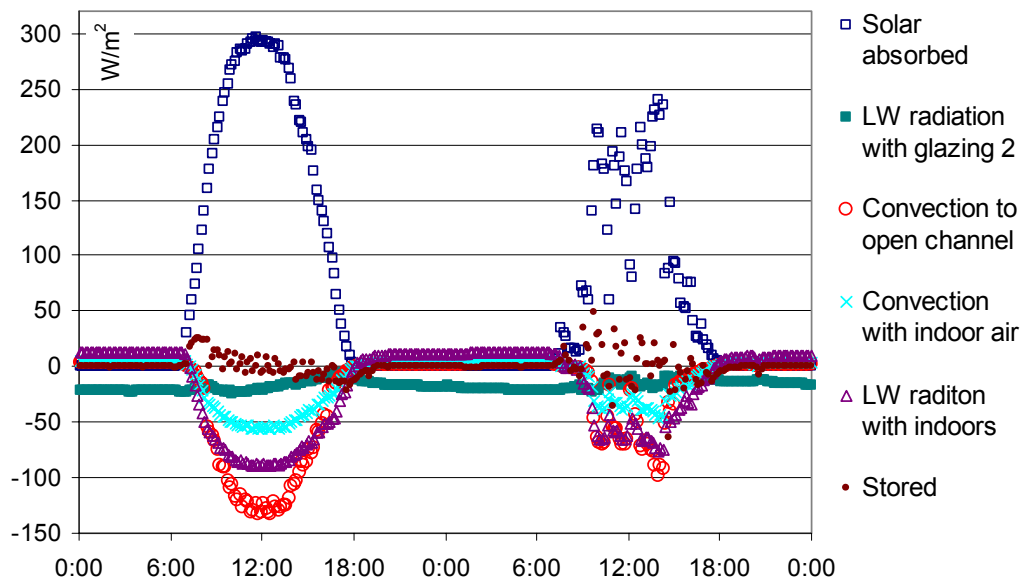


Figure 5-4: Components of the energy balance for the interior glazing in Winter mode.

5.1.2 Summer mode

The same kind of energy flow analysis performed for Winter mode in the previous section is repeated here for the Summer mode. The same climatic boundary conditions (21st-22nd March 2003) were used, so that the results may be compared with those obtained in Winter mode.

Figure 5-5 shows the components of the energy balance for glazing 1. In Summer mode, glazing 1 is the absorptive glazing, and this is clearly reflected in the high values of energy absorbed by the glazing. The positioning of the absorptive glazing to the exterior has a high relevance, since the peak solar radiation absorbed is 500 W/m^2 , while in Winter mode it was only 300 W/m^2 .

Once again, during daytime the glazing reaches temperatures higher than any of the surrounding elements. Therefore, all the other heat balance components are losses, with the exception of the heat storage during some short periods. The main mode of heat dissipation during day time is the convection with the exterior air at the exterior surface. The losses by

long wavelength radiation to the outdoor environment and by heat convection at the open air channel have comparable magnitudes.

Figure 5-6 shows the energy flow components at glazing 2. The energy flows at this glazing are noticeably lower than for the exterior glazing. The main mode of heat dissipation during day time is again the convection to the open air channel.

Finally, the components of the energy balance for glazing 3 are shown in figure 5-7. The exchange of long wavelength radiation with the indoor surfaces seems to be the dominant mode of heat release during daytime and also of heat gain during night time.

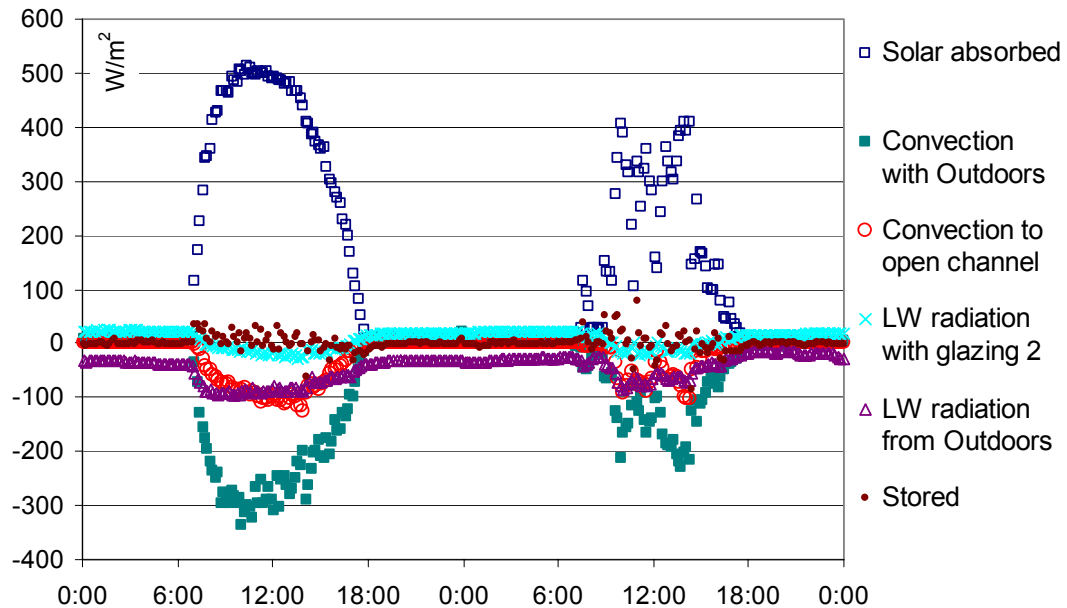


Figure 5-5: Components of the energy balance for the outside glazing in Summer mode.

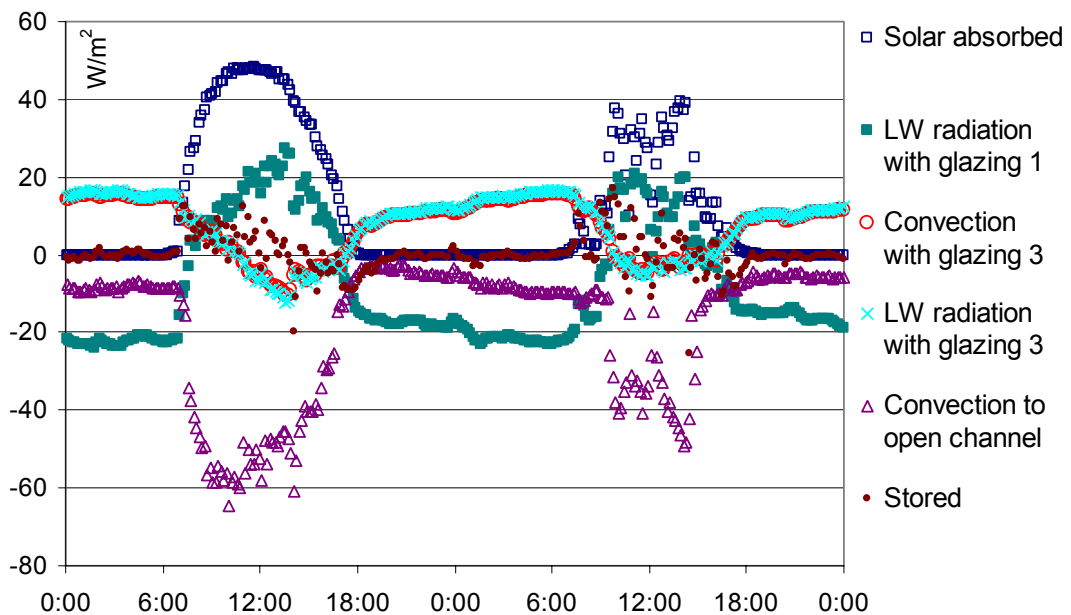


Figure 5-6: Components of the energy balance for the middle glazing in Winter mode.

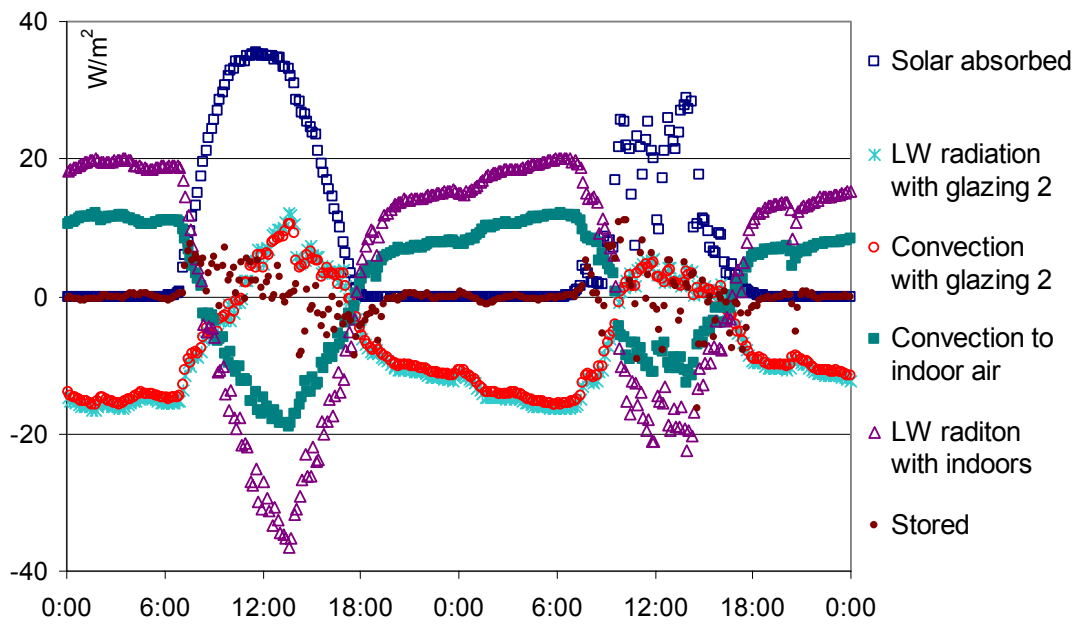


Figure 5-7: Components of the energy balance for the interior glazing in Winter mode.

5.2 ENERGY FLOWS AT THE SYSTEM BOUNDARIES

Following the specific analysis for each component performed in section 5.1, the focus will now be placed at the boundaries of the glazing system, in order to have an indication of the relative magnitude of the several modes of heat collection to indoors and of heat rejection towards outdoors. This also serves as a preparation for the analysis of the fraction of solar radiation that ends as an energy gain, which will be presented later in section 5.3.

The analysis will focus on the same reference days of the previous section (21st and 22nd of March 2003), and also keeping the window with an open channel of 4 cm as reference.

5.2.1 Winter mode

Figure 5-8 shows the calculated energy flows that cross the window boundary to the interior of the room. The results show that the heat collected by the air circulating in the air channel is of the same order or magnitude as the solar radiation that crosses directly through the glazing system. The heat transmitted indoors by the surface of the interior glazing, by free convection and by long wavelength radiation, is also quite relevant.

Figure 5-9 shows the energy flow components that are rejected by the window. In Winter mode these can therefore be labelled as energy losses. The main mode of energy rejection is reflectance, followed by long wavelength radiation exchange with the outdoor environment and closely by convection at the outside surface.

Figure 5-10 shows the energy flows admitted and rejected by the window as function of the incident energy. Some energy flows are also affected by other environmental variables such as outdoor temperature, wind, etc., so a certain dispersion was expected. There is, nevertheless, a basic dependence on the incident energy, which appears clearly in the graph.

Finally, figure 5-11 shows the total energy flows transmitted towards indoors and rejected towards outdoors, showing that the former is, typically, tangibly higher than the later.

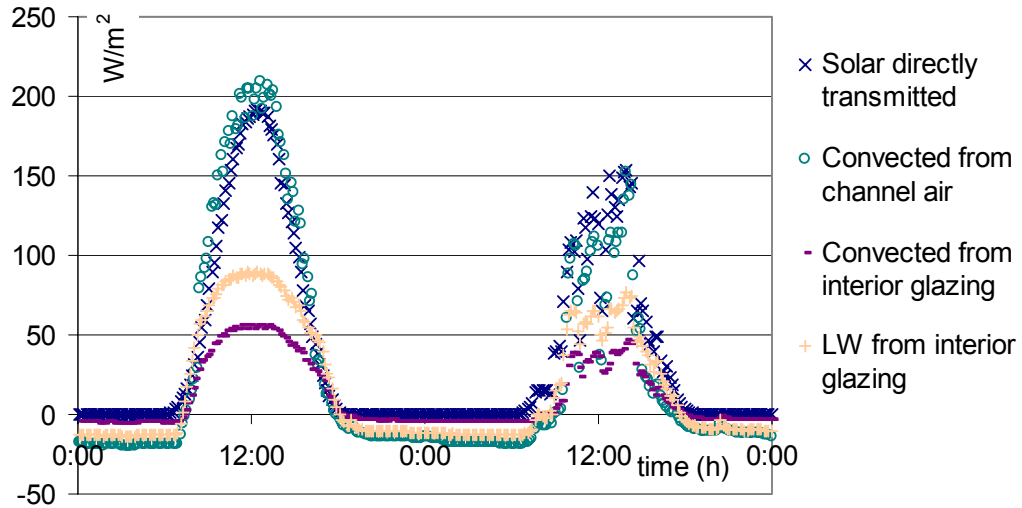


Figure 5-8: Components of the heat flow from the window to the interior space, operating in Winter mode and simulating with the climate of the 21st and the 22nd of March.

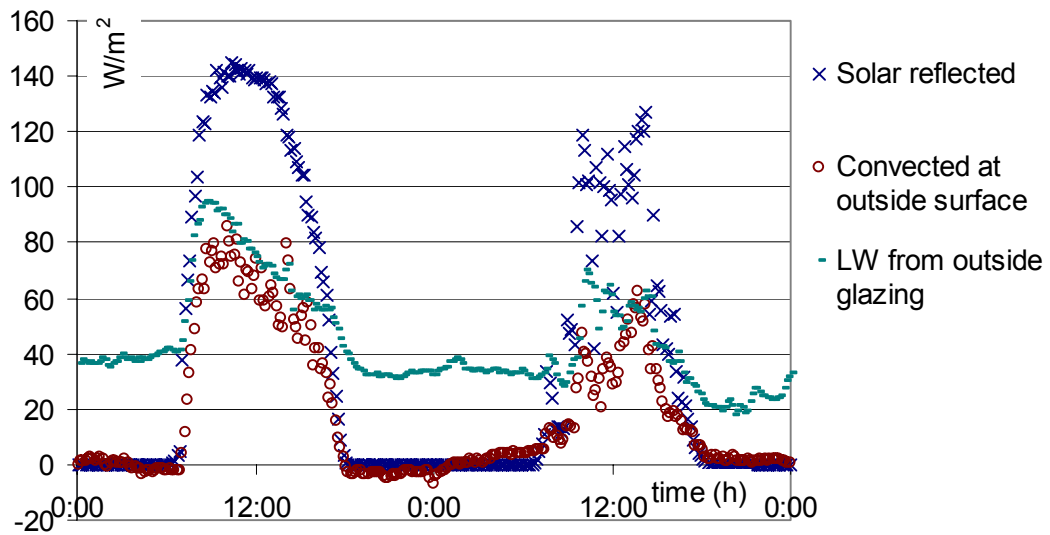


Figure 5-9: Components of the heat flow from the window to the outdoor environment, operating in Winter mode and simulating with the climate of the 21st and the 22nd of March.

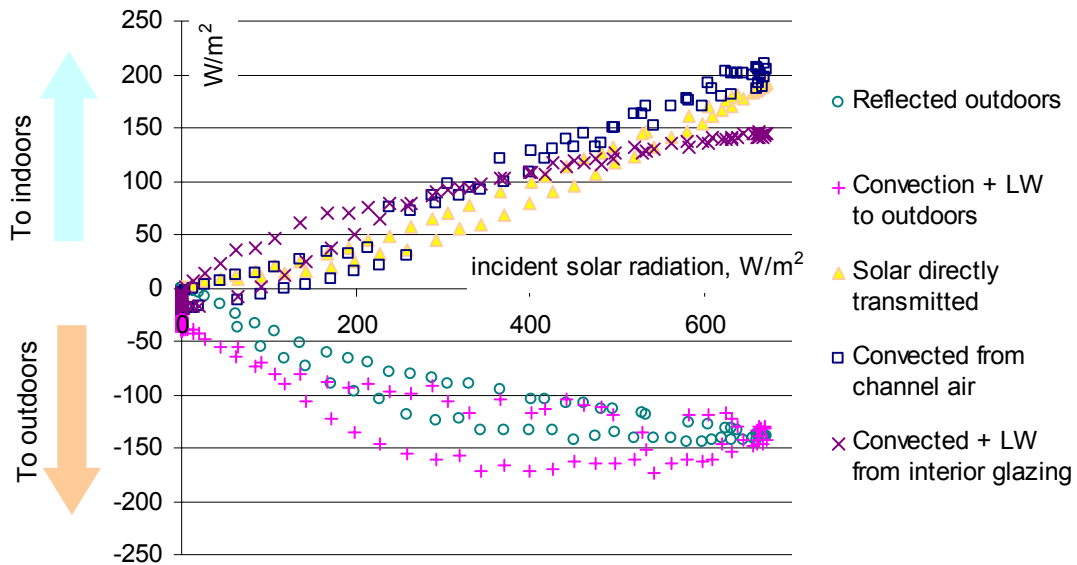


Figure 5-10: Energy flows at the window boundaries, operating in Winter mode and simulating with the climate of the 21st of March.

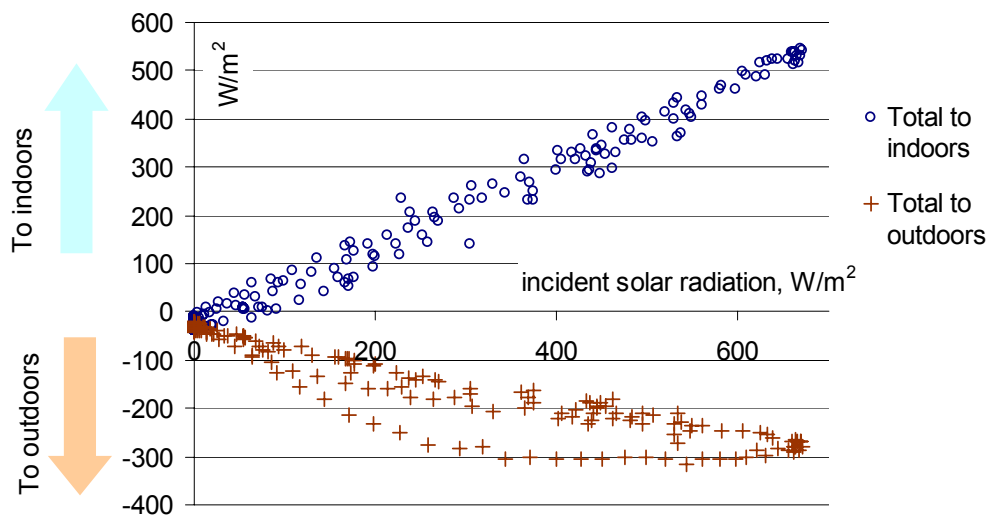


Figure 5-11: Total energy flows to indoors and outdoors, operating in Winter mode and calculating with the climate of the 21st and 22nd of March.

5.2.2 Summer mode

Figure 5-12 shows the energy flows that reach the interior of the room. The main component is, by far, the solar radiation directly transmitted. As could be expected, this term has in Summer mode about the same value as in Winter mode. The results also show that, in this mode of operation, the heat income by convection and LW radiation from the interior glazing is not very significant. This fact could already be somewhat expected, given the relatively moderate glazing temperatures monitored (chapter 4).

Figure 5-13 shows the energy flows that are rejected by the window. The main mode of heat rejection during day time is convection at the outside surface of the exterior glazing,

followed by convection from the air channel. During night time, the rejection is essentially due to long wavelength radiation.

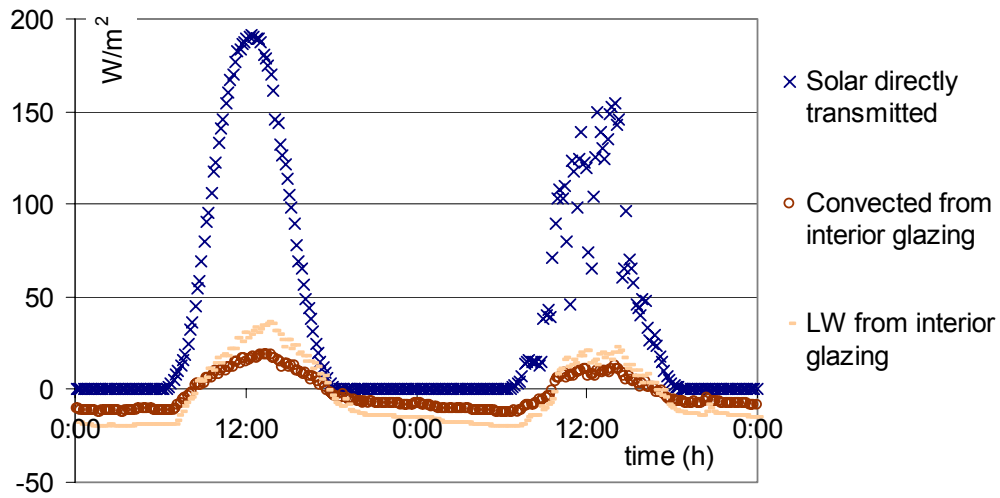


Figure 5-12: Components of the heat flow from the window to the interior space, operating in Summer mode and simulating with the climate of the 21st and the 22nd of March.

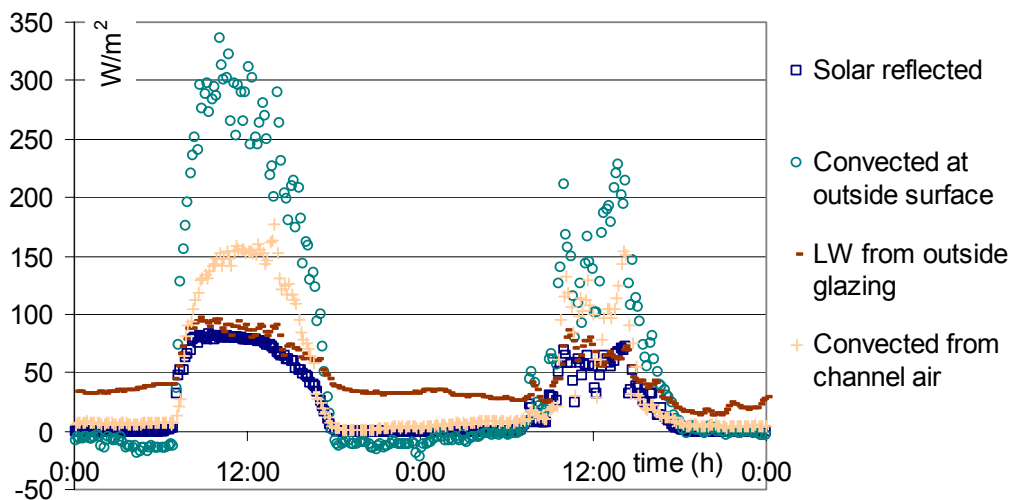


Figure 5-13: Components of the heat flow from the window to the outdoor environment, operating in Summer mode and simulating with the climate of the 21st and the 22nd of March.

As for Winter mode, figure 5-14 shows the energy flow components as function of the incident solar radiation. Figure 5-15 shows the equivalent information in terms of total energy flows towards indoors and towards outdoors. The results confirm that, in this mode, most of the incident solar energy is rejected outdoors, rather than entering the space.

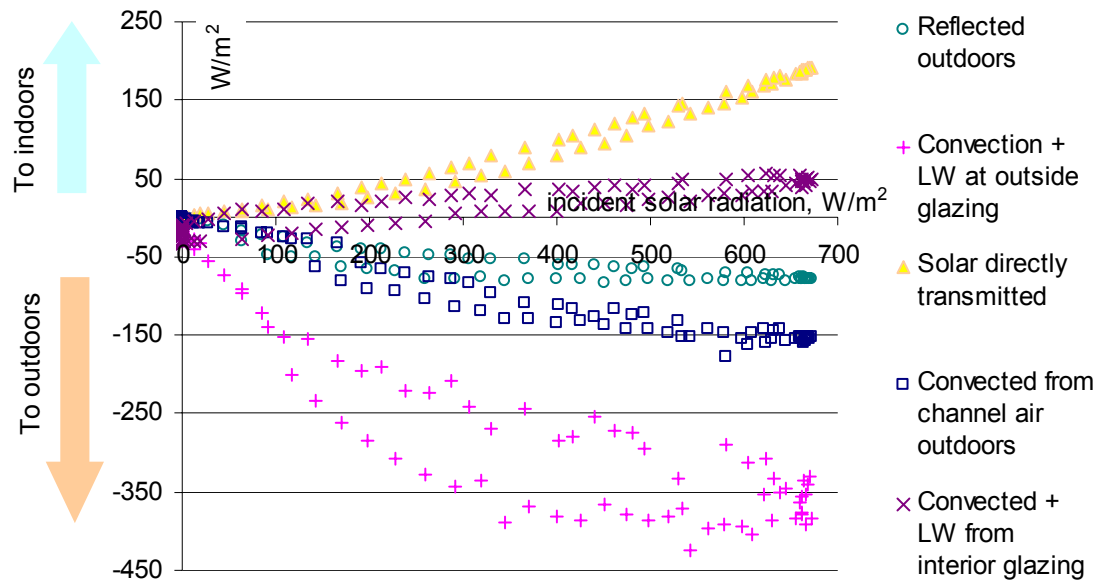


Figure 5-14: Energy flows at the window boundaries, operating in Summer mode and simulating with the climate of the 21st of March.

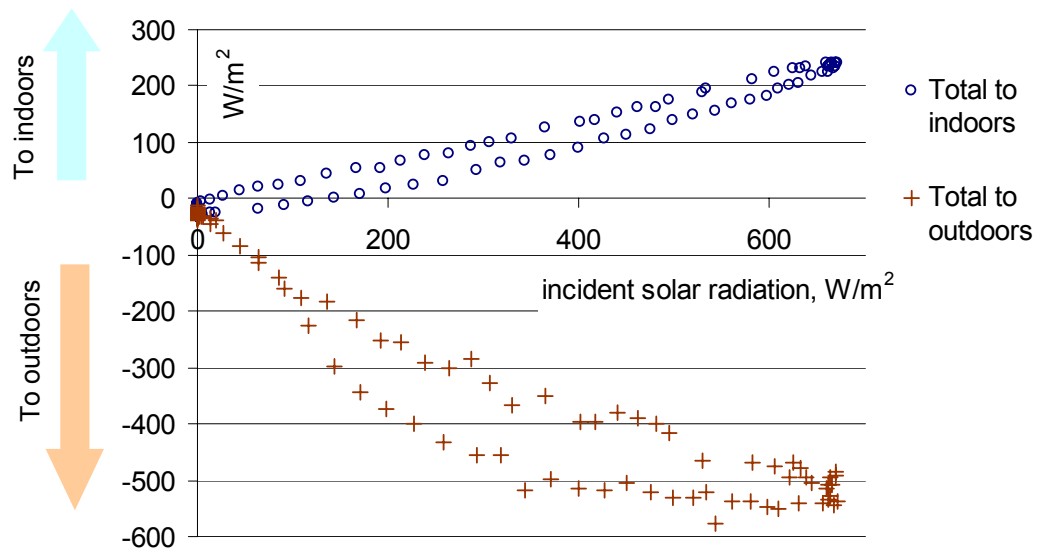


Figure 5-15: Total energy flows to indoors and outdoors, operating in Summer mode and calculating with the climate of the 21st and 22nd of March.

5.3 SOLAR FACTOR

The most used parameter to evaluate a window's capacity to collect the incident solar radiation is the *solar factor*. Conceptually, the solar factor represents the fraction of the incident solar energy that ends up as an energy gain to the interior space. This energy gain includes the component directly transmitted through the glazing, and the component that is absorbed by the window glazings and then transmitted towards the indoor environment by convection and long wavelength radiation.

The value of the solar factor calculated for a window depends to a certain extent on the boundary conditions assumed. Most glazing manufacturers publish the solar factor of their products based on ISO 9050 “Glass in building – Determination of light transmittance, solar direct transmittance, total solar energy transmittance and related glazing factors” (ISO, 1990). The European Committee for Standardization, CEN, adopted a version of ISO 9050 as EN 410 (CEN, 1998). This standard does not account for the possibility of ventilated air layers, as is the case of the SOLVENT window, so it cannot be directly applied to the case under study. There is an ISO standard – ISO 15099 (ISO, 2000) - developed for windows with ventilated air layers. However, it appears adequate mostly for cases when the ventilation is mechanically driven. Furthermore, the values of the solar factor stated by the manufacturers for the double clear glazings and for the double solar control glazings, which are the references for assessing the SOLVENT window, are calculated with the methods and boundary conditions of ISO 9050.

A realistic comparison may be achieved using the calculation model developed and validated in chapters 3 and 4, applying the same boundary conditions that are mentioned or implicitly assumed in the ISO 9050 / EN410 standard.

These boundary conditions are mainly:

- Solar incidence normal to the glazing surface.
- The combined convection and long wavelength radiation exchange coefficients are $8 \text{ W/m}^2\cdot\text{K}$ at the internal surface and $23 \text{ W/m}^2\cdot\text{K}$ at the external surface.
- Environmental wind speed of 4 m/s .

Moreover, in order to eliminate any effect of heat transmission not directly resulting from the solar radiation, it will be assumed that the air temperatures at each side of the glazing system (indoor and outdoor temperature) are the same, with the value of $20 \text{ }^\circ\text{C}$. The mean radiant temperatures of the indoor and outdoor environment are assumed the same as the air temperatures. To assure the directionality of the solar radiation imposed by the standard, only direct radiation was considered.

The conditions regarding normal incidence of solar radiation and wind speed can easily be imposed to the simulation model. Concerning the convection coefficients, since the model developed in this work does not use the concept of combined exchange coefficient, it is necessary to evaluate the value of the apparent LW exchange coefficient and then set the pure convection coefficient as the difference to the reference values fixed by the standard.

The apparent long wavelength exchange coefficient h_r , for a surface at temperature T_s , bounded by a neighbourhood at temperature T_{oth} , is defined in such way that the LW convective flux between a surface and the average temperature of the surroundings surfaces is given by:

$$q_{lw}'' = h_r (T_s - T_{oth}) \quad \text{eq. 5-1}$$

In this simple case of a surface with emissivity ε at temperature T_s , bounded by a neighbourhood at temperature T_{oth} , the LW radiation balance is:

$$q_{lw}'' = \sigma \varepsilon (T_s^4 - T_{oth}^4) \Leftrightarrow q_{lw}'' = \sigma \varepsilon (T_s^2 + T_{oth}^2) (T_s + T_{oth}) (T_s - T_{oth}) \quad \text{eq. 5-2}$$

The apparent LW radiation exchange coefficient is thus given by:

$$h_r = \sigma \varepsilon (T_s^2 + T_{oth}^2)(T_s + T_{oth}) \quad \text{eq. 5-3}$$

This means that the apparent LW exchange coefficient will vary with the surface temperatures. It can however be shown that the variation is limited. Table 5-2 shows the value computed for some combinations of $\varepsilon / T_s / T_{oth}$. In the verified range of temperatures, the radiative exchange coefficient has a value that is about $5.0 \pm 0.5 \text{ W/m}^2\text{.K}$. This means that the “pure” convection coefficient is about $18 \pm 0.5 \text{ W/m}^2\text{.K}$ at the external surface and $3 \pm 0.5 \text{ W/m}^2\text{.K}$ at the internal surface. These values can easily be imposed in the simulation model. In Summer mode these conditions can be met too but, as seen in chapter 4, the channel air velocity and the energy balance will also depend on the environmental wind speed. For the Summer mode the external convection coefficient was calculated maintaining the Rowley’s formula increased by 50 % (as seen in chapter 4), with a constant wind velocity of 4 m/s, as stated by the standard.

Table 5-2: apparent long wavelength radiation exchange coefficient for some temperatures (using glazing emissivity $\varepsilon=0.89$)

T_s (°C)	10	25	30
T_{oth} (°C)	5	15	25
h_r (W/m ² .K)	4.5	5.1	5.5

5.3.1 Solar factor in Winter mode

Figure 5-16 shows the calculated solar factor in Winter mode for the configuration with a 4 cm open channel. Figure 5-17 shows the equivalent information for the configuration with a 2 cm channel.

The results depend slightly on the incident solar radiation, reflecting the fact that the convection in the air channel depends on the glazing temperatures. Table 5-3 shows the average values for incident radiation ranging from 5 to 1000 W/m².

The solar factor of the double-clear glazing window alone is 0.75. The SOLVENT window thus represents a reduction in the solar factor, already expected, of about 10% for the version with a gap of 4 cm, and 13% for the version with the 2 cm air gap.

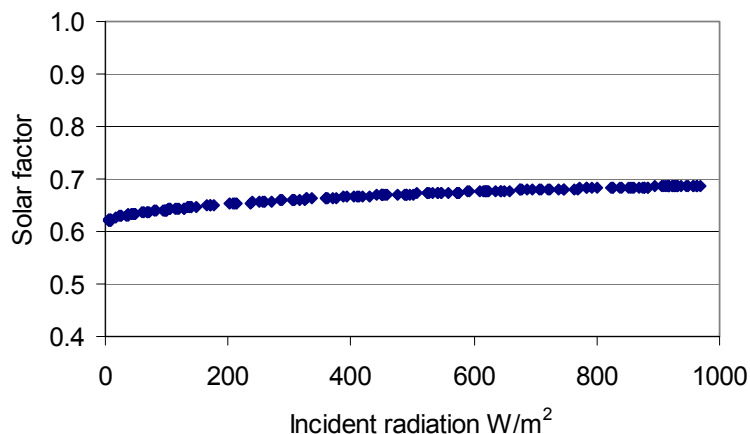


Figure 5-16: Solar factor of the SOLVENT window in Winter mode with a 4 cm channel

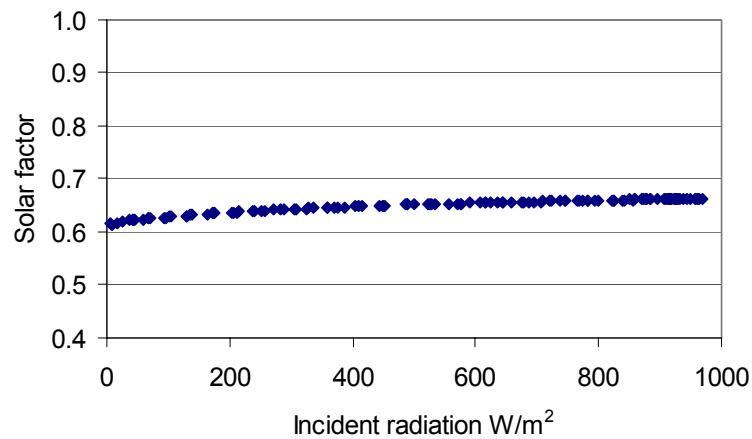


Figure 5-17: Solar factor of the SOLVENT window in Winter mode with a 2 cm channel

Table 5-3: Mean values of the solar factor in Winter mode

<i>4 cm channel</i>	<i>2 cm channel</i>
0.67	0.65

5.3.2 Solar factor in Summer mode

Figure 5-18 and figure 5-19 show the solar factor calculated as a function of the incident radiation, for the channel widths of 4 cm and 2 cm respectively. Table 5-4 shows the average values, for incident radiation between 5 and 1000 W/m^2 .

Globally, the version with a channel of 4 cm has a solar factor slightly lower than the 2 cm version, although the difference is only noticeable at high values of solar incidence.

Comparing with the double clear glazing window, which has a solar factor of 0.75, the SOLVENT window has a much more favourable solar factor. It may however be more realistic to compare the SOLVENT window with a double glazing window having the same visible transmissivity (38%). A “solar control” commercial window with 37% visible transmissivity has a solar factor of 0.46 (Saint-Gobain-Glass, 2000). The SOLVENT window thus has a slightly better performance in Summer mode, even under this more demanding criterion.

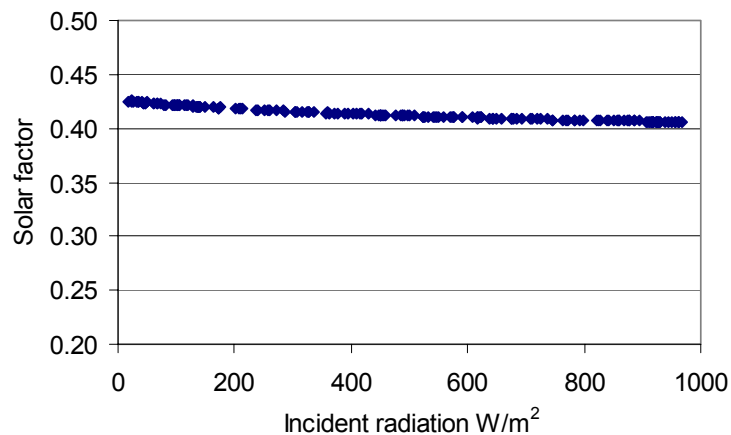


Figure 5-18: Solar factor of the SOLVENT window in Summer mode with a 4 cm channel

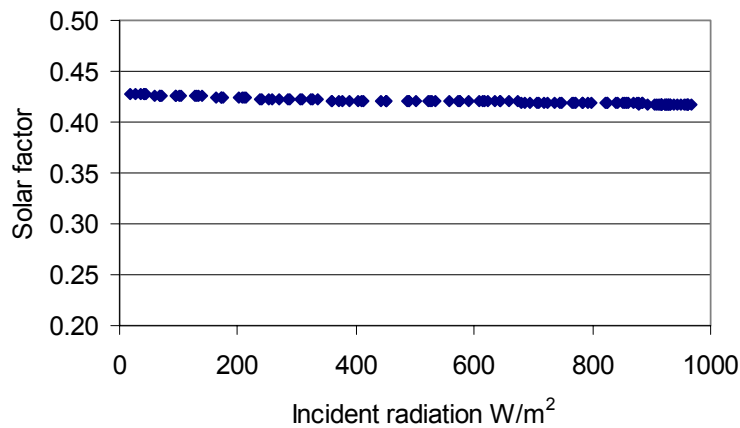


Figure 5-19: Solar factor of the SOLVENT window in Summer mode with a 2 cm channel

Table 5-4: Mean values of the solar factor in Summer mode

4 cm	2 cm
0.41	0.42

5.3.3 Influence of the air channel

One of the most interesting questions about the SOLVENT window, in terms of quantification, is the relevance of the effect of the air flow in the channel upon its solar factor. In order to assess this issue, the window with the channel of 4 cm was simulated with the two air gaps closed.

The graphs of figure 5-20 and figure 5-21 show the results for Winter mode and for Summer mode respectively. Table 5-5 shows the average values.

Considering the air gap closed lowers the solar factor from 0.67 to 0.61 in Winter mode and raises it from 0.41 to 0.44 in Summer mode. The difference is not very large, and it seems to indicate that the effect of the air circulation in the open air gap is not as relevant as it would be desirable. These results could seem somehow contradictory with the heat balances presented in section 5.2, where it was clear that the energy dissipated by convection at the air gap was the main component of heat gain (in Winter mode) and the second component of heat rejection (in Summer mode). Figure 5-22 helps to explain why the difference is not as high as desirable. It shows that, in the version with the air gaps closed, the interior glazing reaches much higher temperatures. This in turn increases the heat release by convection and by LW radiation at the indoor surface, thus partially offsetting the inexistence of the heat gain by channel convection.

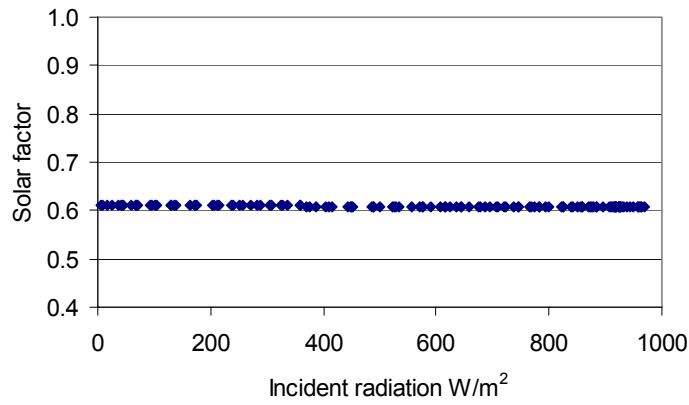


Figure 5-20: Solar factor of the SOLVENT window in Winter mode with a 4 cm channel and no air flow

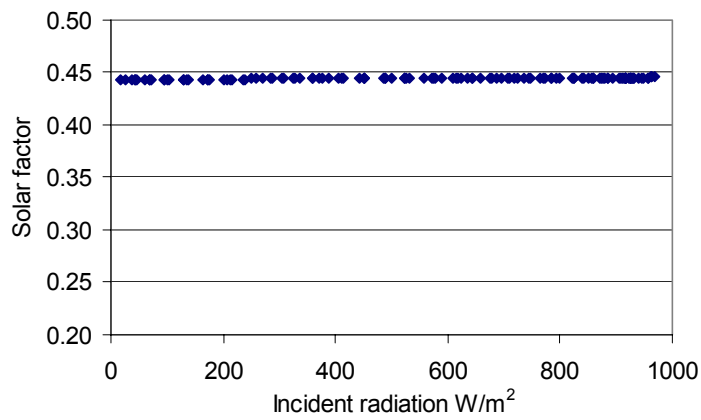


Figure 5-21: Solar factor of the SOLVENT window in Summer mode with a 4 cm channel and no air flow

Table 5-5: Mean values of the solar factor for a window with a channel of 4 cm without air flow

	<i>Winter mode</i>	<i>Summer mode</i>
Normal	0.67	0.41
Closed gap	0.61	0.44

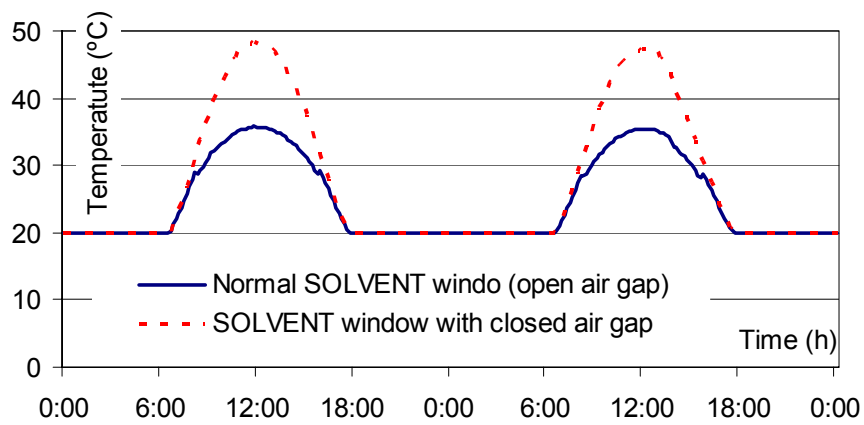


Figure 5-22: Glazing temperature for the interior glazing in Winter mode, with the air gap open and with the air gap closed.

5.3.4 Conclusions

The window achieves the conceptual goal of having very different values of solar factor, according to whether it is operating in Winter mode or in Summer mode. For the configuration with the channel of 4 cm, with the glazings used, the difference is between 0.67 in Winter mode and 0.41 in Summer mode.

Comparing with the double clear glazing window alone, there is an already expected decrease in the solar factor. This is due to increased reflection and LW radiative loss towards outdoors caused by the absorptive glazing. The catalogue value for the double-clear glazing window alone is 0.75. The values obtained for the SOLVENT window in Winter mode were 0.67 and 0.65 for channel widths of 4 cm and 2 cm respectively. This means that, in situations where heating is the main concern, thus operating essentially in Winter mode, there may be a non-negligible penalty in terms of collected solar gains.

In Summer mode, the comparison with the double clear glazing window is of course much favourable to the SOLVENT window, which presents values of 0.41 (4 cm channel) and 0.42 (2 cm channel) compared to 0.75 of the double clear glazing window. Comparing the SOLVENT window with a commercial “solar control” window with the same visible transmissivity, which has a solar factor of 0.46, the advantage of the SOLVENT window becomes less expressive.

Finally, the results of the calculation with both air gaps closed show that the effect of the air flow in the air channel is more noticeable in Winter mode than in Summer mode. For a 4 cm channel in Winter mode, the difference is between 0.67 (with open air channel) and 0.61 (with both air channels closed), while in Summer mode the difference is only between 0.41 and 0.44.

6 INTEGRATION IN WHOLE BUILDING SIMULATION

The previous chapters presented the modelling and analysis of the SOLVENT window at the component level. This chapter intends to be another step towards the ultimate goal of quantifying the impact of the SOLVENT window upon the energy demand, at the building level, for a number of case studies.

Rather than to start by integrating the window into a whole building model, the first step was modelling the PASSYS test cell with the SOLVENT window installed. The availability of data collected in the PASSYS test cell during the experimental campaigns allows making informed decisions on the most appropriate ways to model the SOLVENT window in the whole building software, as well as to evaluate the level of precision obtained.

The whole building simulation software chosen for this study was the Energy Simulation Program, abbreviated by ESP-r (ESRU, 2002). This software has been widely used in many scientific and engineering projects and subjected to numerous validation studies (Strachan, 2000). For the present study, the software presents several advantages, such as:

- A strong emphasis on building physics;
- The possibility to model air flow networks accounting for buoyancy;
- A policy of open-source code, thus enabling the incorporation of user-specific modelling features into the code when necessary;
- A routine that exports the building geometry to lighting software RADIANCE facilitates the process of performing daylight studies.

6.1 BASE MODEL

The initial ESP-r model of the PASSYS test cell, with the SOLVENT window integrated, considering the known geometry and constructions materials, incorporated only options available in the existing standard ESP-r version (version 4.48 a). This shall be considered as the base-case model. Alternative approaches will be presented later. The next sub-sections present a detailed description of the modelling details.

6.1.1 PAS envelope

The PASSYS test cell where the monitoring took place is equipped with nearly-adiabatic walls, which form the so-called pseudo-adiabatic shell (PAS). Basically the PAS consists of a panel of 10 cm of polystyrene enclosed between two thin layers of aluminium (2 mm each). A layer of heating foils is placed behind the panel, adjacent to the layer of aluminium. A network of thermocouples measures the difference of temperature across the panel. In case the temperature sensed at the back of the panel is lower than the temperature sensed at its front, the heating foils are activated to release heat until the temperature difference is offset.

For purposes of modelling in ESP-r, the first approach consisted of considering that the East, West and North walls, as well as the roof and the floor of the test cell, are PAS panels with an adiabatic condition at the back of the panel. It was later verified that this approach leads to large heat storage in the panel (e.g., absorption of solar radiation) and therefore to high thermal inertia of the test cell.

A second approach consisted of considering that the walls are built of the 2 mm aluminium layer alone, with the adiabatic condition right at its back surface. This approach revealed itself much more in line with experimental results. A plausible explanation for this verification will be presented ahead in section 6.1.4.

6.1.2 South face opaque wall

The South wall of the test cell during the SOLVENT experimental campaign was the same used for the round robin test of project IQ-TEST (Borges and Maldonado, 2002). Its composition is, from the exterior to interior: a 12 mm layer of white melamine plywood, 4 layers of expanded polystyrene 50 mm each and another 12 mm panel of plywood. A construction representing this wall was added to the ESP-r constructions library and used in the model.

The wood frame holding the SOLVENT window was also explicitly modelled. It consists of two horizontal layers with 22.4×4.4×123.0 cm, and two vertical layers measuring 22.4×148.0×4.4 cm (thickness, height and width respectively).

6.1.3 Heating and cooling control

During the experimental tests, the temperature of the test cell was tightly controlled to a value around 23 °C. The system was instructed to activate cooling if the sensed average cell temperature was higher than 23.5 °C, and to continue functioning until the cell temperature fell below 22.5 °C. In practice, when the system cuts the circulation of cold water, there is still some cold water left in the heat exchanger inside the cell and, thus, the cooling process continues to a temperature slightly below the prescribed 22.5°C.

The interior temperature recorded in the experimental data was analysed in order to identify the exact heating and cooling set-points to input into the simulation model. As an example, figure 6-1 shows the evolution of the average test cell temperature during the 8th of April. From the analysis of this evolution, the cooling systems set-point was assumed to be as represented in figure 6-2. The heating system was programmed to turn ON if the temperature falls below 21.0 °C and to stay ON until the temperature reaches 22.0°C. However, during the periods used as reference in this study, this condition was never met and the heating system was never activated.

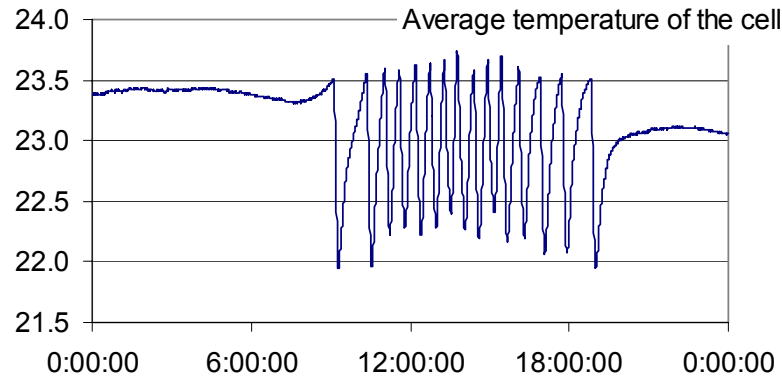


Figure 6-1: Evolution of the measured average test cell temperature during the 8th of April.

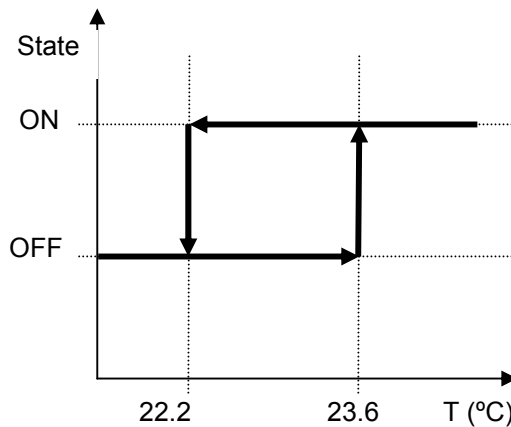


Figure 6-2: Diagram representing the control of the cooling system

6.1.4 Internal gains

In principle, the only internal gain in the test cell is the power dissipated by a fan that continuously circulates the air in the cell. This power is nearly constant at around 46 W.

A detailed analysis also showed that, because the PAS temperature control is able to heat but unable to cool, the average temperature at the back face of the PAS panel is on average a few tenths of degree higher than at its front face. This is particularly evident for the PAS panels located in the ceiling. Figure 6-3 shows the evolution of the temperatures at the surfaces of one of the ceiling PAS panels during the period 2-8 of April, which clearly illustrates the described effect. The average temperature differences across the PAS panels for the same period are shown in table 6-1. Considering that the U-value of the PAS is 0.33 W/m².K, it results that the energy transferred across the PAS panels into the test cell, during this 7 day-period, is 1100 Wh. The total energy delivered for cooling was 24195 Wh. In the week 10-16 May, when the cell was operating in Summer mode, the energy transmitted through the PAS was 1042 Wh, while the measured cooling energy was 11801 Wh. Therefore, for the level of precision desired, the contribution of the energy delivered through the PAS panels is not negligible and must be accounted for. Since the walls themselves were modelled as adiabatic, an alternative way to account for this heat transmission is to treat it as an internal gain.

While the total energy transmitted through the PAS walls can be easily calculated, its distribution over time is difficult to know. It is however expected that the release to the cell air shall occur essentially when the cell air is colder, and this happens when the cooling system is operating (figure 6-1). It was therefore assumed that the heat gain due to transmission through the PAS walls is concentrated between 10:00 and 18:00 h, which means an average gain of 19.1 W during this period. Due to difficulty in its modelling, the differences between the several days were neglected.

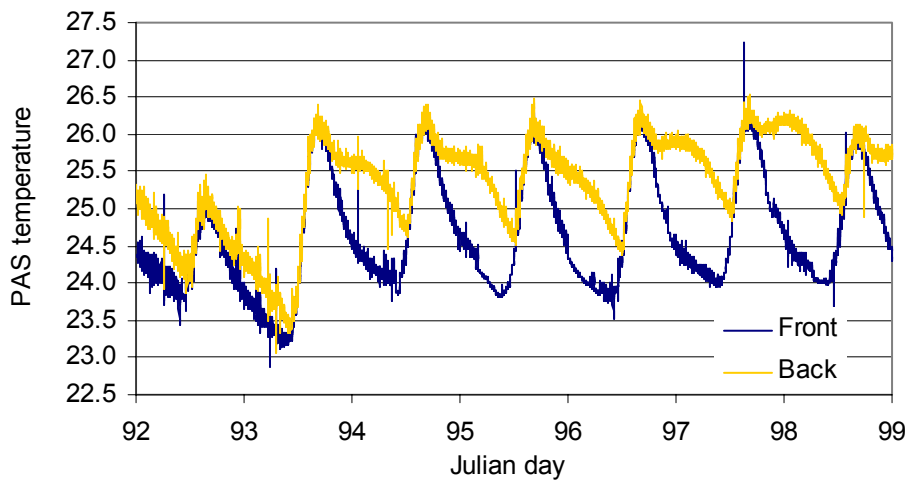


Figure 6-3: Evolution of the temperatures at the faces of one of the ceiling PAS panels.

Table 6-1: Average temperature difference between the outer and the inner surfaces of the PAS panels during the monitoring period.

	Floor	West wall	East wall	North wall	Ceiling
Area	12.08	11.98	11.98	6.1	12.08
PAS Temperature difference	0.39	0.13	0.20	0.26	0.79

6.1.5 Glazings

ESP-r uses a database where the glazing properties are stored. Two database entries were added, one for the double clear glazing and another for the single absorptive glazing used. The program requires detailed angle-dependent data, not usually available in the product technical specifications provided by the manufacturers. LBNL WINDOW 5.2 (Huizenga, Arasteh et al., 2003) was used to compute the angle-dependent data, departing from the general information provided by the manufacturer catalogue (Saint-Gobain-Glass, 2000).

Figure 6-4 shows the optical properties of the double clear glazing and of the absorptive glazing as included in the ESP-r glazings database.

Optical Property Set	Optical Property Set
<pre> a type : d_climalitt b descrip: SGG climalit 4-6-4 c visible transmittance : 0.81 d solar abs & refl (for docu): 0.17 0.13 e U-value (for docu): 3.30 ----- @ 0deg 40deg 55deg 70deg 80deg f direc trn: 0.692 0.667 0.602 0.430 0.201 reflect. : 0.134 0.145 0.198 0.363 0.604 g heat gain (doc): 0.75 0.73 0.67 0.48 0.25 ----- layers: 3 refrac. abs@0 abs@40 abs@55 @70 @80 h 1.520 0.097 0.105 0.115 0.129 0.135 i 1.000 0.001 0.002 0.003 0.004 0.005 j 1.520 0.076 0.081 0.082 0.074 0.055 ----- 1 add/delete/copy layer ? help - exit this menu </pre>	<pre> a type : parsol b descrip: SGG parsol gris 5 mm c visible transmittance : 0.47 d solar abs & refl (for docu): 0.44 0.06 e U-value (for docu): 5.80 ----- @ 0deg 40deg 55deg 70deg 80deg f direc trn: 0.498 0.466 0.422 0.329 0.186 reflect. : 0.060 0.066 0.096 0.202 0.423 g heat gain (doc): 0.62 0.60 0.55 0.46 0.29 ----- layers: 1 refrac. abs@0 abs@40 abs@55 @70 @80 h 1.520 0.442 0.468 0.482 0.469 0.391 ----- 1 add/delete/copy layer ? help - exit this menu </pre>

Figure 6-4: Optical properties of the double clear glazing (left) and absorptive glazing (right), as included into ESP-r glazings database

6.1.6 Shading and insolation

The South wall of the test cell, where the window was installed, and the wood frame used to hold the window, are much thicker than the glazing assembly itself. Since the glazing is located at the middle of the wall, the wall and the frame act as a window reveal that will cause some shading of the window. A shading reveal approx. 10 cm deep was thus included in the ESP-r model to account for this effect.

Furthermore, ESP-r has two modes for distributing the solar radiation entering a zone. The default model, “diffuse distribution”, assigns a uniform distribution through all surfaces. It is possible to use a more advanced model, selecting the optional “shading and insolation” analysis. In this case, for each hour of the day, there is an identification of the surfaces where the solar radiation is impinging. This more detailed option was used in all simulations presented in this chapter.

6.1.7 Air flow network

An essential issue in this study is the ability of the software to simulate the air flow in the open air channel. In ESP-r, the air flow can be modelled in three different ways:

- Pre-defined air changes (possibly time-dependent);
- Computational Fluid Dynamics (CFD) calculation taking into account the “building side” boundary conditions at each time-step.
- Air flow networks linking flow “nodes” and flow “components”, based on the simultaneous solution of the Bernoulli equation for each flow connection at each time-step (Hensen, 1991).

The first option may be adequate for zones with a mechanical ventilation system or for zones with natural ventilation where the average air exchange rates are rather steady and

known. It does not seem adequate for a space where the air flow is very dependent on the environmental conditions.

CFD modelling is probably the approach with the highest potential accuracy. However, it faces several difficulties too, such as the need for very precise data and boundary-conditions to adequately calibrate the models. Several practical studies clearly show the difficulties often encountered in obtaining a good correspondence with experimental results (Benkhelifa, Thomas et al., 2004), (Herrero and Celemin, 2004). Even more important in this case, CFD can only deal with permanent regime or, at most, short time-periods. Developments are under way in the area of coupling building energy and CFD simulations, but it seems clear that for the moment they cannot deal with a simulation for a full month (Djunaedy, Hensen et al., 2004).

The air-flow network approach, albeit theoretically less precise than the CFD approach, is compatible with simulation for long periods, and is easier to calibrate and integrate with other building fluxes such as solar radiation, long-wavelength radiation exchanges between the surfaces, etc. This kind of approach has been used previously with good results in ESP-r, e.g. to simulate photovoltaic (PV) façade elements (Clarke, Johnstone et al., 1997) and double-skin façades with one opaque wall (Hensen, Bartak et al., 2002).

For the base case model, it was decided to arbitrarily divide the air channel in 4 vertically interconnected thermal zones. Each thermal zone is associated with an air flow node. The air flow nodes are linked by “connections” as shown in figure 6-5 (for Winter mode). Other details of the ESP-r air flow network model are shown in table 6-2. Figure 6-6 shows a view of the geometry of the base case model, including the obstruction reveal around the window.

Table 6-2: Main parameters of the ESP-r air flow network for the base case

<i>Item</i>	<i>Option / Value</i>
Connections between channel nodes	Type 210 - General flow conduit component • Hydraulic diameter: 0.70905 m. • Cross-section area (0.0451 m²) • Component length (0.283 m) • Surface roughness: 0.0001
Indoor / outdoor connection	Type 35, flow = 2.77×10^{-6} kg/s
Local pressure loss coefficients	Entry: 0.5; Exit: 1.0
Heat transfer coefficients at channel walls	ESP-r default mode

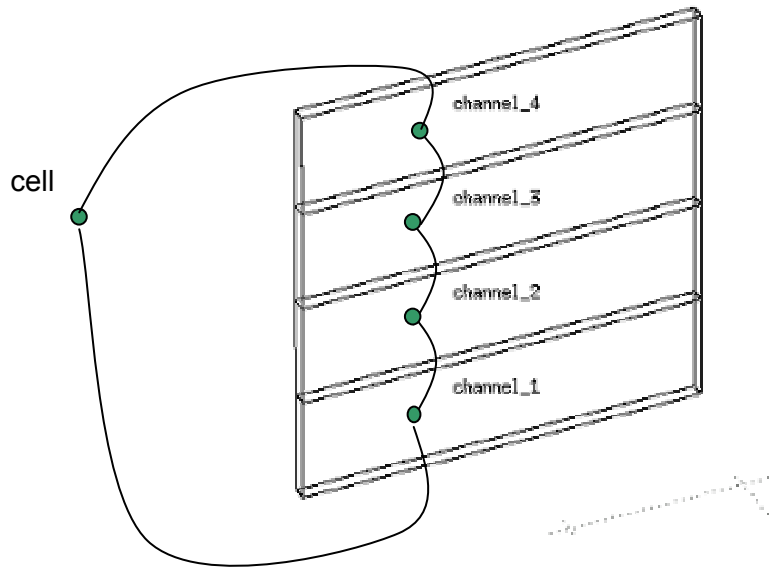


Figure 6-5: Air flow network in Winter mode.

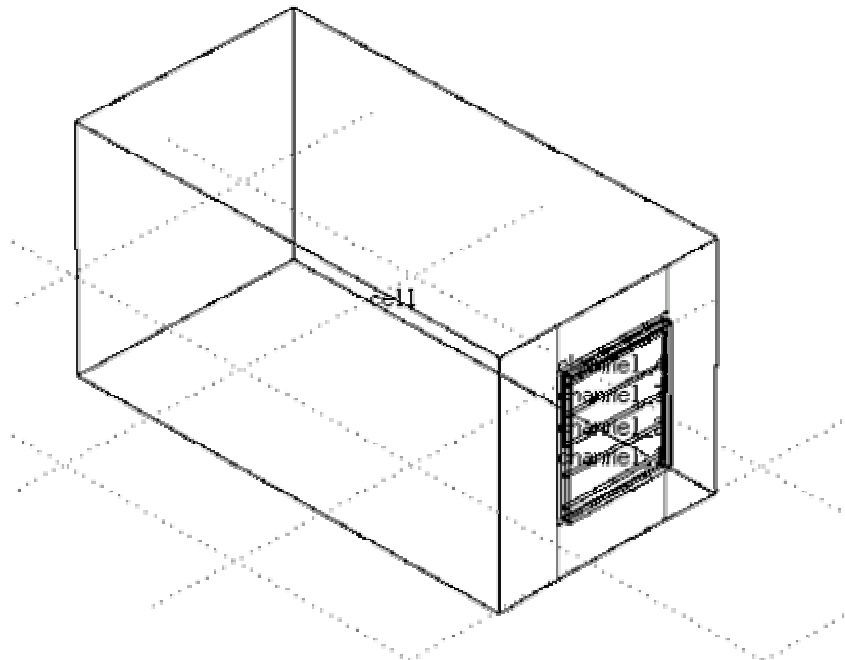


Figure 6-6: Geometry of the base case model

6.1.8 Climatic data

The climatic data measured at the test site during the experimental campaign was treated and input into a climatic file for use in all validation studies. This ensured that the simulation and measurement results are based on the same climatic conditions. The set of climatic variables required by ESP-r consists of dry bulb air temperature, global solar radiation on the horizontal plane, diffuse solar radiation on the horizontal plane, wind speed, wind direction and relative humidity.

6.1.9 Other miscellaneous simulation details

In order to make the control of the heating and cooling system as close as possible to reality, the simulation was run with 1 minute time steps.

The external convection coefficients were calculated with the convection Yazdanian and Klems "MoWitt" correlation, described in chapter 3 (eq. 3-18 and 3-19), because it is the best option for low rise buildings, as is the case of the test cell.

The ground reflectance (albedo) was set to 0.2 and the view factors to ground, surrounding buildings and sky were those typical of a rural site (0.45, 0.10 and 0.45 respectively).

6.2 BASE MODEL RESULTS

Figure 6-7 shows the cooling energy as measured and simulated with the base case model, for the week 2-8th April 2003 (Winter mode, 4 cm air channel). The totals in the period were 24.195 kWh measured and 22.830 kWh simulated, a difference of 5.6 %. The agreement achieved seems satisfactory to most engineering applications for calculating the heating and cooling loads.

When comparing more system specific variables, such as the air velocity in the air channel, the quality of the agreement between the simulation and the experimental data is however not as good as for the energy demand. Figure 6-8 shows the results for the air velocity in the air channel, clearly showing that the simulation results are much lower than measurements. This difficulty in predicting the correct air flow can be important if the simulation is being used to optimise the window properties or to study the comfort conditions near the window, for instance.

If this modelling approach were to be made final, it would be desirable to perform parametric studies to certain model values or options, such as the number of zones in which the channel is divided, the values of the inlet and outlet local pressure drop coefficients and the correlations for calculating the heat transfer coefficients at the channel walls. This was the approach followed in Leal, Erell et al. (2004). The main conclusion was that, while some sets of parameters favoured the performance of the model in some items, none led to precise results simultaneously for all the items of analysis (glazing temperatures, velocity in the air channel and cooling load).

For this study, the approach will be to integrate the specific models for the SOLVENT window, developed in chapters 3 and 4, into the ESP-r code. That will be scope of section 6.3.

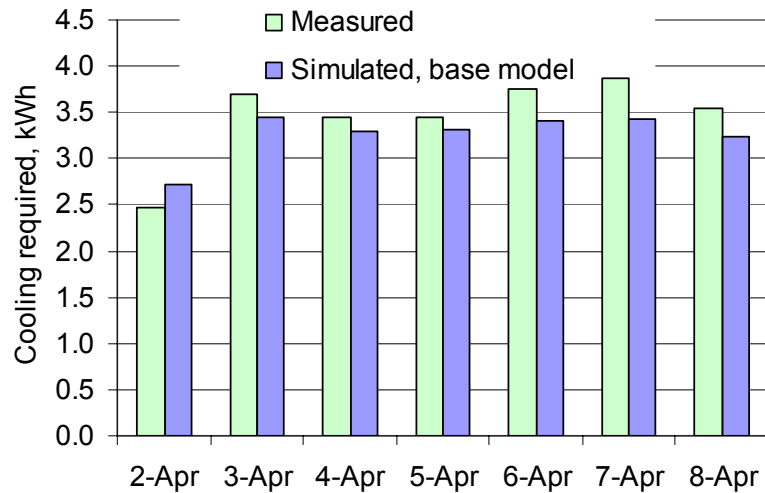


Figure 6-7: Cooling energy required by the test cell, measured and simulated with the base case model.

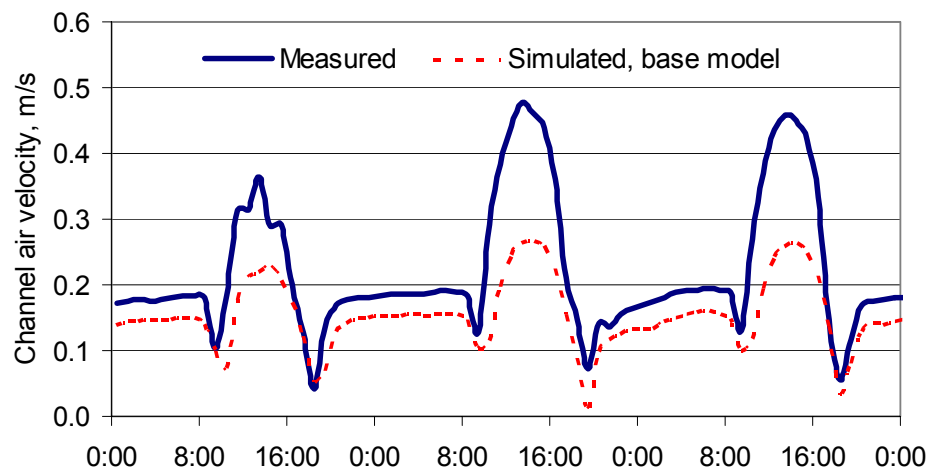


Figure 6-8: Air velocity in the open air channel, measured and simulated with the base case model.

6.3 IMPROVED SOLVENT MODEL

6.3.1 Surface convection

In ESP-r, convection coefficients are recalculated for each surface at each time step. By default, the correlations used for buoyancy-driven flow are those proposed by Alamdari and Hammond (1983). Other options for the calculation of convection coefficients are available optionally, especially those accounting for the influence of HVAC systems in the zone (Beausoleil-Morrison, 2002). It has been clearly confirmed that different options in the treatment of surface convection can result in important differences in the calculated energy demand (Kalema and Haapala, 1995).

In this work, the approach followed for this issue was to add the new blend correlation (eq. 4-4) for the heat convection in the vertical air channel, developed and validated in chapter 4, to the library of correlations available in ESP-r. The options of single-plate convection (eq. 3-42) and fully-developed flow convection (eq. 3-53) were also added. The user graphical interface was also updated to allow the selection of these options (figure 6-9).

The following inputs are required to the user when selecting any of the newly included correlations:

- Origin of the air entering the channel (zone or outdoor)
- Channel width (m)
- Channel height (m)

The details concerning the changes and additions to ESP-r code are documented in detail in annex 3.

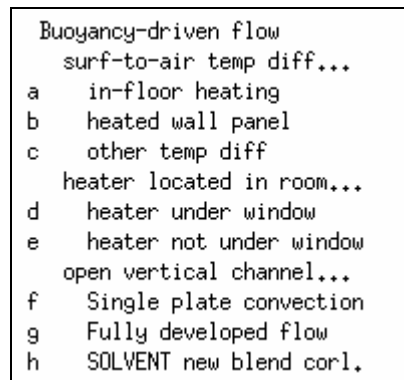


Figure 6-9: ESP-r menu for selecting convection correlations, with the new included options (items f-h).

6.3.2 Channel flow

Even if it could be expected that the inclusion of the correlations specific for the SOLVENT channel heat convection could improve the prediction of the channel air velocity, the division of the channel in several thermal zones would still be required. This could be a severe disadvantage when modelling large buildings. In order to assure both a better air flow prediction and a simpler geometry modelling effort, it was decided to include two new flow components into the ESP-r library of flow components.

The new components were labelled “SOLVENT Winter mode flow component” and “SOLVENT Summer mode flow component”. The need to distinguish between Summer mode and Winter mode is due to the influence of wind, which applies only to Summer mode. The graphical interface for selecting flow components was updated accordingly (figure 6-10). The new components calculate the air flow according to eq. 4-4 (Winter mode) or figures 4-36 and 4-45 (Summer mode) and act as a fan imposing this air flow. This means that a branch of the air flow network having one of these components will have the air flow imposed by the SOLVENT component. Other components also imposing a certain air flow (e.g., fixed flow rate components) shall not be used in the same network branch, as a conflict could arise. The air properties for the SOLVENT components are computed at the temperature of the origin node in the connection. In order to ensure that the reference temperature used is the average temperature of the air in the channel, it is advisable that the SOLVENT component be placed at the exit of the channel.

Figure 6-11 shows the geometric model with the new modelling approach and the associated air flow network. For the connection representing the entry of the channel, a component type 210 (general fluid flow component) was used. The details concerning the changes and additions to ESP-r code are documented in detail in annex 3.

Component type & description		
a	10 : Power law vol. flow component	$m = \rho \cdot a \cdot dP^b$
b	15 : Power law mass flow component	$m = a \cdot dP^b$
c	17 : Power law mass flow component	$m = a \cdot \rho^{.5} \cdot dP^b$
d	20 : Quadratic law vol. flow component	$dP = a \cdot m / \rho + b \cdot (m / \rho)^2$
e	25 : Quadratic law mass flow component	$dP = a \cdot m + b \cdot m^2$
f	30 : Constant vol. flow rate component	$m = \rho \cdot a$
g	35 : Constant mass flow rate component	$m = a$
h	40 : Common orifice vol. flow rate comp.	$m = \rho \cdot f(C_d, A, \rho, dP)$
i	50 : Laminar pipe vol. flow rate comp.	$m = \rho \cdot f(L, R, \mu, dP)$
j	110 : Specific air flow opening	$m = \rho \cdot f(A, dP)$
k	120 : Specific air flow crack	$m = \rho \cdot f(W, L, dP)$
l	130 : Specific air flow door	$m = \rho \cdot f(W, H, dP)$
m	210 : General flow conduit component	$m = \rho \cdot f(D, A, L, k, SCi)$
n	220 : Conduit ending in converging 3-leg junction & Ccp = f(q/qc)	
o	230 : Conduit starts in diverging 3-leg junction & Ccp = f(q/qc)	
p	240 : Conduit ending in converging 4-leg junction & Ccp = f(q/qc)	
q	250 : Conduit starts in diverging 4-leg junction & Ccp = f(q/qc)	
r	310 : General flow inducer component	$dP = a_0 + S_{ai}(m/\rho)^i$
s	410 : General flow corrector component	$m = \rho \cdot f(comp, signal)$
t	420 : Corrector with polynomial flow resistance	$C = f(H/H100)$
u	460 : Fixed flow rates controller	
v	500 : CFD component	
w	600 : SOLVENT Winter mode flow component	
x	610 : SOLVENT Summer mode flow component	

? Help
- Exit

Figure 6-10: ESP-r menu of flow components with the new SOLVENT components included.

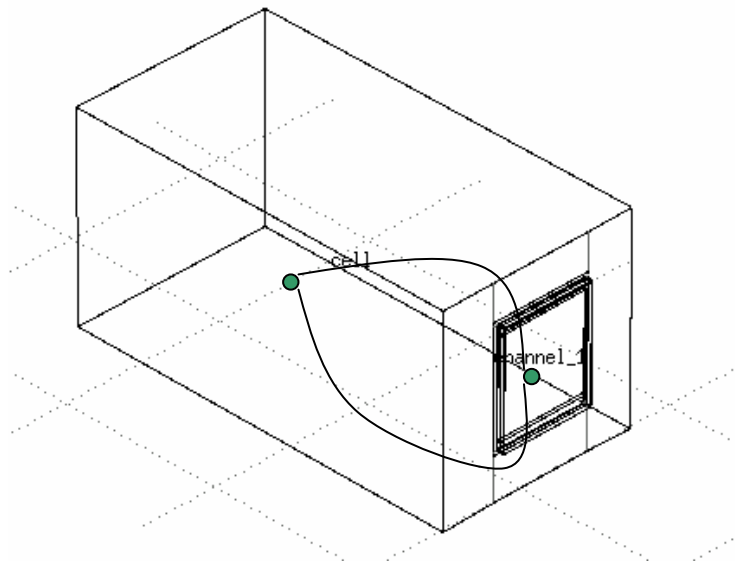


Figure 6-11: Geometric model of the test cell and associated air flow network.

6.4 OPTIMISED MODEL RESULTS

6.4.1 Winter mode

A simulation with the new air flow modelling approach was run for the week 2-8th April, the same used in the base case model. This corresponds to the SOLVENT window in Winter mode with an air channel of 4.1 cm.

Figure 6-12 shows the evolution of the cooling energy required by the test cell as measured and as simulated with the optimised model. Similar results for the air velocity in the open air channel and for the dark glazing temperature are shown in figure 6-13 and figure 6-14 respectively.

The results show a very good agreement in terms of cooling load distribution. For the air velocity, the agreement is very good for most of the day, the exception being the peak at sunny days when the predicted velocity is slightly lower than measurements. This phenomena seems to be linked with the prediction of the glazing temperature, which is also slightly lower than measured at mid afternoon. Several factors can contribute to explain these deviations, such as the uncertainty in the temporal distribution of the cooling load due to the PAS heating, the way how long wavelength radiation exchanges between the exterior surfaces and the outdoor environment are estimated, possible effects of the solar radiation on the temperature measurements, and even the fact that the air velocity and the glazing temperatures were only measured at one point each.

Figure 6-15 shows the daily cooling energy required by the test cell as measured and as simulated by the base model and by the optimised model. Even if the base model was already was in good agreement with the measured cooling energy, the optimised model yields an even better agreement. For the whole week, it predicts an energy demand of 23890 Wh, which means a difference of only 1.3 % from the measurements.

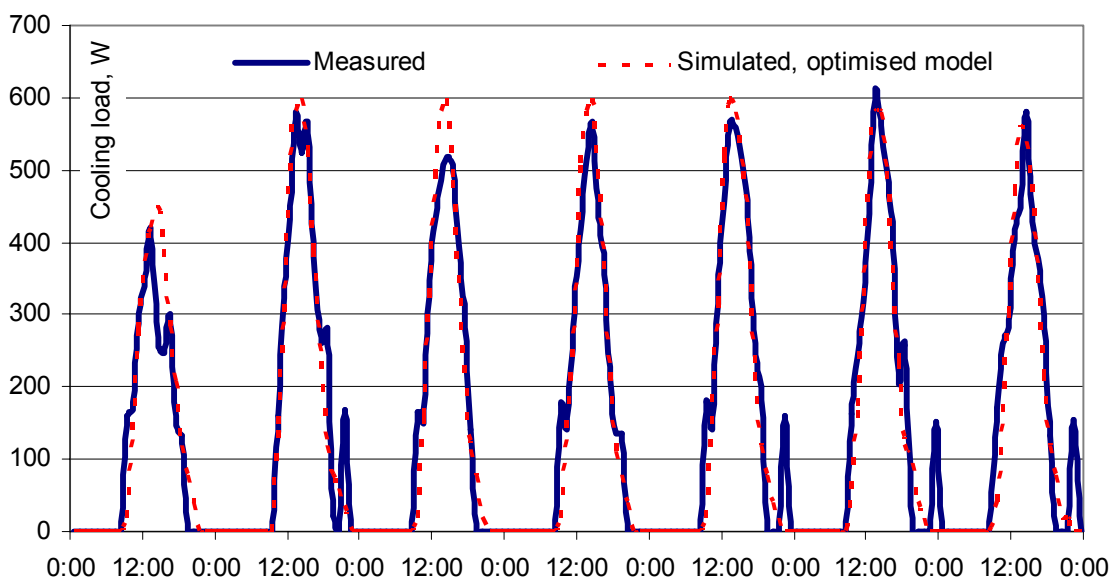


Figure 6-12: Hourly cooling energy required by the test cell as measured and as simulated with the optimised model.

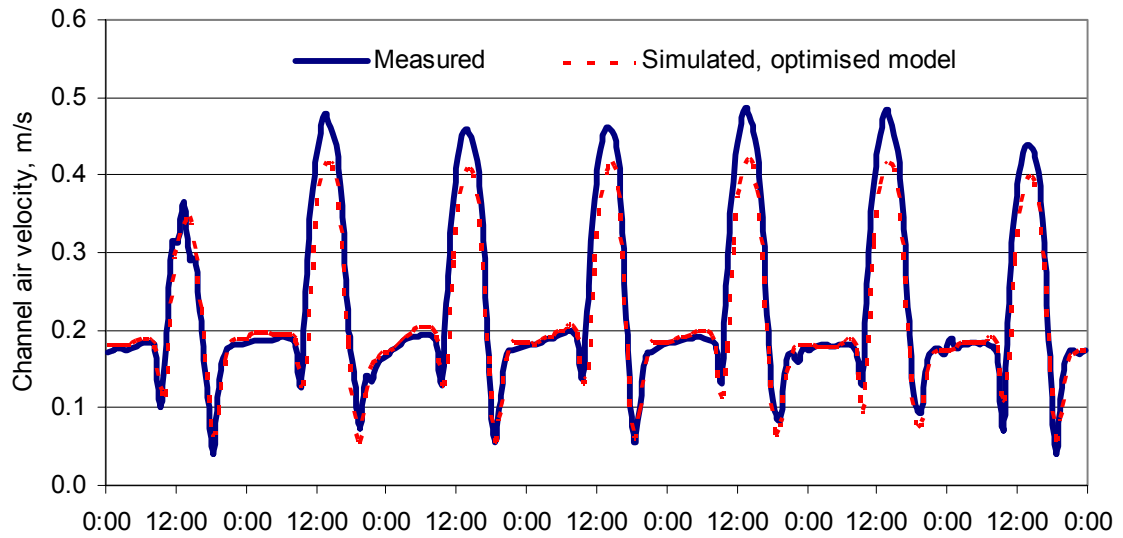


Figure 6-13: Velocity in the air channel as measured and as simulated with the optimised model.

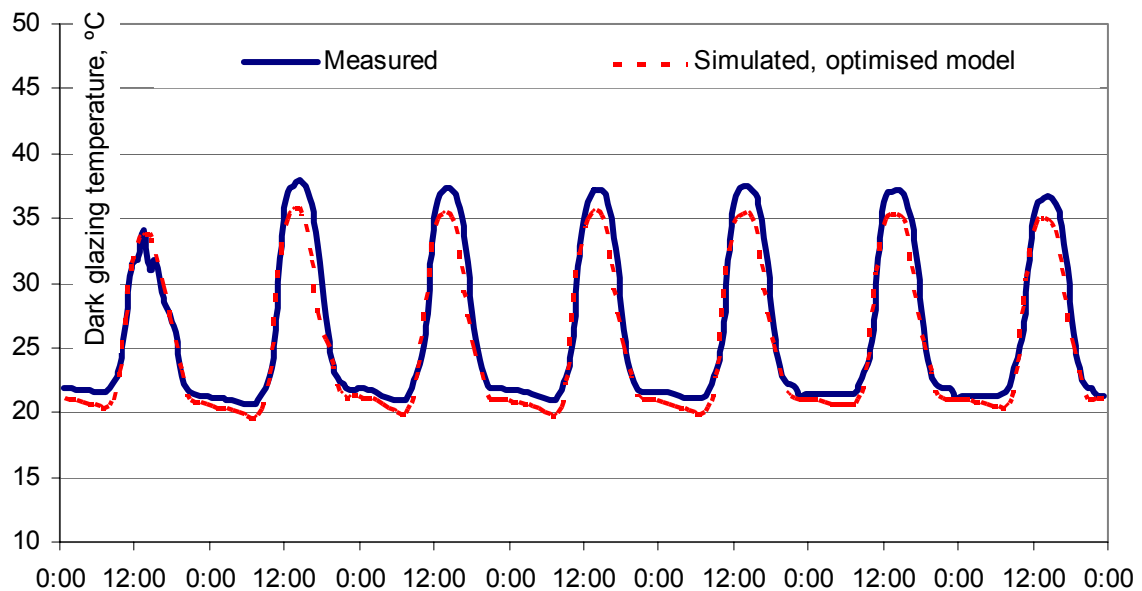


Figure 6-14: Dark glazing temperature as measured and as simulated with the optimised model.

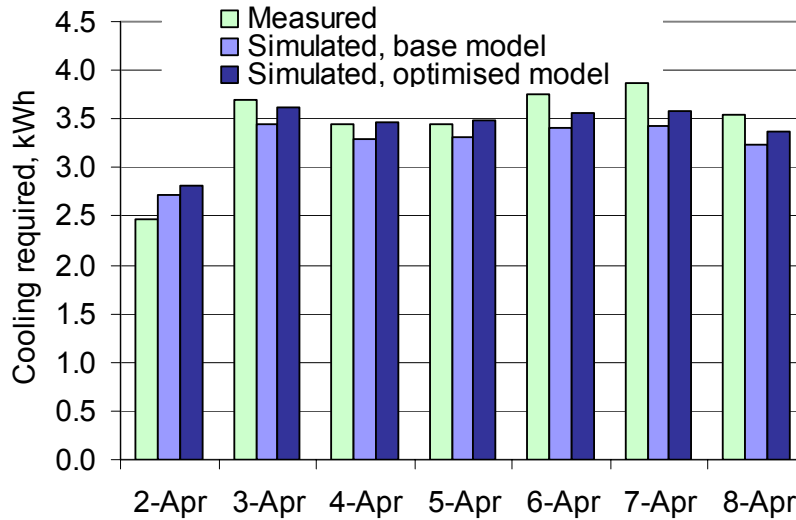


Figure 6-15: Daily cooling energy required by the test cell as measured and as simulated with the base case model and with the optimised model.

6.4.2 Summer mode

The model of the test cell with the SOLVENT window installed was adapted to summer mode. The adaptation consisted of changing the glazing properties accordingly and in reconfiguring the air flow network for Summer mode (figure 6-16). The Winter mode flow component (type 600) was replaced by a Summer mode flow component (type 610), which accounts for the wind effect.

The simulation was run for the period 10-16 May. The hourly results for cooling energy required, air velocity in the open channel and temperature of the absorptive glazing are shown in the graphs from figure 6-17 to figure 6-19. The results seem generally satisfactory, although some underestimation of the temperature of the absorptive glazing can be observed. As for the Winter mode, this can be due to a conjugation of factors, such as the calculation of the LW radiation exchange with the outdoor environment, the convection coefficient at the external glazing and some uncertainty in the cross-section profile of the velocity in the air channel.

Figure 6-20 shows the daily energy demand as measured and as simulated. The totals for the whole week were 11801 Wh measured and 12220 Wh simulated, a difference of 3.6%. This result seems well within the uncertainty associated with the assumptions and simplifications of the several modelling processes.

6.4.3 Conclusion regarding the modelling approaches

The inclusion of the specific SOLVENT convection correlations and air flow models produced a significant improvement in the prediction of the energy flow through the window system. The combined analysis of the results for Winter mode and for Summer mode validates the method for integrating the SOLVENT window in whole building simulation with ESP-r, especially concerning the prediction of heating and cooling loads. The modelling approach can thus be exported to larger, realistic size buildings.

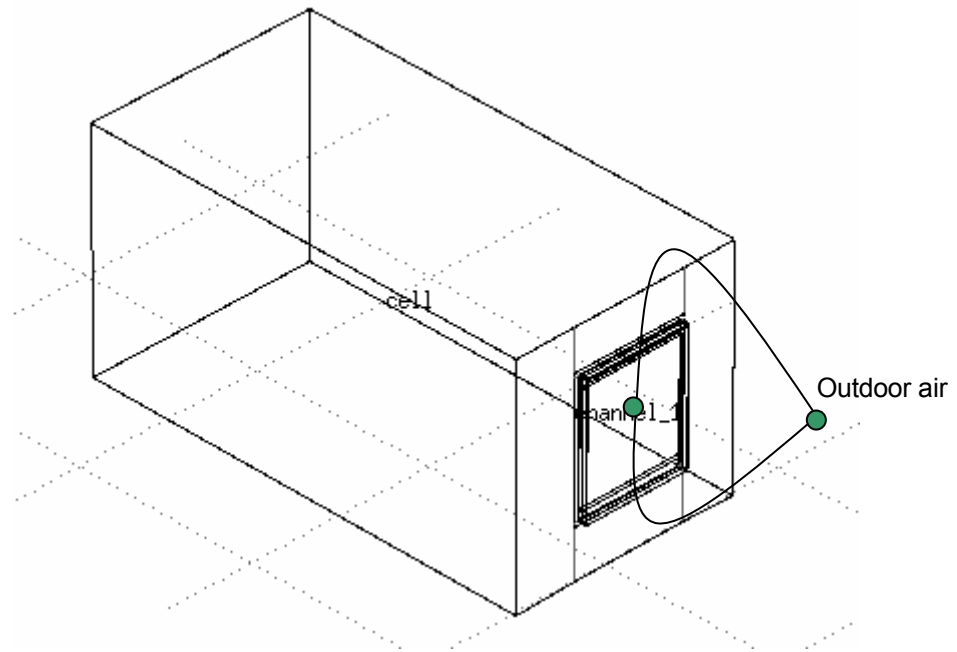


Figure 6-16: Geometric model of the test cell and associated air flow network in Summer mode

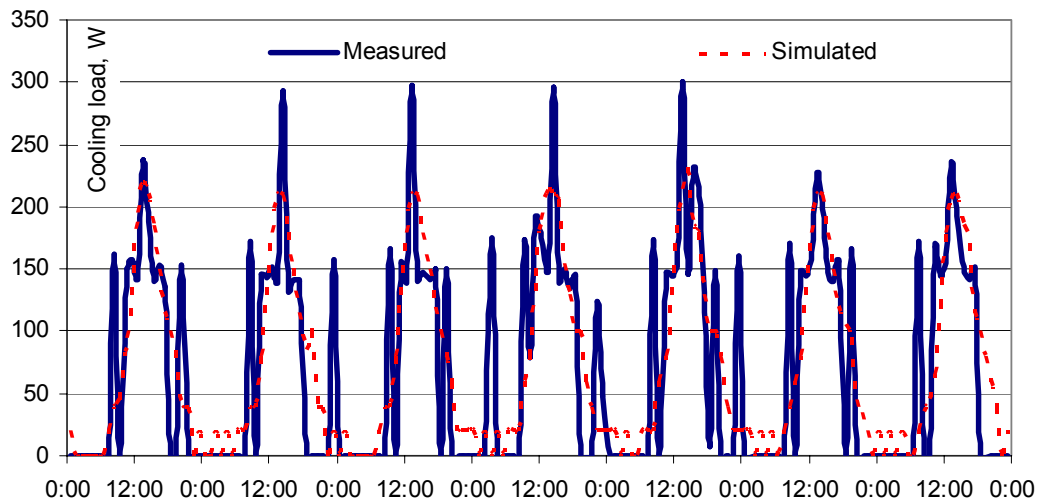


Figure 6-17: Hourly cooling energy required by the test cell as measured and as simulated with the optimised model.

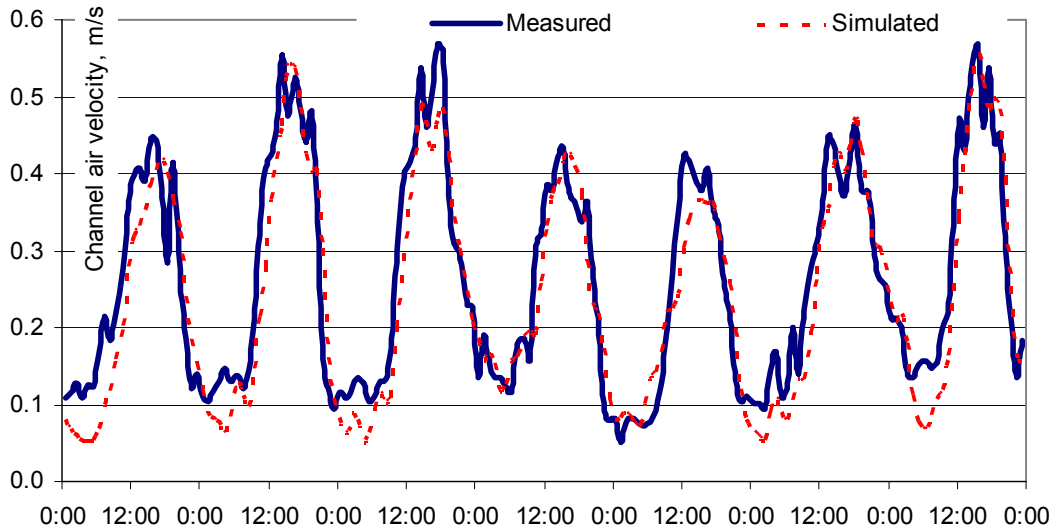


Figure 6-18: Velocity in the air channel as measured and as simulated with the optimised model.

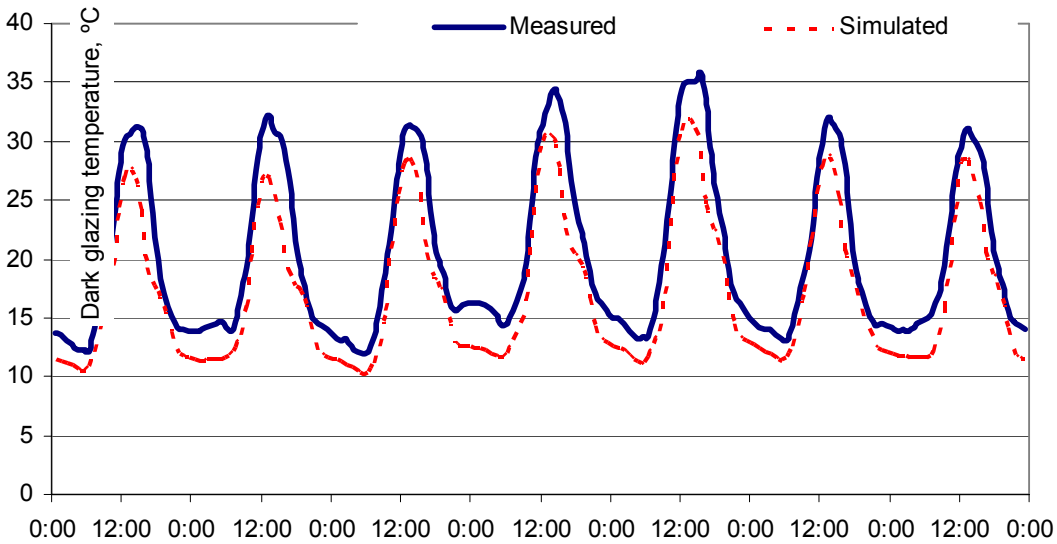


Figure 6-19: Dark glazing temperature as measured and as simulated with the optimised model.

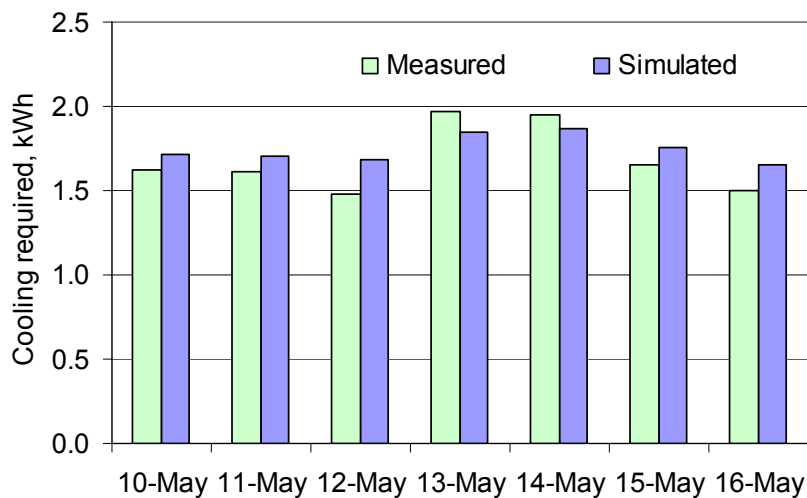


Figure 6-20: Daily cooling energy required by the test cell as measured and as simulated with the optimised model for Summer mode.

6.5 INTEGRATED ENERGY SIMULATION: CONTROL OF BLINDS AND ELECTRIC LIGHTS.

Besides having a direct thermal impact upon the energy demand for heating and cooling, the SOLVENT window may also affect the use of solar protection devices and of electric lighting. As the SOLVENT window has lower transmissivity than double clear glazing, this might result in a higher consumption for electric lighting in low luminance days. Conversely, in sunny days, it may result in less use of internal blinds and, thus, in lower consumption for electric lighting.

The integration of energy demand for heating, cooling and lighting often presents difficulties, both because the simulation software is not flexible enough and because there is a large uncertainty in the occupant criteria for achieving visual comfort, in particular for controlling the electric lights and the blinds.

6.5.1 A review of criteria for visual comfort

Visual comfort is a subjective impression linked to the quantity, distribution and quality of light. It can be said that a condition of visual comfort allows seeing the objects clearly and without fatigue, in a pleasant environment (Herde and Reiter, 2001).

Besides some subjective criteria, such as the distribution of colours in the room, there are two basic factors that characterize visual comfort:

- i) There must be enough light for the task being performed;
- ii) The contrast of luminance levels in the visual field should be limited, otherwise the occupants may experience a sensation of glare.

Mostly because the 20th century studies of illumination in architecture started in climates with predominantly overcast skies, and because it is there where they are more often applied, factor i) has often been considered as almost exclusive, while factor ii) was not always given the proper importance. E.g., some building regulations or codes imposed minimum daylight factors, not caring about appropriate shading (Baker, Fanchiotti et al., 1993). With time, the consequences of not caring about glare, even in Northern European climates, became apparent in many buildings, where complaints about glare became significant. Simultaneously, the technical aspects of daylighting started to gather a wider interest in Mediterranean countries, where the question of glare control is essential. Factor ii) is thus nowadays considered in equal footing with factor i).

The required illumination levels, depending on the task being performed, are reasonably well characterised and available in the scientific and technical literature. Yet, it is now known that occupants generally feel more comfortable with daylighting than with artificial lighting. Furthermore, it appears that with daylighting people accept a wider range of illuminance values than with artificial lighting (McNicholl and Lewis, 1994). These benefits of daylighting do not seem strange, since the human eye has adapted to the spectrum of the daylight for millions of years.

The second main objective criteria that characterizes visual comfort is the absence of glare, which is due to excessive contrast of the luminance level on the vision field. Windows can act as glare sources, either because their luminance is too high or because they allow the entrance of direct solar radiation to the room, which causes the existence of very bright sources inside the room.

There are mainly two approaches to characterize the problem of glare from windows: the calculation of glare indexes and the evaluation of the direct solar radiation entering a room.

The “glare index” approach is based on the “Cornell large source glare formula”, given by eq. 6-1 (Chauvel, Collins et al., 1982).

The glare index was first introduced to deal with artificial lighting. However, humans are usually more tolerant to daylight than to artificial light. So, for daylighting it is more appropriate to use the daylight glare index instead, defined as in eq. 6-2. The relation between DGI and human perception of glare is presented in table 6-3.

$$GI = 10 \log_{10} \left(KP \frac{L_s^{1.6} \omega^{0.8}}{L_b} \right) \quad \text{eq. 6-1}$$

Where:

K is a constant depending on the units used.

P is a “position factor” depending on the position of the source with respect to the line of sight.

L_s is the luminance of the source.

L_b is the field luminance.

ω is the solid angle subtended by the source.

$$DGI = \begin{cases} \frac{2}{3}(GI + 14) & \text{if } GI \leq 28 \\ GI & \text{if } GI > 28 \end{cases} \quad \text{eq. 6-2}$$

Table 6-3: Human glare perception related with DGI (Baker, Fanchiotti et al., 1993) .

<i>Glare Criterion</i>	<i>DGI</i>
Imperceptible	Below 16
Perceptible	16-20
Acceptable	20-24
Uncomfortable	24-28
Intolerable	Above 28

As results from eq. 6-1, the calculation of the DGI value requires an accurate knowledge of the spatial distribution of the illuminance arriving to a certain point and view direction. This information is typically available only from measurements or from detailed lighting simulation. These later can be performed with specific rendering programs like RADIANCE (Larson and Shakespeare, 1998), which requires building a geometric and photometric model of the room and most relevant furniture, selecting reference viewpoints, reference view directions in the room, and reference sky conditions. However, *each* simulation, for determining *one* DGI value, requires several hours of computing time on a state-of-the-art PC, so this method is not suited for simulations comprising the whole year at short time-steps, as is the case of this study.

Furthermore, the idea of using a mathematically-defined index to characterize the glare sensation is not universally accepted (Schiler, 2000; Velds, 2002).

An alternative approach to characterize the problem of glare from windows is to evaluate the intensity of solar radiation that impinges on a window or that enters the space. For this work, the main question is to evaluate how solar radiation affects the use of the blinds. As it often happens with other areas of human behaviour, monitoring results report a significant dispersion in the way how people control the blinds for a given set of environmental conditions. A summary study on this issue presented the following main conclusions (Reinhart and Voss, 2002):

- i) People consciously set their blinds in a certain position. The choice of the blind position is a weighted decision based on mid-term implications.
- ii) Blind occlusion is higher in South than in North-oriented offices, as people tend to use blinds to block direct sunlight.
- iii) There is a strong positive correlation between incident irradiance and mean blind occlusion (Rea, 1984).
- iv) For incidence of solar radiation above 50 W/m^2 , blind occlusion is proportional to the solar penetration depth into a room.
- v) Individual blind manipulation rates for different windows in the same façade ranged from never (0%) to daily (100%). The main driver towards blind activation seems to be glare perception rather than overheating.
- vi) The existence of sunlight patches in the room tends to trigger the use of shading devices.
- vii) For a group of south-oriented offices located in Canada, the automatic lowering of the blinds was only accepted by the occupants if the incident solar gains were higher than 450 W/m^2 , or if direct sunlight above 50 W/m^2 hit the work plane.

The main conclusion seems to be that there is some generic relationship between incident solar radiation and blind activation. Consequently, many authors have been using incident or transmitted solar radiation as the criteria for blind actuation. The triggering values, however, differ considerably. Criteria found varied between considering that blinds are activated if the transmitted direct solar radiation is higher than 94.5 W/m^2 (Lee and Selkowitz, 1995), direct solar radiation impinging on the façade is higher than 233 W/m^2 (Newsham, 1994), or global radiation incident on the façade is higher than 300 W/m^2 (Janak, 1997).

This approach based on the incident solar radiation can be easily integrated in whole building simulation, even for long periods at short time-steps, without significantly affecting the required simulation time.

6.5.2 Adopted strategies of integration

ESP-r allows the control of both blinds and electric lighting, based on some indoor or outdoor environmental criteria. E.g., the blinds can be controlled based on the solar radiation incident on a certain external surface, and the electric lights can be turned ON, OFF or dimmed to complement daylighting and maintain a certain illuminance level at a chosen point. Given the discussion presented in the previous section and the potentialities of ESP-r,

three different scenarios were drawn for integrating the dynamics of electric lighting and blind operation upon the thermal and energetic analysis of the buildings:

- A - No control: blinds are not considered, and lights are always ON during work time. This option is the “worst case” scenario, but it can be representative of some real cases where there is no automatic control and the users do not interact with the envelope.
- B - ON-OFF control: blinds are activated if the solar radiation is above a trigger value, and electric lighting is activated with full power if the sensed daylighting is below the lighting set-point. This option can be representative of some automatic systems or cases where the users are strongly interactive with the envelope and lighting system.
- C - Ideal dimming control: blinds are activated if the solar radiation is above the trigger value, and electric lighting is activated if the calculated daylighting is below the lighting set-point. The lighting power is adjusted proportionally to the difference between the set-point and the sensed daylighting. In practice, this option can only be implemented with an automatic system.

Figure 6-21 summarises this strategy procedure, inherent to scenarios B and C. For these cases, the evaluation of the indoor illuminance was performed through the daylight factor (DF) method, which is easily applicable for long-term simulations at short time-steps.

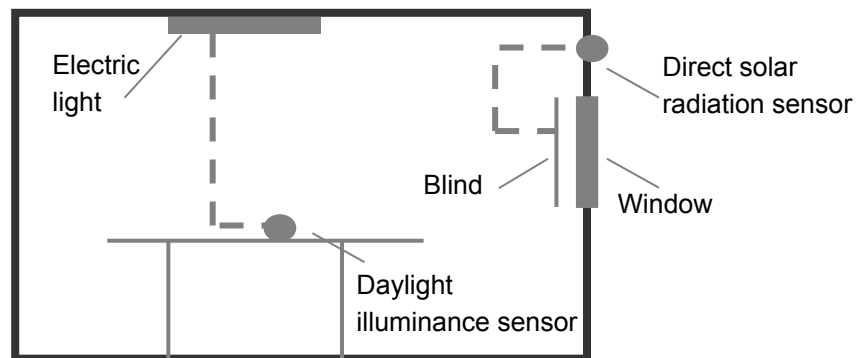


Figure 6-21: Integrated strategy for controlling window blinds and electric lighting. Blinds are assumed to be rolled down when the direct solar radiation passing through the window is higher than a certain set-point, and electric light is ON-OFF controlled or dimmed proportionally to the deficit between the lighting set-point and the measured daylight.

The daylight factor is defined as the ratio between the daylight illuminance measured at a certain point indoors, and the outdoor horizontal diffuse illuminance (King, 1995). Its value depends on the specific location on the room, although an average value can be computed. The daylight factor can be measured in scale models, calculated by simplified analytical formulas or accurately calculated with detailed simulation tools. In this study, whenever necessary, the daylight factor at chosen points in a room will be calculated with RADIANCE. The simulation for determining the DF at one or several points in a room needs to be run only once. Thus, the problem of the significant computation time required by RADIANCE simulations is not critical.

When using this method in ESP-r, the daylight illumination level at the reference point indoors, E_{in} , is given by:

$$E_{in} = E_{out} \times \sum_{i=1}^N DF_i \times VT_i \quad \text{eq. 6-3}$$

where:

- E_{out} is the outdoor horizontal diffuse illuminance;
- N is the number of windows in the room;
- DF_i is the daylight factor due to the window i , at the chosen reference point;
- VT_i is the visible transmissivity of window i .

The outdoor illuminance is computed at each time-step from the weather data, using the method reported by Perez, Ineichen et al. (1990).

Because the DF does not account for the influence of the illuminance associated to direct solar radiation that may enter a space, it tends to underestimate the indoor illuminance. Therefore, if an a set-point of 300 lux is chosen for the model, it is very likely that the real values will be somewhat higher.

Concerning the control of the blinds, in its base version, ESP-r checks if the window is external (i.e., located at an external façade) before allowing the activation of window blinds. This may present a problem for simulating the SOLVENT window. Although the window is to be installed only at external façades, the ESP-r model treats the blinds as located at an interior façade because the air gap is explicitly treated as a thermal zone (figure 6-22).

A specific change to the ESP-r code thus had to be implemented, to skip the necessary condition (external window) and to allow the control of blinds at “internal” façades (*File esrubld/solar.F, line 557. See Annex 3*).

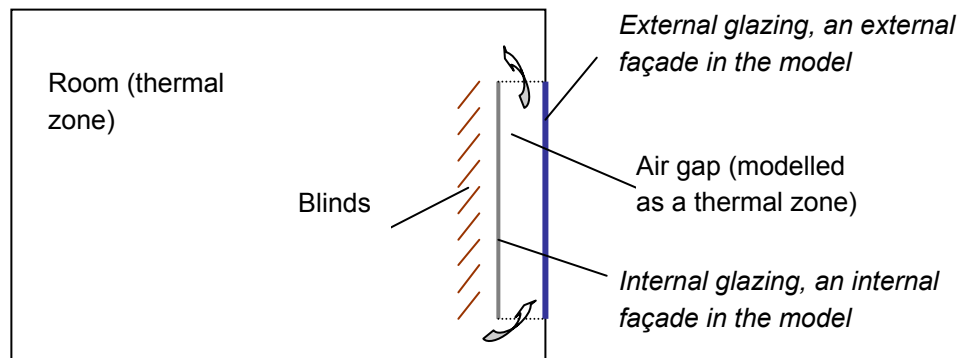


Figure 6-22: Internal blinds in the SOLVENT window. Because the air gap is explicitly modelled as a thermal zone, the blind is located at an “internal” façade.

Given the uncertainty inherent to the phenomena and the scatter in the monitoring results presented in the previous section, it seems impossible to define an unquestionable triggering value for activating the blinds. Probably, the best approach would be to use a probabilistic approach rather than a fixed activation value. However, there are not enough nor adequate monitoring results to implement such an option. Nevertheless, using a fixed triggering value provides some indication of the trends and orders of magnitude. For the present study, it will be assumed that the blinds are closed if the direct solar radiation

passing through the window, measured at its normal, is higher than 150 W/m^2 . This is an intermediate value, near the middle of the interval mentioned in the above listed bibliography. The influence of this set-point will later be subjected to a sensitivity study, in section 7.3.2.

By choosing the radiation that *passes* through the system, it is possible to account for the effect of glazing transmissivity. For instance, for a double clear glazing with a visible transmissivity of 81%, the blinds will be activated when the incident radiation is higher than 185 W/m^2 , while for a SOLVENT window identical to the window tested during the experimental campaign, with a transmissivity of 38%, the blinds will only be activated if the incident solar radiation is higher than 394 W/m^2 .

The solar optical properties of the glazing system with the blinds rolled down were obtained with the software WIS 3.01 (Dijk, 2003). A light internal venetian blind with the geometry shown in figure 6-23 was taken as reference for the blinds. It is considered that when the blind is fully rolled down, the direct solar transmission towards indoors is null. Regarding the transmission of visible light, it was considered that when the blinds are fully rolled down, the visible transmissivity is very low. A value of 5% was assumed as reference.

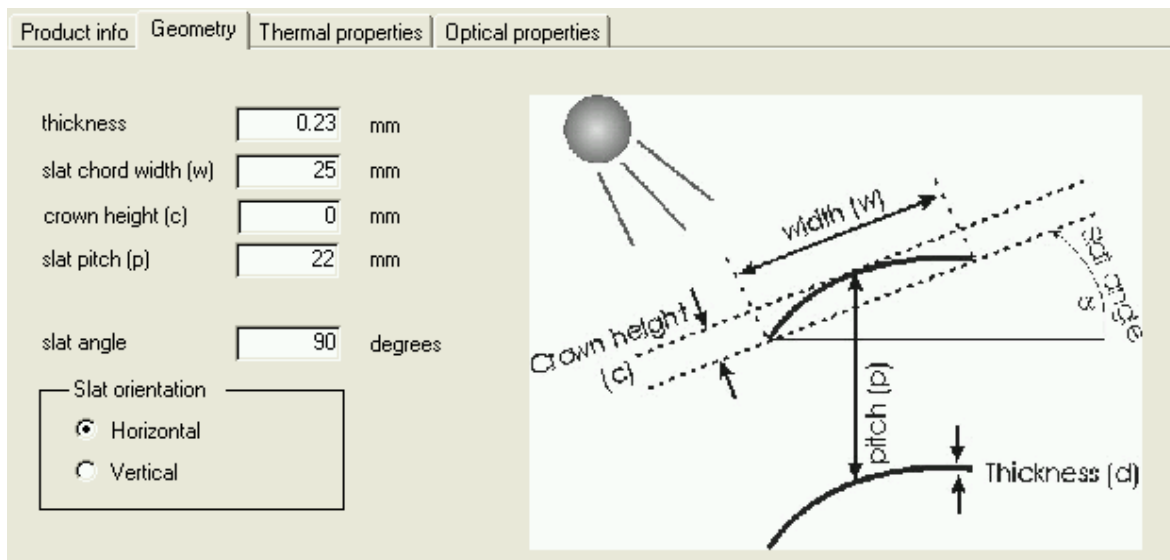


Figure 6-23: Light Internal Venetian blind chosen as reference for calculating the solar properties of the window systems (image obtained from WIS).

In complement to the integration of the dynamics of the lighting and blind control, as defined above, an analysis of the impact of the SOLVENT window upon the DGI, without the effect of blinds and under reference sky conditions, will also be performed. The reference outdoor illuminances are those listed in table 6-4. They correspond to the 80% percentiles at noon in each of the reference locations.

Table 6-4: Outdoor horizontal illuminance availability at mid-day, on a high-luminance day (80% percentile), at the three reference locations (Lux).

	Diffuse	Global
Porto	43473	88670
Berlin	36682	68776
Tel Aviv	39807	104344

The measurements performed at the test cell were also used to calibrate and validate the use of RADIANCE. This is an important point, since the use of RADIANCE for lighting simulations requires the definition of a large number of calculation parameters which are not always easy to set (Jarvis and Donn, 1997).

Figure 6-24 and figure 6-25 show an exterior and an interior view of the model, respectively. Figure 6-26 and figure 6-27 show the “real” photo and a view simulated with radiance for approximately the same location in the test cell.

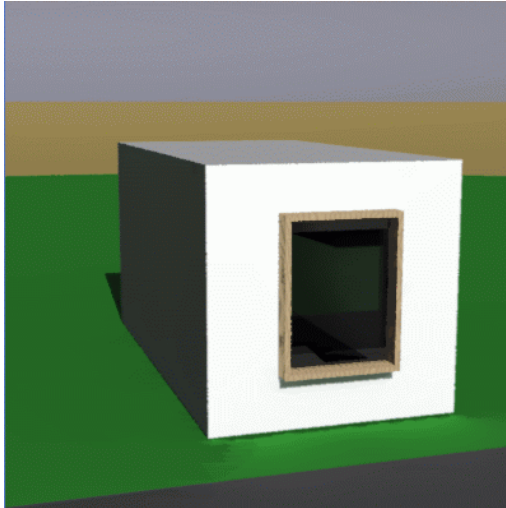


Figure 6-24: Exterior image of the test cell rendered with RADIANCE

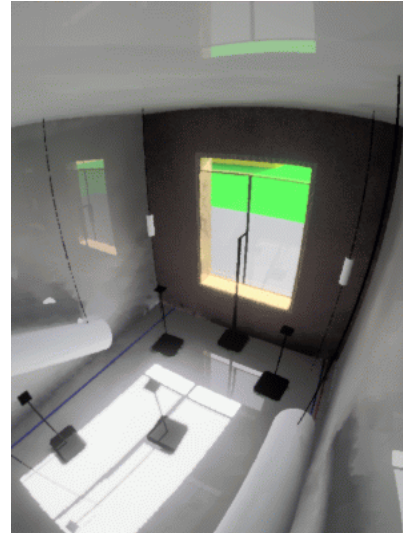


Figure 6-25: Interior image of the test cell rendered with RADIANCE



Figure 6-26: "building" model (photo)

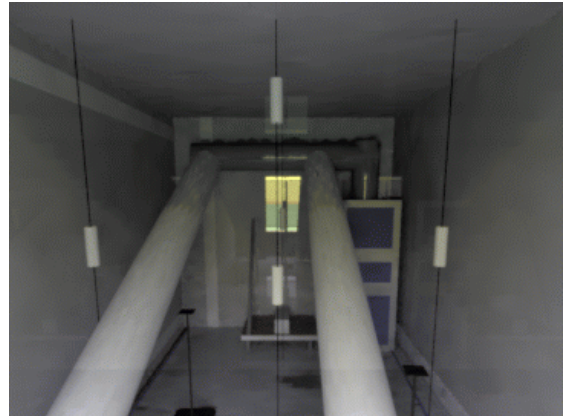


Figure 6-27: "building" model (simulation)

Figure 6-28 shows the illuminance levels computed by Radiance at some reference points (where luxmeters were placed) for a CIE Overcast sky. Between brackets are the values measured on the 5th October 2001 at 12:00 (which was a very cloudy day).

In a similar way, figure 6-29 shows the computed illuminance values for a CIE sunny day and in green measured values at 12:00 of the 11th November 2001. The order of magnitude of the values seems to indicate also a good agreement in this other case too.

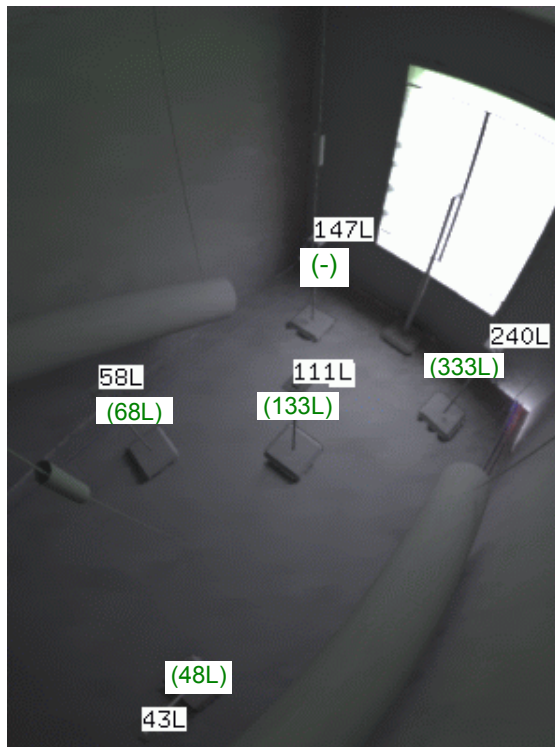


Figure 6-28: Simulated and measured illuminance levels under overcast sky conditions values on the 5th October at 12:00 (measured values between brackets).

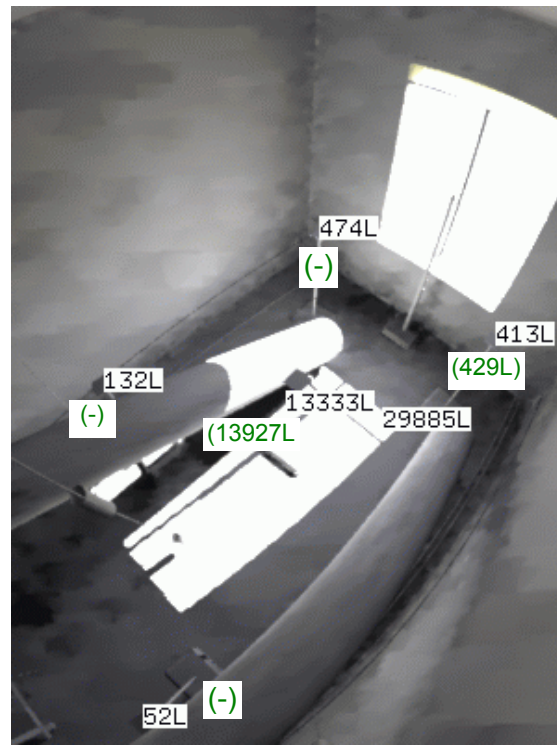


Figure 6-29: Simulated and measured illuminance levels under clear sunny sky conditions on the 11th November at 12:00 (measured values between brackets).

7 CASE-STUDIES

The goal of this chapter is to demonstrate and quantify the impact of the SOLVENT window in real buildings. The strategy for integrating the window in the building simulation model was described in chapter 6. The lights and blinds are therefore controlled based on criteria of visual comfort, while the heating and cooling control is based on the indoor temperatures. The results are thus essentially presented in terms of demand of energy for heating, cooling and artificial lighting, although a complementary study with free-floating temperatures will also be presented.

Two building typologies were selected as case studies to evaluate the impact of the SOLVENT window: a small open-space office and a school room.

In order to obtain a broader assessment of the energy impact of the SOLVENT window, the case-study buildings were studied in an Atlantic climate (Porto, Portugal), a continental climate (Berlin, Germany) and a warm Mediterranean climate (Tel Aviv, Israel). Appropriate changes to the building fabric, recommended by local experts, are performed when “moving” the building between different locations.

Section 7.1 presents an overview of the factors that are subject to analysis. Section 7.2 describes the buildings and the adaptations to local climatic conditions. Section 7.3 then presents results and their analysis. Finally, section 7.4 contains a brief discussion of economic aspects related to the SOLVENT window.

7.1 FRAME OF SIMULATION SCENARIOS

The primary goal of this chapter is mainly to determine the potential of the SOLVENT window in terms of energy savings. However, there are many building characteristics, control features and modelling assumptions that influence such calculations. It is therefore necessary to define a frame of simulation scenarios that captures the dependency on the main variables and, at the same time, that reveals how sensitive the results may be to the modelling assumptions.

The set of simulations were defined to allow the characterization of the impact of the following items upon the energy demand:

- A. Type of window;
- B. Local climate;
- C. Type of lighting and blind control;
- D. Lighting set-point;
- E. Blind actuation trigger value;
- F. Building orientation;

For the impact of items A, B and C, a strategy of “all by all matrix” was adopted. This means, for instance, that all types of windows are studied in all climates and with all control strategies.

Concerning the influence of items D, E and F, a lighter approach was followed. Only reference types of windows with a reference type of control are studied in all the three reference climates.

In order to allow an integrated evaluation of the energy demand, the components of heating, cooling and lighting energy demand are converted to primary energy (equivalent to fossil fuel) and summed up. The assumptions for converting to primary energy were as follows:

- Heating is provided by a boiler with an efficiency of 80%;
- Cooling is provided by an electricity-based system with an average COP (coefficient of performance) of 3;
- Electricity is generated from fuel oil with an overall conversion efficiency of 40%.

7.1.1 Type of window

The alternatives considered for glazing are the following:

- Double clear glazing window (visible transmissivity 81%);
- SOLVENT window with poorly absorptive glazing (visible transmissivity 57%)
- SOLVENT window with medium absorptive glazing (visible transmissivity 38%)
- SOLVENT window with highly absorptive glazing (visible transmissivity 26%)
- Double clear solar control window (visible transmissivity 38%)

Figure 7-1 shows the position of the glazings, blinds and air gaps in each of the alternatives. The detailed angular optical properties used for the glazings that constitute these windows are shown in annex 4.

When studying the alternative SOLVENT windows, both the Winter mode and the Summer mode options are simulated for the full year. The energy demand for lighting is independent of the mode. Concerning the monthly results for heating and for cooling, their values were both taken from the modes which yielded the lowest energy demand for each day. In practice this means that the window is assumed to be always at the optimal mode, and therefore implies that the results obtained with the SOLVENT window will be their maximum potential. In practice, it is realised that users will probably be less efficient in the change of the mode.

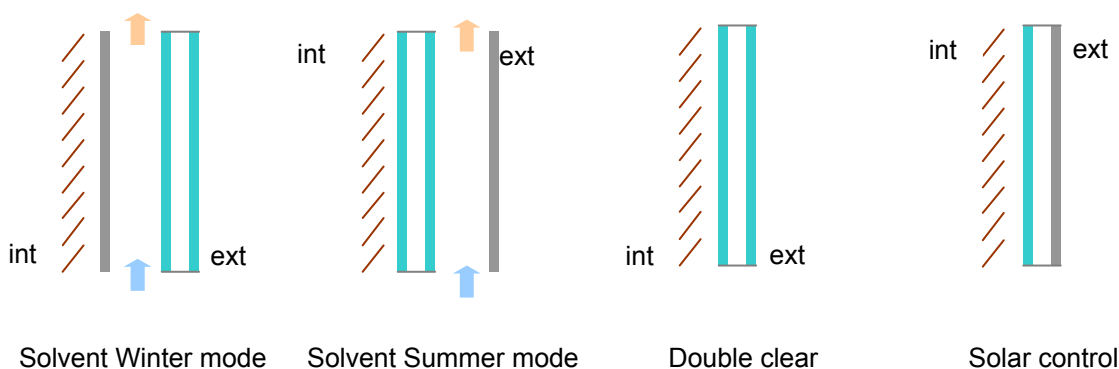


Figure 7-1: Window alternatives studied: SOLVENT window, double clear glazing, solar control double glazing.

7.1.2 Climate

In principle, the design and the performance of the SOLVENT window are intimately linked to the climate of the site where the building is located. It should be expected that in places with frequent sunny sky and high outdoor temperatures, a highly absorptive glazing could be used to improve visual comfort and minimise the cooling loads. Conversely, for places with frequent cloudy sky, a reasonably transmissive glazing should be used to avoid excessive needs for electric lighting. However, only a simulation accounting for the climatic conditions and solar position for every moment of the year may confirm (or not) these expectations.

The following three reference sites were selected to study the impact of the SOLVENT window in a large range of climates:

- Porto, Portugal, representing a mild Atlantic European climate
- Berlin, Germany, representing a cold Continental European climate
- Tel Aviv, Israel, representing a warm Mediterranean climate.

The climatic data files for Porto and for Berlin were taken from the climate ESP-r database, which in turn is based on the IWECD data (ASHRAE, 2001). The files contain information of air temperature, solar radiation, wind speed and direction and relative humidity, for each hour of a “typical” year. For Tel-Aviv there is no data available at the IWECD database. So, for this location, the file was produced by the METONORM software (Remund, Lang et al., 1999), based on data from the Bet-Dagan station, close to Tel Aviv. An important observation is that all these files provide realistic wind data, which is not often the case with weather files.

Figure 7-2 shows the yearly temperature distribution at the three reference sites. Figure 7-3 shows the equivalent information for direct normal solar radiation. The differences between the three climates are clear, and show that, as expected, Berlin has a colder and cloudier climate, Tel Aviv has the warmest and sunniest climate, and Porto has an intermediate climate.

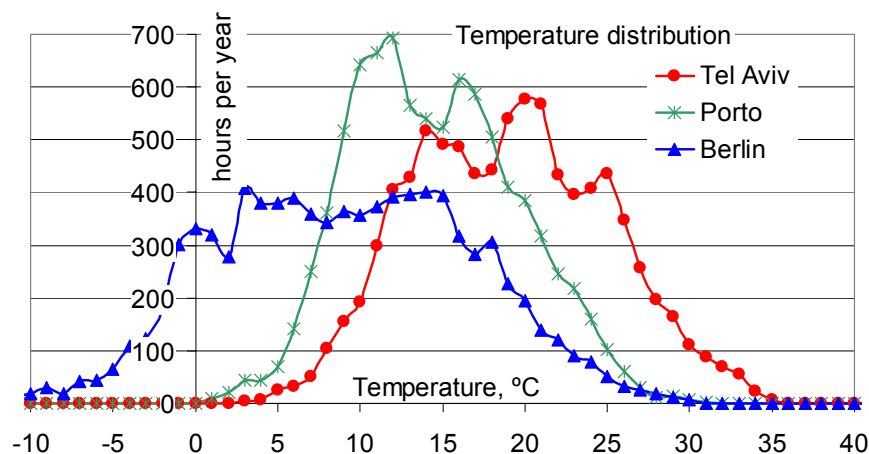


Figure 7-2: Yearly temperature distribution at the reference locations.

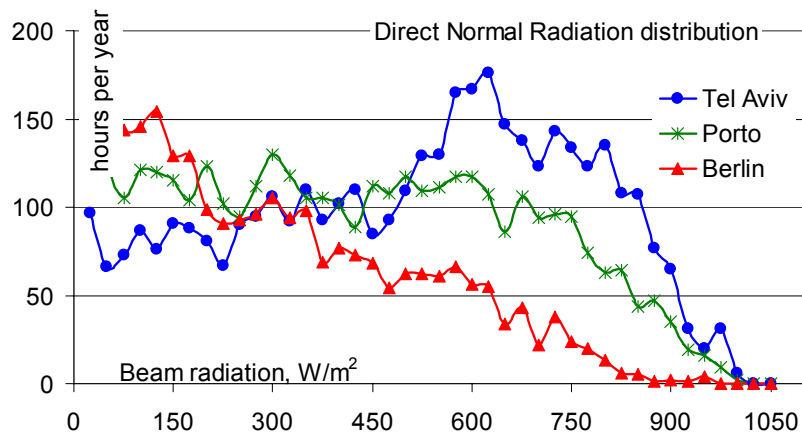


Figure 7-3: Yearly distribution of the direct normal solar radiation at the reference locations.

7.1.3 Type of control

As described in section 6.5.2, the following three control scenarios were considered:

- **No control:** blinds are not considered, and lights are always ON during work time.
- **ON-OFF control:** blinds are activated if the solar radiation passing through the window is above a trigger value, and electric lighting is activated with full power if the sensed daylighting is below the lighting set-point.
- **Ideal dimming control:** blinds are activated if the solar radiation passing through the window is above the trigger value, and electric lighting is dimmed proportionally to the deficit between the set-point and calculated daylighting.

7.1.4 Lighting set-point

For the two spaces being studied, the lighting set-point was set at 300 Lux, which is at the lower limit of the recommendations for schools and offices (Baker, Fanchiotti et al., 1993)². Furthermore, it is known that the required level of lighting varies from one individual to another. Therefore, it is important to assess if the lighting set-point has a significant impact upon the evaluation of the performance of the SOLVENT window. Rather than comparing the direct impact of changing the lighting set-point, it is sought to analyse if the change in the set-point has a significant impact upon the comparison between the SOLVENT window and the double clear glazing window. The difference between the SOLVENT window (in the variant with medium transmissivity, VT=38%) and a double clear glazing window is thus analysed in two scenarios:

- Lighting set-point at 300 Lux (base case);
- Lighting set-point at 500 Lux.

This sensitivity study is performed for all the three reference climates, using the dimming-control strategy.

² This will correspond to higher value in reality, since, for the calculation of the indoor illuminance, the daylight factor method does not account for the direct component of the sun/sky luminance.

7.1.5 Blind actuation trigger value

The monitoring results presented in section 6.5 have shown that there is a significant dispersion in the way how people operate the blinds. In particular, it is not possible to identify a widely accepted trigger value of solar radiation for the blind actuation. It is therefore important to study variations to the base-case assumption that the blinds are activated if the direct solar radiation that passes through the glazing is higher than 150 W/m^2 . The alternatives considered are one trigger value 50% lower another 50% higher. The resulting alternatives in terms of trigger value for blind actuation therefore are:

- Blind activated if direct solar radiation passing $> 150 \text{ W/m}^2$ (base-case);
- Blind activated if direct solar radiation passing $> 75 \text{ W/m}^2$;
- Blind activated if direct solar radiation passing $> 225 \text{ W/m}^2$

The sensitivity study for the lighting set-point analyses the difference between the SOLVENT window and the double clear glazing window, for all the three reference climates, using the dimming-control strategy.

7.1.6 Orientation

In both case-study buildings, the main façade is oriented towards South. This is a good orientation for studying the effect of the SOLVENT window, which deals with the consequences of direct solar radiation. However, it is important to assess how the performance of the SOLVENT window may be affected by the building orientation. Therefore, the difference between the SOLVENT window and a double clear glazing window is studied for the three reference climates and for all the four main orientations:

- Main façade facing South (base-case);
- Main façade facing West;
- Main façade facing East;
- Main façade facing North.

7.1.7 Visual comfort

The main aspects of visual comfort are already incorporated in the criteria for controlling the blinds (avoid excessive solar radiation) and the artificial lighting (assure a minimum lighting level). This section seeks a complimentary analysis, from the perspective of the potential perception of glare when the blinds are not activated.

7.2 DESCRIPTION OF THE CASE-STUDY BUILDINGS

7.2.1 Office building description

This building houses the Department of Mechanical Engineering of the University of Porto, Portugal. It is a recently constructed building, officially inaugurated in 2001. The architectural design imposed no external shading devices on the South façade (figure 7-4).

The office selected as case-study is an open-space room (figure 7-5) with a floor area of 30.1 m^2 , located at the top floor. It has two windows, both facing South. As expected, problems of visual - and thermal - comfort arise when the weather is sunny and the venetian blinds are up (figure 7-6). To overcome this situation, occupants often roll down the interior

shading blades (figure 7-7). When they do so, illumination levels at the opposite side of the room become too low, leading the occupants to turn the electrical lighting on.

It is assumed that the office is occupied by 5 persons, with a simultaneity factor of 70%. 3 personal computers operate continuously during office hours (9-18 h), and 2 others during 50% of the time. A printer in stand-by is also considered. Electric lighting is provided by eight fluorescent lamps of 36 W each.

The building envelope fabric was considered differently in the three reference locations. For Porto, the envelope was considered as built. For Berlin and for Tel-Aviv, local experts indicated the changes that would be required to make the building somehow typical of local offices. For instance, when simulating in Berlin, higher insulation in the walls and low-e double glazings were considered.

The U-values of the resulting constructions are summarised in table 7-1. Detailed description is provided in Annex 5.

As built, the building has no mechanical ventilation. Therefore, the exterior air is only admitted through the windows or cracks. The South façade is very exposed to the predominant wind and to noise from a nearby highway. Consequently, the windows are closed most of the time and the fresh air change rate is very low, typically around 0.3 ach^{-1} (Afonso, Ribeiro et al., 2004). However, this energy study considered a value more typical of offices, 1 ach^{-1} .

The office has hot water radiators for heating, which are almost never used or needed. There is no mechanical cooling system, although one was assumed in this study for the purpose of energy demand calculation.



Figure 7-4: South Façade of the building



Figure 7-5: An interior view of the office



Figure 7-6: Direct sunlight impinging directly on a working surface.



Figure 7-7: A view of the working surface when Venetian blinds are down.

Table 7-1: Main envelope characteristics at each of the three studied locations

	<i>External Walls U-Value ($W/m^2.K$)</i>	<i>Roof U-Value ($W/m^2.K$)</i>	<i>Mean air change rate (ach^{-1})</i>
Porto (real location)	0.51	0.55	1.0
Tel Aviv (virtual loc.)	1.0	0.60	1.0
Berlin (virtual loc.)	0.35	0.25	1.0

7.2.2 Office simulation model

The reference office was modelled with ESP-r, along with two adjacent rooms which will serve as “buffer” zones to increase the accuracy of the results. Figure 7-8 shows the resulting geometry of the ESP-r model with conventional windows.

Table 7-2 lists a summary of the internal gains, corresponding to the typical operation of the office. A more detailed description can be found in annex 5.

For purposes of energy-demand calculation the heating and cooling set-points are virtually set to 20°C and 24°C, respectively, from 09:00 to 18:00 hours, during the whole year.

The daylight sensor inside the room was assumed to be located at a point with a daylight factor of 4%. This value was selected as representative of the workplane at the middle of the zone, after detailed RADIANCE simulations. In practice, in a real building, the sensor can be placed anywhere, provided that its measurements are corrected to the value that would be measured at the workplane position. In coherence with the definition of daylight factor, ESP-r uses only outdoor diffuse illuminance to compute the illumination level indoors. The contribution of luminance associated with direct solar radiation is not considered for this purpose.

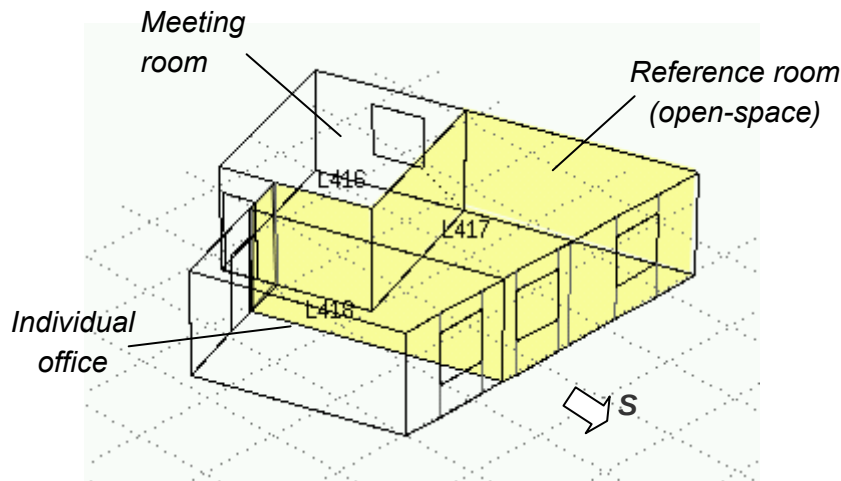


Figure 7-8: A view of the ESP-r model geometry

Table 7-2: Internal gains of the reference room (W/m^2)

Type	Time (h)	Sensible	Latent
Lighting	9-18	9.6	-
Equipment A	0-24	7.3	-
Equipment B	9-18	9.6	-
Occupants	9-18	11.0	5.2

7.2.3 School building description

The second building used to test the potential application of the SOLVENT window was a primary school. It represents a school type used for many years in Portugal and in other European countries. The main façade is oriented towards the South and classrooms only have windows in this façade. Figure 7-9 shows a school of this typology.

For this study, the left module (a fourth of the school) was modelled with ESP-r and the classroom in the ground level was taken as reference to assess the energetic performance. As in the office case-study, modifications in building fabric were introduced when studying the building at other locations, in order to make it representative of a “typical local school”. Annex 6 details the construction and use characteristics, while table 7-3 shows a summary of the main envelope properties. Lighting power is 7.5 W/m^2 and the occupation is assumed 25 children + 1 adult per room, from 8:00 to 18:00 (local legal time). Furthermore, the holidays in primary schools usually cover a large part of summer. E.g., in Portugal the holidays at these schools typically start by the end of June and last until mid-September. Therefore, the building is considered mostly unoccupied, and thus not thermally controlled, during July, August and the first half of September.



Figure 7-9: School of the typology used as base for the case-study.

Table 7-3: Main envelope characteristics at each of the three studied locations

	<i>External Walls U-Value (W/m².K)</i>	<i>Roof U-Value (W/m².K)</i>	<i>Mean air change rate (ach⁻¹)</i>
Porto (real location)	0.51	1.5	1.0
Tel Aviv (virtual loc.)	0.96	0.69	1.0
Berlin (virtual loc.)	0.36	0.46	1.0

For the locations in Portugal and in Israel, the double glazing consisted of the standard type (U-value about 3.0 W/m².K), but for Germany it consisted low-e glazing, with an U-value about 1.8 W/m².K. Other differences assumed for the characteristics of the envelope are detailed in annex 6.

7.2.4 School simulation model

The Esp-r model built included a bottom and a top-room, the roof space, stairwell and a store room at the North side. The operation and airflow were set as described in the previous section and in annex 6. Figure 7-10 shows a view of the geometric model in ESP-r. The bottom room was selected as reference for comparing the results and is highlighted in the figure.

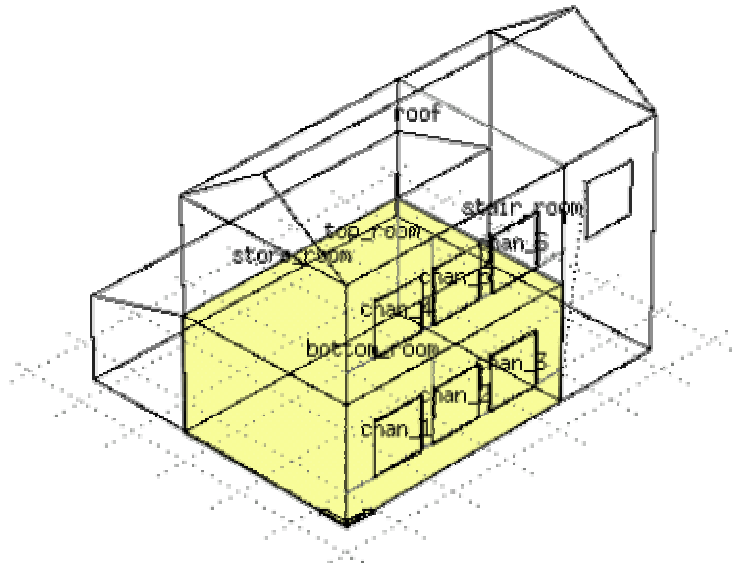


Figure 7-10: Geometry of the ESP-r model of the school, highlighting the bottom room used as reference for the analysis of the results.

7.3 RESULTS

7.3.1 Type of window, control system and location

The results of the energy demand for the complete matrix of the two case-study buildings, three reference locations and three blind and lighting control scenarios (as defined in section 7.1.3) are shown in tables 7-4 to 7-9 and figures 7-11 to 7-16.

The first main conclusion is that, even more than on the type of window, the primary dependence detected was on the type of blind and lighting control adopted in the building. Table 7-10 summarises the potential energy savings achieved with the ON-OFF control and with the ideal dimming control, compared with the “no control” scenario, for the double clear glazing window. The potential energy savings are up to 37% with the ON-OFF system (School in Tel Aviv), and up to 47% with the ideal dimming system (School in Tel Aviv).

Concerning the type of window, the results show that, in most of the cases, the alternative which leads to the lowest energy consumption is one of the variants of the SOLVENT window. The only exceptions were the school in Berlin, with the “ON-OFF” and with the “ideal dimming” strategies, and in Porto with the “no control” and with the “ON-OFF” strategies, where the best option was the double clear glazing window. The specific version of the SOLVENT window that yields the lowest energy consumption depends on the type of lighting control. In the “no control” scenario, which has the lights always ON, the best alternative is the darkest SOLVENT window, since it is the most efficient in reducing the cooling loads. When the control is of the type ON-OFF, the best solution seems to be the SOLVENT window with a poorly absorptive glazing. When considering a more efficient lighting control strategy, the ideal dimming control that maximises the use of daylighting, the best variant of the SOLVENT window then appears to be the one incorporating the glazing with medium absorptivity. Table 7-11 and table 7-12 show a summary of the best SOLVENT option, with the ON-OFF control and with the ideal dimming control, for all the studied combinations building-climate.

Compared with the double solar control glazing, which has a similar performance in terms of lighting and visual comfort, the SOLVENT window always performs better. The savings, however, are typically below 10% of the total primary energy for heating, cooling and lighting.

Table 7-4: Primary energy demand for the office in Porto (kgoe/m².year).

		Double clear	SOLVENT 57%	SOLVENT 38%	SOLVENT 26%	Solar control 38%
No control	Heating	0.1	0.1	0.1	0.1	0.1
	Cooling	3.2	2.9	2.6	2.3	2.6
	Lighting	4.8	4.8	4.8	4.8	4.8
	Total	8.1	7.8	7.5	7.2	7.5
	Difference to double clear		-3%	-8%	-11%	-7%
	Difference to solar control		+ 4%	-1%	-4%	-
ON-OFF	Heating	0.1	0.1	0.1	0.1	0.1
	Cooling	2.5	2.0	1.9	2.1	2.3
	Lighting	3.1	2.8	3.6	4.7	3.6
	Total	5.7	5.0	5.6	6.8	6.0
	Difference to double clear		-14%	-2%	+ 19%	+ 6%
	Difference to solar control		-18%	-7%	+ 13%	-
Ideal dimming	Heating	0.2	0.2	0.1	0.1	0.2
	Cooling	2.4	1.9	1.8	1.7	2.1
	Lighting	2.6	2.2	1.9	2.3	1.9
	Total	5.2	4.3	3.8	4.2	4.1
	Difference to double clear		-17%	-27%	-20%	-21%
	Difference to solar control		+ 5%	- 8%	+ 2%	-

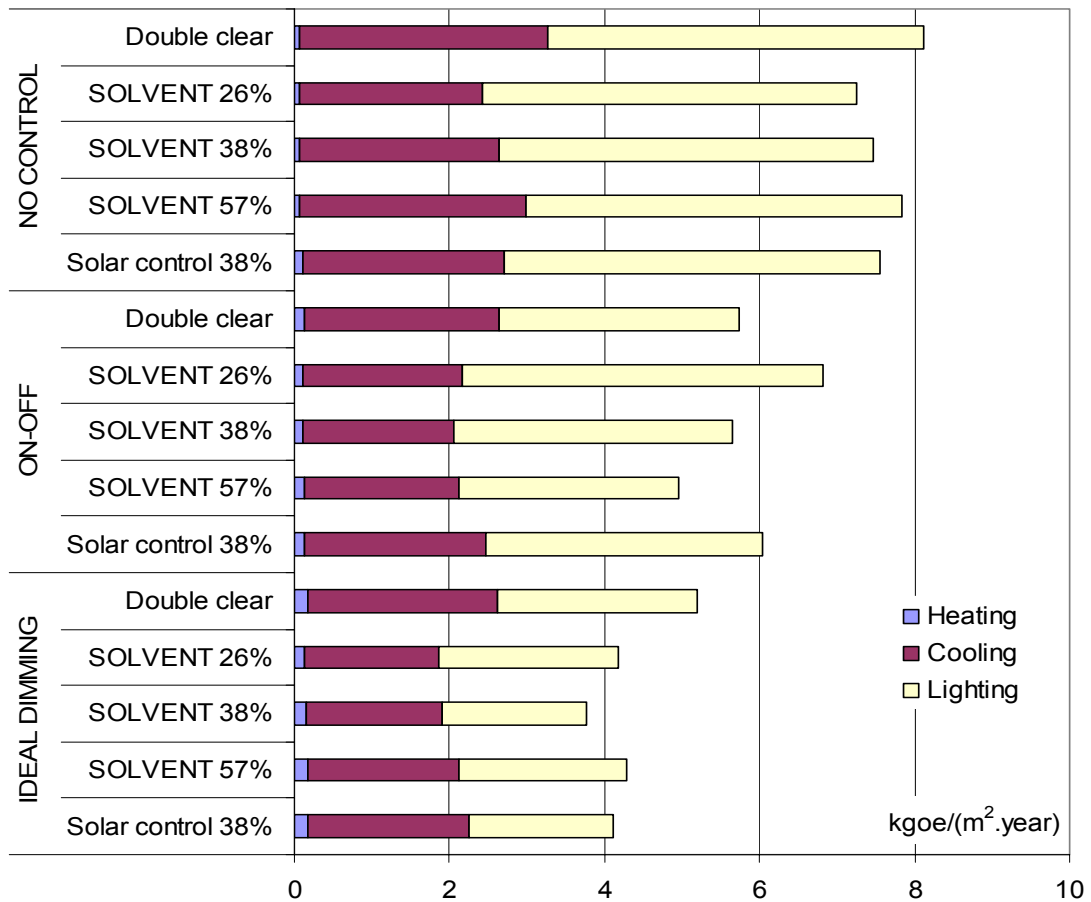


Figure 7-11: Primary energy demand for the office in Porto.

Table 7-5: Primary energy demand for the school in Porto (kgoe/m².year).

		Double clear	SOLVENT 57%	SOLVENT 38%	SOLVENT 26%	Solar control 38%
No control	Heating	1.2	1.5	1.4	1.4	1.5
	Cooling	0.3	0.2	0.2	0.2	0.3
	Lighting	4.7	4.7	4.7	4.7	4.7
	Total	6.2	6.4	6.3	6.3	6.5
	Difference to double clear		+4%	+2%	+1%	+4%
	Difference to solar control		-1%	-2%	-3%	
ON-OFF	Heating	1.7	1.7	1.6	1.5	1.8
	Cooling	0.3	0.2	0.1	0.1	0.2
	Lighting	2.8	3.0	3.1	3.3	3.1
	Total	4.8	4.8	4.8	4.9	5.1
	Difference to double clear		+2%	+1%	+3%	+7%
	Difference to solar control		-5%	-5%	-3%	
Ideal dimming	Heating	1.8	1.9	1.8	1.7	2.0
	Cooling	0.2	0.1	0.1	0.0	0.2
	Lighting	2.1	2.0	2.0	2.1	2.0
	Total	4.2	4.0	3.9	3.9	4.1
	Difference to double clear		-5%	-8%	-8%	-1%
	Difference to solar control		-3%	-7%	-6%	

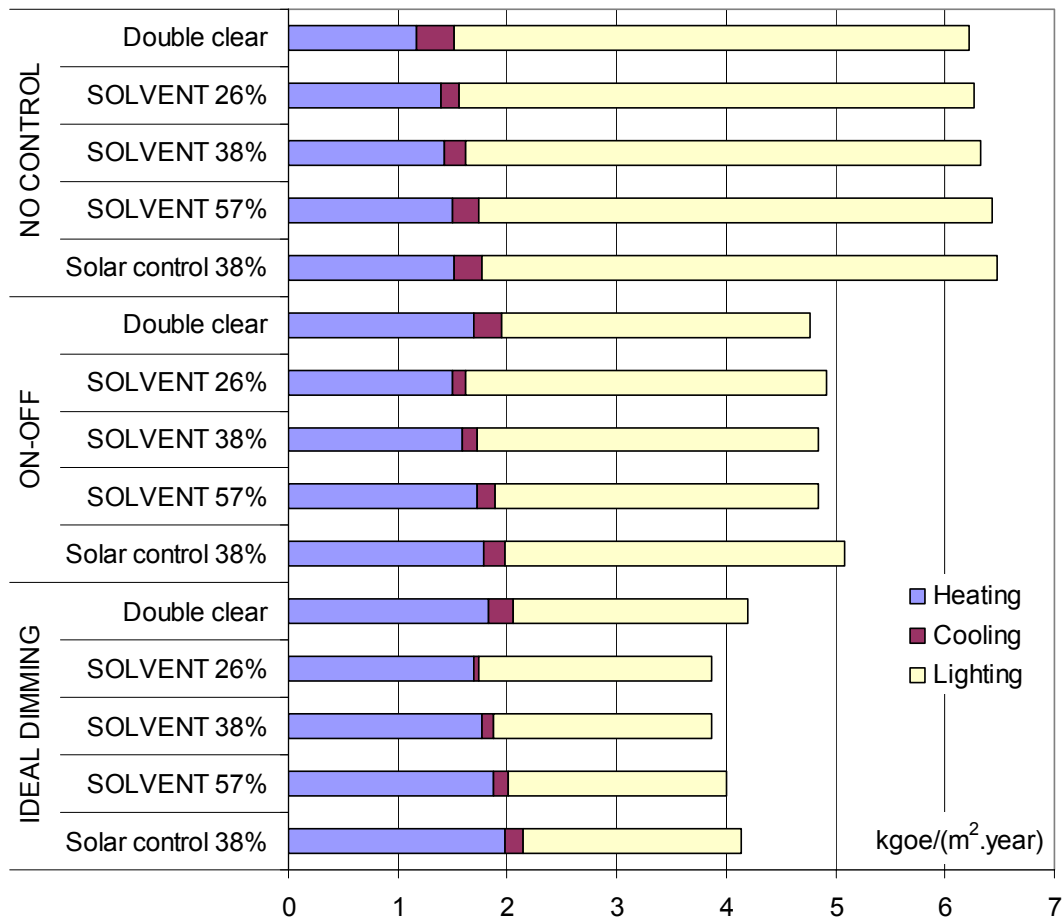


Figure 7-12: Primary energy demand for the school in Porto.

Table 7-6: Primary energy demand for the office in Berlin (kgoe/m².year)

		Double clear	SOLVENT 57%	SOLVENT 38%	SOLVENT 26%	Solar control 38%
No control	Heating	1.8	1.9	1.9	1.9	2.0
	Cooling	2.3	1.9	1.7	1.5	1.8
	Lighting	4.8	4.8	4.8	4.8	4.8
	Total	8.9	8.6	8.4	8.2	8.6
	Difference to double clear		-4%	-5%	-8%	-3%
	Difference to solar control		-1%	-2%	-5%	-
ON-OFF	Heating	2.0	2.0	2.0	1.9	2.1
	Cooling	1.8	1.4	1.3	1.3	1.5
	Lighting	2.9	3.1	3.5	4.4	3.5
	Total	6.8	6.5	6.7	7.6	7.0
	Difference to double clear		-4%	-0%	+13%	+4%
	Difference to solar control		-8%	-4%	+8%	-
Ideal dimming	Heating	2.2	2.2	2.2	2.2	2.3
	Cooling	1.8	1.4	1.2	1.1	1.4
	Lighting	2.2	2.2	2.2	2.6	2.2
	Total	6.2	5.8	5.7	5.9	5.9
	Difference to double clear		-7%	-9%	-4%	-4%
	Difference to solar control		-3%	-4%	0%	-

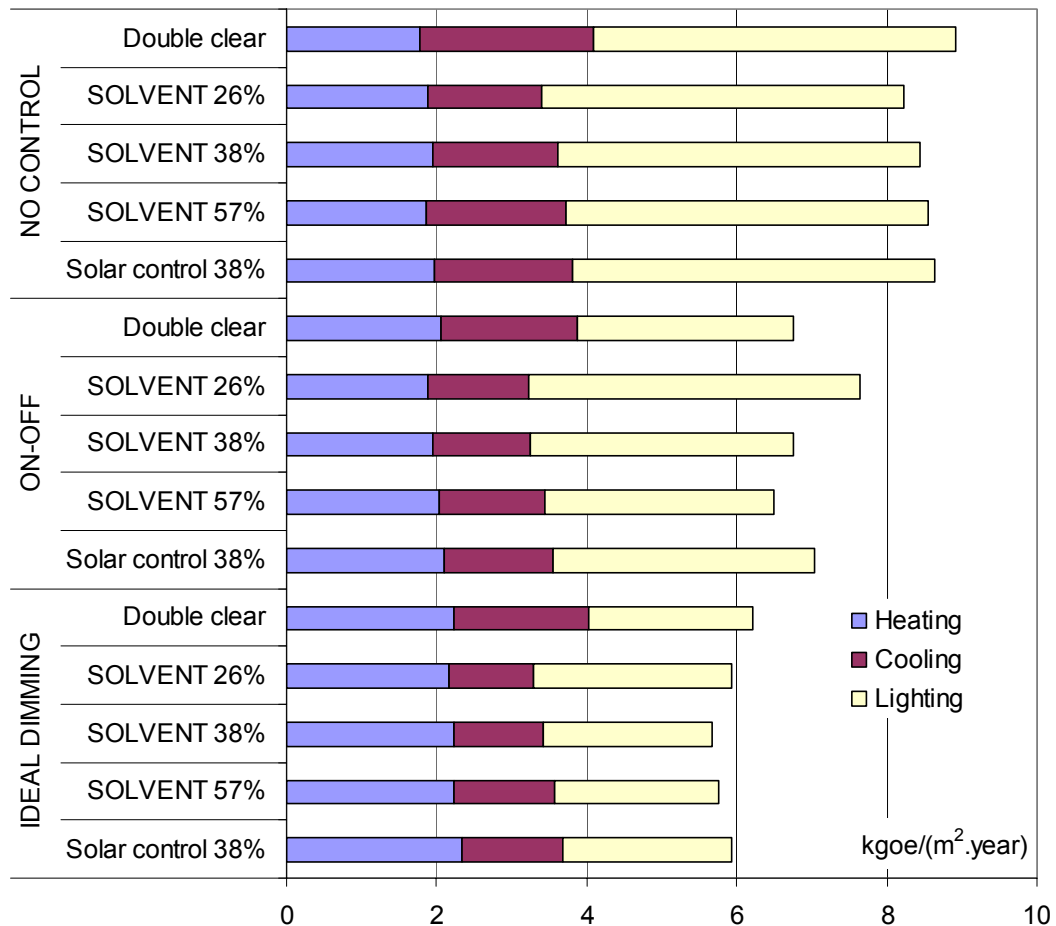


Figure 7-13: Primary energy demand for the office in Berlin.

Table 7-7: Primary energy demand for the school in Berlin (kgoe/m².year)

		Double clear	SOLVENT 57%	SOLVENT 38%	SOLVENT 26%	Solar control 38%
No control	Heating	2.2	2.6	2.6	2.7	2.7
	Cooling	0.8	0.5	0.3	0.3	0.4
	Lighting	4.7	4.7	4.7	4.7	4.7
	Total	7.7	7.8	7.7	7.6	7.8
	Difference to double clear		+1%	0%	-1%	+1%
	Difference to solar control		0%	-2%	-3%	-
ON-OFF	Heating	2.7	2.9	2.9	2.8	3.0
	Cooling	0.5	0.3	0.2	0.2	0.2
	Lighting	2.8	3.0	3.4	3.7	3.4
	Total	6.0	6.2	6.4	6.7	6.6
	Difference to double clear		+4%	+7%	+11%	+10%
	Difference to solar control		-6%	-3%	+1%	-
Ideal dimming	Heating	3.0	3.2	3.1	3.0	3.3
	Cooling	0.4	0.2	0.2	0.1	0.2
	Lighting	2.0	2.1	2.3	2.6	2.3
	Total	5.5	5.5	5.5	5.7	5.8
	Difference to double clear		+1%	+2%	+4%	+6%
	Difference to solar control		-4%	-4%	-2%	-

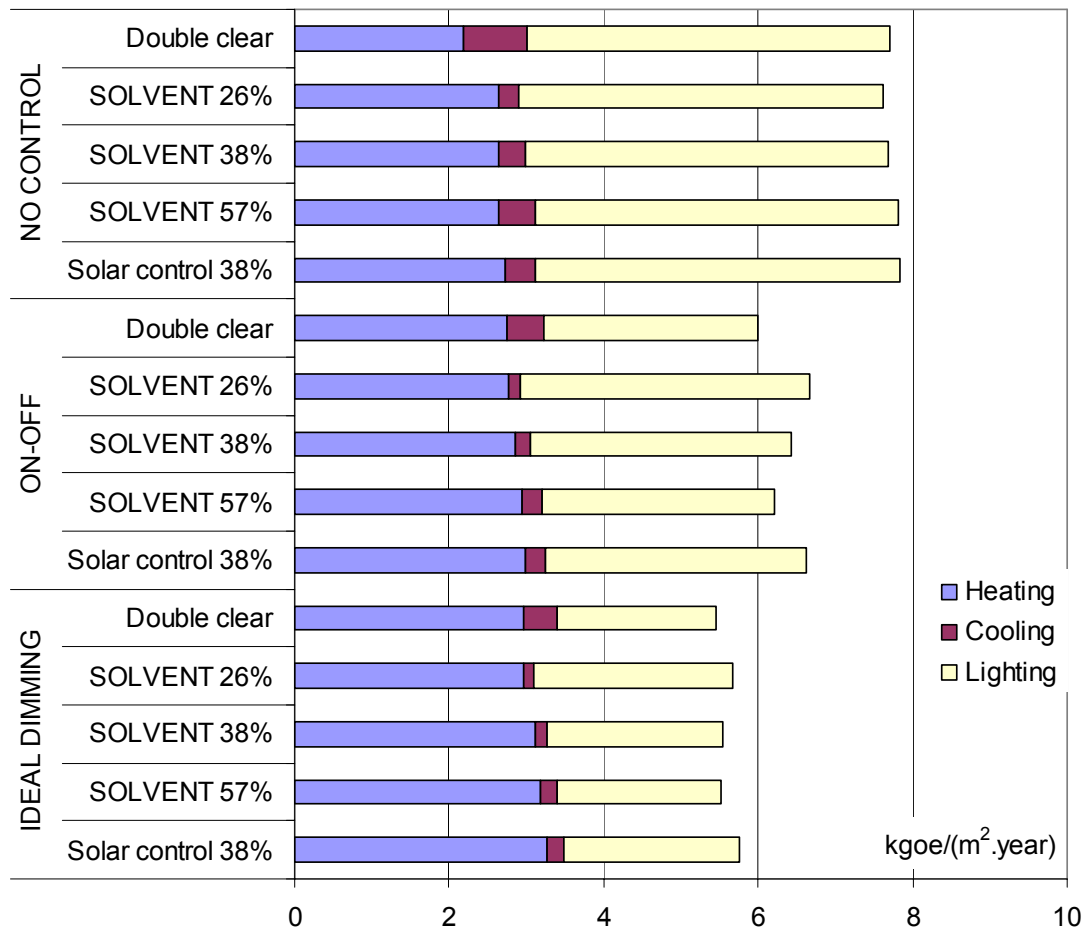


Figure 7-14: Primary energy demand for the school in Berlin.

Table 7-8: Primary energy demand for the office in Tel Aviv (kgoe/m².year)

		Double clear	SOLVENT 57%	SOLVENT 38%	SOLVENT 26%	Solar control 38%
No control	Heating	0.0	0.0	0.0	0.0	0.0
	Cooling	6.5	5.6	5.3	5.1	5.7
	Lighting	4.8	4.8	4.8	4.8	4.8
	Total	11.3	10.5	10.2	9.9	10.6
	Difference to double clear		-7%	-10%	-12%	-7%
	Difference to solar control		-1%	-4%	-6%	-
ON-OFF	Heating	0.0	0.0	0.0	0.0	0.0
	Cooling	5.5	4.9	4.7	4.8	5.1
	Lighting	2.9	2.6	2.9	4.1	2.9
	Total	8.4	7.5	7.6	8.9	8.0
	Difference to double clear		-10%	-9%	+7%	-4%
	Difference to solar control		-6%	-5%	+11%	-
Ideal dimming	Heating	0.0	0.0	0.0	0.0	0.0
	Cooling	5.3	4.8	4.5	4.4	4.8
	Lighting	2.4	2.0	1.8	2.0	1.8
	Total	7.7	6.8	6.3	6.5	6.6
	Difference to double clear		-12%	-18%	-17%	-14%
	Difference to solar control		+3%	-5%	-3%	-

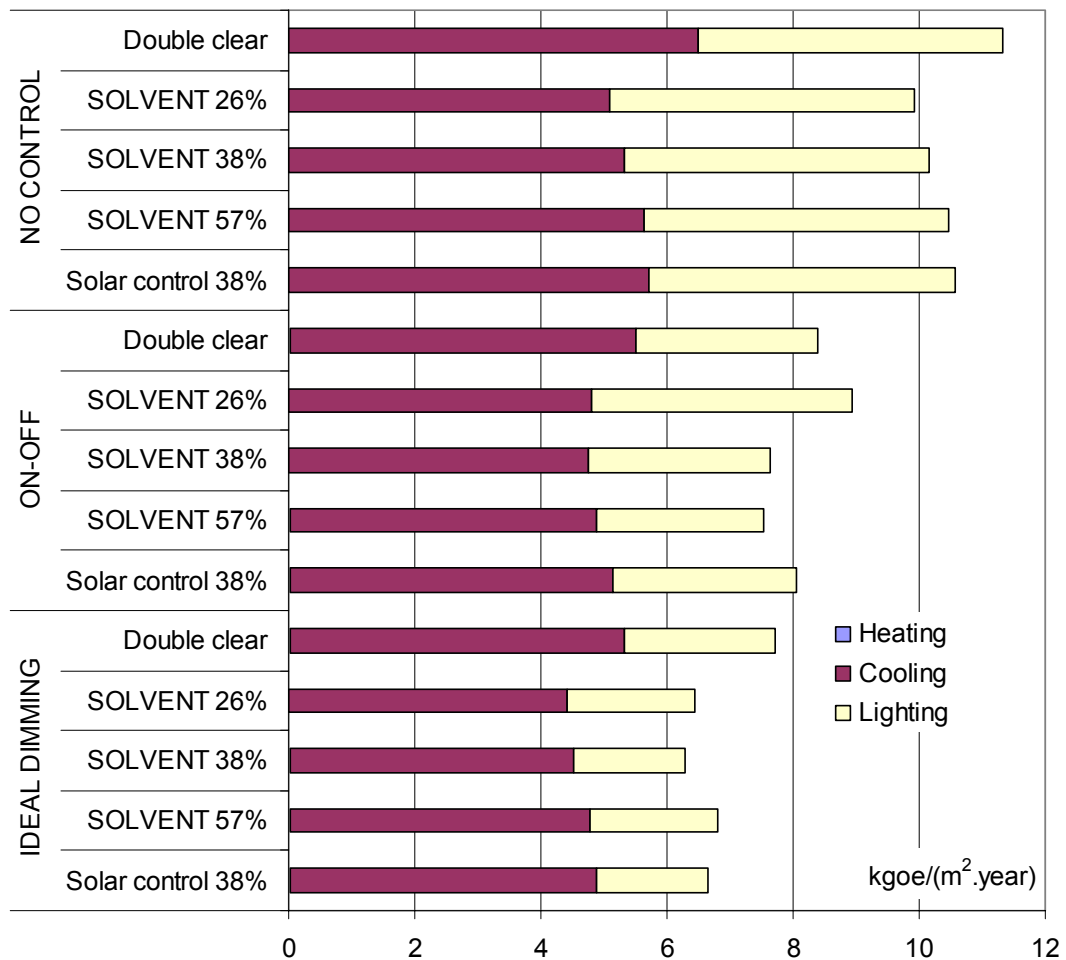


Figure 7-15: Primary energy demand for the office in Tel Aviv.

Table 7-9: Primary energy demand for the school in Tel Aviv (kgoe/m².year)

		Double clear	SOLVENT 57%	SOLVENT 38%	SOLVENT 26%	Solar control 38%
No control	Heating	0.1	0.1	0.1	0.1	0.1
	Cooling	2.8	2.0	1.6	1.5	2.0
	Lighting	4.7	4.7	4.7	4.7	4.7
	Total	7.6	6.8	6.4	6.3	6.8
	Difference to double clear		-10%	-15%	-17%	-10%
	Difference to solar control		0%	-5%	-8%	
ON-OFF	Heating	0.1	0.1	0.1	0.1	0.1
	Cooling	1.9	1.4	1.3	1.2	1.6
	Lighting	2.7	2.7	3.0	3.2	3.0
	Total	4.8	4.2	4.4	4.5	4.7
	Difference to double clear		-11%	-8%	-5%	-1%
	Difference to solar control		-10%	-7%	-4%	
Ideal dimming	Heating	0.1	0.2	0.2	0.1	0.2
	Cooling	1.7	1.3	1.1	1.1	1.4
	Lighting	2.1	1.9	1.8	2.0	1.8
	Total	4.0	3.4	3.1	3.2	3.4
	Difference to double clear		-15%	-22%	-21%	-16%
	Difference to solar control		0%	-8%	-7%	

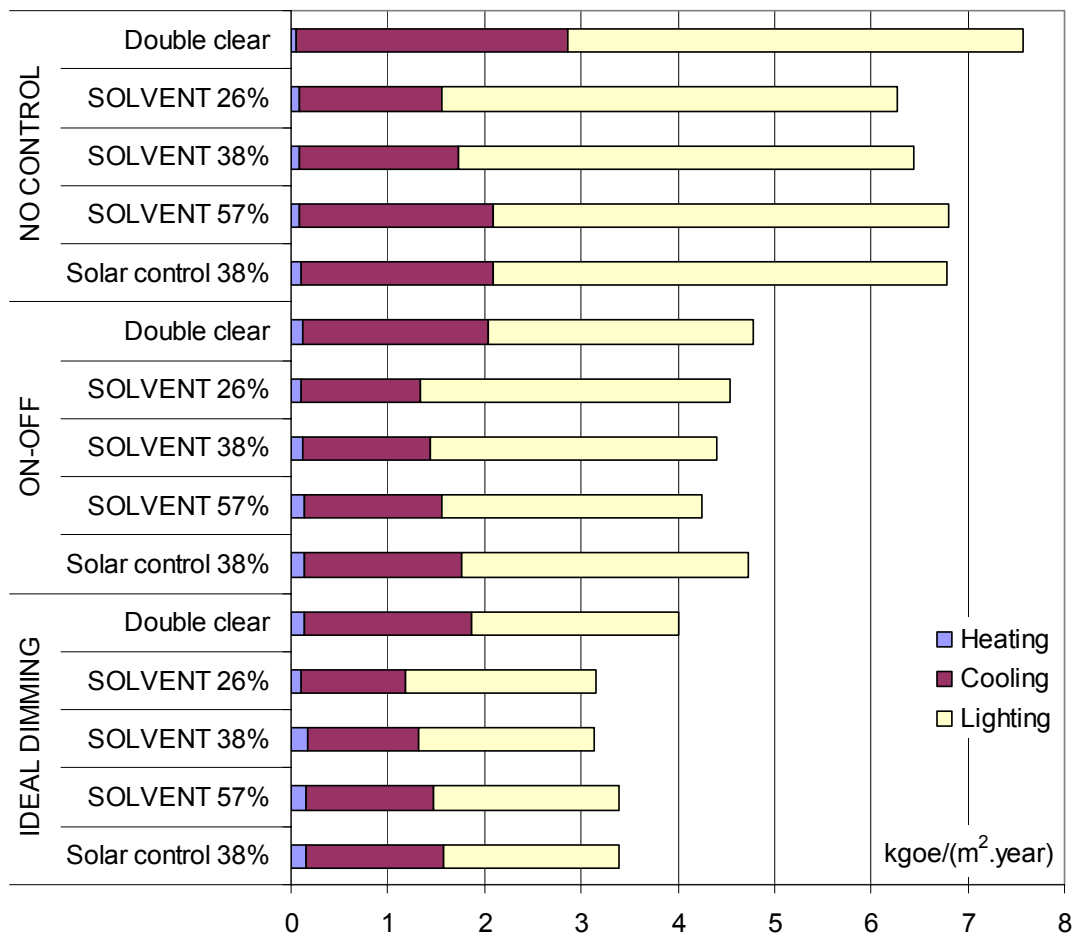


Figure 7-16: Primary energy demand for the school in Tel Aviv.

Table 7-10: Primary energy savings achieved with the strategies “ON-OFF control” and “ideal dimming control”, compared with the “no control” strategy.

	Office			School		
	POR	GER	ISR	POR	GER	ISR
ON-OFF Control	-29%	-24%	-26%	-23%	-22%	-37%
Ideal dimming control	-36%	-30%	-32%	-32%	-29%	-47%

Table 7-11: Best SOLVENT option in the “ON-OFF control” scenario and primary energy savings compared with the double clear glazing window.

	Office			School		
	POR	GER	ISR	POR	GER	ISR
Best SOLVENT option	SVT 57%	SVT 57%	SVT 57%	SVT 38%	SVT 57%	SVT 57%
Difference to Double Clear	-14%	-4%	-10%	+1%	+4%	-11%
Diff. to Solar Control 38%	-18%	-8%	-6%	-5%	-6%	-10%

Table 7-12: Best SOLVENT option in the “ideal dimming control” scenario and primary energy savings compared with the double clear glazing window and with the double glazing solar control window.

	Office			School		
	POR	GER	ISR	POR	GER	ISR
Best SOLVENT option	SVT 38%	SVT 38%	SVT 38%	SVT 38%	SVT 57%	SVT 38%
Difference to Double Clear	-27%	-9%	-18%	-8%	+1%	-22%
Diff. to Solar Control 38%	-8%	-4%	-5%	-7%	-4%	-8%

7.3.2 Influence of the lighting and blind actuation points

Table 7-13 compares the energy consumption of the office with the double clear glazing window and with the SOLVENT window, for the three reference locations, using two different lighting set-points (300 and 500 Lux) and three different blind activation set-points (75, 150 and 225 W/m²). These parametric studies are based on the “ideal dimming” strategy.

Table 7-15 summarises the impact of the lighting set-point in the comparison “double clear “ vs. SOLVENT, and table 7-16 presents similar information for the impact of the blind activation levels.

Relative to the base case, it is found that considering a higher lighting set-point decreases the advantage of the SOLVENT window over the double clear glazing window. This is essentially explained by the fact that the SOLVENT window is more affected by an increase in the energy demand for lighting than the double clear glazing window. Concerning the blind activation set-point, as expected, lower values lead to higher demand for lighting and higher values lead to lower demand. However, the two windows are most of the time quantitatively affected in the same manner. Thus, the comparative result in most combinations building-climate becomes nearly the same. At other conjugations building - climate, the result is a slight decrease in the difference between the two window alternatives.

Overall, it can be observed that the combination of set-points used as reference in this study (the base case), chosen as the most appropriate on the basis of published results, is actually the one which results on a higher advantage of the SOLVENT window over the double clear glazing window.

Table 7-13: Primary energy demand for the office, for two lighting set-points and three blind activation trigger values, simulating with the ideal dimming control strategy (kgoe/m².year).

		Base case 300 Lux; 150 W/m ²		500 Lux 150 W/m ²		300 Lux 75 W/m ²		300 Lux 225 W/m ²	
		Double clear	SVT 38%	Double clear	SVT 38%	Double clear	SVT 38%	Double clear	SVT 38%
PORTO	Heating	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.2
	Cooling	2.4	1.8	2.5	1.9	2.5	1.9	2.4	1.7
	Lighting	2.6	1.9	2.9	2.9	3.3	2.9	2.0	1.4
	Total	5.2	3.8	5.5	4.9	5.9	4.9	4.6	3.3
	Difference	-27.4%		-10.6%		-17.5%		-27.4%	
BERLIN	Heating	2.2	2.2	2.1	2.1	2.2	2.1	2.2	2.2
	Cooling	1.8	1.2	1.8	1.3	1.8	1.2	1.8	1.2
	Lighting	2.2	2.2	2.6	3.0	2.6	2.7	1.9	2.0
	Total	6.2	5.7	6.5	6.4	6.6	6.1	5.9	5.5
	Difference	-8.7%		-2.5%		-8.6%		-7.4%	
TEL AVIV	Heating	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Cooling	5.3	4.5	5.5	4.7	5.4	4.6	5.4	4.5
	Lighting	2.4	1.8	2.7	2.6	3.2	2.6	1.4	1.4
	Total	7.7	6.3	8.1	7.3	8.7	7.2	6.8	5.9
	Difference	-18.5%		-10.8%		-16.6%		-14.0%	

Table 7-14: Primary energy demand for the school, for two lighting set-points and three blind activation trigger values, simulating with the ideal dimming control strategy (kgoe/m².year).

		Base case 300 Lux; 150 W/m ²		500 Lux 150 W/m ²		300 Lux 75 W/m ²		300 Lux 225 W/m ²	
		Double clear	SVT 38%	Double clear	SVT 38%	Double clear	SVT 38%	Double clear	SVT 38%
PORTO	Heating	1.8	1.8	1.8	1.7	1.8	1.7	1.8	1.8
	Cooling	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1
	Lighting	2.1	2.0	2.5	2.6	2.6	2.6	1.7	1.7
	Total	4.2	3.9	4.5	4.4	4.7	4.4	3.8	3.6
	Difference	-7.9%		-4.0%		-6.4%		-5.3%	
BERLIN	Heating	3.0	3.1	2.8	3.0	3.0	3.1	2.9	3.1
	Cooling	0.4	0.2	0.5	0.2	0.4	0.2	0.5	0.2
	Lighting	2.0	2.3	2.5	2.8	2.3	2.6	1.8	2.1
	Total	5.5	5.5	5.8	6.0	5.7	5.8	5.2	5.4
	Difference	1.6%		3.7%		1.1%		3.7%	
TEL AVIV	Heating	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2
	Cooling	1.7	1.1	1.9	1.2	1.8	1.2	1.9	1.1
	Lighting	2.1	1.8	2.5	2.4	2.8	2.4	1.7	1.5
	Total	4.0	3.1	4.5	3.8	4.7	3.8	3.7	2.8
	Difference	-22.1%		-15.7%		-20.6%		-24.0%	

Table 7-15: Primary energy saving of the SOLVENT window, compared with the double clear glazing, for two different minimum lighting levels.

	Office			School		
	POR	GER	ISR	POR	GER	ISR
300 Lux (base case)	-27%	-9%	-18%	-8%	+2%	-22%
500 Lux	-11%	-2%	-11%	-4%	+4%	-16%

Table 7-16: Primary energy saving of the SOLVENT window, compared with the double clear glazing, at three different solar-radiation trigger values for activating the blinds.

	Office			School		
	POR	GER	ISR	POR	GER	ISR
150 W/m ² (base case)	-27%	-9%	-18%	-8%	+2%	-22%
75 W/m ²	-17%	-9%	-17%	-6%	+1%	-21%
225 W/m ²	-27%	-7%	-14%	-5%	+4%	-24%

7.3.3 Influence of the building orientation

Table 7-17 and table 7-18 show the results of the energy consumption, varying the orientation of the main façade where the windows are located. A summary of the difference in the energy demand between the SOLVENT window and the double clear glazing window is then provided in table 7-19.

The results show, in first place, that for the office in all locations and for the school in Tel Aviv, the orientation of the windows towards South is not the option that leads to lowest energy demand. This may be explained by a combination of two factors. The first is that, due to the weak ventilation, high internal loads and/or solar gains, the buildings are dominated by cooling needs. An orientation towards North is thus advantageous in terms of reducing the energy demand for cooling, an effect which offsets the increase in the demand for heating. A second contribution to the apparent good performance of the North orientation seems to be a reduction in the energy needs for lighting. In a case-study for Belgium, not accounting for the effect of shading devices, Bodart and De Herde (2002) concluded that a North-orientation leads to an additional energy demand that is about 25% for weakly transmissive glazings, and negligible increase for highly transmissive glazings. However, when accounting the effect of blinds, it is observed that the North orientation leads to less, or even almost no need to use the blinds, and therefore it does not have the associated penalty in terms of additional requirements of electric lighting.

While this explanation has an effective correspondence with reality, the effect is also being amplified by the model used for calculating the indoor daylighting. The daylight factor is based at the outdoor diffuse illuminance, and it does not account for the illuminance associated with direct solar radiation. Therefore, for the same blind position, the calculated

indoor daylighting for a certain moment of the day is the same, independently of the room orientation. Furthermore, the model used to account for the effect of blinds does not consider variable tilt angles. Since the most accurate methods for indoor daylight prediction are not compatible with dynamic whole year simulation at short time-steps, this may be regarded as a disadvantage of the methods adopted, which is compensated by its agility. Moreover, it is also important to note that the several types of windows under analysis are mostly affected in the same manner, and therefore the comparison between them is even less affected than the results in terms of absolute demands.

Concerning the main question under analysis, the comparison between the SOLVENT window and the double clear glazing window, the maximum advantage of the SOLVENT window is obtained for the South orientation, followed by the orientations towards West and East. For the German climate, and also for the school in Portugal, the benefit of the SOLVENT window in these later orientations becomes negligible. For an orientation towards North, the SOLVENT window actually leads to higher energy consumption than the double clear glazing window at all studied climates, essentially because it requires more energy for lighting.

Table 7-17: Primary energy demand for the office, for the four main orientations of the main façade, simulating with an ideal dimming control strategy (kgoe/m².year).

		Oriented towards South		Oriented towards West		Oriented towards East		Oriented towards North	
		Double clear	SVT 38%	Double clear	SVT 38%	Double clear	SVT 38%	Double clear	SVT 38%
PORTO	Heating	0.2	0.1	0.3	0.2	0.4	0.4	0.5	0.4
	Cooling	2.4	1.8	2.2	1.7	2.1	1.6	1.5	1.3
	Lighting	2.6	1.9	1.8	1.7	1.5	1.7	0.8	1.4
	Total	5.2	3.8	4.3	3.6	4.0	3.6	2.7	3.1
	Difference	-27.4%		-15.6%		-9.8%		+13.0%	
BERLIN	Heating	2.2	2.2	2.5	2.5	2.6	2.6	2.7	2.5
	Cooling	1.8	1.2	1.6	1.1	1.6	1.1	1.2	1.0
	Lighting	2.2	2.2	1.7	2.1	1.6	2.1	1.3	2.0
	Total	6.2	5.7	5.8	5.7	5.8	5.8	5.2	5.5
	Difference	-8.7%		-2.0%		-0.3%		+5.8%	
TEL AVIV	Heating	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
	Cooling	5.3	4.5	5.1	4.3	5.1	4.2	3.9	3.7
	Lighting	2.4	1.8	2.1	1.6	1.7	1.6	0.8	1.3
	Total	7.7	6.3	7.3	6.0	6.9	5.9	4.9	5.1
	Difference	-18.5%		-17.7%		-13.5%		+4.9%	

Table 7-18: Primary energy demand for the school, for the four main orientations of the main façade, simulating with an ideal dimming control strategy (kgoe/m².year).

		Oriented towards South		Oriented towards West		Oriented towards East		Oriented towards North	
		Double clear	SVT 38%	Double clear	SVT 38%	Double clear	SVT 38%	Double clear	SVT 38%
PORTO	Heating	1.8	1.8	3.0	2.8	3.0	3.0	3.5	3.3
	Cooling	0.2	0.1	0.2	0.1	0.3	0.1	0.0	0.0
	Lighting	2.1	2.0	1.5	1.7	1.5	1.8	0.8	1.6
	Total	4.2	3.9	4.7	4.6	4.8	5.0	4.3	4.9
	Difference	-7.9%		-1.5%		+4.9%		+13.8%	
BERLIN	Heating	3.0	3.1	3.6	3.1	3.6	3.6	3.9	3.9
	Cooling	0.4	0.2	0.3	0.0	0.4	0.2	0.2	0.1
	Lighting	2.0	2.3	1.7	2.1	1.7	2.2	1.4	2.1
	Total	5.5	5.5	5.6	5.3	5.7	6.0	5.5	6.1
	Difference	1.6%		-5.5%		5.1%		11.0%	
TEL AVIV	Heating	0.1	0.2	0.3	0.4	0.2	0.3	0.4	0.4
	Cooling	1.7	1.1	1.6	1.1	2.0	1.3	0.9	0.7
	Lighting	2.1	1.8	1.7	1.6	1.6	1.7	0.7	1.4
	Total	4.0	3.1	3.6	3.1	3.8	3.3	2.0	2.6
	Difference	-22.1%		-14.1%		-12.9%		27.9%	

Table 7-19: Primary energy saving of the SOLVENT window, compared with the double clear glazing, for the four main façade orientations.

	Office			School		
	POR	GER	ISR	POR	GER	ISR
Towards South	-27%	-9%	-18%	-8%	2%	-22%
Towards West	-16%	-2%	-18%	-1%	-6%	-14%
Towards East	-10%	0%	-14%	+5%	+5%	-13%
Towards North	+13%	+6%	+5%	+14%	+11%	+28%

7.3.4 Visual comfort

It is assumed that the primary demands for visual comfort (sufficient illuminance and low glare levels) are met all the time, since the criteria for controlling the electric lights and the blinds were set to achieve this goal (section 6.5). There are, nevertheless, secondary implications of the chosen alternative upon visual comfort that must be analysed.

Table 7-20 shows the fraction of use of electric lighting, in the “ideal dimming” control strategy, for the four different levels of window luminous transmissivity considered. Table 7-21 shows the equivalent information for the fraction of time when the blinds are rolled down.

The analysis of the performance of the SOLVENT window now depends on the reference for comparison. If compared with the double clear glazing, it is found that the best SOLVENT option in the “ideal dimming” control strategy generally uses less electric lighting, and therefore relies more on daylighting. Besides the energetic benefit already incorporated

in the results of section 7.3.1, this is also beneficial in terms of visual comfort since, even for equivalent illumination levels, building occupants generally prefer daylighting to artificial lighting. Furthermore, the results also show that, with the SOLVENT window options, the fraction of time when the blinds are activated is considerably reduced. This means that building occupants can have a direct view towards outdoors during a larger portion of the time, which is also beneficial in terms of visual comfort.

However, if compared with a solar control window with the same visual transmissivity, the SOLVENT window has exactly the same visual performance. Therefore, in this particular aspect, it presents neither any penalty nor any advantage.

Table 7-20: Year-round average of electric lighting fraction with the ideal dimming control strategy

		VT=26%	VT=38%*	VT=57%	VT=81%**
Office	Porto	48%	39%	45%	53%
	Berlin	55%	46%	45%	45%
	Tel Aviv	42%	37%	42%	49%
School	Porto	45%	42%	43%	45%
	Berlin	55%	48%	45%	43%
	Tel Aviv	42%	39%	41%	45%

* Best SOLVENT option in this control strategy

** Double clear glazing

Table 7-21: Year-round average of the fraction of time when the blinds are activated.

		VT=26%	VT=38%*	VT=57%	VT=81%**
Office	Porto	2%	13%	28%	39%
	Berlin	1%	7%	14%	20%
	Tel Aviv	3%	12%	26%	40%
School	Porto	3%	16%	31%	41%
	Berlin	1%	8%	16%	21%
	Tel Aviv	4%	18%	34%	49%

* Best SOLVENT option in this control strategy

** Double clear glazing

A complementary analysis that may be performed is the determination of the daylight glare index (as defined in section 6.5.1). To calculate it, there is need for a geometric and photometric model of the reference rooms to use with the software RADIANCE. The walls were considered as having a reflectivity of 80%, the ceiling 90% and the floor 50%.

Figure 7-17 shows a top view of the office room as rendered by Radiance. Figure 7-18 shows the view from a selected first reference viewpoint for DGI evaluation, and figure 7-19 shows the view from a selected second reference point for the same purpose. The graphs from figure 7-20 to figure 7-22 show the calculated DGI values, for the two office reference points, and for the reference sky conditions adopted for each of the three reference locations (table 6-4).

Figure 7-23 and Figure 7-24 show the views from the reference points in the school room. The DGI results for the school room, also under the reference sky conditions of table 6-4 , are shown from figure 7-25 to figure 7-27.

The results indicate that, compared with the double clear glazing window, the SOLVENT window yields a reduction of about 2 points in the DGI scale. Again, if compared instead with a double solar control glazing with the same luminous transmissivity, the performance is exactly the same, therefore without foreseeable advantages or disadvantages.

An important observation is that, despite the verified reductions, the glare indexes obtained with the (medium transmissivity) SOLVENT window are often still above the 24 points considered as upper limit for visual comfort conditions. Even considering that the DGI criteria is more demanding than the criteria based on solar radiation, the results are in line with those of this last criterion (table 7-21). This means that the additional shading devices will sometimes be required to control glare.



Figure 7-17: Top view of the office (image rendered with RADIANCE).



Figure 7-18: View from reference point 1 (VP1) for DGI evaluation (Radiance-rendered image)

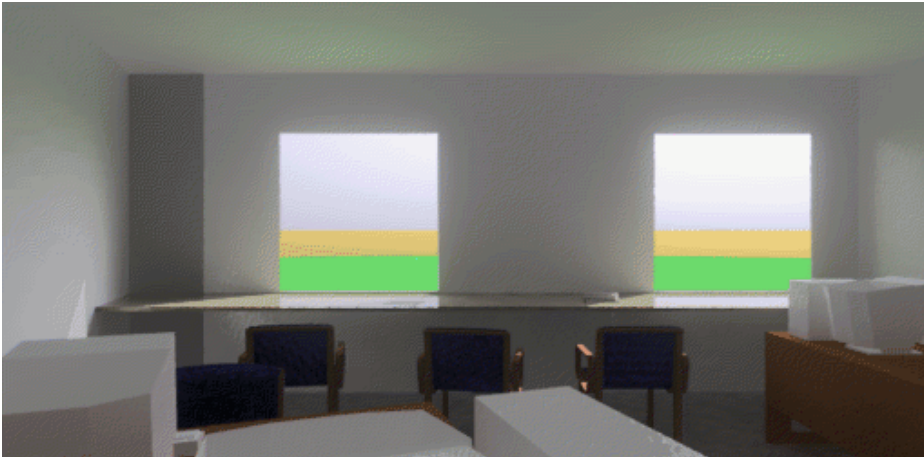


Figure 7-19: View from reference point 2 (VP2) for DGI evaluation (Radiance-rendered image)

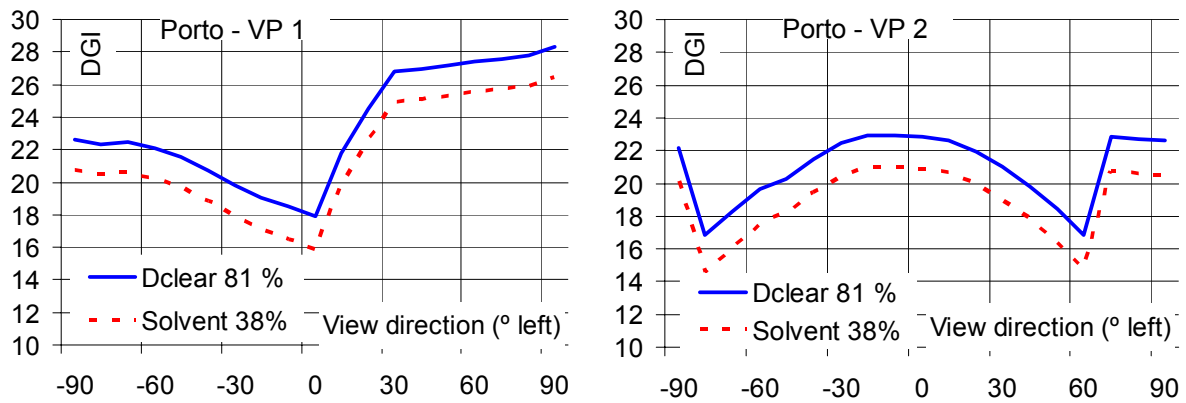


Figure 7-20: DGI values at the reference viewpoints, at mid-day of a high luminance day in Porto.

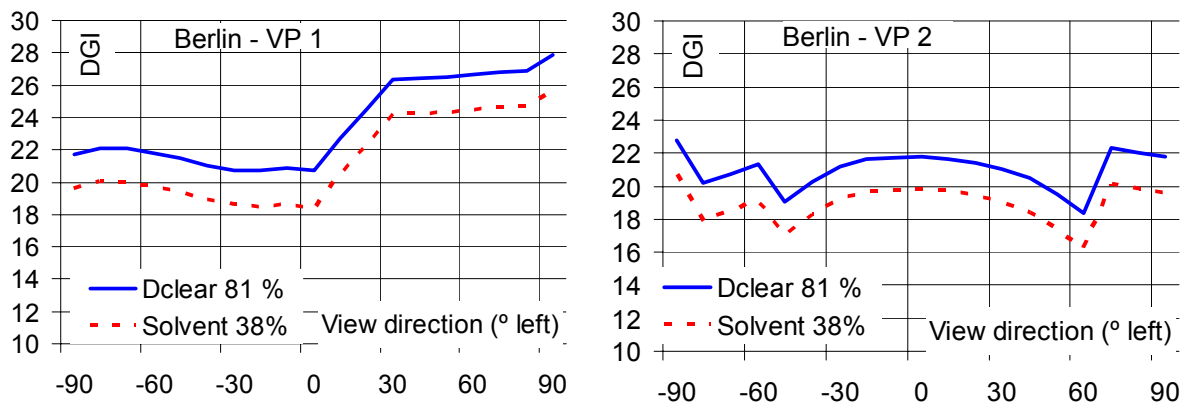


Figure 7-21: DGI values at the reference viewpoints, at mid-day of a high luminance day in Berlin.

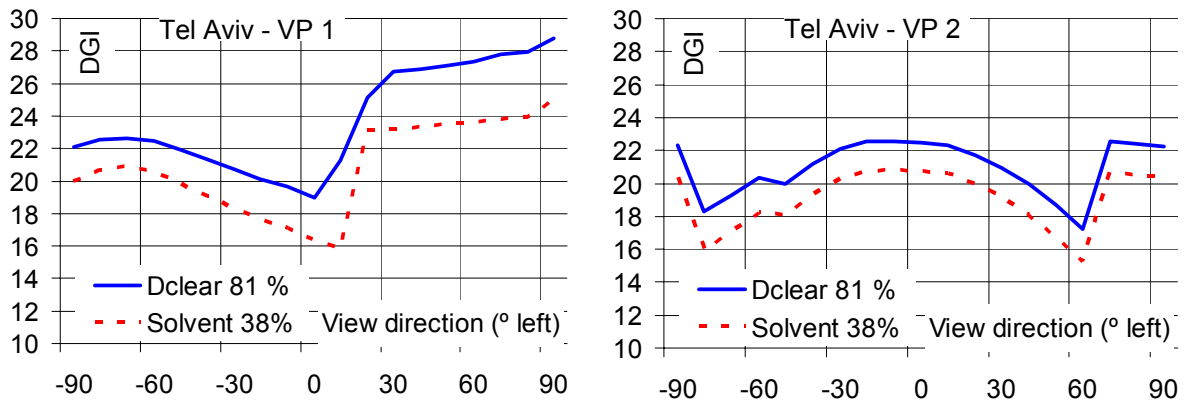


Figure 7-22: DGI values at the reference viewpoints, at mid-day of a high luminance day in Tel Aviv.



Figure 7-23: Radiance image of viewpoint 1 (VP1)



Figure 7-24: Radiance image of viewpoint 2 (VP2)

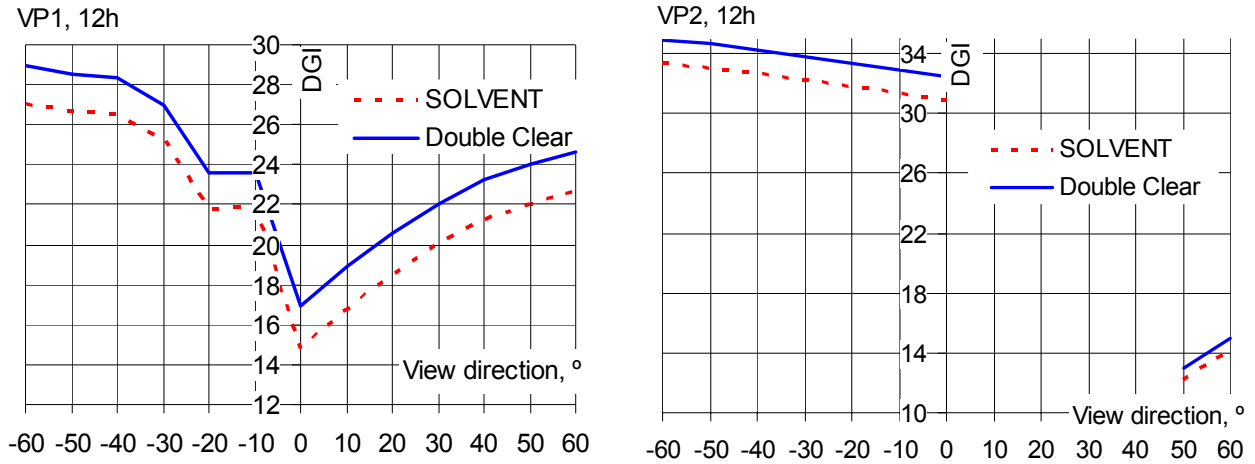


Figure 7-25: DGI values at the reference viewpoints, at mid-day of a high luminance day in Porto.

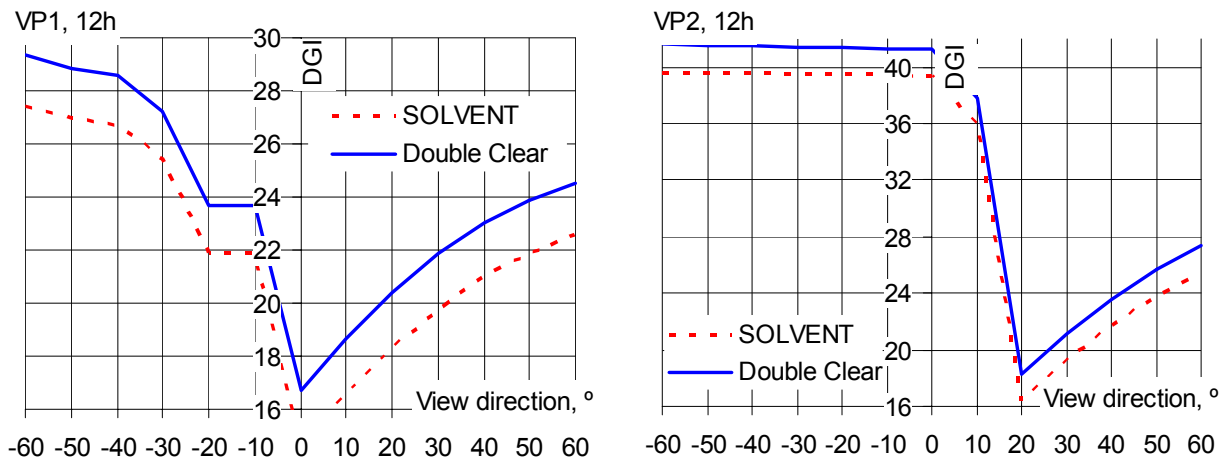


Figure 7-26: DGI values at the reference viewpoints, at mid-day of a high luminance day in Berlin.

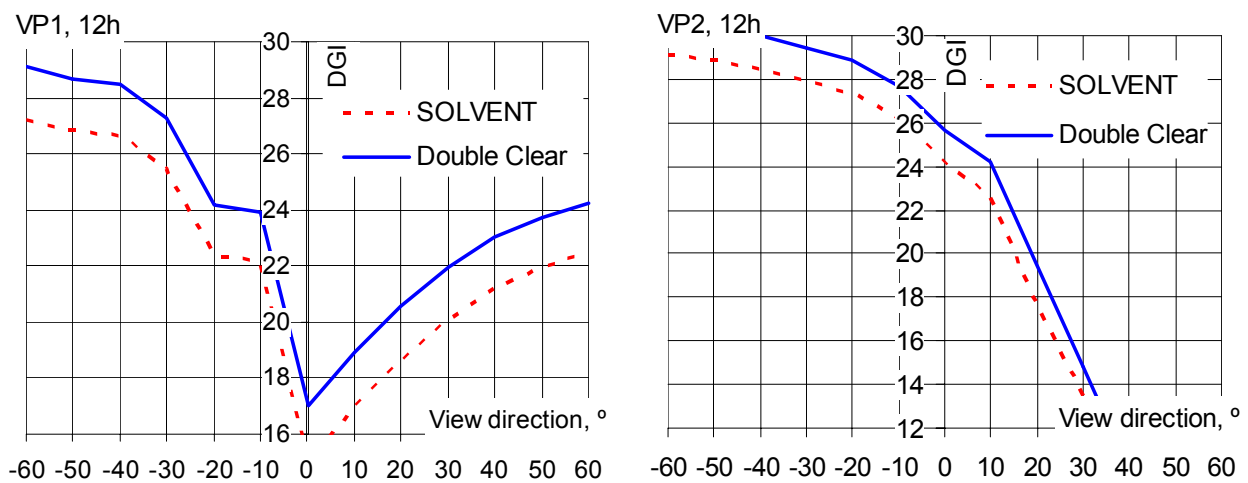


Figure 7-27: DGI values at the reference viewpoints, at mid-day of a high luminance day in Tel-Aviv.

7.3.5 Impact upon free-float temperatures

So far in this chapter, the evaluation of the performance of the SOLVENT window has been made essentially in terms of its consequences upon the energy demand for heating and cooling. Given the typologies of the buildings and the range of climates analysed, this procedure seems realistic and enables an easier comparison of the results. However, it must also be recognised that some buildings of these typologies may not have HVAC, or at least may not feature the availability of both heating and cooling. For instance, most Schools in Portugal and in Germany have no air conditioning.

It is thus interesting to have some estimative about the potential impact of the SOLVENT window upon the indoor temperatures in free-float mode, i.e., when the building is not mechanically heated and cooled. Assuming that there is no significant time superposition between the heating and cooling seasons, the results are also representative for cases when the building is only heated or only cooled. Table 7-22 shows the results for the number of hours above 25°C (applicable if the building is not cooled) and below 18°C, maximum and minimum temperatures verified and average temperatures accounting only the values above 25°C or below 18°C. The study considers the building located in Porto, with the “ON-OFF” strategy for blinds and lights. Only the occupied periods (weekdays, between 8 and 18 h) were considered. Results for temperatures higher than 25°C apply if the building is not cooled, and those relative to temperatures lower than 18°C apply if the building is not heated.

The results show that the SOLVENT window yields a reduction both in the number of hours when the temperature is below 18°C as in the number of hours when it is above 25°C. Comparing with the solar control glazing, this reduction varies between 7% (hours above 25°C at the office) and 19% (hours below 18°C at the school).

It also yields a reduction of the absolute maximum temperature, which is of 0.3°C when comparing with the solar control widow. In terms of minimum temperature, the effect is negligible, because this situation occurs at moments when the influence of solar radiation is very weak.

The results thus indicate that the effect of the SOLVENT window, at the free-float mode, is qualitatively in the right direction. The quantitative expression of this effect, however, seems not to be very significant.

Table 7-22: Impact of the windows over the indoor temperatures in free-floating mode for Porto (results for the hours between 8 and 18 h, legal time).

	Office			School		
	Double Clear	Solar Control	SVT. 38%	Double Clear	Solar Control	SVT. 38%
Hours above 25°C	1245	1208	1123	468	430	390
Max. T. (°C)	36.8	36.7	36.0	30.4	30.0	29.3
Average T. > 25°C	29.8	29.5	29.2	27.0	26.6	26.3
Hours below 18 °C	143	120	104	570	626	506
Min. T. (°C)	13.3	13.2	13.5	10.7	10.7	10.6
Average T. < 18°C	16.8	16.7	16.7	16.1	16.2	16.1

7.4 ECONOMIC CONSIDERATIONS

As shown in the previous sections, the SOLVENT window has the potential to save energy, when compared with conventional alternatives like the double clear glazing window and the double glazing solar control window. However, compared with them, the SOLVENT window requires an extra glazing and a special frame able to rotate between winter and summer mode. This special frame will probably use more material and weight more than a conventional one, and its production will probably be more complex as well. It is thus to be realistically expected that the SOLVENT window will be more expensive in terms of initial cost.

Determining whether or not the economic savings through the life of the window, due to less energy consumption, will offset the additional initial cost is a classical question of investment plans. The equations for performing this analysis are well known and characterised. The difficulty of obtaining such an assessment lies essentially in the uncertainty associated with obtaining reliable data for the inputs that the equations require, such as the interest rates and the energy inflation rate for a long-term future. Furthermore, the initial cost of the SOLVENT window is not known, since it is not yet commercialised, and, at the present, it cannot be reliably estimated.

To overcome these limitations, an analysis will be made for the case studies already presented in this chapter. The values assumed for the interest rate (capital cost) and for the energy inflation rate are 5% and 4% respectively.

Given the lack of knowledge about the initial cost, the strategy that will be adopted will be to calculate the accumulated savings with time. This information will enable an estimative of the admissible extra initial cost, given a certain payback period defined by the designer, and may be the input that potential manufacturers need to decide on its production.

Concerning the costs of electricity and gas, they were assumed as the simple rates for small and medium commercial buildings in Porto, as of July 2005 (table 7-23).

Table 7-24 shows the economic savings provided by the SOLVENT window in the analysed case-studies, for a typical year and with the previously described assumptions concerning the energy sources, conversion coefficients and energy prices. The results cover the three analysed control strategies and the comparisons with either double clear and double solar control glazing.

The accumulated saving after N years, at current value, is given by:

$$S_N = \sum_{k=1}^N S_0 \cdot \frac{(1+e)^{k-1}}{(1+j)^k} = S_0 \frac{(1+j)^N - (1+e)^N}{(j-e)(1+j)^N} \quad \text{eq. 7-1}$$

Where S_N is the accumulated economic saving at current value after N years, S_0 is the economic saving in a typical year (table 7-24), e is the energy inflation rate and j is the interest rate.

Figure 7-28 shows the accumulated economic savings at current value, comparing the SOLVENT window with a double clear glazing window, in the “no control” scenario. Figure 7-29 shows the equivalent results for the comparison with the double clear glazing in the “ON-OFF” scenario, and figure 7-30 shows the results for the comparison with the double solar control window in the “ideal dimming” scenario. The glazed areas at the façade were 3.38 m² at the office and 8.9 m² at the school.

As expected, large discrepancies can be observed depending on the specific binomial building/climate. It is also clear that the saving potential due to the window is smaller when there are efficient controls for the blinds and lights. When comparing with the most efficient conventional solution, the double solar control glazing in the ideal dimming strategy, the economic savings have a poor expression – always below 200 Euros after 25 years. Even in the ON-OFF strategy, which can be interpreted as approaching manual operation, the savings also have a poor expression – always below 300 Euros after 25 years. These values, which may represent the extra initial cost allowed seem rather low and may render the use of the SOLVENT window often uninteresting from the strictly economic point of view.

Table 7-23: Energy costs assumed for the economic study.

Energy source	Rate	Cost
Electricity	EDP “BTN simples”	0.10374 €/kWh + 5% VAT
Gas	Portgas “Natural 3”	0.522323 €/m ³ + 5%VAT

Table 7-24: Yearly energy savings provided by the SOLVENT window, in the analyzed case-studies and scenarios of energy sources, conversion efficiencies and energy prices (Euros).

<i>Strategy</i>	<i>Comparing with</i>	Office			School		
		Porto	Berlin	Tel Aviv	Porto	Berlin	Tel Aviv
NO CTRL	Double Clear	12.51	9.18	20.29	-2.49	-2.53	29.76
ON-OFF	Double Clear	11.42	3.71	12.39	-1.00	-7.13	12.29
IDEAL DIMMING	Double Clear	20.73	7.91	20.77	8.03	-3.70	20.12
	Solar Control 38%	5.00	4.59	5.11	7.57	6.86	5.88

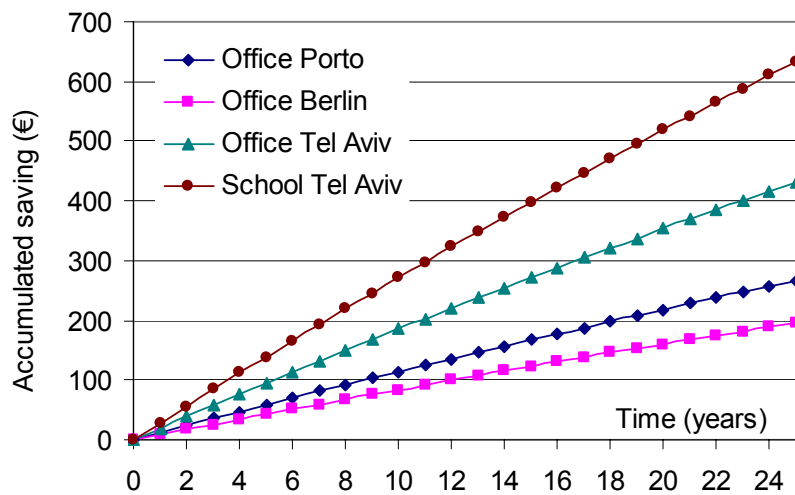


Figure 7-28: Accumulated savings at current value, comparing the SOLVENT window with a double clear glazing window, in the “no control” scenario.

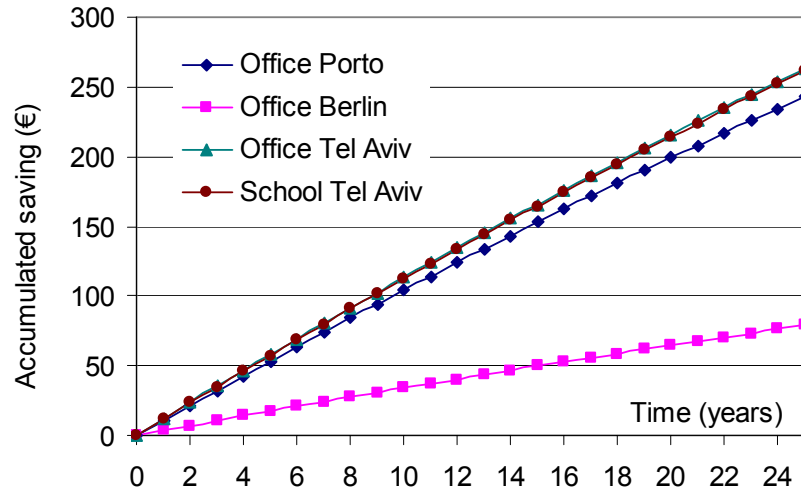


Figure 7-29: Accumulated savings at current value, comparing the SOLVENT window with a double clear glazing window, in the “ON-OFF” scenario.

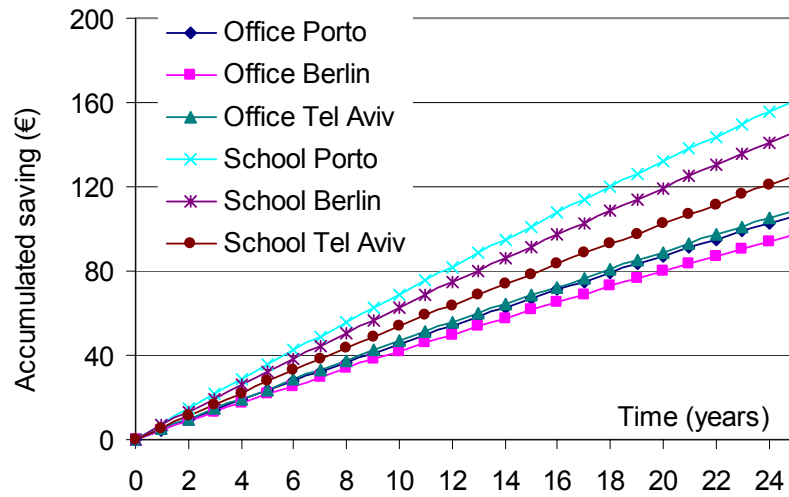


Figure 7-30: Accumulated savings at current value, comparing the SOLVENT window with a double solar control window, in the “Ideal dimming” scenario.

8 CONCLUSIONS AND OPPORTUNITIES FOR FUTURE WORK

8.1 CONCLUSIONS

Developing glazing systems that perform well both from the thermal and from the visual comfort points of view remains a challenging task. In the current work, a new system developed with this goal in mind, the SOLVENT window, was studied in-depth.

Regarding the modelling issues, it was found that it is possible to develop models which satisfactorily characterize the system performance. The most critical issues in this process were the treatment of the heat convection at the walls of the open air channel, and the influence of wind in Summer mode.

For the heat convection in the open air channel, it was found that the behaviour of the phenomenon lies between that of single vertical plate natural convection and that of fully developed natural convection channel flow. These are considered the two “limiting cases” of the phenomenon. However, the existing correlations, which combine the two limiting cases, did not lead to good agreement with the experimental results. In this frame, a “new blend” correlation was developed. It was found that the new correlation led to considerably improved results.

The second critical aspect, in terms of modelling approach, was the effect of environmental wind. A first important influence appears through the heat convection coefficient at the external wall, where the correlation proposed by Yazdanian and Klems for low rise buildings produced good results. A second, even more important influence, is related specifically with the SOLVENT window when operating in Summer mode (which has the bottom and the top extremities open to the outdoor environment). The results showed that, in this configuration, the wind is the driving factor for the air velocity in the air gap, instead of the buoyant force due to the temperature gradients. Furthermore, wind and its short-term fluctuations also increase the heat convection coefficient at the external glazing. Both the influence upon the air velocity and upon the heat convection coefficient were accounted for through empirical corrections obtained from the experimental data of the prototype mounted in a PASSYS test cell.

Globally, the mean average deviation, in absolute value, between the measured temperatures and those calculated by the model developed within this work was 1.1 °C, which shall be considered good when considering all the possible uncertainty sources that affect the measurement of the temperatures and of the climatic data, as well as the degree of simplification inherent to the model.

After the window simulation model was calibrated and validated, it was used to characterize the energy flows at the several glazings and at the system boundaries. It was found that, in Winter mode, the heat gain from channel convection becomes dominant for incident solar radiation above 400 W/m^2 (normal to the window). In Summer mode, the heat convected from the channel air is the second most important mode of heat dispersion towards outdoors, following the losses by combined convection and LW radiation at the external surface.

The window model also produced a value for the solar factor of the window, applying the boundary conditions of the standard ISO 9050 / EN 410. For the version with an air channel of 4 cm, with the glazings used in the prototype, the computed values were 0.67 for Winter mode and 0.41 in Summer mode. These results thus confirm that the goal of having different values for the solar factor, according to the operating mode, was clearly achieved. The value for Winter mode is slightly worse than that of a double clear glazing window (about 0.75), and the value for Summer mode is slightly better than that of a double glazing solar control window (about 0.44).

It was also found that the reduction of the channel width from 4 to 2 cm would only have a small effect upon the calculated solar factor, which would become 0.65 in Winter mode and 0.42 in Summer mode. Finally, the results showed that if the air gap were closed, the solar factor would suffer only a limited effect, passing from 0.67 to 0.61 in Winter mode, and from 0.41 to 0.44 in Summer mode.

The window was modelled as an individual building component and then integrated into the whole building simulation software ESP-r. The PASSYS test cell with the SOLVENT window prototype mounted was taken as a reference case for evaluating the quality of the model results.

A first approach towards the integration of the SOLVENT window used only the standard features available at the base version of ESP-r, including a nodal air flow network to account for the buoyancy in the open air channel. The results of this approach were satisfactory at the level of the global energy balance. The difference between the energy demand calculated and the measured performance, for a reference week in Winter mode, was less than 6%, thus validating its use for purposes of energy evaluations. However, in terms of specific system variables, such as the air flow in the channel and the glazing temperatures, there were significant differences between simulated and experimental results.

A second approach consisted of the integration of the specifically developed window model into the ESP-r source code. This approach led to a significant improvement of the agreement with the experimental results. The difference between the simulated and the measured energy demand for the reference week fell to only 1.3%, featuring also an excellent temporal distribution. Furthermore, the agreement at specific variables as the channel air velocity and the glazing temperature also evolved to a good behaviour. In Summer mode, where the influence of wind is more difficult to characterize, the difference in the energy demand was still below a satisfying 4%.

The experimental results from the PASSYS test cell were also used to validate the use of RADIANCE. The difference between the measured and the simulated illuminances was below 10%, thus enabling a good level of confidence in the use of RADIANCE at other case-study buildings.

Concerning the definition of criteria to characterize the interaction of building occupants with the transparent envelope, for controlling daylighting and glare, a literature review showed, in first place, that there seems to exist a considerable dispersion in the human behaviour towards the control of the systems. However, it was also confirmed that the activation of blinds or shading devices is strongly connected with the penetration of strong direct solar radiation and with the occurrence of glare. Three scenarios for the control of lighting and shading systems were drawn, ranging from constant electric lighting and no blinds to dimmed lights and blinds controlled based on the incident solar radiation.

Two building typologies were selected to be used as case-studies to assess the impact of the SOLVENT window. The first was a small open-space office, and the second a room of a primary school. Both have the main façade oriented towards South, and both were studied in three reference locations with different climates: Porto (Portugal), Berlin (Germany) and Tel Aviv (Israel).

The results confirmed, in the first place, that an efficient system for controlling, in an integrated way, the shading devices and the electric lighting of non-residential buildings can result in very important savings of primary energy for heating, cooling and lighting. Compared with the “no control” scenario, the potential savings detected ranged from 22% to 37% at the scenario “ON-OFF control”, and from 29% to 47% at the scenario “ideal dimming control”.

A second generic conclusion is that a careful selection of the glazing type can also result in significant energy savings. The differences between several glazing alternatives were, in some cases, above 20% of the total primary energy consumption for heating, cooling and lighting together.

Concerning the performance of the SOLVENT window when compared with conventional alternatives, the results showed that in most cases it performs better in terms of energy demand for heating, cooling and lighting. Compared with a double clear glazing window, the potential savings achievable with the SOLVENT window ranged between 0% and 14% in the ON-OFF strategy, and between 0% and 27% in the “ideal dimming” strategy. The specific value depends on the binomium building-climate. Compared to a double glazing solar control window with the same transmissivity, the savings become more modest though. With this reference, in the “ideal dimming strategy”, the potential savings fall to between 4% and 8%.

For façade orientations other than South, the advantage of the SOLVENT window over the double clear glazing becomes smaller, or even vanishes, due to the decrease in availability of daylighting. For a North orientation, the SOLVENT window would always lead to higher energy consumption than the double clear glazing window. For orientations towards West and towards East, the SOLVENT window only keeps a significant advantage at locations such as Tel-Aviv.

Even considering that the basic requirements for visual comfort were incorporated in the procedures for controlling the lights and the blinds, and thus are considered to be always met, there are collateral effects that can be analysed. The most significant result in this particular point is the fact that the SOLVENT window requires significantly less use of the blinds. E.g., for Porto, the blinds need to be activated about 39% of the working time, when using a double clear glazing window, but only 13% of the time when using a SOLVENT window. This may be regarded as a potential advantage, since allowing a direct view towards outdoors is beneficial in terms of visual comfort. However, this advantage disappears when

comparing instead with a solar control window, which has the same performance of the SOLVENT window in all aspects involving visual comfort.

When studying the buildings without heating and cooling, i.e., in the “free float” mode, the SOLVENT window decreases the maximum indoor temperature observed, the number of hours with temperatures above 25°C and the number of hours with temperatures below 18°C. However, the quantitative expression of these reductions is limited. For Porto, comparing with a double clear glazing window, the reduction in the maximum temperature was 0.6°C at the office and 0.7°C at the school. These values decrease to 0.3°C if comparing with a double glazing solar control window.

Combining the energy savings provided by the SOLVENT window with the energy prices, using a conservative economic scenario, it was possible to estimate the potential accumulated economic savings achievable with a SOLVENT window when compared with the conventional windows. The results showed that the increase in the initial cost allowed to make the SOLVENT window economically advantageous, for the two analysed case studies, is considerably limited. For the segments of the building market driven essentially by economic rationality, this may be a significant difficulty for the penetration of the SOLVENT window.

8.2 OPPORTUNITIES FOR FUTURE WORK

During the development of this work, many issues were identified which would be interesting to analyse with further detail. Some, such as the convection in the air gap or the measurement of the cooling load in the PASSYS test cell, were in fact subjected to in-depth analysis and development. Others, which were not considered critical for the present work, and which would require incompatible time or physical resources, are left as suggestions for future work, as independent projects on their own.

One of the identified questions that would be interesting to develop with further detail would be the characterization of the natural heat convection at the open air gap. This should be done preferably at an indoor laboratory, which would allow more precise measurement of temperatures and air velocities, as well as easier variation of the channel dimensions. A possibility for further research could be the expansion of the factor C in the new blend correlation (eq. 4-4), obtaining its value as a function of H and S (or, eventually, of the aspect ratio H/S).

Another issue where there seems to be margin for progress is the characterization of the human preferences towards the control of electric lights and shading devices in real buildings. There are only a few case-studies on the issue, and there is a clear lack of consensus in aspects such as the characterization of glare. The very high influence that the operation of lights and blinds has on the building energy consumption, confirmed in this work, stresses the importance of the need for more comprehensive and solid criteria for integration in whole building simulation software and for assisting design.

Complementarily to a more solid definition of the criteria for visual comfort, there seems to exist also some margin for progress in the methods for calculating indoor illuminance and for characterizing the luminous behaviour of blinds, both in ways compatible with long-term simulations at short time-steps.

Regarding specifically the SOLVENT window, the next main development should probably be its installation and monitoring in a real building. Despite all the efforts to be as realistic and as accurate as possible, the fact that the building occupants may play an important role in the system performance makes it important to have some observation of how it works, *in practice*. A field study of this type could also provide additional data for further improvement, calibration and validation of the simulation models, with an emphasis on the issues related to the human interaction.

A second suggested development related with the SOLVENT window would be the replacement of the absorptive glazing, which has fixed optical properties, by a glazing with variable optical properties, such as the electrochromic glazing or the thermotropic glazing. Such setup would have the potential to eliminate the main drawback of the SOLVENT window, which is the fact that it cuts often needed daylight in low luminance days. At the same time, it could maximise even further its benefits in terms of thermal performance and protection against glare in days with strong solar radiation.

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ANNEX 1: LISTING OF THE PROGRAM SIMSOLWIN

restart;

input file:

> read "input_WM_41.txt";

Glazing properties for solar radiation (from LBL Window or WIS)

Fraction of incident radiation absorbed in glazings 1,2,3 (angle-dependent) and global transmissivity

Winter mode

if WSM=1 then

> glzdif=[.114, .084, .282, .268, .242]:
> glzdir00=[.100, .080, .308, .348, .164]:
> glzdir10=[.100, .080, .308, .348, .164]:
> glzdir20=[.101, .081, .311, .342, .164]:
> glzdir30=[.105, .083, .314, .332, .166]:
> glzdir40=[.109, .085, .316, .314, .176]:
> glzdir50=[.115, .088, .309, .285, .203]:
> glzdir60=[.124, .089, .282, .234, .269]:
> glzdir70=[.136, .086, .218, .153, .407]:
> glzdir80=[.141, .071, .106, .050, .632]:
> glzdir90=[.000, .000, .000, .000, 1.00]:

else

Summer mode

> glzdif=[.497, .047, .034, .268, .143]:
> glzdir00=[.470, .048, .038, .350, .094]:
> glzdir10=[.472, .049, .038, .348, .094]:
> glzdir20=[.478, .049, .038, .342, .093]:
> glzdir30=[.488, .049, .038, .332, .093]:
> glzdir40=[.501, .050, .038, .314, .097]:
> glzdir50=[.516, .050, .037, .285, .112]:
> glzdir60=[.531, .049, .034, .235, .152]:
> glzdir70=[.530, .046, .026, .153, .244]:
> glzdir80=[.451, .034, .014, .050, .451]:
> glzdir90=[.000, .000, .000, .000, 1.00]:

end if;

Initializations

> Tg1:=20+273.15:
> Tg2:=20+273.15:
> Tg3:=20+273.15:
> Vel12:=0.20:
> Vel23:=0.20:

```

> for i from Nstart to Nfinish do
> print("Now in timestep",i):
> datain:=fscanf(datafile, "%f %f %f %f %f %f %f %f %f %f %f %f");
print ("datain at this time step is", datain);

```

```

> timey:= datain[1]:
> Text:= datain[2]+273.15:
> Igh:= datain[3];
> Idifh:= min(datain[4],datain[3]):
> windv:= datain[5]:
> windd:= datain[6]:
> Ilwext:= datain[7]:

```

```

> Tint:= datain[8]+273.15:
Tg1Meas:=datain[10]+273.15:
Tg2Meas:=datain[11]+273.15:
Tg3Meas:=datain[12]+273.15:
Vel23Meas:=datain[13]+273.15:

```

Choose temperature for air entering the channel

```

> if WMSM=1 then
> Tin:=Tint:
> else
> Tin:=Text:
> end if;

```

Set possible negative values of solar radiation to zero

```

> if Igh < 0 then
> Igh:=0:
> end if;
> if Idifh<0 then
> Idifh:=0:
> end if;

```

Compute solar position and incidence angles (Clarke, page 223/4):

Y= day of year; decli=solar declination; solalt=solar altitude (in degrees); hourangle=hour angle; soltime=solar time; timed=legal time of day; dsc=daylight saving correction; solazi=solar azimuth (in degrees);

```

> Y:=trunc(timey):
> timed:= (timey-Y)*24:
> if Y>88 and Y<300 then
> dsc:=-1.0:
> else
> dsc:=0.0:
> end if;
> pival:=evalf(Pi);
> decli:=23.45*sin((280.1+0.9863*Y)*pival/180);

```

```

>      et:=(9.87*sin((1.978*Y-160.22)*pival/180)-7.53*cos((0.989*Y-
80.11)*pival/180)-1.5*sin((0.989*Y-80.11)*pival/180))/60;
> soltime:= timed+longdif/15+et+dsc;
> hourangle:=15*(12-soltime);
>
solalt:=arcsin(cos(lat*pival/180)*cos(decli*pival/180)*cos(hourangle
*pival/180)+sin(lat*pival/180)*sin(decli*pival/180))*180/pival;
solazi_old:=
180/pival*arcsin(cos(decli*pival/180)*sin(hourangle*pival/180)/cos(s
olalt*pival/180)):
changed to ASHRAE method
> solazi:=180/pival*arccos((sin(solalt*pival/180)*sin(lat*pival/180)-
sin(decli*pival/180))/(cos(solalt*pival/180)*cos(lat*pival/180))):
> if (solalt > 3 and abs(solazi) < 85) then
if (solalt > 3 and abs(solazi) < 75) then
>
incidang:=
180/pival*arccos(cos(solalt*pival/180)*cos(solazi*pival/180)):
> else
> incidang:=90:
> end if ;

print (solalt,solazi_old,solazi):

```

Compute direct and diffuse incident on South Vertical surface

Use isotropic model for diffuse radiation

```

> Idirv:=(Igh-Idifh)/sin(solalt*pival/180)*cos(incidang*pival/180);
> Idirn:=min((Igh-Idifh)/sin(solalt*pival/180), 1200):
> Idifv:=0.5*Idifh;
print (timey,Y,timed,decli,soltime,solalt, solazi, incidang, Idirn,
Idifv);
> Ivtotcalc:=Idirv+Idifv+0.5*Igh*albedo:

```

Compute glazing absorptivity and transmissivity depending on incidence angle

```

> if (incidang > 0 and incidang <= 10) then
> glzdir:=glzdir00+(glzdir10-glzdir00)/(10-0)*(incidang-0):
> elif (incidang > 10 and incidang <= 20) then
> glzdir:=glzdir10+(glzdir20-glzdir10)/(10-0)*(incidang-10):
> elif (incidang > 20 and incidang <= 30) then
> glzdir:=glzdir20+(glzdir30-glzdir20)/(10-0)*(incidang-20):
> elif (incidang > 30 and incidang <= 40) then
> glzdir:=glzdir30+(glzdir40-glzdir30)/(10-0)*(incidang-30):
> elif (incidang > 40 and incidang <= 50) then
> glzdir:=glzdir40+(glzdir50-glzdir40)/(10-0)*(incidang-40):
> elif (incidang > 50 and incidang <= 60) then

```

```

> glzdir:=glzdir50+(glzdir60-glzdir50)/(10-0)*(incidang-50):
> elif (incidang > 60 and incidang <= 70) then
> glzdir:=glzdir60+(glzdir70-glzdir60)/(10-0)*(incidang-60):
> elif (incidang > 70 and incidang <= 80) then
> glzdir:=glzdir70+(glzdir80-glzdir70)/(10-0)*(incidang-70):
> elif (incidang > 80 and incidang <= 90) then
> glzdir:=glzdir80+(glzdir90-glzdir80)/(10-0)*(incidang-80):
> end if;

```

Iterate until temperatures converge at each time-step:

```
unassign ('Tg1prev','Tg2prev','Tg3prev','Vel12prev','Vel23prev');
```

```

> if i=1 then
> Tg1prev:=273.0:
> Tg2prev:=273.0:
> Tg3prev:=273.0:
> Vel12prev:=0.15:
> Vel23prev:=0.15:
> else
> Tg1prev:=Tg1lts:
> Tg2prev:=Tg2lts:
> Tg3prev:=Tg3lts:
> Vel12prev:=Vel12lts:
> Vel23prev:=Vel23lts:
end if;
print (Tg1prev, Tg2prev, Tg3prev):

```

```

> countiter:=0:
> Residual:=100.0;
> while Residual > Maxerror do
> unassign ('Residual','AAG1','AAG2','AAG3','AAVel12','AAVel23'):
Residual:= abs(Tg1-Tg1prev)+abs(Tg2-Tg2prev)+abs(Tg3-Tg3prev):
print (Residual);
> countiter:=countiter+1:
print ("iteration number ", countiter):
Procedure to accelerate the convergence:
> AAG1:=(Tg1+Tg1prev)/2:
> AAG2:=(Tg2+Tg2prev)/2:
> AAG3:=(Tg3+Tg3prev)/2:
> unassign ('Tg1','Tg2','Tg3'):
> Tg1:=AAG1:
> Tg2:=AAG2:
> Tg3:=AAG3:

```

External convection: YAZDANIAN & Klems in Winter mode and ASHRAE convection *1.5 in Summer mode

```
> if WMSM=1 then
>   if (((windd>90)) and (windd<270)) then
>     hext:=((0.84*(abs(Tg1-
Text))^(1/3))^2+(2.38*windv^0.89)^2)^0.5;
>   else
>
>                                     hext:=((0.84*(abs(Tg1-
Text))^(1/3))^2+(2.86*(abs(windv))^0.617)^2)^0.5;
>   end if;
> else
> hext:=((8.23-5.11)+3.83*windv-0.047*windv^2)*1.5:
> end if;
```

Other correlations, not currently used

Saint-Gobain correlation (maybe update later) with 2.23 instead of 8.23...:

```
hext:=2.23+3.33*windv-0.036*windv^2;
hext:=0.0;
```

Yazdanian and Klems correlations (Winward/Leeward):

```
if (((windd>90)) and (windd<270)) then
hext:=((0.84*(abs(Tg1-Text))^(1/3))^2+(2.38*windv^0.89)^2)^0.5;
else
hext:=((0.84*(abs(Tg1-
Text))^(1/3))^2+(2.86*(abs(windv))^0.617)^2)^0.5;
end if;
```

Rowley/ASHRAE-DOE-2 (citted in Yaz & Klems)

```
hext:=((8.23-5.11)+3.83*windv-0.047*windv^2):
```

```
print ("windd",windd,"windv",windv,"hext",hext);
```

Convection in closed channels: set open chan h's to zero and compute Uij

According to ISO 15099 / Wright 1996

First the channel 1-2

```
> if T12=1 then
> h12g1:=0;
> h12g2:=0;
> Vel12:=0.001:
> Qchan12out:=0:
```

Compute air properties:

```
> Tref:= (Tg1+Tg2)/2;
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
```

```

> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> cp:=1007;
> Ras12:=9.8*beta*abs(Tg1-Tg2)*S12^3/(niu*alfa);
> Nus0:=0.035*Ras12^0.38;
> if Ras12<1E4 then
> Nu1:=1+1.7596678E-10*Ras12^2.2984755:
> elif (Ras12 > 1E4 and Ras12 < 5E4) then
> Nu1:= 0.028154*Ras12^0.4134:
> elif (Ras12 > 5E4 and Ras12 < 1E6) then
> Nu1:= 0.0673838*Ras12^(1/3):
> else
> print ("Ras12>1E6"):
> Nu1:=0.035*Ras12^0.38:
> end if;
> Nu2:=0.242*(Ras12/(H/S23))^0.272:
> Nus:=max(Nu1,Nu2):
if Nu1>Nu2 then print ("unsing Nu1") else print ("using Nu2") end
if:
print ("Nu0 is", Nus0, "Nu1 is", Nu1, "Nu2 is", Nu2, "Nus is", Nus):
> U12:=Nus*k/S12;
U12:=10;
print (U12);
> else
> U12:=0.0
> end if;

```

Now the channel 2-3

```

> unassign ('Tref', 'beta', 'niu', 'alfa', 'k', 'Nu0', 'Nu1', 'Nu2', 'Nus');
> if T23=1 then
> h23g2:=0;
> h23g3:=0;
> Vel23:=0.001:
> Qchan23out:=0:
Compute air properties:
> Tref:= (Tg2+Tg3)/2;
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> cp:=1007;
> Ras23:=9.8*beta*abs(Tg2-Tg3)*S23^3/(niu*alfa);
> Nus0:=0.035*Ras23^0.38;

```

```

> if Ras23<1E4 then
> Nu1:=1+1.7596678E-10*Ras23^2.2984755:
> elif (Ras23 > 1E4 and Ras23 < 5E4) then
> Nu1:= 0.028154*Ras23^0.4134:
> elif (Ras23 > 5E4 and Ras23 < 1E6) then
> Nu1:= 0.0673838*Ras23^(1/3):
> else
> print ("Ras23>1E6"):
> Nu1:=0.035*Ras23^0.38:
> end if;
> Nu2:=0.242*(Ras23/(H/S23))^0.272:
> Nus:=max(Nu1,Nu2):
if Nu1>Nu2 then print ("using Nu1") else print ("using Nu2") end
if:
print ("Nu0 is", Nus0, "Nu1 is", Nu1, "Nu2 is", Nu2, "Nus is", Nus):
> U23:=Nus*k/S23;
Changed to ISO 15099 / Wright 1996
U23:=10;
print (U23);
> else
> U23:=0.0:
> end if;

```

----- Now the convection in open channels -----

if mark 100

```

> if CVTYPE=1 then
    if T12=1 then h12g1:=0: h12g2:=0: else
unassign
('Ts','Tref','beta','niu','alfa','k','Pr','ro','Rah','Ras','Nuhsp','
Nussp','Nusfd','Nus');
> Ts:=Tg1:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> h12g1:=Nuhsp*k/H;
> Ras:=0:

```

```

unassign
('Ts','Tref','beta','niu','alfa','k','Pr','ro','Rah','Ras','Nuhsp','
Nussp','Nusfd','Nus');
> Ts:=Tg2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> h12g2:=Nuhsp*k/H;
    end if;

    if T23=1 then h23g2:=0: h23g3:=0: else
unassign
('Ts','Tref','beta','niu','alfa','k','Pr','ro','Rah','Ras','Nuhsp','
Nussp','Nusfd','Nus');
> Ts:=Tg2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> h23g2:=Nuhsp*k/H;
unassign
('Ts','Tref','beta','niu','alfa','k','Pr','ro','Rah','Ras','Nuhsp','
Nussp','Nusfd','Nus');
> Ts:=Tg3:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;

```

```

> h23g3:=Nuhsp*k/H;
    end if;

> elif CVTYPE=2 then
Fully developed vertical channel with average surface temperature
    if T12=1 then h12g1:=0: h12g2:=0: else
> Ts:=(Tg1+Tg2)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Ras:=9.8*beta*abs(Ts-Tin)*S12^3/(alfa*niu);
> Nuh:=Ras/24;
> h12g1:=Nuh*k/H;
> h12g2:=Nuh*k/H;
    end if;

> if T23=1 then h23g2:=0: h23g3:=0: else
> Ts:=(Tg2+Tg3)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Ras:=9.8*beta*abs(Ts-Tin)*S23^3/(alfa*niu);
> Nuh:=Ras/24;
> h23g2:=Nuh*k/H;
> h23g3:=Nuh*k/H;
    end if;

> elif CVTYPE=3 then
    if T12=1 then h12g1:=0: h12g2:=0: else
> Ts:=(Tg1+Tg2)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);

```

```

> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Ras:=9.8*beta*abs(Ts-Tin)*S12^3/(alfa*niu);
> Nus:=(576/(Ras*S12/H)^2+2.87/(Ras*S12/H)^0.5)^(-1/2);
> h12g1:=Nus*k/S12:
> h12g2:=Nus*k/S12:
    end if;

    if T23=1 then h23g2:=0: h23g3:=0: else
> Ts:=(Tg2+Tg3)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Ras:=9.8*beta*abs(Ts-Tin)*S23^3/(alfa*niu);
> Nus:=(576/(Ras*S23/H)^2+2.87/(Ras*S23/H)^0.5)^(-1/2);
> h23g2:=Nus*k/S23:
> h23g3:=Nus*k/S23:
    end if;

> elif CVTYPE=4 then
>     if T12=1 then h12g1:=0: h12g2:=0: else
> Ts:=(Tg1+Tg2)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S12/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> Nussp:=Nuhsp*(S12/H);
Correlation for the fully developed vertical channel:
> Nusfd:=Ras*(S12/H)/24;
And now the blend:
> Nus:=exp(-Ras/C12)*Nussp+(1-exp(-Ras/C12))*Nusfd:
> h12g1:=Nus*k/S12:
> h12g2:=Nus*k/S12:
>     end if;

```

```

>      if T23=1 then h23g2:=0: h23g3:=0: else
> Ts:=(Tg2+Tg3)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S23/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> Nussp:=Nuhsp*(S23/H);
Correlation for the fully developed vertical channel:
> Nusfd:=Ras*(S23/H)/24;
And now the blend:
> Nus:=exp(-Ras/C23)*Nussp+(1-exp(-Ras/C23))*Nusfd:
> h23g2:=Nus*k/S23:
> h23g3:=Nus*k/S23:
>      end if;

> elif CVTYPE=5 then
unassign ('Tref', 'beta', 'niu', 'alfa', 'k', 'Nus');
>      if T12=1 then h12g1:=0: h12g2:=0: else
Correlation for the channel convection coefficient - Channel 12, glazing g1 side -, based on
the last know temperatures:
> unassign ('Tref', 'beta', 'niu', 'alfa', 'k', 'Nus');
Correlation for free vertical surface (Churchill):
> Ts:=Tg1:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S12/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> Nussp:=Nuhsp*(S12/H);
Correlation for the fully developed vertical channel:
> Nusfd:=Ras*(S12/H)/24;
And now the blend:
if (Idirv-Idifv)<10 then

```

```

Nus:=Nussp:
h12g1:=Nus*k/S12:
else
> Nus:=exp(-Ras/C12)*Nussp+(1-exp(-Ras/C12))*Nusfd:
> h12g1:=Nus*k/S12;
  end if;
Correlation for free vertical surface (Churchill):
>
                                                                    unassign
('Ts','Tref','beta','niu','alfa','k','Pr','ro','Rah','Ras','Nuhsp','
Nussp','Nusfd','Nus');
> Ts:=Tg2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S12/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16))^(8/27))^2;
> Nussp:=Nuhsp*(S12/H);
Correlation for the fully developed vertical channel:
> Nusfd:=Ras*(S12/H)/24;
And now the blend:
if (Idirv-Idifv)<10 then
Nus:=Nussp:
h12g2:=Nus*k/S12;
else
> Nus:=exp(-Ras/C12)*Nussp+(1-exp(-Ras/C12))*Nusfd:
> h12g2:=Nus*k/S12;
  end if;
>
  end if;
-----
>
  if T23=1 then h23g2:=0: h23g3:=0: else
Correlation for the channel convection coefficient - channel 23, glazing g2 side -, based on
the last know temperatures:
>
                                                                    unassign
('Ts','Tref','beta','niu','alfa','k','Pr','ro','Rah','Ras','Nuhsp','
Nussp','Nusfd','Nus');
Correlation for free vertical surface (Churchill):
> Ts:=Tg2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;

```

```

> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S23/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> Nussp:=Nuhsp*(S23/H);
Correlation for the fully developed vertical channel:
> Nusfd:=Ras*(S23/H)/24;
And now the blend:
if (Idirv-Idifv)<10 then
Nus:=Nussp;
h23g2:=Nus*k/S23;
else
> Nus:=exp(-Ras/C23)*Nussp+(1-exp(-Ras/C23))*Nusfd;
> h23g2:=Nus*k/S23;
  end if;
>
                                                                    unassign
('Ts','Tref','beta','niu','alfa','k','Pr','ro','Rah','Ras','Nuhsp','
Nussp','Nusfd','Nus');
unassign('Tref','beta','niu','alfa','k','Nus');
Correlation for free vertical surface (Churchill):
> Ts:=Tg3;
> Tref:=(Ts+Tin)/2;
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S23/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> Nussp:=Nuhsp*(S23/H);
Correlation for the fully developed vertical channel:
> Nusfd:=Ras*(S23/H)/24;
And now the blend:
if (Idirv-Idifv)<10 then
Nus:=Nussp;
h23g3:=Nus*k/S23;
else
> Nus:=exp(-Ras/C23)*Nussp+(1-exp(-Ras/C23))*Nusfd;

```

```

> h23g3:=Nus*k/S23;
  end if;
>      end if;

> elif CVTYPE=6 then
>      if T12=1 then h12g1:=0: h12g2:=0: else
> Ts:=(Tg1+Tg2)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S12/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> Nussp:=Nuhsp*(S12/H);
Correlation for the fully developed vertical channel:
> Nusfd:=Ras*(S12/H)/24;
And now the blend:
      if Ras<Rascritical then Nus:=Nussp: else
> Nus:=exp(-Ras/C12)*Nussp+(1-exp(-Ras/C12))*Nusfd:
      end if:
> h12g1:=Nus*k/S12:
> h12g2:=Nus*k/S12:
>      end if;

>      if T23=1 then h23g2:=0: h23g3:=0: else
> Ts:=(Tg2+Tg3)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S23/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> Nussp:=Nuhsp*(S23/H);
Correlation for the fully developed vertical channel:
> Nusfd:=Ras*(S23/H)/24;
And now the blend:

```

```

        if Ras<Rascritical then Nus:=Nussp: else
> Nus:=exp(-Ras/C23)*Nussp+(1-exp(-Ras/C23))*Nusfd:
        end if:
> h23g2:=Nus*k/S23:
> h23g3:=Nus*k/S23:
>     end if;
----- CV TYPE 7 -----
> elif CVTYPE=7 then
>     if T12=1 then h12g1:=0: h12g2:=0: else
> Ts:=(Tg1+Tg2)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S12/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> Nussp:=Nuhsp*(S12/H);
Correlation for the fully developed vertical channel:
> Nusfd:=Ras*(S12/H)/24;
And now the blend:
        if Ras<Rascritical then Nus:=Nussp: else
> Nus:=exp(-Ras/C12)*Nussp+(1-exp(-Ras/C12))*Nusfd:
        end if:
> h12g1:=Nus*k/S12:
> h12g2:=Nus*k/S12:
>     end if;
>     if T23=1 then h23g2:=0: h23g3:=0: else
> Ts:=(Tg2+Tg3)/2:
> Tref:= (Ts+Tin)/2:
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Rah:=9.8*beta*abs(Ts-Tin)*H^3/(alfa*niu);
> Ras:=Rah*(S23/H)^3;
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> Nussp:=Nuhsp*(S23/H);

```

Correlation for the fully developed vertical channel:

```
> Nusfd:=Ras*(S23/H)/24;
```

And now the blend:

```

                if Ras<Rascritical then Nus:=Nussp: else
> Nus:=exp(-Ras/C23)*Nussp+(1-exp(-Ras/C23))*Nusfd:
                end if:
> h23g2:=Nus*k/S23:
> h23g3:=Nus*k/S23:
>     end if;
endif mark 100
> end if;

print ("h12g1 is", h12g1, "h12g2 is", h12g2,"h23g2 is", h23g2,
"h23g3 is", h23g3);
-----

```

Correlation for the interior surface (single plate - Churchill and Chu):

```

unassign ('Tref', 'beta', 'niu', 'alfa', 'k', 'Rah', 'Nuhsp');
>
                                unassign
('Ts', 'Tref', 'beta', 'niu', 'alfa', 'k', 'Pr', 'ro', 'Rah', 'Ras', 'Nuhsp', 'N
Nussp', 'Nusfd', 'Nus');
> Tref:= (Tg3+Tin)/2;
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
Rah:=abs(9.8*beta*((Tg1+Tg2)/2-Tref)*H^3/(alfa*niu));
> Rah:=9.8*beta*abs(Tg3-Tin)*H^3/(alfa*niu);
> Nuhsp:=(0.825+0.387*Rah^(1/6)/(1+(0.492/Pr)^(9/16)))^(8/27))^2;
> hint:=Nuhsp*k/H;
-----

```

Equation for the air temperature in the gap -12:

```

unassign
('Ts', 'Tref', 'beta', 'niu', 'alfa', 'k', 'Pr', 'ro', 'Rah', 'Ras', 'Nuhsp', 'N
ussp', 'Nusfd', 'Nus');
Tref:= (Tg1+Tg2)/2;
beta:= 1/Tref;
niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
cp:=1007;
> if T12=2 then

```

```

> T12x:= x-> (h12g1*Tg1+h12g2*Tg2)/(h12g1+h12g2) - (h12g1*(Tg1-
Tin)+h12g2*(Tg2-Tin))/(h12g1+h12g2)*exp(-
(h12g1+h12g2)*x/(ro*Vel12*S12*cp)):
> T12mean:= int(T12x(x), x=0..H)/H;
> Tout12:=T12x(H):
> else
> T12mean:=0.0:
> Tout12:=Tin:
> end if;

```

Equation for the air temperature in the gap -23:

```

> if T23=2 then
> T23x:= x-> (h23g2*Tg2+h23g3*Tg3)/(h23g2+h23g3) - (h23g2*(Tg2-
Tin)+h23g3*(Tg3-Tin))/(h23g2+h23g3)*exp(-
(h23g2+h23g3)*x/(ro*Vel23*S23*cp)):
> T23mean:= int(T23x(x), x=0..H)/H;
> Tout23:=T23x(H):
> else
> T23mean:=0.0;
> Tout23:=Tin:
> end if;

```

Air channel Temperature at 1/2*H:

```

T1212H:= (h12g1*Tg1+h12g2*Tg2)/(h12g1+h12g2) - (h12g1*(Tg2-
Tin)+h12g2*(Tg2-Tin))/(h12g1+h12g2)*exp(-
(h12g1+h12g2)*0.5*H/(ro*Vel23*S23*cp)):
T2312H:= (h23g2*Tg2+h23g3*Tg3)/(h23g2+h23g3) - (h23g2*(Tg2-
Tin)+h23g3*(Tg3-Tin))/(h23g2+h23g3)*exp(-
(h23g2+h23g3)*0.5*H/(ro*Vel23*S23*cp)):

```

text

balance equation for the exterior clear glazing (C1):

```

> unassign('Tg3prev', 'Tg1prev', 'Tg2prev');
> Tg1prev:=Tg1;
> Tg2prev:=Tg2;
> Tg3prev:=Tg3;
print (Tg1prev,Tg2prev,Tg3prev);
> unassign('Tg1', 'Tg2', 'Tg3', 'storg1', 'storg2', 'storg3');
> if (i=1) then
> storg1:=0:
> storg2:=0:
> storg3:=0:
> else
> storg1:= 2500*e1*750*(Tg1-Tg1lts)/(Dtempo*60):
> storg2:= 2500*e2*750*(Tg2-Tg2lts)/(Dtempo*60):
> storg3:= 2500*e3*750*(Tg3-Tg3lts)/(Dtempo*60):
> end if;

```

```

> eqn1:= glzdir[1]*Idirn+glzdif[1]*(Idifv+0.5*Igh*albedo)+hext*(Text-
Tg1)+U12*(Tg2-Tg1)+sigma*(Tg2^4-Tg1^4)/(1/epsilon+1/epsilon-
1)+epsilon*(Ilwext-sigma*Tg1^4)+h12g1*(T12mean-Tg1)=storg1;
print(absg1);
Balance equation for the middle glazing (g2):
>
glzdir[2]*Idirn+glzdif[2]*(Idifv+0.5*Igh*albedo)+sigma*(Tg1^4-
Tg2^4)/(1/epsilon+1/epsilon-1)+U12*(Tg1-Tg2)+U23*(Tg3-
Tg2)+sigma*(Tg3^4-Tg2^4)/(1/epsilon+1/epsilon-1)+h12g2*(T12mean-
Tg2)+h23g2*(T23mean-Tg2)=storg2;
Balance equation for the interior glazing (g3):
>
glzdir[3]*Idirn+glzdif[3]*(Idifv+0.5*Igh*albedo)+sigma*(Tg2^4-
Tg3^4)/(1/epsilon+1/epsilon-1)+U23*(Tg2-Tg3)+h23g3*(T23mean-
Tg3)+hint*(Tint-Tg3)+epsilon*sigma*(Tint^4-Tg3^4)=storg3;
> E1:=fsolve ( {eqn1, eqn2, eqn3},
{ Tg1=Tg1prev, Tg2=Tg2prev, Tg3=Tg3prev }, { Tg1=223..373, Tg2=223..373,
Tg3=223..373 } );
> assign(E1);
print
(absg1, absg2, absd, Idirv, Idifv, Igh, albedo, hext, Text, U12, sigma, epsilon
, Ilwext, storg1, storg2, storg3, hint, hc, DTlm, H);
print (Tg1, Tg2, Tg3);
texto
Balance components:
Glazing 1:
> Qsabs1:=glzdir[1]*Idirn+glzdif[1]*(Idifv+0.5*Igh*albedo):
> Qcvext1:=hext*(Text-Tg1):
> Qcv12:=U12*(Tg2-Tg1):
> Qlw12:=sigma*(Tg2^4-Tg1^4)/(1/epsilon+1/epsilon-1):
> Qlwext1:=epsilon*(Ilwext-sigma*Tg1^4):
> Qcvchan12:=h12g1*(T12mean-Tg1):
> Qstorg1:=storg1:
Glazing 2:
> Qsabs2:=glzdir[2]*Idirn+glzdif[2]*(Idifv+0.5*Igh*albedo):
> Qlw12:=sigma*(Tg1^4-Tg2^4)/(1/epsilon+1/epsilon-1):
> Qcv12:=U12*(Tg1-Tg2):
> Qcv13:=U23*(Tg3-Tg2):
> Qlw13:=sigma*(Tg3^4-Tg2^4)/(1/epsilon+1/epsilon-1):
> Qcvchan12:=h12g2*(T12mean-Tg2):
> Qcvchan23:=h23g2*(T23mean-Tg2):
> Qstorg2:=storg2:
Dark Glazing:
> Qsabs3:=glzdir[3]*Idirn+glzdif[3]*(Idifv+0.5*Igh*albedo):
> Qlw13:=sigma*(Tg2^4-Tg3^4)/(1/epsilon+1/epsilon-1):

```

```

> Qcvg2g3:=U23*(Tg2-Tg3):
> Qcvchan23g3:=h23g3*(T23mean-Tg3):
> Qcvintg3:=hint*(Tint-Tg3):
> Qlwintg3:=epsilon*sigma*(Tint^4-Tg3^4):
> Qstorg3:=storg3:
Solar transmitted through the window:
>
Qstrans:=glzdir[4]*Idirn*cos(incidang*pival/180)+glzdif[4]*(Idifv+0.5*Igh*albedo):
Solar reflectd to outdoors by the window:
>
Qsrefl:=glzdir[5]*Idirn*cos(incidang*pival/180)+glzdif[5]*(Idifv+0.5*Igh*albedo):
Thermal load to the cell due to the window (positive if gain, negative if loss):
> Qcell:=(Qstrans-Qcvchan12g1-Qcvchan12g2-Qcvchan23g2-Qcvchan23g3-Qcvintg3-
Qlwintg3)*H*W+Clarea*Clstrans*(Idirv+Idifv+0.5*Igh*albedo)+Clarea*Uclear*(Text-Tint):

print ("AAA"):
writeline("testa2.txt",QSabsg3,Qlwg2g3);

```

Calculation of the air velocity (actualize):

Cálculo da velocidade actualizada:

```

> if T12=2 then
> unassign ('Tref', 'beta', 'niu', 'alfa', 'k', 'Pr');
> Tref:= T12mean;
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Dh12:=4*W*S12/(2*W+2*S12);
> Red12:=Vel12*Dh12/niu;
> if Red12<2300 then
> f12:=91.4/Red12*fredution:
> else
> print ("turbulent flow"):
> f12:=0.316/Red12^0.25*91.4/64:
> end if;
> unassign('Vel12');

> h12:=(h12g1+h12g2)/2:

```

```

> Ts12:=(Tg1+Tg2)/2:
>
eqn4:=Vel12^2=(9.81*(ro*Vel12*S12*cp*(exp(-
(2*W*H*h12/(ro*Vel12*W*S12*cp)))-
1)+2*H*h12)/(h12*(1+f12*H/(2*S12)+Kin12+Kout12))*(Ts12-Tin)/Tin):
> Vel12:= abs(fsolve (eqn4, Vel12));
Put here the condition for velocity as function of exterior wind in Summer mode
> if (WMSM=2 and windv>1.0) then
> Velnat:=Vel12:
> unassign ('Vel12'):
> Vel12:=max(CwindC*windv, Velnat):
> end if:
Protect against very low values of U that cause convergence problems:
The typical value here would be 0.05
> if Vel12<0.001 then
> unassign('Vel12');
> Vel12:=0.001:
> end if;

> Qchan12out:=ro*Vel12*S12*cp*(Tout12-Tin)/H:
print (Tin,Tout12,"Qchan12out",Qchan12out):

elif T23=2 then
> unassign ('Tref', 'beta','niu','alfa','k','Pr');
> Tref:= T23mean;
> beta:= 1/Tref;
> niu:=15.89E-6+(Tref-300)/(350-300)*(20.92E-6-15.89E-6);
> alfa:=22.5E-6+(Tref-300)/(350-300)*(29.9E-6-22.5E-6);
> k:=26.3E-3+(Tref-300)/(350-300)*(30.0E-3-26.3E-3);
> Pr:=0.707+(Tref-300)/(350-300)*(0.700-0.707);
> ro:=1.1614+(Tref-300)/(350-300)*(0.9950-1.1614);
> Dh23:=4*W*S23/(2*W+2*S23);
> Red23:=Vel23*Dh23/niu;
> if Red23<2300 then
> f23:=91.4/Red23*fredution:
print ("laminar flow"):
> else
f:=0.316/Red^0.25
> print ("turbulent flow"):
> f23:=0.316/Red23^0.25*91.4/64:
> end if;
> unassign('Vel23','h23','Ts23');
eqn5:=
ro*9.8*(int((((h23g2*Tg2+h23g3*Tg3)/(h23g2+h23g3)-
(h23g2*(Tg2-Tin)+h23g3*(Tg3-Tin))/(h23g2+h23g3)*exp(-

```

```
(h23g2+h23g3)*x/(ro*Vel23*S23*cp))-  
Tin)/Tin),x=0..H))=(ro/2*Vel23^2*(1+f23*H/(2*S23)+Kin23+Kout23));  
> h23:=(h23g2+h23g3)/2:  
> Ts23:=(Tg2+Tg3)/2:  
>  
eqn5:=Vel23^2=(9.81*(ro*Vel23*S23*cp*(exp(-  
(2*W*H*h23/(ro*Vel23*W*S23*cp)))-  
1)+2*H*h23)/(h23*(1+f23*H/(2*S23)+Kin23+Kout23))*(Ts23-Tin)/Tin):  
> Vel23:=abs(fsolve(eqn5,Vel23));  
Protect against very low values of U that cause convergence problems:  
> if Vel23<0.001 then  
> unassign('Vel23');  
> Vel23:=0.001:  
> end if;  
> else  
> Vel12:=0.001:  
> Vel23:=0.001:  
> end if;  
> Qchan23out:=ro*Vel23*S23*cp*(Tout23-Tin)/H:  
print(Tin,"Tout23",Tout23,"Qchan23out",Qchan23out);  
print(Tg1,Tg2,Tg3,Vel12,hcg2,hcg3,T12H);  
print("Tg1",Tg1,"Tg2",Tg2,"Tg3",Tg3,"Vel12",Vel12,"Vel23",Vel23);  
  
Compute residual. Set to zero if maximum number of iterations has been met.  
> Residual:=abs(Tg1-Tg1prev)+abs(Tg2-Tg2prev)+abs(Tg3-Tg3prev):  
> if countiter >= Maxiter then  
> Residual:=0.0:  
> print("did not converge at this time-step");  
> end if:  
  
print(Residual);  
print(Residual, hint_and_hext_are, hint, hext);  
> end do:  
> fprintf("Output.txt","%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f  
%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f  
\n", Tg1, Tg2, Tg3, Vel12, Vel23, T12mean, T23mean, Qsabsg1, Qcvextg1,  
Qcvvg2g1, Qlwvg2g1, Qlwgxtg1, Qcvchan12g1, Qstorg1,  
>  
Qsabsg2, Qlwvg1g2, Qcvg1g2, Qcvg3g2, Qlwvg3g2, Qcvchan12g2, Qcvchan23g2, Qsto  
rg2, Qsabsg3, Qlwvg2g3, Qcvg2g3, Qcvchan23g3, Qcvintg3, Qlwintg3, Qstorg3, Qc  
ell, Qstrans, Qsrefl);  
  
fprintf("Output_B.txt","%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f  
\n",Text,Tint,Tg1,Tg2,Tg3,T12mean,Vel12,T23mean,Vel23,h12g1,h12g2,h2  
3g2,h23g3);
```

Save present values as "last time-step" values for next time-step calculations

```
> Tg1lts:=Tg1;  
> Tg2lts:=Tg2;  
> Tg3lts:=Tg3;  
> Vel12lts:=Vel12;  
> Vel23lts:=Vel23;  
  
> end do;  
> fclose(datafile);  
> fclose ("Output.txt");
```

ANNEX 2: LISTING OF THE SIMSOLWIN INPUT FILES

File "input WM 41.txt"

```

Nstart:=1;
Nfinish:=1008; #last time step to be simulated
Dtempo:=10; #timestep in minutes
WMSM:=1: # 1 for Winter mode, 2 for Summer mode
T12:=1: # Type of channel, 1 for closed, 2 for open
T23:=2:
CVTYPE:=5:
# 1 for single plate,
# 2 for fully developed,
# 3 for Bar-Cohen and R.
# 4 for New exponential blending with average Ts;
# 5- new exponential blending with individual Ts.
# 6- New exponential blending with average Ts, but SP at low Ras numbers;
# 7- New exponential blending with individual Ts and SP at low Ras numbers
Kin12:=0.5: # local pressure drop coeffs (only used if open channel)
Kout12:=1.0:
Kin23:=0.5:
Kout23:=1.0:
freduction:=1.0: #friction reduction factor (1= no reduction)
C12:=4.0E5: # constant controlling the blend in mixed convection
C23:=4.0E5:
Rascritical:=4.5E4: # constant controlling the jump between sp and mixed convection
CwindC:=1.0: #coefficient of wind to channel velocity (only used in Summer mode)
Maxiter:=10: #iteration limit to protect against (rare) unconvergence in solving the equations
Maxerror:=0.3: # maximum residual accepted
H:=1.13: # window height
W:=1.10: # window width
S12:=0.006: # gap 1 width
S23:=0.041: # gap 2 width
e1:=0.004: # thickness of the glazings
e2:=0.004:
e3:=0.005:
CIH:=0.14:
Clarea:=CIH*W:
lat:=41: # Latitude
longdif:=-8.3: # Longitude difference to ref merid (+E,-W)
albedo:= 0.20: # site albedo
epsilon:=0.89: # glazing emissivity
sigma:=5.67E-8; # Stefan-Boltzmann constant
Clstrans:=0.70: # (Hemispheric) transmissivity of the clear glazing
Uclear:=3.3: # U-value of the clear glazing
datafile:="data_2_8_april.txt": #file with the numerical input data

```

File "input SM 40.txt"

```

Nstart:=1;
Nfinish:=1296; #last time step to be simulated
#Nfinish:=180; #last time step to be simulated
Dtempo:=10; #timestep in minutes
WMSM:=2: # 1 for Winter mode, 2 for Summer mode
T12:=2: # Type of channel, 1 for closed, 2 for open
T23:=1:
CVTYPE:=5:
# 1 for single plate,
# 2 for fully developed,
# 3 for Bar-Cohen and R.
# 4 for New exponential blending with average Ts;
# 5- new exponential blending with individual Ts.
# 6- New exponential blending with average Ts, but SP at low Ras numbers;
# 7- New exponential blending with individual Ts and SP at low Ras numbers
Kin12:=0.5: # local pressure drop coeffs (only used if open channel)
Kout12:=1.0:
Kin23:=0.5:
Kout23:=1.0:
freduction:=1.0: #friction reduction factor (1= no reduction)
C12:=4.0E5: # constant controlling the blend in mixed convection
C23:=4.0E5:
Rascritical:=4.5E4: # constant controlling the jump between sp and mixed convection
CwindC:=0.1307: #coefficient of wind to channel velocity (only used in Summer mode)
Maxiter:=10: #iteration limit to protect against (rare) unconvergence in solving the equations
Maxerror:=0.6; # maximum residual accepted
H:=1.13: # window height
W:=1.10: # window width
S12:=0.040: # gap 1 width
S23:=0.006: # gap 2 width
e1:=0.005: # thickness of the glazings
e2:=0.004:
e3:=0.004:
CIH:=0.14:
Clarea:=CIH*W:
lat:=41: # Latitude
longdif:=-8.3: # Longitude difference to ref merid (+E,-W)
albedo:= 0.20: # site albedo
epsilon:=0.89: # glazing emissivity
sigma:=5.67E-8; # Stefan-Boltzmann constant
Clstrans:=0.70: # (Hemispheric) transmissivity of the clear glazing
Uclear:=3.3: # U-value of the clear glazing
datafile:="data_10_18_may.txt": #file with the numerical input data

```

File "input WM 20.txt"

```

Nstart:=1;
Nfinish:=864; #last time step to be simulated
Dtempo:=10; #timestep in minutes
WMSM:=1: # 1 for Winter mode, 2 for Summer mode
T12:=1: # Type of channel, 1 for closed, 2 for open
T23:=2:
CVTYPE:=5:
# 1 for single plate,
# 2 for fully developed,
# 3 for Bar-Cohen and R.
# 4 for New exponential blending with average Ts;
# 5- new exponential blending with individual Ts.
# 6- New exponential blending with average Ts, but SP at low Ras numbers;
# 7- New exponential blending with individual Ts and SP at low Ras numbers
Kin12:=0.5: # local pressure drop coeffs (only used if open channel)
Kout12:=1.0:
Kin23:=0.5:
Kout23:=1.0:
freduction:=1.0: #friction reduction factor (1= no reduction)
C12:=1.0E3: # constant controlling the blend in mixed convection
C23:=1.0E3:
Rascritical:=5.5E3: # constant controlling the jump between sp and mixed convection
CwindC:=1.0: #coefficient of wind to channel velocity (only used in Summer mode)
Maxiter:=10: #iteration limit to protect against (rare) unconvergence when solving the equations
Maxerror:=0.6; # maximum residual accepted
H:=1.13: # window height
W:=1.10: # window width
S12:=0.006: # gap 1 width
S23:=0.021: # gap 2 width
e1:=0.004: # thickness of the glazings
e2:=0.004:
e3:=0.005:
CIH:=0.14:
Clarea:=CIH*W:
lat:=41: # Latitude
longdif:=-8.3: # Longitude difference to ref merid (+E,-W)
albedo:= 0.20: # site albedo
epsilon:=0.89: # glazing emissivity
sigma:=5.67E-8; # Stefan-Boltzmann constant
Clstrans:=0.70: # (Hemispheric) transmissivity of the clear glazing
Uclear:=3.3: # U-value of the clear glazing
datafile:="data_20_25_march.txt": #file with the numerical input data

```

File "input SM 20.txt"

```

Nstart:=1;
Nfinish:=719; #last time step to be simulated
Dtempo:=10; #timestep in minutes
WMSM:=2: # 1 for Winter mode, 2 for Summer mode
T12:=2: # Type of channel, 1 for closed, 2 for open
T23:=1:
CVTYPE:=5:
# 1 for single plate,
# 2 for fully developed,
# 3 for Bar-Cohen and R.
# 4 for New exponential blending with average Ts;
# 5- new exponential blending with individual Ts.
# 6- New exponential blending with average Ts, but SP at low Ras numbers;
# 7- New exponential blending with individual Ts and SP at low Ras numbers
Kin12:=0.5: # local pressure drop coeffs (only used if open channel)
Kout12:=1.0:
Kin23:=0.5:
Kout23:=1.0:
freduction:=1.0: #friction reduction factor (1= no reduction)
C12:=1.0E3: # constant controlling the blend in mixed convection
C23:=1.0E3:
Rascritical:=5.5E3: # constant controlling the jump between sp and mixed convection
CwindC:=0.0589: #coefficient of wind to channel velocity (only used in Summer mode)
Maxiter:=10: #iteration limit to protect against (rare) unconvergence when solving the equations
Maxerror:=0.6; # maximum residual accepted
H:=1.13: # window height
W:=1.10: # window width
S12:=0.020: # gap 1 width
S23:=0.006: # gap 2 width
e1:=0.005: # thickness of the glazings
e2:=0.004:
e3:=0.004:
CIH:=0.14:
Clarea:=CIH*W:
lat:=41: # Latitude
longdif:=-8.3: # Longitude difference to ref merid (+E,-W)
albedo:= 0.20: # site albedo
epsilon:=0.89: # glazing emissivity
sigma:=5.67E-8; # Stefan-Boltzmann constant
Clstrans:=0.70: # (Hemispheric) transmissivity of the clear glazing
Uclear:=3.3: # U-value of the clear glazing
datafile:="data_4_8_may.txt": #file with the numerical input data

```

ANNEX 3: LISTING OF THE CHANGED AND ADDED ESP-r CODE

Based on the standard distribution of ESP-r version 10.8 with project manager version 4.48a, July 2004. Changes are signalled in *italic*.

Modifications to file "include/net_flow.h"

```
C Include file for network flow.

C      Maximum number of nodes, components, connections.
      PARAMETER (MNOD=50,MCMP=50,MCNN=99)
C      Maximum number of node supplementary data items
      PARAMETER (MNDS=2)
C      Number of valid fluid flow component types
C      MCMV changed from 22 to 24 to account for the SOLVENT components
C      PARAMETER (MCMV=22)
      PARAMETER (MCMV=24)
C      Maximum number of component supplementary data items
      PARAMETER (MCMS=17)

(...)
```

- Modifications to file "esrubld/convect2.F"

```
(...)      SUBROUTINE HTBUOY(HC, ICOR, ICOMP, ISUR, DT, HEIGHT, APRAT)

      ELSEIF(ICOR.EQ.14)THEN

C Awbi and Hatton.
C Note that this need to be changed. Rather than operating on the hydraulic
C diameter of the model surface, this needs to operate on the hydraulic
C diameter of the entire surface.
      HC = (1.823*DT**0.293) / (APRAT**0.121)
      write(outs,'(A,2F9.3)')
      & ' Awbi & Hatton (vert): HC & DT',HC,DT
      if(dotrace)call edisp(itu,outs)
      ELSEIF(ICOR.EQ.15)THEN

C Correlations for the ventilated channels
C Molina & Maestre correlation for SOLVENT ventilated channel
C -- Note: this correlation is currently not accessible from the graphical
C interface --
C TFAIRIN is the temperature of the air entering the channel
```

```

    if (IAORZ.EQ.0) then
      TFAIRIN=TF
    else
      TFAIRIN=TFA(IAORZ)
    endif
    HC=3.00*(ABS(TFS(ICOMP,ISUR)-TFAIRIN))**0.333

C CVSTORE is an array storing HC,TSURF and TIN for use in the SOLVENT mass
flow components 600 and 610
    CVSTORE(ICOMP,ISUR,1)=HC
    CVSTORE(ICOMP,ISUR,2)=TFS(ICOMP,ISUR)
    CVSTORE(ICOMP,ISUR,3)=TFAIRIN

    write(outs,'(A,F4.1,A,F4.1)') 'Surf Temp* ',TFS(ICOMP,ISUR),
&    ' AORZ Temp ',TFA(IAORZ)
    if(dotrace)call edisp(itu,outs)
    write(outs,'(A,I2,A,F4.1)') 'Just used ICOR ',ICOR,' HC = ',HC
    if(dotrace)call edisp(itu,outs)
  ELSEIF (ICOR.EQ.16) THEN

C Bar-Cohen and Rosenhow general correlation for buoyancy driven flow in
vertical channels.
C -- Note: this correlation is currently not accessible from the graphical
interface --
C Air entering from outdoors.
C CWIDTH is the Channel width and CHEIGHT the channel height
C RAS is the Raleigh number and CNUSS the Nussel number
C Air properties fixed at 300 K values.
C TFAIRIN is the temperature of the air entering the channel
    if (IAORZ.EQ.0) then
      TFAIRIN=TF
    else
      TFAIRIN=TFA(IAORZ)
    endif
    RAS=9.8*1/(TFA(ICOMP)+273.15)*ABS(TFS(ICOMP,ISUR)-TFAIRIN)*
&    CWIDTH**3*0.707/(1.59E-5)**2.0
    CNUS=(576.0*(RAS*CWIDTH/CHEIGHT)**(-2.0)+
&    2.87*(RAS*CWIDTH/CHEIGHT)**(-0.5))**(-0.5)
    HC=CNUS*0.0263/CWIDTH

C CVSTORE is an array storing HC,TSURF and TIN for use in the SOLVENT mass
flow components 600 and 610
    CVSTORE(ICOMP,ISUR,1)=HC
    CVSTORE(ICOMP,ISUR,2)=TFS(ICOMP,ISUR)
    CVSTORE(ICOMP,ISUR,3)=TFAIRIN

    write(outs,'(A,E10.2,E10.2,F4.1)') 'RAS,CNUS,HC ',RAS,CNUS,HC
    if(dotrace)call edisp(itu,outs)
  ELSEIF (ICOR.EQ.17) THEN

C Correlation for natural convection along a single vertical plate
C Correlation by Churchill and Chu for the entire range of RAL (see
Incropera & DeWitt)
C TFAIRIN is the temperature of the air entering the channel
    if (IAORZ.EQ.0) then
      TFAIRIN=TF
    else
      TFAIRIN=TFA(IAORZ)
    endif
    RAL=9.8*1/(TFA(ICOMP)+273.15)*ABS(TFS(ICOMP,ISUR)-TFAIRIN)*
&    CHEIGHT**3*0.707/(1.59E-5)**2.0

```

```

    CNUL=(0.825+(0.387*RAL**(1./6.))/
&      ((1+(0.492/0.707)**(9./16.))**(8./27.))**2.0
    HC=CNUL*0.0263/CHEIGHT

C CVSTORE is an array storing HC,TSURF and TIN for use in the SOLVENT mass
flow components 600 and 610
    CVSTORE(ICOMP,ISUR,1)=HC
    CVSTORE(ICOMP,ISUR,2)=TFS(ICOMP,ISUR)
    CVSTORE(ICOMP,ISUR,3)=TFAIRIN

    write(outs,'(A,I2,I2,F5.2,F5.2)')'ICOR,IAORZ,CWIDTH,CHEIGHT '
&      ,ICOR,IAORZ,CWIDTH,CHEIGHT
    if(dotrace)call edisp(itu,outs)
    write(outs,'(A,E10.2,E10.2,F4.1)')'RAL,CNUL,HC ',RAL,CNUL,HC
    if(dotrace)call edisp(itu,outs)

    ELSEIF (ICOR.EQ.18) THEN
C Correlation for nat. conv. fully developed flow (see Bejan)
    if (IAORZ.EQ.0) then
        TFAIRIN=TF
    else
        TFAIRIN=TFA(IAORZ)
    endif
    RAS=9.8*1/(TFA(ICOMP)+273.15)*ABS(TFS(ICOMP,ISUR)-TFAIRIN)*
&      CWIDTH**3*0.707/(1.59E-5)**2.0
    CNUS=RAS/24.0*(CWIDTH/CHEIGHT)
    HC=CNUS*0.0263/CWIDTH

C CVSTORE is an array storing HC,TSURF and TIN for use in the SOLVENT mass
flow components 600 and 610
    CVSTORE(ICOMP,ISUR,1)=HC
    CVSTORE(ICOMP,ISUR,2)=TFS(ICOMP,ISUR)
    CVSTORE(ICOMP,ISUR,3)=TFAIRIN

    write(outs,'(A,I2,I2,F5.2,F5.2)')'ICOR,IAORZ,CWIDTH,CHEIGHT '
&      ,ICOR,IAORZ,CWIDTH,CHEIGHT
    if(dotrace)call edisp(itu,outs)
    write(outs,'(A,F4.1,F4.1,F4.1,E10.2,E10.2,F4.1)')
&      'TFA,TS,TAIRIN,RAS,CNUS,HC '
&      ,TFA(ICOMP),TFS(ICOMP,ISUR),TFAIRIN,RAS,CNUS,HC
    if(dotrace)call edisp(itu,outs)

    ELSEIF (ICOR.EQ.19) THEN
C New blend correlation (see Leal thesis when available...)
    if (IAORZ.EQ.0) then
        TFAIRIN=TF
    else
        TFAIRIN=TFA(IAORZ)
    endif
C Next line: Cblend is interpolated from the two points known:
C C=1E3 for S=2.1 cm and C=4E5 for S=4.1 cm
    CBLEND= 1.0E3+(4.0E5-1.0E3)/(0.041-0.021)*(CWIDTH-0.021)

    RAL=9.8*1/(TFA(ICOMP)+273.15)*ABS(TFS(ICOMP,ISUR)-TFAIRIN)*
&      CHEIGHT**3*0.707/(1.59E-5)**2
    CNULSP=(0.825+(0.387*RAL**(1./6.))/
&      (1+(0.492/0.707)**(9./16.))**(8./27.))**2
    CNUSSP=CNULSP*CWIDTH/CHEIGHT

    RAS=9.8*1/(TFA(ICOMP)+273.15)*ABS(TFS(ICOMP,ISUR)-TFAIRIN)*
&      CWIDTH**3*0.707/(1.59E-5)**2

```

```

CNUSFD=RAS/24*(CWIDTH/CHEIGHT)

CNUS=EXP(-RAS/CBLEND)*CNUSP+(1-EXP(-RAS/CBLEND))*CNUSFD
HC=CNUS*0.0263/CWIDTH
C CVSTORE is an array storing HC,TSURF and TIN for use in the SOLVENT mass
flow components 600 and 610
CVSTORE(ICOMP,ISUR,1)=HC
CVSTORE(ICOMP,ISUR,2)=TFS(ICOMP,ISUR)
CVSTORE(ICOMP,ISUR,3)=TFAIRIN

write(outs,'(A,I2,I2,F5.2,F5.2)')'ICOR,IAORZ,CWIDTH,CHEIGHT '
&      ,ICOR,IAORZ,CWIDTH,CHEIGHT
if(dotrace)call edisp(itu,outs)
write(outs,'(A,E10.2,E10.2,F4.1)')'RAS,CNUS,HC ',RAS,CNUS,HC
if(dotrace)call edisp(itu,outs)

ELSEIF(ICOR.EQ.30)THEN

(...)

```

- Modifications to file “esrucom/emfnetw.F”

```

C ***** MFCMPSUPCHECK
C Mfcmpsupscheck: check flow components for correct number of supplemental
C data items.
subroutine mfcmpsupscheck(ICMP,IER)

#include "net_flow.h"
(...)
C Type 470 range based flow rate controller (defunct type).
call MFERR(ICMP,' Use type 30 or 35 comp with range ctl.',IER)
C added messages for components 600 and 610
ELSE IF(ITPCMP(ICMP).EQ.600) THEN
    if (NSDC.NE.8) then
        call MFERR(ICMP,'unsufficient datafor compon. type 600',IER)
        goto 999
    end if
ELSE IF(ITPCMP(ICMP).EQ.610) THEN
    if (NSDC.NE.9) then
        call MFERR(ICMP,'unsufficient datafor compon. type 610',IER)
        goto 999
    end if

ELSE
    call edisp(iuout,' Unknown component type...')
    goto 999
ENDIF
return

(...)

C ***** MFLIST
C MFLIST Fluid flow file: list common block contents.
SUBROUTINE MFLIST(itru)

(...)

```

```

ELSE IF(ITPCMP(ICMP).EQ.460) THEN
  call edisp(itru,
    & ' Fluid, flow when S < Ssp, flow when S > Ssp.')
C component type 600 added here
  ELSE IF(ITPCMP(ICMP).EQ.600) THEN
    WRITE(outs,
      & '(a,F4.1,4(a,f6.3),3(a,f3.0))')
      & ' Fluid ', SUPCMP(ICMP,1),'W ',SUPCMP(ICMP,2),' H',
      & SUPCMP(ICMP,3),' S ',SUPCMP(ICMP,4),' SumK ',SUPCMP(ICMP,5),
      & ' Ref zone ', SUPCMP(ICMP,6),' 1st ref surf ',SUPCMP(ICMP,7),
      & ' 2nd ref surf ',SUPCMP(ICMP,8)
    CALL EDISP(itru,outs)
    written=.true.
C component type 610 added here
  ELSE IF(ITPCMP(ICMP).EQ.610) THEN
    WRITE(outs,
      & '(a,F4.1,4(a,f6.3),3(a,f3.0),a,f6.4)')
      & ' Fluid ', SUPCMP(ICMP,1),'W ',SUPCMP(ICMP,2),' H',
      & SUPCMP(ICMP,3),' S ',SUPCMP(ICMP,4),' SumK ',SUPCMP(ICMP,5),
      & ' Ref zone ', SUPCMP(ICMP,6),' 1st ref surf ',SUPCMP(ICMP,7),
      & ' 2nd ref surf ',SUPCMP(ICMP,8),'WINCVEL',SUPCMP(ICMP,9)
    CALL EDISP(itru,outs)
    written=.true.

  endif

C If not already written out.
  if(.NOT.written)then
(...)

C Type 470 range based flow rate controller (defunct type).
  call MFERR(ICMP,' Use type 30 or 35 comp with range ctl.',IER)
C added messages for components 600 and 610
  ELSE IF(ITPCMP(ICMP).EQ.600) THEN
    if (NSDC.NE.8) then
      call MFERR(ICMP,'unsufficient datafor compon. type 600',IER)
      goto 999
    end if
  ELSE IF(ITPCMP(ICMP).EQ.610) THEN
    if (NSDC.NE.9) then
      call MFERR(ICMP,'unsufficient datafor compon. type 610',IER)
      goto 999
    end if

  ELSE
    call edisp(iuout,' Unknown component type...')
    goto 999
  ENDIF
  return
(...)

```

- Modifications to file “esruprj/hcfmk.F”

```

(...)
C EconvD Controls input for mechanical-driven convective regime D.

```

C EconvE Controls input for mixed flow convective regime E.
C *EconvF Controls input for open vertical channel convection, regime F*

C ***** HCFMK *****
C HCFMK controls the creation and editing of a convection-regime
C control file.

(...)

C Determine the convective regime (A-G)..

```
20 INO = -2
write(ITEM(1),'(a)') ' Buoyancy-driven flow      '
ITEM(2) =           ' surf-to-air temp diff...   '
ITEM(3) =           'a   in-floor heating        '
ITEM(4) =           'b   heated wall panel       '
ITEM(5) =           'c   other temp diff         '
ITEM(6) =           '   heater located in room... '
ITEM(7) =           'd   heater under window     '
ITEM(8) =           'e   heater not under window '
ITEM(9) =           'f   open vertical channel... '
ITEM(10)=           'f   Single plate convection '
ITEM(11)=           'g   Fully developed flow '
ITEM(12)=           'h   SOLVENT new blend corl. '
ITEM(13)=           '                               '
write(ITEM(14),'(a)') ' Mechanically driven flow '

```

(...)

C Convective regime `B'. Buoyancy caused by heater not under window.

```
iopt=2
call EconvB(ITRU,IUF,ICOMP,iopt,IER)
ELSEIF(INO.EQ.10)then

```

C Open vertical channel convection - Single plate convection

```
iopt=1
call EconvF (ITRU,IUF,ICOMP,iopt,IER)
ELSEIF(INO.EQ.11)then

```

C Open vertical channel convection - Fully developed flow

```
iopt=2
call EconvF (ITRU,IUF,ICOMP,iopt,IER)
ELSEIF(INO.EQ.12)then

```

C Open vertical channel convection - SOLVENT new blend corrl.

```
iopt=3
call EconvF (ITRU,IUF,ICOMP,iopt,IER)
ELSEIF(INO.EQ.16)then

```

C Convective regime `C'. Convection dominated by mechanical forces caused
C by an air-handling system delivering heated or cooled air to the room
C through ceiling or floor mounted diffusers. VAV with CV heating.

(...)

```
h(33)=(e.g. radiator, stove) located either undeer a window'
h(34)='or at some other location in the zone.'
h(35)=' '
h(36)='Options f-h are specific for treating convection inside'
h(37)='open vertical channels with bouyancy driven flow.'

```

```

h(38)='The correlations apply to the vertical surfaces'
h(39)='and operate all the time'
h(40)=' '

```

(...)

```

C ***** EconvF *****
C EconvF controls the input of data related to convective regime F,
buoyancy
C      driven flow in open vertical channels.
C Derived from code in EconvA.
C IOPT: 1 = Single plate, 2 = Fully developed, 3 = SOLVENT new blend corrl.
C IOPT: 4 = Molina & Maestre, 5 = Bar-Cohen correlation.
      SUBROUTINE EconvF(ITRU,IUF,ICOMP,IOPT,IER)
#include "building.h"
      common/pophelp/h(60)
      COMMON/G7/SSNA(MCON),SSPAZI(MCON),SSPELV(MCON),SSPERIM(MCON),
&          SSUREQN(MCON,4),SSURCOG(MCON,3),SSURVN(MCON,3)
      COMMON/HCFP/IHCFP,ST(MP),EN(MP),HCI(MP,MS),HCE(MP,MS),
&          ICTL(MP),IHCI(MP,MS),IHCE(MP,MS),CVdata(MP,MS,8)
      common/UDESC/AIRF(MCOM),CASG(MCOM),LVVIEW(MCOM),LHCCO(MCOM),
&          LTWIN(MCOM),LCGCIN(MCOM),ZOBS(MCOM)
      COMMON/OUTIN/IUOUT,IUIN
      COMMON/C20/NZSUR(MCOM),NZTV(MCOM)
      COMMON/C24/IZSTOCN(MCOM,MS)

C IAORZ is the air origin zone. '0' if outdoor air, zone number otherwise.
C CWIDTH and CHEIGHT are the channel width and height
      COMMON/VERTC/IAORZ,CWIDTH,CHEIGHT
      common/HCFPHI/hcfpdescr(MP)

      CHARACTER outs*124,h*72
      character hcfpdescr*72
      character*24 hcphrase(5)
      CHARACTER*72 AIRF,CASG,LVVIEW,LHCCO,LTWIN,LCGCIN,ZOBS
      logical ok

C These approaches are active for all time-steps of the simulation
C (i.e. there is only one convection-calculation control period).
      IPER = 1
      IHCFP = 1
      ST(IPER) = 0.
      EN(IPER) = 24.

C All employ `type 3', or `adaptive', control over the convection
calculations.
      ICTL(IPER) = 3

C: Initalize channel variables
      IAORZ=-1
      CWIDTH=0.0
      CHEIGHT=0.0

C Use the G7 orientation of the surfaces in the zone.
C Provide a synopsis.
      call easkok('View a synopsis of Bouyancy-driven flow',
&          'options and background?',ok)
      if(ok)then

```

```

C Context help for vertical channel.
  h(1)='This choice is appropriate for open vertical channels'
  h(2)='with flow driven primarily by buoyancy resulting from'
  h(3)='surface-to-air temperature differences.'
  h(4)=' '
  h(5)='Single plate convection is the correlation from'
  h(6)='Churchill & Chu for natural conv. along a single'
  h(7)='vertical surface. See Fundamentals of Heat and '
  h(8)='Mass Transfer, Incropera and DeWitt for more details. '
  h(9)=' '
  h(10)='Fully developed flow is the analytical solution for '
  h(11)='fully developed flow in a vertical channel. See '
  h(12)=' "Convective heat transfer", A. Bejan (1984) for details'
  h(13)=' '
  h(14)='SOLVENT new blend correlation is the correlation '
  h(15)='presented in the Leal Ph.D. thesis for the SOLVENT '
  h(16)='window. It was tested for a channel 1.13 m high '
  h(17)='and channel widths 2.1 and 4.1 cm. For other widths'
  h(18)='the blending constant is interpolated / extrapolated'
  h(19)='Details in Leal thesis or Roomvent 2004 proceedings'

  CALL PHELPD('Channel correlations',19,'-',0,0,IER)
endif

C Establish the cause of the buoyancy driving force.
C Choose where is the air coming into the channel.
  IF((IOPT.EQ.1).OR.(IOPT.EQ.2).OR.(IOPT.EQ.3)) THEN
    CALL EASKAB(' ', 'Air enters channel from', 'Outdoor',
    & 'Another zone', IW, 0)
    IF (IW.EQ.1) THEN
      IAORZ=0
      hcphrase(3) = 'from outdoor'
    ELSE
      CALL ASKZONE(IAORZ,0, ' Air enters channel from which zone?',
    & 'Air origin zone', '-', 'A zone must be selected', ier)
    ENDIF
    IF (IAORZ.EQ.ICOMP) THEN
      CALL USRMSG('This selection is typical of CLOSED channels',
    & ' ', 'W')
    ENDIF
    write(outs, '(A,I2)') 'The air enters from zone number ', IAORZ
    call edisp(itru, outs)
    hcphrase(3) = 'from other zone'
  ENDIF

  IF(IOPT.EQ.1) THEN

C Natural convection along a free vertical surface (Churchill and Chu).
C The control law ICOR= 17 will be assigned to all vertical surfaces in the
channel
    hcphrase(1) = 'convec. vert channel'
    hcphrase(2) = 'Single plate'

C Ask Channel width
    h(1)='Enter the channel width'
    h(2)='(inside pane-to-pane distance)'
    CALL EASKR(CWIDTH, 'Channel width ?',
    & ' ', 0.01, 'W', 1.0, 'W', 0.05, 'Channel width', IER, 2)

C Ask Channel height
    h(1)='Enter the channel height'
    CALL EASKR(CHEIGHT, 'Channel height ?',

```

```

&      ' ',0.1,'W',100.0,'W',1.0,'Channel height',IER,1)

DO 10 ISUR=1,NZSUR(ICOMP)
  icc=izstocn(icmp, isur)
  ANGLE = SSPELV(icc)
  if(ANGLE.LE.45..AND.ANGLE.GE.-45.) then

C Vertical surface. Apply correlation
  CVdata(IPER, ISUR,1) = 1.
  CVdata(IPER, ISUR,2) = 17.
  CVdata(IPER, ISUR,3) = 17.
  CVdata(IPER, ISUR,4) = 0.
  CVdata(IPER, ISUR,5) = 99.
  CVdata(IPER, ISUR,6) = 99.
  CVdata(IPER, ISUR,7) = 99.
  CVdata(IPER, ISUR,8) = 99.
  elseif(ANGLE.LT.-45.) then

C Floor.
  CVdata(IPER, ISUR,1) = 1.
  CVdata(IPER, ISUR,2) = -1.
  CVdata(IPER, ISUR,3) = -1.
  CVdata(IPER, ISUR,4) = 0.
  CVdata(IPER, ISUR,5) = 99.
  CVdata(IPER, ISUR,6) = 99.
  CVdata(IPER, ISUR,7) = 99.
  CVdata(IPER, ISUR,8) = 99.
  elseif(ANGLE.GT.45.) then

C Ceiling.
  CVdata(IPER, ISUR,1) = 1.
  CVdata(IPER, ISUR,2) = -1.
  CVdata(IPER, ISUR,3) = -1.
  CVdata(IPER, ISUR,4) = 0.
  CVdata(IPER, ISUR,5) = 99.
  CVdata(IPER, ISUR,6) = 99.
  CVdata(IPER, ISUR,7) = 99.
  CVdata(IPER, ISUR,8) = 99.
  endif
10    CONTINUE
    ELSEIF(IOPT.EQ.2)THEN

C Natural convection fully developed flow (Bejan)
C The correlation will be assigned to the vertical surfaces
C independently of the heating being turned on of off
C This correlation will have ICOR = 18.
  hcphrase(1) = 'convec. vert channel'
  hcphrase(2) = 'Fully developed flow'

C Ask Channel width
  h(1)='Enter the channel width'
  h(2)='(inside pane-to-pane distance)'
  CALL EASKR(CWIDTH, 'Channel width ?',
&      ' ',0.01,'W',1.0,'W',0.05,'Channel width',IER,2)

C Ask Channel height
  h(1)='Enter the channel height'
  CALL EASKR(CHEIGHT, 'Channel height ?',
&      ' ',0.1,'W',100.0,'W',1.0,'Channel height',IER,1)

C Examine each surface in the zone. Select ICOR based on surface
orientation.
C ANGLE=0 for walls and other vertical surfaces; ANGLE=-90 for floors;

```

```

C and ANGLE=+90 for ceilings.
  DO 11 ISUR=1,NZSUR(ICOMP)
    icc=izstocn(icmp,isur)
    ANGLE = SSPELV(icc)
    if(ANGLE.LE.45..AND.ANGLE.GE.-45.) then

C Vertical surface. Apply correlation
    CVdata(IPER,ISUR,1) = 1.
    CVdata(IPER,ISUR,2) = 18.
    CVdata(IPER,ISUR,3) = 18.
    CVdata(IPER,ISUR,4) = 0.
    CVdata(IPER,ISUR,5) = 99.
    CVdata(IPER,ISUR,6) = 99.
    CVdata(IPER,ISUR,7) = 99.
    CVdata(IPER,ISUR,8) = 99.
    elseif(ANGLE.LT.-45.) then

C Floor.
    CVdata(IPER,ISUR,1) = 1.
    CVdata(IPER,ISUR,2) = -1.
    CVdata(IPER,ISUR,3) = -1.
    CVdata(IPER,ISUR,4) = 0.
    CVdata(IPER,ISUR,5) = 99.
    CVdata(IPER,ISUR,6) = 99.
    CVdata(IPER,ISUR,7) = 99.
    CVdata(IPER,ISUR,8) = 99.
    elseif(ANGLE.GT.45.) then

C Ceiling.
    CVdata(IPER,ISUR,1) = 1.
    CVdata(IPER,ISUR,2) = -1.
    CVdata(IPER,ISUR,3) = -1.
    CVdata(IPER,ISUR,4) = 0.
    CVdata(IPER,ISUR,5) = 99.
    CVdata(IPER,ISUR,6) = 99.
    CVdata(IPER,ISUR,7) = 99.
    CVdata(IPER,ISUR,8) = 99.
  endif
11 CONTINUE
  ELSEIF(IOPT.EQ.3)THEN

C SOLVENT new blend corrl.
C The correlation will be assigned to the vertical surfaces
C independently of the heating being turned on of off
C This correlation will have ICOR = 19.
    hcphrase(1) = 'convec. vert channel'
    hcphrase(2) = 'SOLVENT new blend'

C Ask Channel width
    h(1)='Enter the channel width'
    h(2)='(inside pane-to-pane distance)'
    CALL EASKR(CWIDTH,'Channel width?',
    & ' ',0.01,'W',1.0,'W',0.05,'Channel width',IER,2)

C Ask Channel height
    h(1)='Enter the channel height'
    CALL EASKR(CHEIGHT,'Channel height?',
    & ' ',0.1,'W',100.0,'W',1.0,'Channel height',IER,1)

C Examine each surface in the zone. Select ICOR based on surface
orientation.
C ANGLE=0 for walls and other vertical surfaces; ANGLE=-90 for floors;
C and ANGLE=+90 for ceilings.

```

```

DO 12 ISUR=1,NZSUR(ICOMP)
  icc=izstocn(icmp, isur)
  ANGLE = SSPELV(icc)
  if (ANGLE.LE.45..AND.ANGLE.GE.-45.) then

C Vertical surface. Apply correlation
  CVdata(IPER, ISUR, 1) = 1.
  CVdata(IPER, ISUR, 2) = 19.
  CVdata(IPER, ISUR, 3) = 19.
  CVdata(IPER, ISUR, 4) = 0.
  CVdata(IPER, ISUR, 5) = 99.
  CVdata(IPER, ISUR, 6) = 99.
  CVdata(IPER, ISUR, 7) = 99.
  CVdata(IPER, ISUR, 8) = 99.
elseif (ANGLE.LT.-45.) then
C Floor.
  CVdata(IPER, ISUR, 1) = 1.
  CVdata(IPER, ISUR, 2) = -1.
  CVdata(IPER, ISUR, 3) = -1.
  CVdata(IPER, ISUR, 4) = 0.
  CVdata(IPER, ISUR, 5) = 99.
  CVdata(IPER, ISUR, 6) = 99.
  CVdata(IPER, ISUR, 7) = 99.
  CVdata(IPER, ISUR, 8) = 99.
elseif (ANGLE.GT.45.) then
C Ceiling.
  CVdata(IPER, ISUR, 1) = 1.
  CVdata(IPER, ISUR, 2) = -1.
  CVdata(IPER, ISUR, 3) = -1.
  CVdata(IPER, ISUR, 4) = 0.
  CVdata(IPER, ISUR, 5) = 99.
  CVdata(IPER, ISUR, 6) = 99.
  CVdata(IPER, ISUR, 7) = 99.
  CVdata(IPER, ISUR, 8) = 99.
endif
12 CONTINUE
ENDIF

C Concatenate the phrases to make hcfpdescr.
lhcp1=lnblnk(hcphrase(1))
lhcp2=lnblnk(hcphrase(2))
lhcp3=lnblnk(hcphrase(3))
write(hcfpdescr(IPER), '(5a)') hcphrase(1)(1:lhcp1), ' ',
& hcphrase(2)(1:lhcp2), ' ', hcphrase(3)(1:lhcp3)

C Write .htc file then return to higher level menu.
CALL EMKHTC(LHCCO(ICOMP), ICOMP, IU, ITRU, IER)
RETURN

END

(...)

C Control laws and associated data for each surface
do 37 J=1,NZSUR(ICOMP)
  WRITE(IU, '(8(f5.0))', IOSTAT=ISTAT, ERR=990)
  & (CVdata(I, J, jj), jj=1, 8)
37 continue

```

```

C Additional information for air channels
  WRITE(IUF, '(I3,F6.3,F6.3,A)', IOSTAT=ISTAT, ERR=990)
  &   IAORZ, CWIDTH, CHEIGHT,
  & '# Air origin zone (+ chan. width and height if Bar-Cohen corr.)'
  endif
930 CONTINUE
  CALL ERPFREE(IUF, ISTAT)
  RETURN

```

- Modifications to file “esrumfs/mfcdat.F”

```

(...)
  &'Fixed flow rates controller
  IVALCM(22)=500
  LVALCM(22)=
  &'CFD component
C Data for components 600 and 610 added here
  IVALCM(23)=600
  LVALCM(23)=
  &'SOLVENT Winter mode flow component
  IVALCM(24)=610
  LVALCM(24)=
  &'SOLVENT Summer mode flow component

  RETURN
  END

```

- Modifications to file “esrumfs/mfmach.F”

```

(...)
C MF460C
C MF500C
C added here reference to SOLVENT components MF600C and MF610C
C MF600C
C MF610C
C Whenever a new fluid flow component is added, a new MFnnnC
C subroutine should be provided. In addition a new MFnnnI, a
C new entry in MFCDAT and extra lines in MFPROB, MFSOLV and
C MFLOAD have to be added.
(...)

      ELSE IF(ITCN.EQ.500) THEN
        IF(FIRST)THEN
          ICFND=ICFND+1
          CALL MF500C(ICNN, DP, DFDDP, ICFND)
          IF(ICNN.EQ.NCNN)FIRST=.FALSE.
        ENDIF
C Add here SOLVENT flow components type 600 and 610

```

```

ELSE IF(ITCN.EQ.600) THEN
    CALL MF600C(ICNN,DP,DFDDP)
ELSE IF(ITCN.EQ.610) THEN
    CALL MF610C(ICNN,DP,DFDDP)
ELSE
    call edisp(IMFTU,' MFSOLV: unresolvable error !')
    call epwait
    call epagend
    STOP
END IF
ENDIF
(...)

VEL=-Wf(I,J,K+1)
IF(K.EQ.NKM1)VEL=0.0
RHO=0.5*(DENf(i,j,K)+DENf(i,j,K+1))
AREA=SEW(I)*SNS(J)
FLW1(ICNN)=FLW1(ICNN)+RHO*VEL*AREA
10 CONTINUE

RETURN
END

C New routine for SOLVENT flow component in Winter mode
C ***** MF600C
C Fluid mass flow calculation routine for flow component type:
C SOLVENT buoyancy flow in a narrow vertical air channel, Winter mode
C      SUPCMP(ICMP,1) - fluid type (1=air, 2=water)
C      SUPCMP(ICMP,2) - Width of the window (m)
C      SUPCMP(ICMP,3) - Height of the Channel (m)
C      SUPCMP(ICMP,4) - Width of the open air channel (m)
C      SUPCMP(ICMP,5) - Sum of the local pressure loss factors
C (typically 1.5)
C      SUPCMP(ICMP,6) - Number of the zone associated with the
channel
C      SUPCMP(ICMP,7) - Number of the 1st surface bounding the
channel
C      SUPCMP(ICMP,8) - Number of the 2nd surface bounding the
channel
C In the case of range based control FLOW is multiplied by the
C control ratio returned in ctlpos.

SUBROUTINE MF600C(ICNN,DELP,DERIV)

#include "net_flow.h"
#include "building.h"

COMMON/MFLOW4/ITND(MNOD),TNOD(MNOD)
COMMON/MFLOW5/RHON(MNOD)
COMMON/MFLOW9/ITPCMP(MCMP),ISDCMP(MCMP),ISDCNN(MCMP),
&      SUPCMP(MCMP,MCMS)
COMMON/MFLW10/NODPS(MCNN),HGTPS(MCNN),NODNE(MCNN),HGTNE(MCNN),
&      ITPCON(MCNN),NDSCNN(MCNN,MCNS)
COMMON/MFLRES/FLW1(MCNN),FLW2(MCNN),PRES(MNOD),
&      RESID(MNOD),SAFLW(MNOD)
COMMON/MFLCTL/IRY,IRM,IRD,IRH,FLWTIM,IHOUR,IYD,IFYD,ILYD,IPROG
COMMON/MFLITR/MAXITF,FERREL,FERMFL,PMAX,STEFFR,MFTRAC,ITER,IOK
COMMON/mfctl/ctlpos(MCNN)
COMMON/CVSTORED/CVSTORE(MCOM,MS,3)

DOUBLE PRECISION FLW1,FLW2,PRES,RESID,SAFLW,FLW1p

```

```

DOUBLE PRECISION DELP,DERIV

PARAMETER      (SMALL=1.0E-15)

IDPS=NODPS(ICNN)
IDNE=NODNE(ICNN)
ICMP=ITPCON(ICNN)

IFLD=INT(SUPCMP(ICMP,1))
W=SUPCMP(ICMP,2)
H=SUPCMP(ICMP,3)
S=SUPCMP(ICMP,4)
SUMK=SUPCMP(ICMP,5)

ICOMP=INT(SUPCMP(ICMP,6))
ISURF1=INT(SUPCMP(ICMP,7))
ISURF2=INT(SUPCMP(ICMP,8))

HCSURF1=CVSTORE(ICOMP,ISURF1,1)
HCSURF2=CVSTORE(ICOMP,ISURF2,1)
HC=(HCSURF1+HCSURF2)/2

TSURF1=CVSTORE(ICOMP,ISURF1,2)
TSURF2=CVSTORE(ICOMP,ISURF2,2)
TS=(TSURF1+TSURF2)/2

TIN=CVSTORE(ICOMP,ISURF1,3)

C      WRITE(ICOUT,*)
C      &'W ',W,' H ',H,' S ',S,' SUMK ',SUMK
C      WRITE(ICOUT,*)
C      &'HC ',HC,' TS ',TS,' TIN ',TIN

C: Next line sets the specific heat of air, constat at 1007 J/Kg.K
      CP=1007
C It is actually indiferent wether flow is +ve or - ve.
C But the air density will be calculated with the "previous node"
temperature
C Therefore this component connection shall be placed at the channel exit

C calculate hidraulic diameter, Reynolds number and friction coeficient

C      FLOWI=FLW1(ICNN)

      DO 10 LNIT=1,MAXITF
      FLW1p=MAX(FLOW,0.001)
      FMU=DYVISC(IFLD,TNOD(IDPS))
      DIAH=4*W*S/(2*W+2*S)
      REY=FLW1p/(W*S)*DIAH/FMU
      IF(REY.LT.1.) REY=1.

      IF (REY.LE.2300.0) THEN
      FRIC=91.4/REY
      ELSE
      FRIC=0.316/REY**0.25*91.4/64.0
      END IF

      FLOW=RHON(IDPS)*W*S*(2*9.81*(FLW1p*CP*
&(EXP(-2*W*H*HC/(FLW1p*CP))-1)+2*W*H*HC)
&/(2*W*HC*(1+FRIC*H/(2*S)+SUMK))*ABS(TS-TIN)/(TIN+273.15))**0.5

```

Annex 3: Listing of the changed and added ESP-r code

```

C Check error <= tolerance (relative to initial mass flow rate (& REY)).
C This is not desirable in the case where the velocity is small.
  IF(DABS(FLOW-FLW1p).LE.FERREL*DABS(FLW1p)
    & .OR.DABS(FLOW-FLW1p).LE.FERMFL) GOTO 20

10 CONTINUE

  CALL DAYCLK(IYD,FLWTIM,ICOUT)
  call edisp(icout,' MF600C warning: max. number of iterations')
C  WRITE(outs,'(A,I4,A,I4)') ' exceeded: ',LNIT,' connection', ICNN
C  call edisp(icout,outs)

20 FLW1(ICNN)=FLOW*ctlpos(icnn)
  FLW2(ICNN)=0.
  DERIV=0.0
C  WRITE(ICOUT,*)
C  &'FLW1prev g/s',FLW1p*1000,' REY ',REY, 'FLOW g/s', FLOW*1000

C  call edisp(IMFTU,outs)
C  if(dotrace)call edisp(itu,outs)

  RETURN
  END

C New routine for SOLVENT flow component in Summer mode
C ***** MF610C
C Fluid mass flow calculation routine for flow component type:
C SOLVENT buoyancy flow in a narrow vertical air channel, Summer mode
C      SUPCMP(ICMP,1) - fluid type (1=air, 2=water)
C      SUPCMP(ICMP,2) - Width of the Window (m)
C      SUPCMP(ICMP,3) - Height of the Channel (m)
C      SUPCMP(ICMP,4) - Width of the open air channel (m)
C      SUPCMP(ICMP,5) - Sum of the local pressure loss factors
C (typically 1.5)
C      SUPCMP(ICMP,6) - Number of the zone associated with the
channel
C      SUPCMP(ICMP,7) - Number of the 1st surface bounding the
channel
C      SUPCMP(ICMP,8) - Number of the 2nd surface bounding the
channel
C      SUPCMP(ICMP,9) - Coefficient of proportionality between
channel air velocity and wind velocity
C In the case of range based control FLOW is multiplied by the
C control ratio returned in ctlpos

  SUBROUTINE MF610C(ICNN,DELP,DERIV)

#include "net_flow.h"
#include "building.h"

  COMMON/MFLOW4/ITND(MNOD), TNOD(MNOD)
  COMMON/MFLOW5/RHON(MNOD)
  COMMON/MFLOW9/ITPCMP(MCMP), ISDCMP(MCMP), ISDCNN(MCMP),
&      SUPCMP(MCMP,MCMS)
  COMMON/MFLW10/NODPS(MCNN), HGTPS(MCNN), NODNE(MCNN), HGTNE(MCNN),
&      ITPCON(MCNN), NDSCNN(MCNN,MCNS)
  COMMON/MFLRES/FLW1(MCNN), FLW2(MCNN), PRES(MNOD),
&      RESID(MNOD), SAFLW(MNOD)
  COMMON/MFLCTL/IRY, IRM, IRD, IRH, FLWTIM, IHOOR, IYD, IFYD, ILYD, IPROG
  COMMON/MFLITR/MAXITF, FERREL, FERMFL, PMAX, STEFFR, MFTRAC, ITER, IOK
  COMMON/mfctl/ctlpos(MCNN)

```

```

COMMON/CVSTORED/CVSTORE(MCOM,MS,3)
COMMON/MFLCLM/DRYB,QDIF,QDNR,IRVH,WDIR,WSPD,WRED

DOUBLE PRECISION FLW1,FLW2,PRES,RESID,SAFLW,FLW1p
DOUBLE PRECISION DELP,DERIV

PARAMETER      (SMALL=1.0E-15)

IDPS=NODPS(ICNN)
IDNE=NODNE(ICNN)
ICMP=ITPCON(ICNN)

IFLD=INT(SUPCMP(ICMP,1))
W=SUPCMP(ICMP,2)
H=SUPCMP(ICMP,3)
S=SUPCMP(ICMP,4)
SUMK=SUPCMP(ICMP,5)

ICOMP=INT(SUPCMP(ICMP,6))
ISURF1=INT(SUPCMP(ICMP,7))
ISURF2=INT(SUPCMP(ICMP,8))
WINCVEL=SUPCMP(ICMP,9)

HCSURF1=CVSTORE(ICOMP,ISURF1,1)
HCSURF2=CVSTORE(ICOMP,ISURF2,1)
HC=(HCSURF1+HCSURF2)/2

TSURF1=CVSTORE(ICOMP,ISURF1,2)
TSURF2=CVSTORE(ICOMP,ISURF2,2)
TS=(TSURF1+TSURF2)/2

TIN=CVSTORE(ICOMP,ISURF1,3)

C      WRITE(ICOUT,*)
C      &'W ',W,' H ',H,' S ',S,'SUMK',SUMK
C      WRITE(ICOUT,*)
C      &'HC ',HC,' TS ',TS,' TIN ',TIN

C: Next line sets the specific heat of air, constat at 1007 J/Kg.K
      CP=1007
C It is actually indiferent wether flow is +ve or - ve.
C But the air density will be calculated with the "previous node"
temperature
C Therefore this component connection shall be placed at the channel exit

C calculate hidraulic diameter, Reynolds number and friction coefficient

C      FLOWI=FLW1(ICNN)

      DO 10 LNIT=1,MAXITF
      FLW1p=MAX(FLOW,0.001)
      FMU=DYVISC(IFLD,TNOD(IDPS))
      DIAH=4*W*S/(2*W+2*S)
      REY=FLW1p/(W*S)*DIAH/FMU
      IF(REY.LT.1.) REY=1.

      IF (REY.LE.2300.0) THEN
      FRIC=91.4/REY
      ELSE
      FRIC=0.316/REY**0.25*91.4/64.0
      END IF

```

```

      FLOW=RHON(IDPS)*W*S*(2*9.81*(FLW1p*CP*
      &(EXP(-2*W*H*HC/(FLW1p*CP))-1)+2*W*H*HC)
      &/(2*W*HC*(1+FRIC*H/(2*S)+SUMK))*ABS(TS-TIN)/(TIN+273.15))**.5
C Check error <= tolerance (relative to initial mass flow rate (& REY)).
C This is not desirable in the case where the velocity is small.
      IF(DABS(FLOW-FLW1p).LE.FERREL*DABS(FLW1p)
      & .OR.DABS(FLOW-FLW1p).LE.FERMFL) GOTO 20

10 CONTINUE

      CALL DAYCLK(IYD,FLWTIM,ICOUT)
      call edisp(icout,' MF610C warning: max. number of iterations')
C      WRITE(outs,'(A,I4,A,I4)') ' exceeded: ',LNIT,' connection', ICNN
C      call edisp(icout,outs)

C      Compute flow induced by the wind in the air channel
20 WINFLOW=WSPD*WINCVEL*RHON(IDPS)*W*S
C      Choose the maximum
      FLW1(ICNN)=MAX(FLOW,WINFLOW)*ctlpos(icnn)
      FLW2(ICNN)=0.
      DERIV=0.0
C      WRITE(ICOUT,*)
C      &'FLW1prev g/s',FLW1p*1000,' REY ',REY, 'FLOW g/s', FLW1(ICNN)*1000

C      call edisp(IMFTU,outs)
C      if(dotrace)call edisp(itu,outs)

      RETURN
      END
(...)

```

- Modifications to file “esruprj/mfprb1.F”

```

(...)
      ELSE IF(ITPCMP(IFCMP).EQ.420) THEN
          CALL MF420I(IFCMP,IERL)
          ELSE IF(ITPCMP(IFCMP).EQ.460) THEN
              CALL MF460I(IFCMP,IERL)
C add here components 600 and 610
              ELSE IF(ITPCMP(IFCMP).EQ.600) THEN
                  CALL MF600I(IFCMP,IERL)
              ELSE IF(ITPCMP(IFCMP).EQ.610) THEN
                  CALL MF610I(IFCMP,IERL)
              ELSE
                  CALL USRMSG(' Unknown component type',' try again..','W')
                  goto 20
              END IF
          END IF
      END IF
(...)

```

- Modifications to file "esrupri/mfprb2.F"

(...)

C MF420I

C MF460I

C added MF600I and MF610I for SOLVENT type flow component

C MF600I

C MF610I

(...)

CALL EGETWR(hold,K,VAL3,0.,0.,'-','flow >ssp',IER)

IF(IER.NE.0) GOTO 43

SUPCMP(ICMP,2)=VAL2

SUPCMP(ICMP,3)=VAL3

RETURN

END

C New SOLVENT flow component, Winter mode

SUBROUTINE MF600I(ICMP,IER)

#include "net_flow.h"

#include "building.h"

COMMON/OUTIN/IUOUT,IUIN

common/pophelp/h(60)

COMMON/MFLOW8/CMNAM(MCMP),LTPCMP(MCMP)

COMMON/MFLOW9/ITPCMP(MCMP),ISDCMP(MCMP),ISDCNN(MCMP),

& SUPCMP(MCMP,MCMS)

COMMON/MFLOWIT/fndegc,imix

*CHARACTER LTPCMP*60,CMNAM*12*

*character H*72,outs*124,hold*48,prompt*48*

logical OK,close

C Set number of supplementary data items.

*PI=4.*ATAN(1.)*

IER=0

ISDCMP(ICMP)=8

ISDCNN(ICMP)=0

C Show short description of flow component.

WRITE(outs,'(1X,A60)') LTPCMP(ICMP)

WRITE(H(1),'(A)') LTPCMP(ICMP)

H(2)='Type 600 is a component which calculates the flow '

H(3)='due to buoyancy in a vertical narrow air channel'

H(4)='This component must be associated with a connection at'

H(5)='the exit of the air channel'

H(6)='It only works combined with convection type'

H(7)=' "SOLVENT channel correlation" (ICOR 19) '

H(8)=' '

H(9)='Supplemental data:'

H(10)=' fluid type,window width W, window heith H, '

h(11)=' channel width S, sum of local loss factors sumK, '

H(12)=' Nr. of the zone associated with the channel, '

H(13)=' Nr. of the first reference surface '

H(14)=' Nr. of the second reference surface '

H(15)=' '

H(16)='See Leal thesis for more details'

```

CALL EASKOK(outs, ' Synopsis of this component type ? ',OK)
if(OK) CALL PHELPD('comp 600',16,'-',0,0,IER)

C Input fluid type.
  if(imix.eq.1)then
    SUPCMP(ICMP,1)=1.0
  elseif(imix.eq.2)then
    SUPCMP(ICMP,1)=2.0
  else
    write(prompt,'(a,a,a)') 'Fluid through ',CMNAM(ICMP),': '
    CALL EASKAB(' ',prompt,'air','water',IW,16)
    SUPCMP(ICMP,1)=REAL(IW)
  endif

C Window width, window height, channel width, sum of local loss factors
  write(hold,'(4f6.3,3f3.0)')SUPCMP(ICMP,2),SUPCMP(ICMP,3),
& SUPCMP(ICMP,4),SUPCMP(ICMP,5),SUPCMP(ICMP,6),
& SUPCMP(ICMP,7),SUPCMP(ICMP,8)
43 CALL EASKS(hold,
& 'W(m), H(m), S(m), SumK(-), Zone, Surf A, Surf B',
& ' ',48,'1.100 1.130 0.041 1.5 4. 1. 3.', 'comp 600',IER,16)
  K=0
  CALL EGETWR(hold,K,VAL2,0.001,99.,'W','wind. width',IER)
  CALL EGETWR(hold,K,VAL3,0.0,99.,'W','chan height',IER)
  CALL EGETWR(hold,K,VAL4,0.01,999.,'W','chan width',IER)
  CALL EGETWR(hold,K,VAL5,0.01,999.,'W','SumK',IER)
  CALL EGETWR(hold,K,VAL6,1.,99.,'W','Ref zone',IER)
  CALL EGETWR(hold,K,VAL7,1.,99.,'W','1st ref surf',IER)
  CALL EGETWR(hold,K,VAL8,1.,99.,'W','2nd ref surf',IER)
  IF(IER.NE.0) GOTO 43
  SUPCMP(ICMP,2)=VAL2
  SUPCMP(ICMP,3)=VAL3
  SUPCMP(ICMP,4)=VAL4
  SUPCMP(ICMP,5)=VAL5
  SUPCMP(ICMP,6)=VAL6
  SUPCMP(ICMP,7)=VAL7
  SUPCMP(ICMP,8)=VAL8

  RETURN
END

C New SOLVENT flow component, Summer mode
  SUBROUTINE MF610I(ICMP,IER)

#include "net_flow.h"
#include "building.h"
  COMMON/OUTIN/IUOUT,IUIN
  common/pophelp/h(60)
  COMMON/MFLOW8/CMNAM(MCMP),LTPCMP(MCMP)
  COMMON/MFLOW9/ITPCMP(MCMP),ISDCMP(MCMP),ISDCNN(MCMP),
& SUPCMP(MCMP,MCMS)
  COMMON/MFLOWIT/fndegc,imix

  CHARACTER LTPCMP*60,CMNAM*12
  character H*72,outs*124,hold*48,prompt*48
  logical OK,close

C Set number of supplementary data items.
  PI=4.*ATAN(1.)
  IER=0
  ISDCMP(ICMP)=9

```

```
ISDCNN(ICMP)=0
```

```
C Show short description of flow component.
```

```
WRITE(outs, '(1X,A60)') LTPCMP(ICMP)
WRITE(H(1), '(A)') LTPCMP(ICMP)
H(2)='Type 610 is a component which calculates the flow '
H(3)='due to buoyancy in a SOLVENT vertical narrow air '
H(4)='channel with influence of wind '
H(5)='This component must be associated with a connec- '
H(6)='tion at the exit of the air channel '
H(7)='It only works combined with convection type '
H(8)=' "SOLVENT channel correlation" (ICOR 19) '
H(9)=''
H(10)='Supplemental data:'
H(11)=' fluid type,window width W, window heith H, '
H(12)=' channel width S, sum of local loss factors sumK, '
H(13)=' Nr. of the zone associated with the channel, '
H(14)=' Nr. of the first reference surface '
H(15)=' Nr. of the second reference surface'
H(16)=' Coeff. of prop. betwenn wind and channel veloc. '
H(17)='See Leal theis for more details'
CALL EASKOK(outs, ' Synopsis of this component type ? ',OK)
if(OK) CALL PHELPD('comp 610',17,'-',0,0,IER)
```

```
C Input fluid type.
```

```
if(imix.eq.1)then
  SUPCMP(ICMP,1)=1.0
elseif(imix.eq.2)then
  SUPCMP(ICMP,1)=2.0
else
  write(prompt, '(a,a,a)') 'Fluid through ',CMNAM(ICMP), ':'
  CALL EASKAB(' ',prompt, 'air', 'water', IW, 16)
  SUPCMP(ICMP,1)=REAL(IW)
endif
```

```
C Window width, window height, channel width, sum of local loss factors
```

```
write(hold, '(4f6.3,3f3.0,f6.4)')SUPCMP(ICMP,2),SUPCMP(ICMP,3),
& SUPCMP(ICMP,4),SUPCMP(ICMP,5),SUPCMP(ICMP,6),
& SUPCMP(ICMP,7),SUPCMP(ICMP,8), SUPCMP(ICMP,9)
43 CALL EASKS(hold,
& 'W(m), H(m), S(m), SumK(-), Zone, Surf A, Surf B, WINCVEL',
& ' ',48,'1.10 1.13 0.041 1.5 4. 1. 3. 0.1307','comp 610',IER,16)
K=0
CALL EGETWR(hold,K,VAL2,0.001,99., 'W', 'wind. width', IER)
CALL EGETWR(hold,K,VAL3,0.0,99., 'W', 'chan height', IER)
CALL EGETWR(hold,K,VAL4,0.01,999., 'W', 'chan width', IER)
CALL EGETWR(hold,K,VAL5,0.01,999., 'W', 'SumK', IER)
CALL EGETWR(hold,K,VAL6,1.,99., 'W', 'Ref zone', IER)
CALL EGETWR(hold,K,VAL7,1.,99., 'W', '1st ref surf', IER)
CALL EGETWR(hold,K,VAL8,1.,99., 'W', '2nd ref surf', IER)
CALL EGETWR(hold,K,VAL9,0.,5., 'W', 'WINCVEL', IER)
IF(IER.NE.0) GOTO 43
SUPCMP(ICMP,2)=VAL2
SUPCMP(ICMP,3)=VAL3
SUPCMP(ICMP,4)=VAL4
SUPCMP(ICMP,5)=VAL5
SUPCMP(ICMP,6)=VAL6
SUPCMP(ICMP,7)=VAL7
SUPCMP(ICMP,8)=VAL8
SUPCMP(ICMP,9)=VAL9
```

```

RETURN
END

```

- Modifications to file “esrucom/nwkrewr.F”

```

(...)
        ISDCMP(NCMP)=7
        elseif(ITPCMP(NCMP).eq.420)then
            ISDCMP(NCMP)=6
C SOLVENT component type 600 added here
            elseif(ITPCMP(NCMP).eq.600)then
                ISDCMP(NCMP)=8
C SOLVENT component type 610 added here
            elseif(ITPCMP(NCMP).eq.610)then
                ISDCMP(NCMP)=9
            endif
            do 62 ijk=1,ISDCMP(NCMP)
                read(ATTRCN(I,ijk+1,1),*,IOSTAT=IOS,ERR=1001)
                SUPCMP(NCMP,ijk)
        &
62      continue
        endif
    endif
endif

```

- Modifications to file “esrubld/solar.F”

```

C IB: eliminate test of external surface to allow also control of
C blinds placed in internal TMC's
C-----BLIND CONTROL - EXTERNAL and internal SURFACES
C-----
C
C If external or internal TMC, determine whether blind/shutter active.
    ITMC=ITMCFL(ICOMP,I)
    IBOFOT(ICOMP,I)=0
    ECRAT(ICOMP,I)=1.0
    NBPONT(ICOMP,I)=0

C*****
C If bidirectional, no control possible for the moment.
C*****

C Test here if blind/shutter control is on for this surface TMC.
    IF(ITMC.GT.0)then
        C      if(IBCMT(ICOMP,ITMC).EQ.1.AND.IE(ICOMP,I).EQ.0)THEN
              if(IBCMT(ICOMP,ITMC).EQ.1)THEN
C Window blind/shutter in place on this TMC. Test if it is active.
C NP is no. of control periods for this TMC type.
        NP=NBCTMC(ICOMP,ITMC)
        DO 5 K=1,NP
            IT1=IBCST(ICOMP,K,ITMC)
            IT2=IBCFT(ICOMP,K,ITMC)
            IF(IHRF.GT.IT1.AND.IHRF.LE.IT2) THEN
                IF(BACTPT(ICOMP,K,ITMC).LT.-98.0) THEN

```

```

(...)

```

```

C Radiation activation; check which surface the sensor is on;
C - if IBCSUR()==0, then current surface.
C P00/P002 contains shading factor on corresponding opaque surface.
      ISUR=IBCSUR(ICOMP,ITMC)
      IF(ISUR.EQ.0)THEN
C changed here to operate on incident direct radiation alone
C      RAD=(SRADD0(I)*(1.-P00))+SRADF(I)
      RAD=(SRADD0(I)*(1.-P00))+SRADF(I)*0.0
      ELSE
      IF(ISHD(ICOMP).EQ.0.OR.ISHD(ICOMP).EQ.2)THEN
        P002=0.0
      ELSE
        (...)

C Compute declination.
      A=280.1+0.9863*DAY
      DEC=23.45*ESIND(A)
      SDEC=SIN(DEC*R)
      CDEC=COS(DEC*R)

C Compute solar altitude.
C: Take 1h from solar time to account for daylight saving time between
C day and day (based in 2003)
C      TIME=HOUR+(EQT+SLON/15.)
      IF ((DAY.LT.88.0).OR.(DAY.GT.289.0)) THEN
        TIME=HOUR+(EQT+SLON/15.)
      ELSE
        TIME=HOUR+(EQT+SLON/15.)-1.0
      END IF

      TIMCOE=15.*(12.-TIME)
      CDTIME=COS(TIMCOE*R)
      ABST=ABS(TIMCOE)
      SABST=SIN(ABST*R)
      SSLAT=SIN(SLAT*R)
      CSLAT=COS(SLAT*R)
      SALT=ASIN(SSLAT*SDEC+CSLAT*CDEC*CDTIME)/R
      IF(SALT.LT.0.)goto 1
      (...)

C Solar radiation values are Global and Diffuse Horizontal.
      QD=(QDF-QFF)/SIN(SALT*R)
      IF(QD.GT.1353.0)goto 2
      IF(QD.LT.0.0)goto 3
      goto 1
C 19 Oct 2004
C Change next line to warn and correct instead of abort (fatal error)
C      2 IF(SALT.GT.12.0)goto 4
      2 If (SALT.GT.12)then
        write(outs,'(a,I7,a,F6.1,a)')' MZSINT: increment',NSINC,
        & ' direct n.',QD,' > solar constant '
        call edisp(iuout,outs)
        write(outs,'(a,F6.1,a,F6.1)')' and solar altitude is ',SALT,
        & ' and azimuth is ',SAZI
        call edisp(iuout,outs)
        call edisp(iuout,
        & ' Default invoked; diffuse h.= global h.; direct n.=0.')
        end if
      IF(ICOMP.GT.1)goto 5
      (...)

```

- Modifications to file “esrures/table.F”

```

C If there is occupancy filter and occupancy then include in check.
C Assume fully occupied.
      ih=int(ATIME+1.)
      ioc=1
      if(iocupf.eq.1) call getocup(IZONE,IDAY,ih,ioc,ier)
      if(ioc.ne.0) then
C changed from f11.2 to f11.3 to obtain increased precision in cell coolg
power
C
          write (outs(K:KE),'(f11.2)') VAL2(IG,J)
          write (outs(K:KE),'(f11.3)') VAL2(IG,J)
      elseif (IGETNO(IG,1).ge.50.AND.IGETNO(IG,1).le.59) then
          if (VAL2(IG,J).gt.100.0) then
              write (outs(K:KE),'(a)') ' invl dT '
              IINLVDT=1
          else
C changed from f11.2 to f11.3 to obtain increased precision in cell coolg
power
C
              write (outs(K:KE),'(f11.2)') VAL2(IG,J)
              write (outs(K:KE),'(f11.3)') VAL2(IG,J)
          endif
      else
          write (outs(K:KE),'(a)') ' not occ '
      endif
      K=K+11
    endif
410      continue
      call eddisp(itru,outs)
421      CONTINUE
10      continue

```

- Modifications to file “esrubld/casual.F”

```

(...)
C Case of On/Off with chosen lighting systems and sensors.
      ELSEIF(ICGCFL(ICOMP,N).EQ.1)THEN
          ZFRAC(N)=0.0
C The SETPT should not be summed with the zelum in the next line (?)
C remove it
C
          zell=zelum(N)+SETPT(ICOMP,N)
          zell=zelum(N)
      IF(zell.GE.SOFFRL.AND.IDTM(ICOMP,N).GE.IOFFDT(ICOMP,N))THEN
(...)

```


ANNEX 4: ANGLE-DEPENDENT OPTICAL PROPERTIES OF THE GLAZINGS

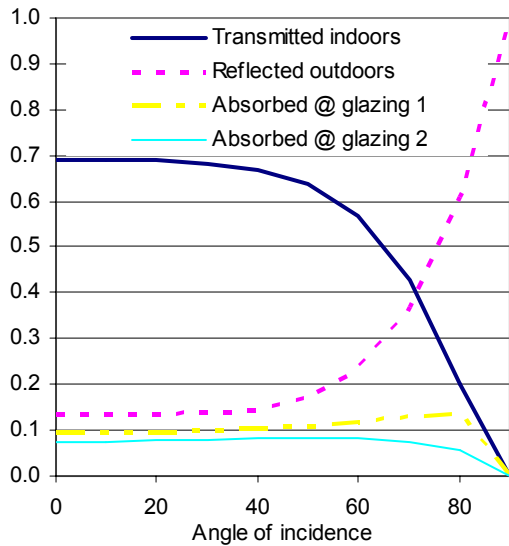


Figure A4 - 1: Solar optical properties of the double clear glazing.

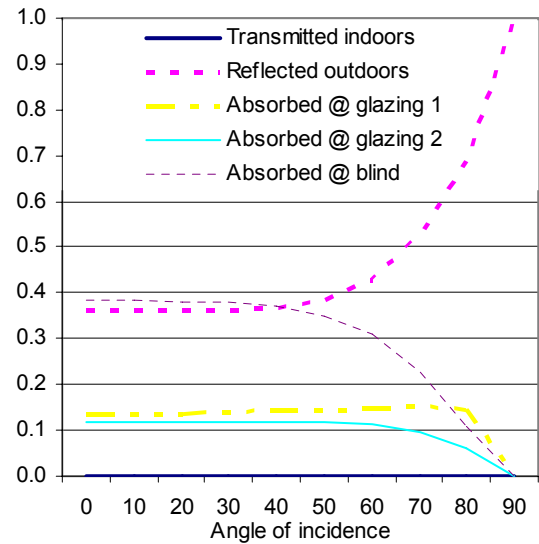


Figure A4 - 2: Solar optical properties of the double clear glazing with a closed internal blind.

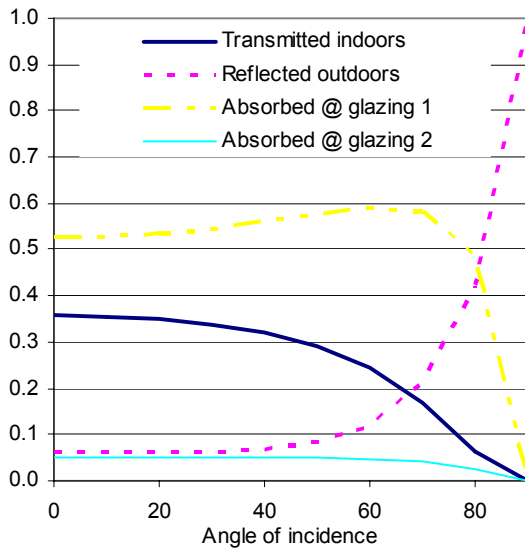


Figure A4 - 3: Solar optical properties of the solar control double glazing.

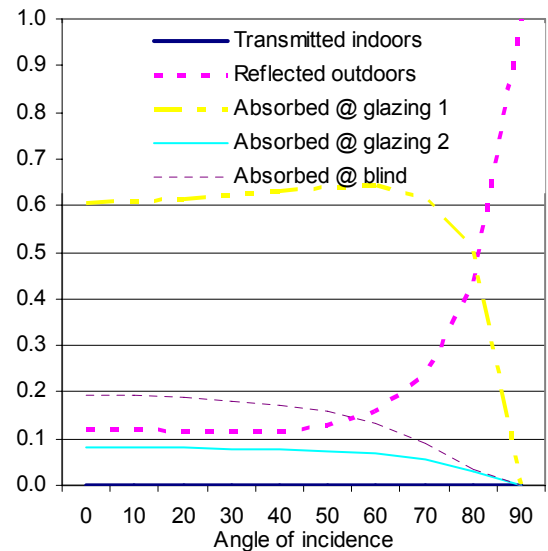


Figure A4 - 4: Solar optical properties of the solar control double glazing with a closed internal blind

Annex 4: Optical properties of the glazings used in the simulations

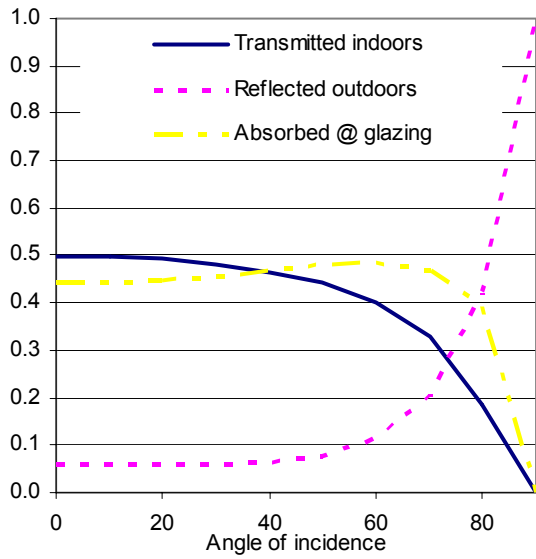


Figure A4 - 5: Solar optical properties of the medium absorptive glazing.

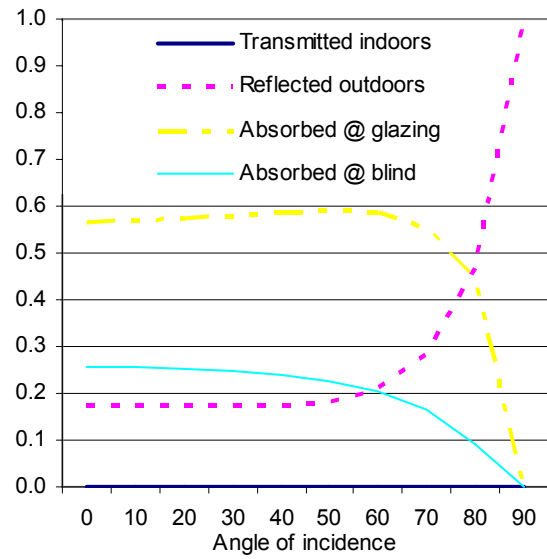


Figure A4 - 6: Solar optical properties of the medium absorptive glazing with a closed internal blind.

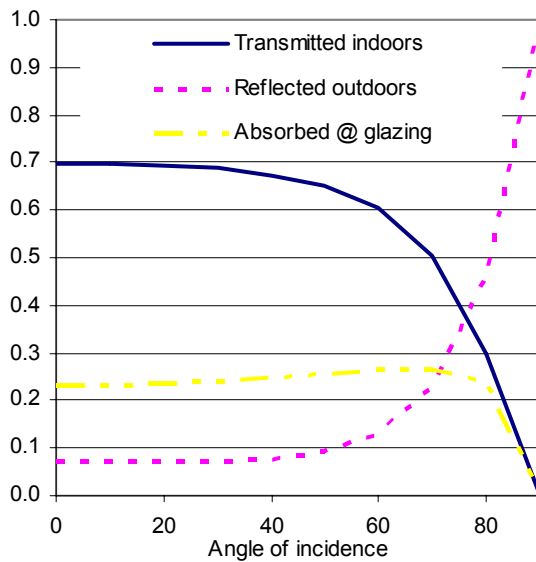


Figure A4 - 7: Solar optical properties of the poorly absorptive glazing.

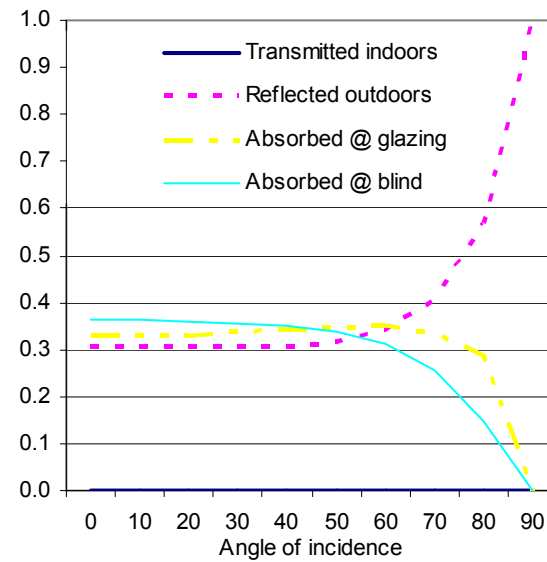


Figure A4 - 8: Solar optical properties of the poorly absorptive glazing with a closed internal blind.

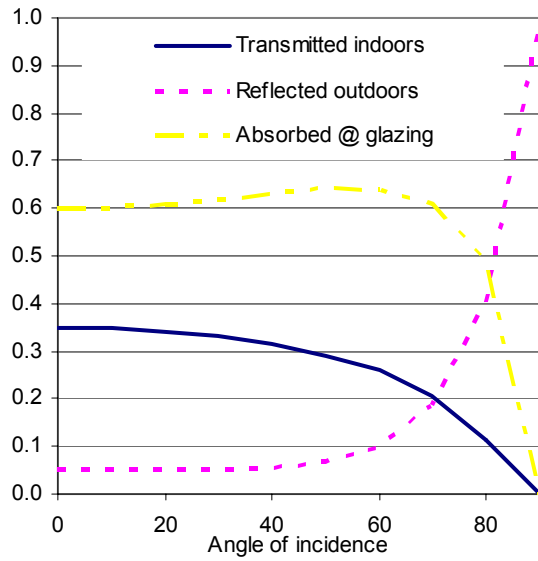


Figure A4 - 9: Solar optical properties of the highly absorptive glazing.

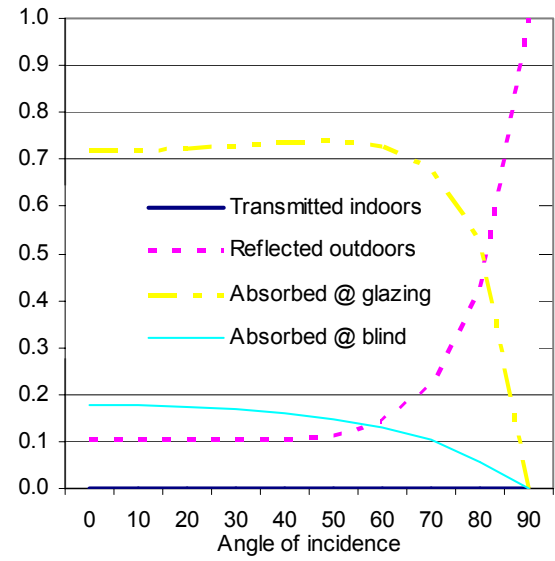


Figure A4 - 10: Solar optical properties of the highly absorptive glazing with a closed internal blind.

ANNEX 5: MAIN ENVELOPE AND OPERATION CHARACTERISTICS OF THE OFFICE

Main envelope and operation characteristics for the office in the three reference locations

	Location: PORTO	U – value (W/m ² .K)	Location: TEL AVIV	U – value (W/m ² .K)	Location: BERLIN	U – value (W/m ² .K)
Walls (exterior to interior)	Brick (15 cm) + air layer (4 cm) + exp. polystyrene (4 cm) + 11 cm brick	0.51	Limestone (4cm) + exp. polystyrene (2m) + hollow brick (20cm)	0.97	plaster (2 cm) + polystyrene (8 cm) + sand-lime brick (24 cm)	0.35
Interior walls	cement coating (1 cm) + brick (11 cm) + cement coating (1 cm)	2.45	cement coating (1 cm) + brick (10 cm) + cement coating (1 cm)	2.55	As in Porto	
Roof	Concrete (2 cm) + exp. polystyrene (5 cm) + concrete (15 cm) + cement coating (1 cm)	0.55	Foamed concrete (5cm) + exp. Polystyrene (3 cm) + light concrete (5cm) + concrete block (20 cm)	0.61	sealing + polystyrene (14 cm) + concrete (12 cm)	0.25
Slabs (between floors)	Concrete (25 cm) + Plastic flooring (2 cm)	1.17	concrete block (20 cm) + foamed block (5 cm)	0.77	As in Porto	
Interior doors	Softwood 2 cm		As in Porto		As in Porto	
Air change(outdoor air)	1 air change per hour on average		As in Porto		As in Porto	
Equipment	3 PC's 100% time + 2 PC's 50% time (each PC 72.5 W on average) + 1 laser printer (220 W on average)		As in Porto		As in Porto	
Lighting	Eight 36 W lamps from 9 to 18 h					
Occupation	5 people. Simultaneity factor 70%.					
Reference comfort conditions (heating and	20 – 24 °C		As in Porto		As in Porto	

ANNEX 6: MAIN ENVELOPE AND OPERATION CHARACTERISTICS OF THE SCHOOL

Main envelope and operation characteristics for the school in the three reference locations

	Location: PORTO	U – value (W/m ² .K)	Location: TEL AVIV	U – value (W/m ² .K)	Location: BERLIN	U – value (W/m ² .K)
Walls (exterior to interior)	Brick (15 cm) + air layer (4 cm) + exp. polystyrene (4 cm) + (11 cm)	0.51	Limestone (4cm) + concrete block (20cm)	0.96	plaster (2 cm) + polystyrene (8 cm) +bricks (24 cm) + plaster (2 cm)	0.36
Interior walls	cement coating (1 cm) + brick (11 cm) + cement coating (1 cm)	2.45	cement coating (1 cm) + brick (20 cm) + cement coating (1 cm)	1.81	cement coating (1 cm) + brick (20 cm) + cement coating (1 cm)	1.81
Roof	Clay tile (1.5 cm)	5.1	As in Porto		As in Porto	
Slabs (between roof and rooms and between floors))	concrete slab (24 cm)	1.5	Concrete (20 cm) + ceramic tile (2m)	0.69	concrete (12 cm) + insulation (8 cm) + floor pavement (6 cm)	0.46
Interior doors	Softwood 2 cm	3.0	As in Porto		As in Porto	
Air change(outdoor air)	1air change per hour on average		As in Porto		As in Porto	
Lighting	7.5 W/m ²		As in Porto		As in Porto	
Occupation	25 children+ 1 adult					
Reference comfort conditions (heating and cooling set-points)	20-24 °C		As in Porto		As in Porto	

