Master in Chemical Engineering

Numerical Analysis of the influence of Temperature and Moisture in the Remaining Life estimation of Power Transformers

Master Dissertation

of

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Muito Obrigada!

Abstract

To improve and develop the electrical network distribution, Power Transformers are complex devices that are used to support the energy demand in current industrialized society. Even though its operational efficiency is very high, the manufacture and maintenance involved in this device are expensive, hence the need to assure its best performance. The analysis of the condition of a Power Transformer can be directly related to the mechanical state of its insulation paper. Particularly in the active part, this insulation material is exposed to temperature and moisture conditions favorable to its degradation.

Through simulated data in Computational Fluid Dynamics (CFD) Simulation for a Core-type transformer, whose winding geometry is described in detail, four simulations were performed exposing the winding into a specified set of conditions. It allowed to understand the impact of the inlet fluid velocity, the inlet fluid temperature, and the heat source of the disks. Furthermore, the winding was also exposed to different water concentrations, which allowed to analyze the impact of moisture in the estimation of the Remaining Life of the Power Transformer.

Several methodologies were approached to determine the water content in paper, where different temperature were used, such as, inlet and outlet fluid temperature, hot spot temperature, average temperature, and both solid and fluid temperature profiles obtained along the winding. Results showed that these methodologies present more impact on a winding exposed to lower water concentration. Furthermore, results also show the limitation of the equilibrium curves applicability for elevated temperatures.

Finally, a parallel study was performed to understand the possibility of water migration in the transformer's system. Since lower temperatures allow higher water concentration, the application of thermal models could present some limitations. Therefore, it highlighted the importance of the paper-oil-water systems and water migration acknowledgment, which could result in winding zones with higher water content in the paper.

Keywords: Power Transformers, Remaining Life Estimation, Paper Insulation; Temperature; Moisture; Non-thermal Models.

Resumo

O continuo desenvolvimento cientifico e tecnológico tem proporcionado uma otimização do mercado energético. A rede elétrica apresenta cada vez maior eficiência e amplitude, atendendo às necessidades desta sociedade industrializada. Esta melhoria deve-se, em parte, à incoporação de Transformadores de Potência na rede de distribuição, que são capazes de suportar a atual procura energética. Ainda que estes equipamentos apresentem uma uma eficiência elevada, os seus custos de produção e manutenção são elevados, havendo assim uma necessidade de garantir a sua melhor condição e extensão do seu tempo de vida. A análise da condição de um transformador pode ser relacionada com propriedades mecânicas do seu papel isolante. Principalmente na sua parte ativa, este material está exposto a condições de temperatura e humidade favoráveis à sua degradação.

A partir de simulações computacionais da dinâmica dos fluidos (CFD software), para um transformador do tipo Core cujas dimensões do enrolamento são minuciosamente descritas, realizaram-se quatro simulações que permitiram compreender o impacto de diferentes variáveis, tais como a velocidade e temperatura de entrada do fluido, o calor dissipado pelos discos e o conteúdo de água ao qual o enrolamento estava exposto, na estimativa da Vida Remanescente de um Transformador de Potência.

Diferentes metodologias de cálculo foram aplicadas para estimar o conteúdo de água no papel, onde foram abordados diferentes cenários de temperaturas, tais como as temperaturas de entrada e saída do fluido, temperaturas médias, temperaturas de pontos quentes e temperaturas referentes aos componentes sólido e fluido em diferentes posições do enrolamento. Os resultados demonstraram um maior impacto da metodologia aplicada quando o material está exposto a concentrações de água no óleo mais elevadas, principalmente no fundo do enrolamento. Para além disso, permitiram realçar as limitações na utilização de curvas de equilíbrio quando o material é exposto a temperaturas elevadas.

Finalmente, dois métodos foram realizados para abordar a possibilidade de migração de água no sistema. Uma vez que temperaturas mais baixas conduzem a concentrações de água no óleo mais elevadas, a aplicação de modelos exclusivamente térmicos pode apresentar algumas limitações. Assim, realçou-se a importância de expandir os conhecimentos nas relações entre papel, água e óleo para este sistema, assim como compreender melhor o comportamento migratório da água no papel isolante, que conduz a zonas do enrolamento com valores de conteúdo de água no papel superiores.

Palavras-chave: Transformadores de Potência; Vida Remanescente; Papel Isolante; Temperaura; Humidade; Modelos Não Térmicos.

Declaration

I hereby declare, on my word of honor, that this work is original and that all non-original contributions were properly referenced with source identification.

Márcia Guedes 01 / 07 / 2019

(Student Signature) (Date of issue)

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Notation and Glossary

A	Pre-exponential factor	h^{-1}
c	Total water concentration	$\mathrm{kg} \cdot \mathrm{m}^{-3}$
d	Thickness	mm
D	Difusion	$\mathrm{m}^2 \cdot \mathrm{s}^{-1}$
D_0	Difussion coefficient	$\mathrm{m}^2 \cdot \mathrm{s}^{-1}$
$\mathrm{DP}_{\mathrm{end}}$	Degree of Polymerization of degraded paper insulation	
$\mathrm{DP}_{\mathrm{start}}$	Degree of Polymerization of new paper insulation	
E_a	Activation Energy	$\mathrm{J} \cdot \mathrm{mol}^{-1}$
k	Kinetic constant	h^{-1}
L	Loss of Life	years
P	Pressure	Pa
R	Gas constant	$\mathrm{J} \cdot \mathrm{mol}^{-1} \cdot \mathrm{K}^{-1}$
RL	Remaining Life	years
T	Temperature	K (°C)
T_0	Temperature of reference	K (°C)
v	Fluid velocity	
V	Relative Aging Rate	
wcp	Water Content in Paper	%
Wco	Water Concentration in oil	ppm
W	Moisture Content	%

Greek Letters

ρ	*Density*	$\mathrm{kg} \cdot \mathrm{m}^{-3}$
ρ_s	*Saturation vapor pressure*	Pa
τ	*Difusion time constant*	s

Indexes

i	index or counter
oxi	oxidation
hyd	hydrolysis
pyr	pyrolisys
fluid	fluid temperature profiles in the transformer winding
solid	solid temperature profiles in the transformer winding
hot spot	hot spot on the winding

List of Acronyms

CFD	Computational Fluid Dynamics
NKT	Normal Kraft Paper
TUP	Thermally Upgraded Paper
NCGA	Non-controlled Gas Atmosphere
CGA	Controlled Gas Atmosphere

1 Introduction

1.1 Framework and Project Submission

The continuous development of the scientific and technological sectors has empowered an optimization on the energy market. The electrical network distribution gets broader and more efficient over time, which leads to a faster trading and simpler industrialization, but also to a better information network and attendance to the energetic needs.

The use of Power Transformers has raised, and the research investment of materials and methods has allowed a decrease in the limits of the machine’s operation. However, progress is also achieved by adopting new methodologies and ideas. New paths showed that one of the keys to operational improvement is the ability to monitor and predict possible malfunctions on the transformer.

Different types of sensors have been incorporated into the transformer's design, that are able to collect continuous data for online or deferred analysis. Nonetheless, there is still a limitation in the variables reading. Currently, the sensors are not capable of obtaining all the variables involved in the transformer’s operation as well as providing the values in different places. Consequently, the information is obtained in specific conditions, which leads to the use of average or approximate values.

One of the specifications of a Power Transformer is the Remaining Life, which depends on physical and chemical variables, specifically on the chemical degradation of the paper insulation. This process causes a decrease of the tensile strength of the paper insulation, and thus a change in the heat transfer process, mechanical resistance and operational control of the machine. Although mathematical models have been developed to estimate the Remaining Life, the results displayed are inaccurate and unreliable, hence the need to optimize them.

1.2 Efacec

Established over 100 years, Efacec is a Portuguese Company set in the Global Energy Market, involved in several projects regarding sustainable energy production. Its work reaches more than 65 countries over four continents, and it strives to achieve new solutions in the energy, mobility, and environment sectors.

Efacec is one of the biggest Power Transformers producers (core, shell, and mobile substations), with vast knowledge in design, specifications and quality products, as information in production strategies, technologies, and technical skills.

1.3 Work Contributions

In order to guarantee the best performance, both in asset development and management, Efacec continuously invests in research and acknowledgment regarding its products. The incorporation of current sensor technology has allowed more control over the variables implied on the transformer performance, and its physical and mechanical condition. In their latest developments, they applied the finest digital solutions bringing their transformers to the technology forefront.

The work that I developed presents a contribution to the generation of knowledge for the combined behavior and influence of the two main variables involved in the degradation and damage of Power Transformers, temperature and moisture. Even though my results are academical, it allows introducing new perspectives and pathologies on the Remaining Life estimation, as the reconsideration of the thermal methodologies currently applied.

1.4 Thesis Arrangement

The thesis is organized in six main chapters following a logic line which allows a better understanding of the project developed.

After the project's presentation and the description of the entities involved, Chapter 2 presents a brief State of Art of Power Transformers, focusing on its insulation components. It approaches several theoretical concepts that allow comprehending better the work developed.

All the methodology applied to the thesis' elaboration is described in Chapter 3. It also includes a detailed abstract on the previous work developed, which worked as a fundamental base for the good performance of this thesis elaboration.

Chapter 4 presents detailed information regarding the results obtained from the analysis of temperature and moisture influence in the winding of a Power Transformer, and its main conclusions are described, posteriorly, in Chapter 5.

Chapter 6 approaches an overall assessment of the work performed and its importance for related future work.

Finally, the appendix and the annexes are also incorporated at the end of the document, where other information obtained in the work performed, and external information used are described, respectively.

2 State of the Art

2.1 Power Transformers

2.1.1 Principles and Structure

By definition, a Power Transformer is a static electrical equipment, exclusively used in electrical network systems, that transfers power by electromagnetic induction between two circuits, usually with the same frequency but different values of intensity and voltage. It can be compartmentalized in four main principles: thermal, mechanical, electrical, and vibratory (acoustic and component's vibration).[1] This device presents a very high efficiency, around 96 %, and an operation time close to 60 years.[2] In Figure 2.1 is represented a typical Power Transformer and its main parts.

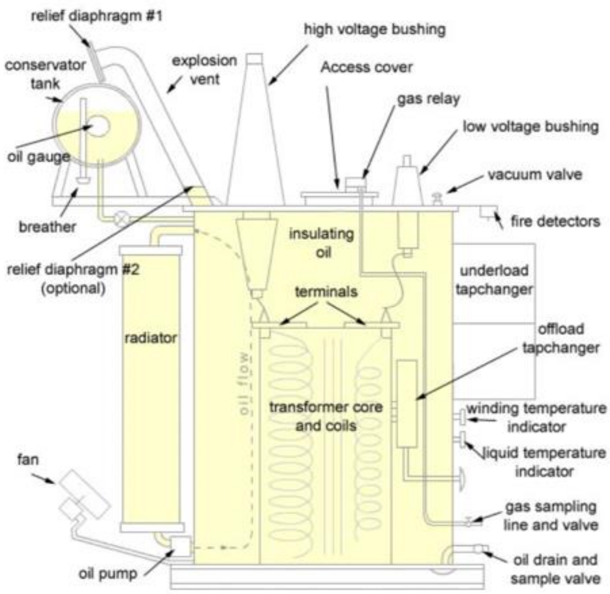


Figure 2.1 - Main parts of a typical Power Transformer.[3]

Usually, Power Transformers are grouped in two main parts: an active part, which represents the elements that are in contact with the voltage and the current, and a non-active part, which represents the ancillary components. The active part is made, primarily, by the windings, the ferromagnetic core and the insulation materials. Since these elements are exposed to a set of conditions favorable to their degradation, they are often associated with the transformers operational condition.

In Figure 2.2 is represented a transformer winding, which is mainly composed of copper wrap in paper insulation submerged in oil. The fluid crosses between each disk, from the bottom to the top, allowing heat exchange between the two insulation materials. Disks are organized according to sets, where the inlet channel changes in the axial zone. Temperature profiles can be obtained from paper or oil, even though solid temperature (paper + copper) is always superior when compared to the fluid temperature at the same position. Furthermore, temperature profiles also allowed to determine the hot spot temperature on the winding, which corresponds to the higher temperature achieved during transformer operation. This temperature is usually obtained in the last set but not on top of the winding.

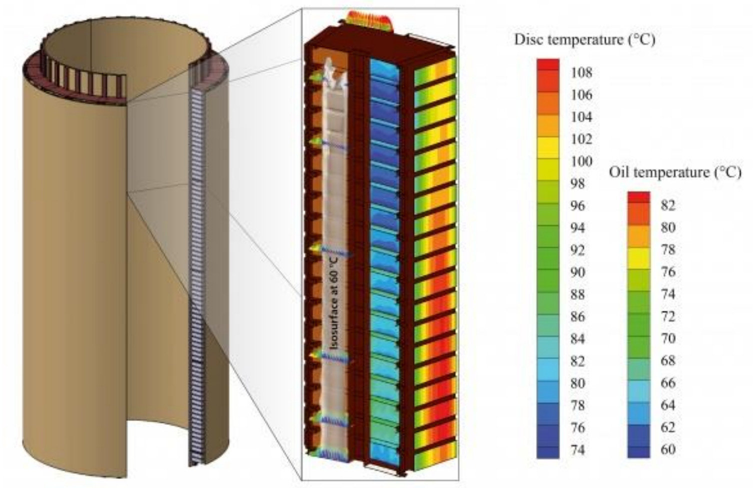


Figure 2.2 – Transformer's winding scheme, adapted. [4]

During the transformer operation, the conditions are described and influenced by a set of variables that can interfere with the transformer condition. Usually, the data is gathered by sensor technology either inside of the machine or in its surrounding. The main purpose of data's monitoring is to lower the risk of operation, allowing the transformer to operate for the most extended period under the best possible conditions. This is of the utmost importance due to the high costs of Power Transformers manufacture and maintenance.

The key variables approached in the study of paper's aging are, generally, type of paper insulation (thermally and non-thermally upgraded paper), temperature (operational, ambient and hot spot), moisture (water content), gas, insulation oil properties, and the transformer design. In Appendix A, some of these variables are described in detail.

2.1.2 Insulation Materials

Due to its dielectric properties, Transformers insulation are mostly oil and paper - both have a controlled interference with the electrical magnetic field created in the transformer operation. Both are present in the active part of the transformer and are responsible for the heat exchange process, mechanical resistance and the control of the equipment.

Oil temperature is a very important variable to closely monitor since it can also act as a cooling fluid. Temperature-related property behavior makes mineral oil the most adequate, despite presenting some issues when it comes to environmental concerns.[5]

Transformer aging, during the operational period, can be related to several situations, but the main focus is on the electric charge and the insulation materials degradation. Instead of working at the nominal power allowed, sometimes, transformers operate with very high-power values, which raises the operating temperature. As a result, insulant properties are affected, which can lead to inadequate heat exchange, the formation of hot spots, and, consequently, degradation of insulation materials.[6]

2.2 Insulant Paper and Cellulose Degradation

2.2.1 Thermally and Non-thermally upgraded paper

For transformer's manufacturer, one of the essential components is the paper, which is used as insulation material due to its dielectric properties. A dielectric material is characterized as a poor conductor of electric current since it does not have free electrons to drift through the material. In other words, a dielectric material presents the ability to be polarized and to support an electrostatic field as electrical properties.[7]

Paper insulation is mostly composed by cellulose ($75 - 85\,\%$), which is a "linear condensation polymer made by anhydroglucose joined together by glycosidic bonds", as represented in Figure 2.3, but also by hemicelluloses ($10 - 20\,\%$), lignin ($2 - 6\,\%$) and inorganics ($< 0.5\,\%$).[8] Chemically, cellulose fibers are an aggregation of molecules with different lengths, joined by hydrogen bonds involving hydroxyl groups (OH) on the adjacent molecules.[6 9]

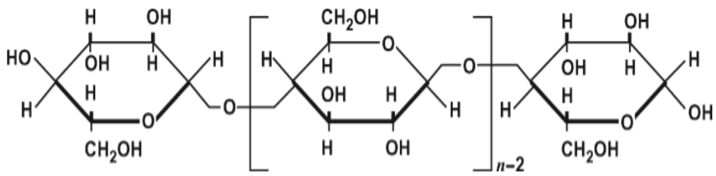


Figure 2.3 - Structural formula of cellulose polymer.[11]

The insulation paper used in the transformer manufacturing can be classified into two main categories: normal kraft paper (NKP) and thermally upgraded paper (TUP). Normal kraft paper (or non-thermally upgraded paper) is produced from unbleached softwood pulp under the sulfate process without addition of stabilizers, while the thermally upgraded paper is cellulose based paper which has been chemically modified to reduce the rate of paper decomposition.[6]

Thermally upgraded paper production can be summarized according to two main processes: modification of the cellulose chains, specifically, at hydroxyl groups (OH) by cyanoethylation and acetylation, or by the addition of chemicals that protect the cellulose from acidic by-products of aging. In other words, nitrogen compounds are added, between $1 - 4\,\%$, to work as stabilizing agents that delay cellulose degradation - these agents react with water, which results in the decrease of the amount of water in the paper.

Cyanoethylation process consists of the replacement of OH groups by stabler cyanoethyl groups, which are more resistant to water formation. Although this process reduces the number of hydrogen bridges between the molecules, leading to a decrease of mechanical strength, it causes lower water absorption and shrinkage. [6] [10] [11] [9]

One of the most critical parameters influenced by the type of paper is the operational temperature. For normal kraft paper, the maximum hot spot design temperature allowed on the winding is 98 °C, while for the thermally upgraded paper it is 110 °C. [8] At higher temperatures paper becomes brittle and incapable of withstand short circuit forces, which leads to the decrease of transformer lifetime.

2.2.2 Oxidation, Hydrolysis, and Pyrolysis

During the transformer operation, paper insulation is often exposed to conditions that lead to its degradation and, consequently, to the decrease of its tensile strength and other mechanical properties. From a chemical point of view, it is considered that the main reactions responsible in the decomposition of the insulation material are the oxidation, hydrolysis, and pyrolysis of cellulose.

At lower temperatures, cellulose oxidation is the predominant reaction for paper degradation, as described in Equation 2.1. During this process, catalyzed by hydroxyl radicals ($HO^{\bullet}$), oxygen interacts with the glucose carbon rings, which results in two acid or aldehyde groups, in addition to the release of water, carbon dioxide, and carbon monoxide. As a result, glycosidic bonds between monomers disrupt, and cellulose molecules are depolymerized releasing a molecule of water per chain split, which attacks new bonds and, consequently, causes additional splits of the cellulose chain.

$$Cellulose\ Polymer\ \rightarrow CO + CO_2 + H_2O + acids \qquad (2.1)$$

The hydrolysis of cellulose is a catalytically process related to water content. As represented in Equation 2.2, these molecules react directly with the hydrogen bonds in the cellulose chain, which leads to the break of the glucose ring and the formation of two smaller acid groups (OH), each connected to a monomer. Unlike the other reactions, in hydrolysis, there is not any gas by-product.

Of all the products derived from hydrolysis, the main problem is the lower molecular weight compounds. Due to their easier adsorption, the dielectric strength of the material insulation decreases. At high temperatures, close to 100 °C, the rate of the hydrolysis process rises quickly due to a series of dehydration reactions, leading to the formation of smaller compounds and water.

$$Cellulose\ Polymer\ \rightarrow Polymer\ chains\ of\ lower\ molecular\ weight \qquad (2.2)$$

Pyrolysis is a thermal process – it only depends on the system's temperature. As represented in Equation 2.3, its main products are mainly gas components, such as carbon dioxide, carbon monoxide, and hydrogen, water, furan compounds, and mud.[12]

$$Cellulose\ Polymer\ \rightarrow Polymer\ chains\ of\ lower\ molecular\ weight + CO + CO_2 + H_2O + furan\ compouns \tag{2.3}$$

During these reactions, the break of the cellulose chains results in the decrease of the degree of polymerization, which describes the average number of the monomer or repeating unit in the polymer chain. This specification is usually related to several paper mechanical properties, such as tensile strength, elongation and folding endurance, as represented in Figure 2.4.[6 8 12]

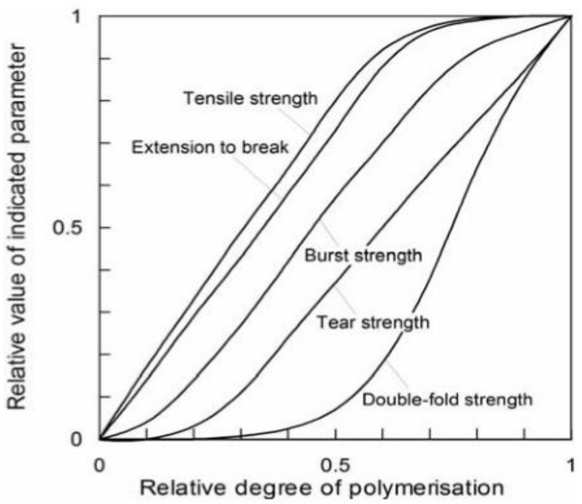


Figure 2.4 - Relative decrease of mechanical parameters with a decrease of DP *of cellulose paper.*[8]

Although these reactions co-occur, each one is accelerated with heat as temperatures increase and can be described by the Arrhenius Equation. According to different studies, the activation energy for each reaction is, approximately, $80 - 210\ \mathrm{kJ\ mol^{-1}}$ for oxidation, $111\ \mathrm{kJ\ mol^{-1}}$ for hydrolysis and $238\ \mathrm{kJ\ mol^{-1}}$ for pyrolysis. Even though the Activation Energy and the pre-exponential factor depend on the type of reaction and, in theory, the correct equation should describe the behavior of all reactions, as shown in Equation 2.4. However, in real analysis, it has used a single Arrhenius Equation, as represented in Equation 2.5.[13 14 15]

$$k = A_{oxi}\, e^{-\frac{E_{a,oxi}}{R\,T}} + A_{hyd}\, e^{-\frac{E_{a,hyd}}{R\,T}} + A_{pyr}\, e^{-\frac{E_{a,pyr}}{R\,T}} \tag{2.4}$$

$$k = Ae^{-\frac{E_a}{R\,T}} \tag{2.5}$$

Where A is the pre-exponential $(\mathrm{h^{-1}})$, $\mathrm{E_a}$ the Activation Energy $(\mathrm{J\ mol^{-1}})$, T the temperature of the hot spot in the windings (K) and R the molar gas constant $(8.314\ \mathrm{J\ mol^{-1}K^{-1}})$.

The pre-exponential factor and the Activation Energy used in the empirical equation depends on different variables such as the type of paper, the moisture present in the system and the oxygen levels inside of the transformer. In Table 2.1 is displayed the adopted values according to these variables in different calculations.

Table 2.1 - Activation Energy and pre-exponential factor values according to the operation conditions of the transformer [6]

			A / h^{-1}		
	Gas Atmosphere*	E_a / kJ mol^{-1}	$Moisture = 0.5$ %	Moisture = 1.0 %	Moisture = 1.5 %
Normal kraft paper	Controlled	128	4.1×10^{10}	1.5×10^{11}	4.5×10^{11}
	Non-controlled	89	4.6×10^{5}	4.6×10^{5}	4.6×10^{5}
Thermally upgraded paper	Controlled	86	1.6×10^{4}	3.0×10^{4}	6.1×10^{4}
	Non-controlled	82	3.2×10^{4}	3.2×10^{4}	3.2×10^{4}

*The control of the gas atmosphere interfers with the oxygen levels present in the system.

Another concern to consider is the polymer's structure. Since different components compose the paper, the material is characterized in amorphous and crystalline regions. In the polymer, cellulose chains create a fiber structure that is associated with both amorphous and crystalline regions, which can be related to the mechanical strength of the material. However, hemicelluloses and lignin are associated with amorphous regions, which leads to different rates of degradation. On the one hand, amorphous regions show higher degradation rates because of the presence of weak bonding links and more reactive areas.[16] [17] On the other hand, crystalline regions of cellulose present lower degradation rate because of the high degree of order within the cellulose chain, which causes a limited access of aging agents and an increase of strength induced by crystallinity.[8]

2.3 Water Paper Systems

2.3.1 Water adsorption and cellulose insulation

One of the problems faced in a transformer operation is the amount of water present in the machine, which is responsible for the damage of the equipment (such as corrosion) and cellulose degradation. There are, mostly, three reasons that justify the presence of water in a Power Transformer: residual moisture, ingress from the atmosphere, or cellulose degradation.

During manufacture, the transformer goes through several drying processes, including the impregnation's process of the materials in oil. However, the amount of water is never totally removed, since the process is highly complex - between the processes, materials are exposed to atmospheric conditions, usually uncontrolled. Therefore, for a new transformer, there is already a certain amount of water present, usually between $0.5\ \% - 1.0\ \%$, which continuously increases over time. Even though water is under a vapor state, it is absorbed by the oil and, posteriorly, absorbed by the paper insulation, leading to its degradation. This is a result of the attraction between the water and the oil, due to the presence of aromatic compounds or impurities. Finally, the last action responsible for the presence of water is the degradation of the insulation material, which, as previously mentioned, goes through specific chemical reactions in which water is one of the by-products.

The water measurement is a variable that presents high uncertainty associated, mostly because there are four conditions in which water can be present in the transformer: vapor, free water in capillaries, absorbed free water and absorbed in surfaces. According to IEEE Std C57.106 – 2002, maximum values for the water concentrations in the transformer are stipulated in order to guarantee the proper operation of the transformer, as represented in Table 2.2. Since transformers category influences its operational conditions, the maximum values of water concentration in oil are stipulated depending on the temperature at which the material is exposed. When such limits are exceeded, the transformer must be stopped, and it is usually exposed to processes for treating the oil by removing water and other impurities.[18 19]

Table 2.2 - Maximum water content in oil and paper for different voltage ratings [18]

Transformer rated voltage / kV	Maximum water content in oil / ppm			Equivalent water content in the paper / %
	50 ℃	60 ℃	70 ℃	
≤ 69	27	35	55	3.00
69 − 230	12	20	30	2.00
≥ 230	10	12	15	1.25

Through diffusion processes, water present in the transformer migrates to the insulation material and, therefore, adsorption of water to cellulose materials occurs. This process is fast, requiring lower activation energy as well as the amount of energy involved. The opposite mechanism, desorption, is very slow and requires high amounts of energy to break the bonds. In Figure 2.5 is represented the isotherms for the adsorption and desorption of water in cellulose materials, which represents the relationship between the amount of water in the cellulose materials and the amount of water vapor pressure or relative saturation, in equilibrium.

The absorption process occurs due to the presence of polar glucose chains, that have the ability to dissolve high quantities of water in different states, such as, strongly bound to $OH - groups$ of glucose chains by hydrogen bonds, weakly bound by Van Der Waals bonds and water molecules formed due to the multiple layers attracted to glucose chains and held by capillary forces. However, it is very important to consider that these isotherms represent a behavior related to the system in equilibrium, which barely ever happens during the transformer operation. [19 20]

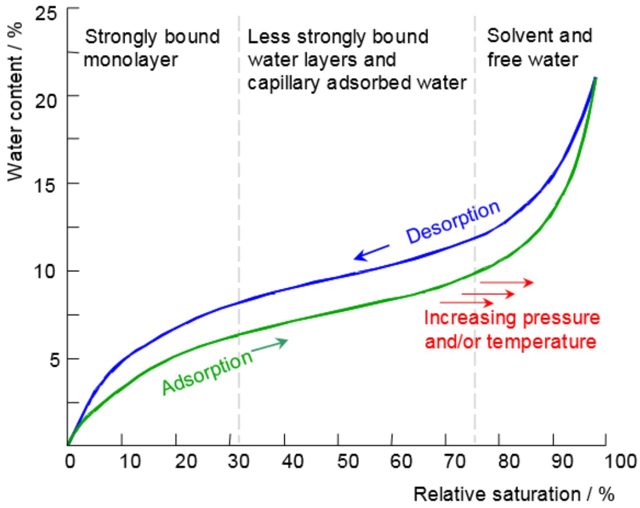


Figure 2.5 - General moisture adsorption and desorption isotherms with the influence of water bonds.[19]

Finally, during water migration, not only the climatic conditions are essential but also the dimensions of the paper insulation, especially its thickness. Most of the paper insulation is considered as "thick structures" and, although it can absorb a substantial amount of water, they play a minor role in water migration, due to its high thickness and low surface areas. "Thin cold structures" operate at oil temperature and are the highest contributor to the water migration process. Due to the ability to contain high amounts of water during a small period, the water migration happens to satisfy the natural balance (equilibrium), in which the driving forces are the heat and the moisture potential. At last, "thin hot structures" are the ones operating at temperatures close to the conductor temperature, and, as a result, they are the materials that present faster water migration. However, the amount of water in these materials is lower than "thin cold structures", thus its contribution is small. Besides in the interaction mechanisms between water and cellulose insulation, it is also important to consider the role of the oil in this systems. This cooling fluid also retains a small percentage of the total amount of water, and it slows down the moisture coming from atmospheric air.[19]

2.3.2 Moisture Content

Within the variables involved in the transformer aging process, the measurement of water content is one of the most difficult to determine accurately. Although oil analysis can determine the average concentration of moisture, most of the water content is present in the paper, since cellulose presents hydrophilic nature while oil presents hydrophobic nature. Therefore, water content in paper is a problem since the current sensors technology can only performed measurements in the oil and not on the paper.[21]

Moisture in the paper (water content in paper) is obtained using moisture equilibrium oil-paper systems. These results present a very high uncertainty because not only are these curves obtained in laboratory conditions but also because the equilibrium in transformer operation rarely happens. Usually, oil-paper equilibrium curves used in moisture analysis are Oommen's Curves, which consider the same temperature to the relative saturation of oil and paper, as represented in Figure 2.6.

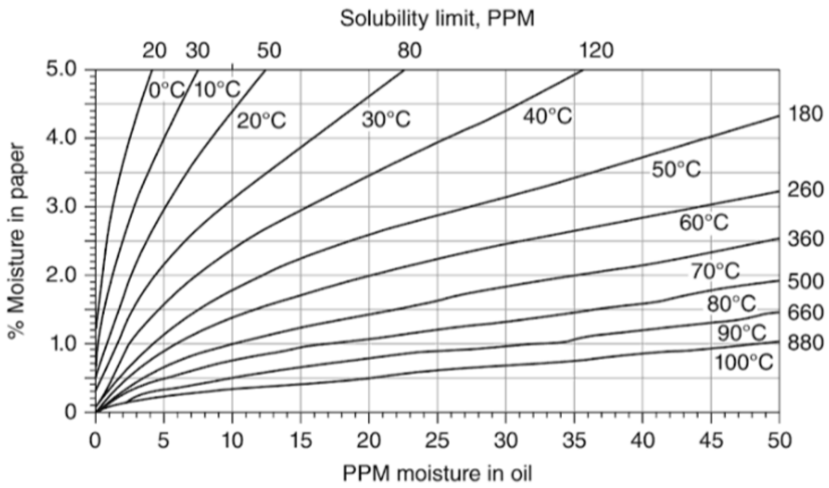


Figure 2.6 – Oommen's curves for low moisture region of moisture equilibrium for paper-oil system.[22]

Indirect methods can also be adopted to understand moisture dynamics. Since moisture migration is a process mostly influenced by heat transfer and mass diffusion, mathematical models have been developed using Fick's 1st Law for diffusion to describe it. Generally, Fick's Law can be expressed by Equation 2.6, where D is the diffusion coefficient in the solid insulation and c the total local moisture concentration.

$$\frac{\partial \mathrm{c}}{\partial \mathrm{t}} = \frac{\partial}{\partial \mathrm{x}}\left(D \frac{\partial \mathrm{c}}{\partial \mathrm{x}}\right) \tag{2.6}$$

Since water in the transformer is not exposed in the same conditions, diffusion coefficients for liquid and vapor water should be different. However, it is difficult to determine them separately, so the total concentration of moisture is considered.

Regarding the diffusion coefficient, this parameter can be estimated through Equation 2.7, where T is the absolute temperature (K), T_0 the reference temperature of $298\,\mathrm{K}$, k a dimensionless parameter, and D_0 $(\mathrm{m}^2 \cdot \mathrm{s}^{-1})$ and E_a $(\mathrm{J} \cdot \mathrm{mol}^{-1})$ parameters that depend on the type of paper and the system relationship (free oil or impregnated oil). [23]

$$D = D_0\, e^{kc + E_a\left(\frac{1}{T_0} - \frac{1}{T}\right)} \tag{2.7}$$

Other mathematical models developed for the estimation of the diffusion coefficient are represented in Equation 2.8, where it is used the moisture content percentage, W, and the saturation pressure vapor (Pa), $\mathrm{p_s}$, for estimation. [19]

$$D = \frac{10.64 \times 10^{-12}\, p_s\, e^{0.52\, W}}{3600} \tag{2.8}$$

At last, a rough analysis can be made to the diffusion time constant for moisture (s),τ, using Equation 2.9, where d is the insulation thickness (m) and D the diffusion coefficient $(\mathrm{m}^2 \cdot \mathrm{s}^{-1})$. This estimation presents very low accuracy and cannot be considered in continuous models because it frequently changes under different conditions, such as temperature, porosity and concentration. [19 22]

$$\tau = \frac{d^2}{\pi^2 D} \quad (2.9)$$

2.4 Aging of Paper Insulation and Remaining Life

Among others, the Remaining Life (RL) of a Power Transformer is a crucial characteristic to understand and evaluate the product. It can be calculated according to Equation 2.10, in which is considered most of the variables approached before, such as, temperature, water concentration in oil, and the degree of polymerization of the paper insulation. However, this algorithm assembles significant uncertainty in its calculations. The result is based on specific values for each variable, and the transformers' operation rarely works on those same conditions. For this reason, there is a constant search for knowledge and predictive methods to evaluate the Remaining Life (years) of a Power Transformer.[17 24 25]

$$\mathrm{RL} = \frac{\frac{1}{\mathrm{DP_{end}}} - \frac{1}{\mathrm{DP_{start}}}}{A \times 24 \times 365} e^{\frac{E_a}{R\,T}} \quad (2.10)$$

The calculation of the Remaining Life of a Power Transformer has as main parameters the type of insulation and the kinetics of the degradation process. Therefore, it is considered that, regardless of the type of paper, the degree of polymerization of the new insulation paper is around 1200, which decreases over time, in an exponential behavior. Although the degree of polymerization can be calculated by using viscosimetry, it is an invasive method, which forces the transformer to stop in order to collect the sample of the insulation material.

Regarding the kinetics of the degradation process, the activation energy, and the pre-exponential factor depend on the physical, mechanical, and chemical variables, as mentioned above in Table 2.1.

The Remaining Life of a Power Transformer can also be estimated through the $\mathrm{Loss\ of\ Life}$ of the paper insulation. This method considers two parameters, the type of paper insulation and the temperature to which it is exposed. Therefore, Equation 2.11 and Equation 2.12 allow calculating the Relative Aging Rate (V), for normal kraft paper and thermally upgraded paper, respectively.

$$V_{\mathrm{NKP}} = 2^{\frac{T-98}{6}} \quad (2.11)$$

$$V_{\mathrm{TUP}} = e^{\frac{15000}{110+273} - \frac{15000}{T+273}} \quad (2.12)$$

This calculation compares the aging of a specific type of paper exposed to a given temperature with the aging at the limit temperature stipulated for each insulation paper. After that, the Loss of Life, L, is calculated through Equations 2.13 and 2.14, depending on whether it is in the integrative or derivative method.[6]

$$L = \int_{t_1}^{t_2} V\, dt \quad (2.13)$$

$$L \approx \sum_{n=1}^{N} V_n \times t_n \quad (2.14)$$

At last, another method to study the Remaining Life of a Power Transformer is through a thermal model, as represented in Equation 2.15, where the only parameter is the temperature at which the insulation material is exposed, where A and B are constants and T the temperature of the hottest spot in the windings.[26]

$$Per\ unit\ life = A\, e^{\frac{B}{T+273}} \quad (2.15)$$

3 Materials and Methods

3.1 Previous Development

In 2018, at EFACEC, the behavior of two variables directly involved in the degradation of the transformer, temperature, and moisture, were studied.[27] Although both paper and oil contribute to the proper performance of the equipment, it is believed that the paper state is a much more concerning subject than oil. When oil loses its properties (such as density, thermal conductivity, viscosity, among others), there are treatments available to regenerate them, even though not completely. In some cases, oil replacement is also considered as a solution.

The following work described was performed by Leonardo Rodrigues during its thesis development. The results allowed a solid and well-structured starting point of this thesis.

3.1.1 Winding Geometry

From Computational Fluid Dynamic (CFD) Simulations, a 2D asymmetrical model was used to represent a Core-type winding with specific geometry, provided by Efacec, in order to understand the distribution of the temperature along the winding. The winding is composed of six sets of nine disks, as represented in Figure 3.1. The fluid flows upwards, between the disks, which justifies the higher temperatures at the top of the transformer as well as the lower temperatures at the bottom.

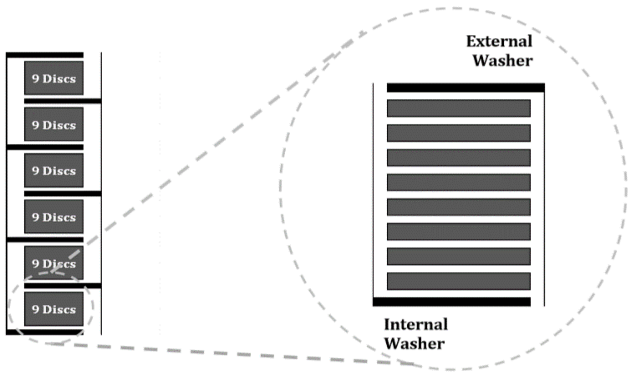
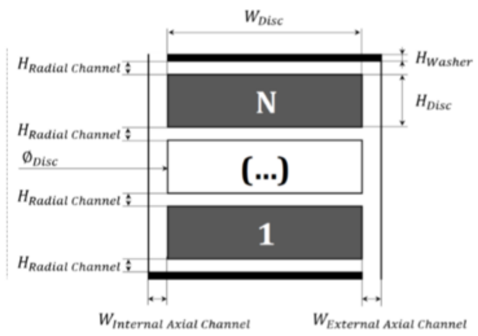


Figure 3.1 - Schematic representation of a) the total winding; b) one set of the winding.[27]

Transformers are designed to require certain characteristics to work for a specific operation, which infers a project with precise detail regarding its geometry and features. Therefore, the work was developed for a cylindrical winding, with specific characteristics and dimensions, as represented in Figure 3.2.



Dimensions / mm	
$Ø_{Disc}$	735.00
H_{Disc}	17.30
W_{Disc}	58.14
H_{Washer}	2.00
$W_{(Internal\ Axial\ Channel)}$	6.00
$W_{(External\ Axial\ Channel)}$	6.00

Figure 3.2 - Schematic representation of the winding and its dimensions.[27]

The disks have all the same dimensions along the winding, unlike the fluid circulation channels. All axial channels have the same dimensions in the entire winding, while the radial channels change depending on the set. Radial channels dimensions are described in Table AA.1, in Annex A.

As represented in Figure 3.3, there are two main parts in the winding simulation, the solid (pink) and the fluid (blue). The fluid represents the oil insulation that circulates along the winding, while the solid represents the copper wrapped in paper insulation.[27]

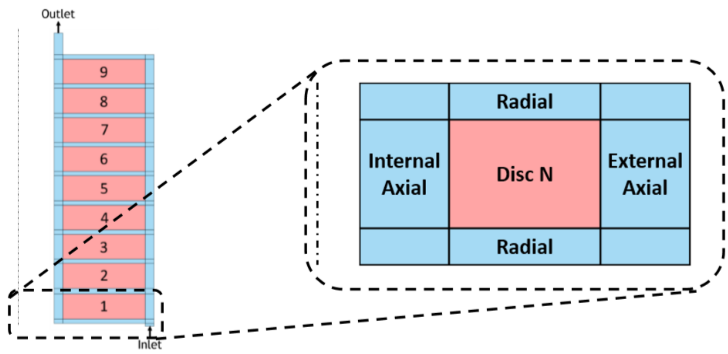


Figure 3.3 - Schematic representation of the solid and fluid components in the winding.[27]

3.1.2 Numerical Analysis and Assumptions

When a transformer is exposed to high amounts of energy, its temperature increases considerably, which leads to a change in its operation, namely the activation of pumps and fans installed in the equipment. The research to understand how the temperature distribution occurs in the winding of a Power Transformer was made according to four simulations, whose parameters are described in Table 3.1. The variables analyzed in the simulations were the inlet velocity of the fluid (Simulation 2), the inlet temperature of the fluid (Simulation 3) and the heat losses on the disks (Simulation 4), all compared to a standard condition (Simulation 1). The heat loss on each disk used in all the simulations is represented in Annex A, Table AA.2.

Table 3.1 - Parameters used in each of the simulations performed, adapted [27]

Simulation	1	2	3	4
Inlet fluid velocity	$v_1 = 0.1\ \mathrm{m\ s^{-1}}$	$v_2 = 0.2\ \mathrm{m\ s^{-1}}$	$v_1 = 0.1\ \mathrm{m\ s^{-1}}$	$v_1 = 0.1\ \mathrm{m\ s^{-1}}$
Inlet fluid temperature	$T_{inlet\ fluid,1} = 30\ ℃$	$T_{inlet\ fluid,1} = 30\ ℃$	$T_{inlet\ fluid,2} = 40\ ℃$	$T_{inlet\ fluid,1} = 30\ ℃$
Disc heat source	Set 1	Set 1	Set 1	Set 2

All simulations described were performed according to some considerations. To start, the transformer winding was in steady-state - the distribution of temperatures in the winding is kept over time. Consequently, the calculations may be subject to some degree of uncertainty, and the results obtained are set to a specific range of transformer operation. Furthermore, the simulations performed did not consider the moisture distribution on the winding. The calculation did not include the dynamic behavior of the temperature and the moisture simultaneously, but only the influence of temperature. Therefore, the amount of water over the winding was assumed to be the same as the amount in the inlet fluid. Although it is a significant limitation, in a real case, it is quite frequent. Measuring the amount of water along the winding is not easy, given the sensor technology available. Thus, an alternative to considering the amount of water present in the transformer may consist of measuring the value in a particular region and assuming a close approximation value for all the winding.

In contrast, the measurement of temperature does not have the same difficulties, since it is possible to measure the temperature of the oil in several places of the equipment. According to Standard IEC, 60814, $20\ \mathrm{ppm}$ is the maximum value accepted for water concentration during the operation of the transformer. If it exceeds such value, the operation must come to a halt.

During all simulations, there is no distinction between the paper and the copper. Even though copper always presents a higher temperature than paper, since they present different natures (metal and polymer), the temperature data obtained represents a temperature of the mix of those two materials.

Finally, the calculations of the water content in the paper along the winding were performed according to the Oommen's equilibrium curves. It represents one of the most critical limitations since during the transformer operation equilibrium state is rarely achieved. Therefore, the water content in the paper along the winding was calculated through the temperature obtained in the simulation for each disk and the water concentration in the inlet fluid.[27]

3.2 Remaining Life Estimation

The purpose of the work was to understand the influence of temperature and moisture in paper degradation as well as comprehend the limitations of thermal models in the estimation of the Remaining Life of Power Transformers. Through Equation 2.10, the Remaining Life for different scenarios was estimated, where the values of the parameters considered are described in Table 3.2.

Table 3.2 –Parameters used in the estimation of the Remaining Life

Parameters			
$\mathbf{DP_{start}}$	1200	$\boldsymbol{A_{dry}}$ / $\mathbf{h^{-1}}$	4.60×10^5
$\mathbf{DP_{end}}$	200	$\boldsymbol{A_{\mathbf{not\ dry}}}$ / $\mathbf{h^{-1}}$	$f(moisture)^*$
$\boldsymbol{E_{a,dry}}$ $(\mathbf{J.mol^{-1}})$	89 000	$\boldsymbol{R}$ / $\mathbf{J.mol^{-1}}.\boldsymbol{K^{-1}}$	8.314
$\boldsymbol{E_{a,not\ dry}}$ $(\mathbf{J.mol^{-1}})$	128 000		

* In this case, A-value depends on the amount of moisture present in oil, which is explained above.

3.2.1 Temperature Distribution

As a result of the previous work performed, temperature distribution along the winding was obtained for the four simulations mentioned above, which is represented in Figure B.1, in Appendix B. These values correspond to the average temperatures on each of the four zones (axial and radial), for both solid and fluid compounds.

Focusing on the range of the temperature in the simulations, the original data obtained is not appropriate when the transformer Remaining Life is evaluated. Usually, during the transformer operation, the temperatures are between $80\ °C$ and $120\ °C$. As an alternative to overcome this problem, a uniform increment of 50 °C was applied to both temperature profiles (solid and fluid) obtained along the winding, whose results are described in Figure 3.4. This escalation leads to a range of 80 °C and 113 °C, as lower and higher temperatures, which are closer to real operational temperatures.

Through the data represented in Figure 3.4, it was possible to verify that for each simulation performed, different temperature behaviour was found. However, the solid temperature is always higher than the fluid temperature at the same position, which is a very important detail since it describes a real condition. Since solid represents copper wrapped in the paper it represents a combined material made of polymer and metal, and metal usually achieves very high temperatures.Another important information collected through the temperature profiles is its variation depending on the position on the winding. Results show that radial zones present always higher temperatures than axial zones.

As a result, the transformer Remaining Life analysis is carried out using the temperature profiles of the bottom radial zone since not only presents the higher temperature range but also includes the hot spot temperature values obtained for each simulation performed.

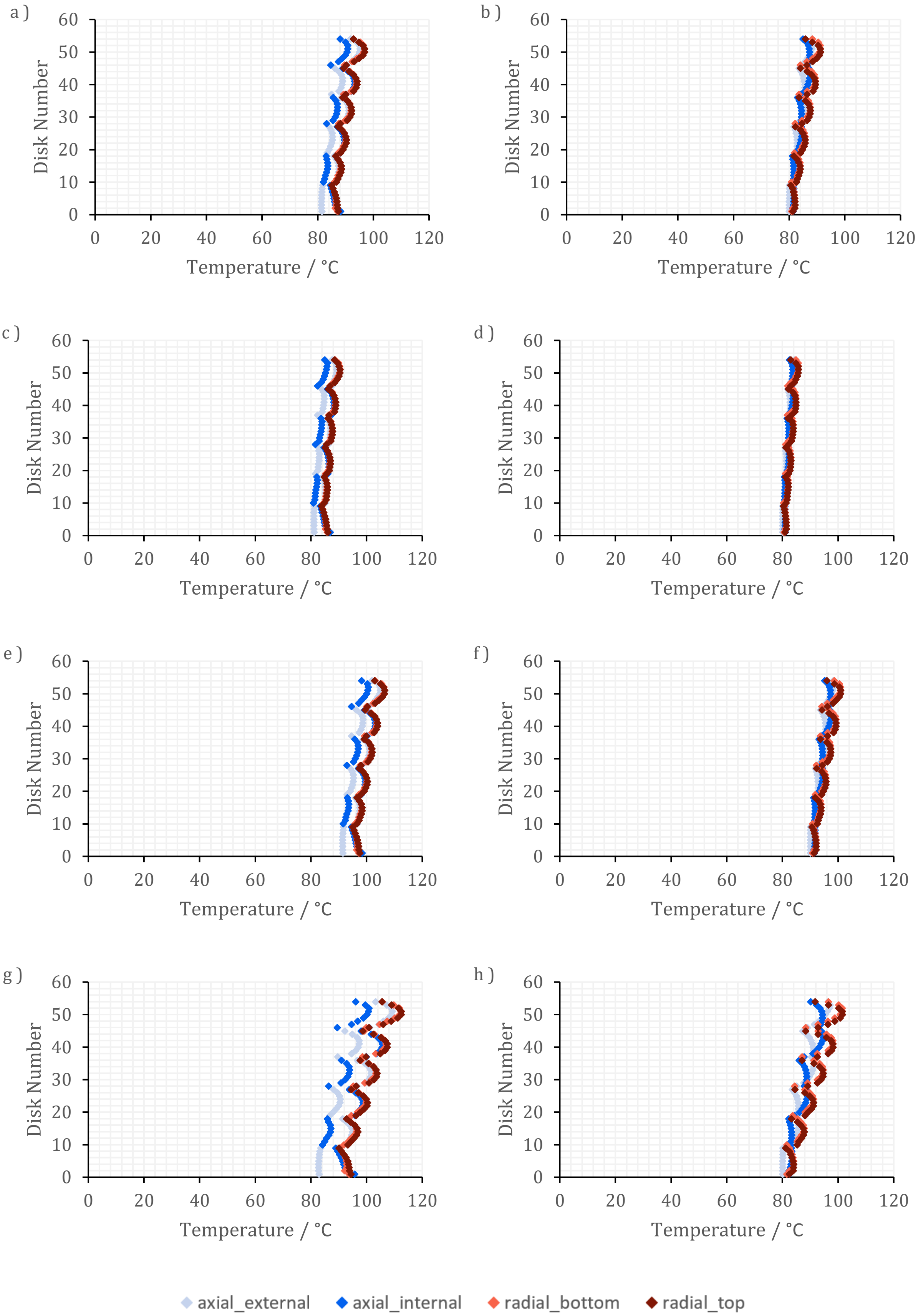


Figure 3.4 -Temperature profiles in the transformer winding for: a) solid in Simulation 1; b) fluid in Simulation 1; c) solid in Simulation 2; d) fluid in Simulation 2; e) solid in Simulation 3; f) fluid in Simulation 3; g) solid in Simulation 4; and g) fluid in Simulation 4.

3.2.2 Temperature and Moisture Impact

Of the several parameters involved in the equation to estimate the Remaining Life, the pre-exponential factor and the activation energy are the only ones that present a possible correlation with the moisture present in the winding.

The values represented in Table 2.1 regarding normal kraft paper allowed to create a function able to estimate the pre-exponential factor depending on the percentual amount of moisture, as represented in Figure 3.5. The regression function is described in Equation 3.1, with a determination coefficient of one. Although the value for the non-controlled gas atmosphere case did not incorporate the correlation, that case was considered as a parallel situation, where the Remaining Life estimation does not involve the moisture as a variable.

$$A = 1.367 \times\ 10^{10}\,\mathrm{wcp}^{\ 2} + 8.167\ \times\ 10^{10}\,\mathrm{wcp} - 3.250\ \times\ 10^{9} \qquad (3.1)$$

As represented in Eqaution 3.1, the pre-exponetial factor depends on the water content in paper, which was estimated from the Oommen's equilibrium curves though the the temperature profiles and the moisture in the oil of the system, in the previous work developed.

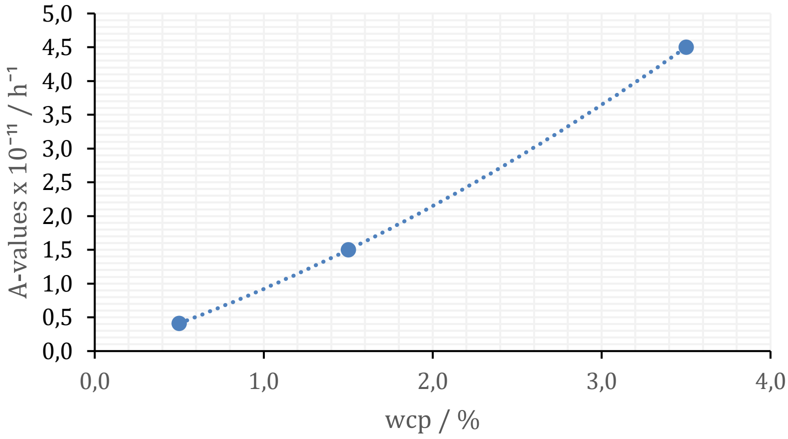


Figure 3.5 - Representation of A-values depending on moisture percentage in the paper.

In order to understand the impact of temperature and moisture on the winding, the study was grouped according to seven different cases, where the method applied to calculate the water content in paper is different as well as the pre-exponential factor.

For all the cases approached, the water content in paper was estimated through the Oommen's equilibrium curves, as mentioned in Figure 2.6. The estimation was performed using temperature values and water concentration in oil of $5, 10, 15$ and $20\ \mathrm{ppm}$, for all the four simulations performed.

In Case 1, the water content in paper was estimated using the temperature obtained in each disk, which was represented in Figure 3.4. The estimation is performed using solid and fluid temperature profiles, separately. Currently, transformers are incorporated with sensor technology during its manufacture. The use of fiber optic allows to collect temperatures in different positions of the winding, during the operation of the equipment.

In Case 2 it is used the temperature of the inlet fluid. It corresponds to one of the lower temperature values present in the transformer operation since, in that position, the fluid has not yet performed heat exchanges with the solid component.

Case 3 uses the outlet fluid temperature. Although it is not the highest temperature present in the transformer winding during its operational time, it is a very important temperature. If its values are very high, it can interfere with the inlet fluid temperature in the next fluid circulation.

In Case 4, the water content in paper is estimated through the hot spot temperature. It correspondes to the highest temperature achived in the transformer winding, which usually describes the position with higer paper degradation. The calculations performed for this case used the hot spot temperature values represented in Appendix B, Table B.1.

Case 5 uses the average temperature along the winding. In several real situations, the average temperatures are used to assess the transformer condition, even though it is associated with a high inaccuracy.

For all the cases described above, after the water content in paper is estimated, it is estimated the pre-exponetial factor. For that, it is used the water content in paper and the regression function represented in Equation 3.1. Finally, the Remaining Life of the Power Transformer is calculated through Equation 2.10, using the operation temperature obtained along the winding for each component, solid and fluid. Therefore, it is possible to analyze and compare the behavior of each case using different temperature profiles. A very detailed description of the calculations performed in presented in Appendix C.

Unlike the cases above, Case 6 presents a Remaining Life estimation using both solid and fluid temperature profiles. According to Oommen's equilibrium curves, these are design assuming that both components are at the same temperature in the system. However, Figure 3.4 showed that solid temperature is always higher. Therefore, for Case 6, the water content in paper is estimated only through the fluid temperature in each position along the winding, and the pre-exponential factor using Equation 3.1. After that, the Remaining Life estimation uses only the solid temperature in each position as the operational temperature. Thus, the Remaining Life estimation is performed using both component temperature profiles.

Finally, Case 7 represents the transformer analysis when the equipment is exposed to a non-controlled gas atmosphere. In this situation, the Remaining Life is estimated through a constant pre-exponential factor, which is represented in Table 2.1, and the temperature profiles for both solid and fluid along the winding as the operational temperature. Furthermore, for this case the activation energy value used is different of all the other cases, which is also described in Table 2.1. A very summarized description of all the methodologies described is represented in Table 3.3.

Table 3.3 – Summarized description of the methodology applied

Case	Temperature used in wcp estimation	Regression Function (Equation 3.1)	Operational Temperature used in Equation 2.10
1	$T_{x,solid}$ $T_{x,fluid}$	✓ ✓	$T_{x,solid}$ $T_{x,fluid}$
2	$T_{inlet\ fluid}$	✓	$T_{x,solid}$ $T_{x,fluid}$
3	$T_{outlet\ fluid}$	✓	$T_{x,solid}$ $T_{x,fluid}$
4	$T_{hotspot}$	✓	$T_{x,solid}$ $T_{x,fluid}$
5	$T_{average}$	✓	$T_{x,solid}$ $T_{x,fluid}$
6	$T_{x,fluent}$	✓	$T_{x,solid}$
7	$T_{x,solid}$ $T_{x,fluid}$	× ×	$T_{x,solid}$ $T_{x,fluid}$

3.2.3 Assessment of the Temperature and Moisture in a winding

Even though the presence of moisture is studied in different cases through the water concentration in oil, the calculations made assume the same water concentration value for the entire winding. In other words, although the presence of moisture is a variable when the inlet water concentration changes, for a winding exposed to a specific condition, it counts as a parameter. Therefore, in order to analyze the moisture as a variable along the transformer winding, a parallel study was made. To performed this research, results from Simulation 1 for an inlet water concentration of $5\ \text{ppm}$ was used.

Among all the cases studied, Case 1 was the one selected to perform this study since it considers not only the presence of moisture but also its calculation use the higher quantity of temperature values, which can decrease the associated error in the estimation. Since paper temperature is always higher than oil temperature at the same point, the study was performed using the solid temperature profile along the winding.

Two different methods were adopted to perform the assessment of moisture as a variable along a winding exposed to a set of specific conditions, still considering the calculations in steady state. Through the same logic line as the one explained in the fist part, both methods are performed using the same variables involved in the Remaining Life estimation of Power Transformers. However, for this study, the input and output variables change. In other words, the input variable now is the Reamining Life, and the output variable is the water concentration in oil, which the values used in the Simulations were $5, 10, 15$ and 20 ppm.

The first method, which is defined as Method A, was based on the study of the temperature variation for a same Remaining Life value. In other words, the winding was forced to present the same Remaining Life value obtained at each position in Case 1 of Simulation 1, but at a lower temperature. In Figure 3.6 is described the process flow adopted, in detail.

Through Figure 3.4, solid temperature profiles along the transformer winding show that maximum temperature gradient obtained is 11.7 ℃ - variation between the maximum and minimum temperature obtained for Simulation 1. Therefore, the decrease of temperature along the transformer winding was 5 ℃.

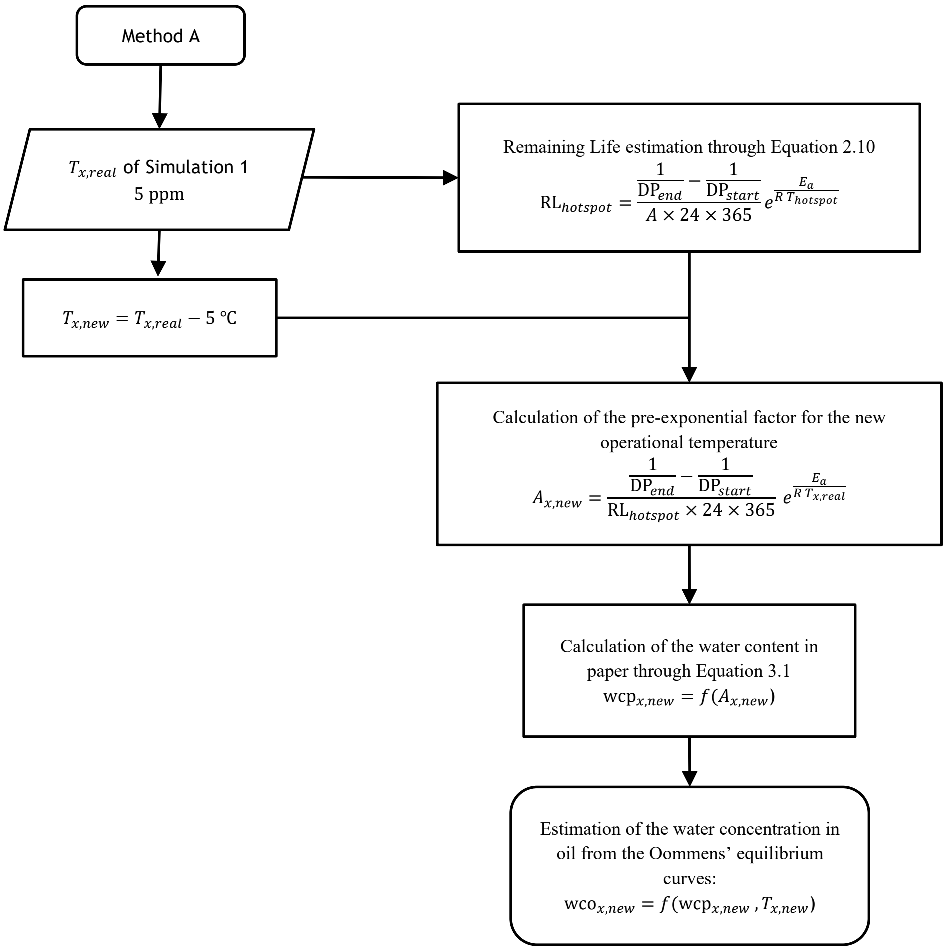


Figure 3.6 - Process flow of Method A.

The second method, Method B, is related to the hot spot temperature, which corresponds to the lower value of the Remaining Life estimation. Like the previous method, this one also consisted of toggling the inlet and outlet variables involved in Equation 2.10. However, in Method B, the complete winding was forced to present the same Remaining Life as the one obtained in the hot spot zone. The process flow adopted is described in Figure 3.7.

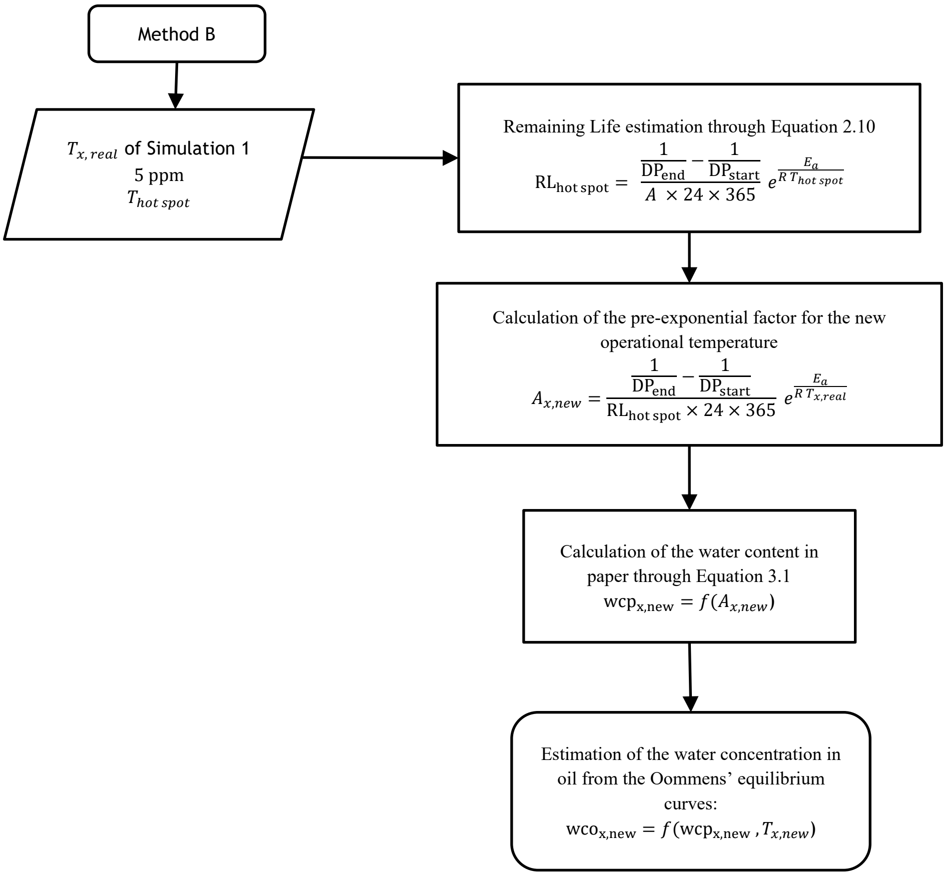


Figure 3.7 – Process Flow of Method B.

It is imperative to retain that the study developed does not present a high level of accuracy on the moisture reading. The study is merely intended to demonstrate that perhaps for lower temperatures and, consequently, higher moisture values, it is possible to have winding zones with a lower Remaining Life. The moisture obtained is calculated from interpolations through the Oommen's equilibrium curves, which are represented in Figure 2.6.

4 Results and Discussion

4.1 Remaining Life Estimation along the winding

Figure 4.1 represents the results of the Remaining Life estimation along the winding for Simulation 1, for both solid and fluid temperatures, for $5, 10, 15$ and $20\ \text{ppm}$ as water inlet concentration in oil.

Through an overall analysis, results indicate that Remaining Life estimation using the solid (paper + coper) temperature profiles show lower values when compared to results from the fluid (oil) temperature profiles. By comparing Figure 4.1a and 4.1e, which represent the transformer winding exposed to the same operation conditions (in this case $5\ \text{ppm}$ for inlet water concentration in oil), the results show a difference between the Remaining Life values through solid and fluid temperature profiles of almost $40\ \text{years}$. These outcomes were expected since solid profiles present higher temperature values, which leads to a higher degradation of cellulose insulation and, consequently, a lower value of the Remaining Life of a Power Transformer.

Nonetheless, this variation gets less pronounced when the values of inlet water concentration get higher. As demonstrated by Figure 4.1d and 4.1h, for $20\ \text{ppm}$, the variation between the results of the Remaining Life through solid and fluid temperatures is close to $10\ \text{years}$, which is considerably lower when compared to $40\ \text{years}$. Therefore, the impact of solid and fluid temperatures in the Remaining Life estimation is more pronounced when moisture is considered as a variable, especially at low inlet water concentrations.

For a transformer winding exposed to the same solid temperature profile, Remaining Life values are lower for higher water concentrations. When compared the results from Figure 4.a and 4.d the Remaining Life values present a variation of 70 years, approximately. These results are very important since it allows to verify that the moisture present in the system is been considered as a variable, and has an impact in the Remaining Life estimation. It is important to always take into consideration that this component acts as a catalyst for the predominant reaction responsible for the degradation of insulating paper.

The methodologies applied in the estimation of water content in paper show that Case 4 ($T_{hotspot}$) presents the highest Remaining Life values, regardless of the temperature profiles and the water inlet concentration, and it is always followed by Case 3 ($T_{outlet\ fluid}$). Since Case 4 estimates the water content in paper through the highest temperature obtained in the transformer's winding, this leads to lower values of water content in paper. As a consequence, A-values calculated are lower and the Remaining Life higher.

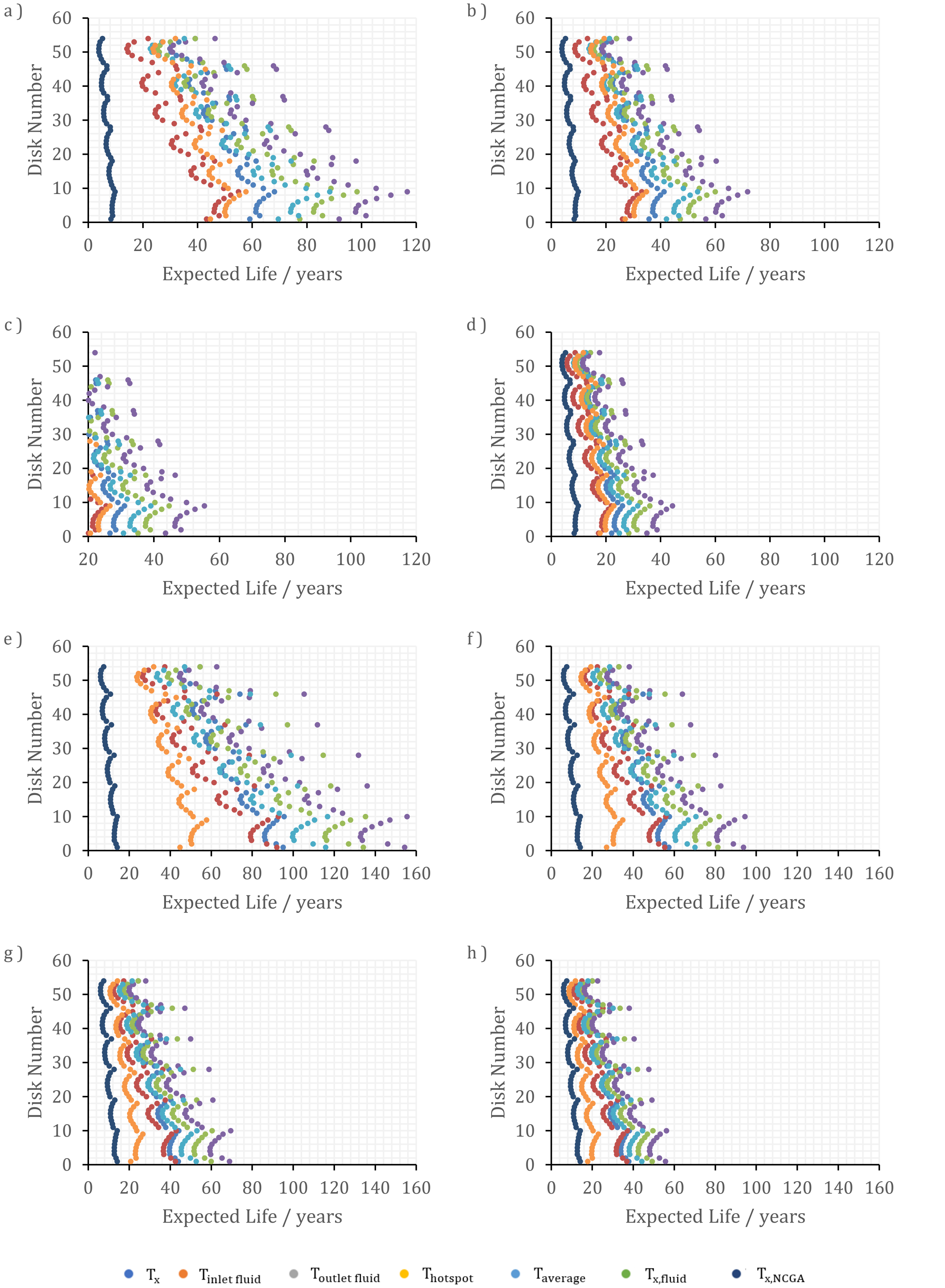


Figure 4.1 - Remaining Life estimation data from Simulation 1 from solid temperature profile: a) 5 ppm; b) 10 ppm; c) 15 ppm; d) 20 ppm; and fluid temperature profile: e) 5 ppm; f) 10 ppm; g) 15 ppm profile; h) 20 ppm.

In contrast, Case 2 ($T_{inlet\ fluid}$) and Case 6 ($T_{x,fluid}$) present the lowest values for the Remaining Life estimation through solid and fluid temperature profiles, respectively. Both temperatures used in these methodologies are the lowest ones present in the transformer operation, especially the inlet fluid temperature – at that position, the fluid has not yet exchanged heat with the solid component. Therefore, through Oommen's equilibrium curves, it was showed that lower temperatures lead to higher amounts of water in the system. As a result, A-values estimated by equation 3.1 are higher and Remaining Life results are lower.

Thus, the extreme temperatures found in a winding during the transformer operation present very different values of water content in paper estimation and, consequently, Remaining Life values very distinctive.

Another information present in Figure 4.1 is the behavior of the cases along the winding when exposed to the same conditions. In each one of the scenarios, it is clearly shown that Remaining Life values exhibit a higher distinction as one gets close to the bottom of the winding. Regardless of the methodology applied, cases' results tend to converge as the disk position gets higher on the winding. This information demonstrates that at higher temperatures there is a less distinction of the applied methodologies. In other words, the influence of the methodology applied is lower on the top of the transformer winding. To validate this information, the Absolute Variation was calculated between the results along the winding, through Equation 4.1.

$$\text{Absolute Variation} = \text{RL}_{\text{Case i}} - \text{RL}_{\text{Standard Case}} \qquad (4.1)$$

The analysis was made for the cases where moisture was considered a variable (Case 1, 2, 3, 4, 5 and 6), for each of the extreme water concentration conditions ($5\ \text{ppm}$ and $20\ \text{ppm}$). Each of the cases was compared to a standard situation, which corresponded to the case where lower values of Reamining Life were obtained – Case 2 ($T_{inlet\ fluid}$) and Case 6 ($T_{x,fluid}$), depending on the temperature profile used, as mentioned above. Results are displayed in Table 4.1. The behavior analyzed in each scenario, for both $5\ \text{ppm}$ and $20\ \text{ppm}$, is very similar.

For most of the results, it is demonstrated that higher variation appears on the bottom of the winding, and it decreases as the position ascends along the winding. However, this behavior does not occur for all the cases' variation. For the results provided by solid temperature, the opposite behavior occurs on the interaction between Case 2 with Case 1 (T_x) and Case 6, since the variation gets higher on the top of the winding. Unlike the other cases, Case 1 and Case 6 estimates the water content in paper through a temperature that variates along the winding. Since Case 2 ($T_{inlet\ fluid}$) uses the lowest temperature present on the winding, the temperature in both these cases presents a higher distintion when compared with $T_{inlet\ fluid}$ as the position in the winding increases, which is due to the heat exchange between the two compounds. As a consequence, the Remaining Life variation between these cases presents a different behavior when compared to the others.

Table 4.1 - Variation of the Remaining Life along the winding to 5 ppm (left) and 20 ppm (right) for both solid and fluid temperature profiles, from Simulation 1

	5 ppm										20 ppm									
	Fluent					Solid					Fluent					Solid				
Disk Number	**Case 1 & 6**	**Case 2 & 6**	**Case 3 & 6**	**Case 4 & 6**	**Case 5 & 6**	**Case 1 & 2**	**Case 3 & 2**	**Case 4 & 2**	**Case 5 & 2**	**Case 6 & 2**	**Case 1 & 6**	**Case 2 & 6**	**Case 3 & 6**	**Case 4 & 6**	**Case 5 & 6**	**Case 1 & 2**	**Case 3 & 2**	**Case 4 & 2**	**Case 5 & 2**	**Case 6 & 2**
54	23	5	23	31	15	17	17	25	13	10	8	3	8	11	6	6	6	9	4	3
53	20	2	15	22	10	16	13	19	10	11	7	2	6	8	4	6	4	7	3	3
52	20	2	15	21	9	16	12	16	9	10	7	2	6	7	4	6	4	6	3	3
51	21	3	15	21	10	16	11	16	9	10	7	2	6	7	4	6	4	6	2	3
50	22	4	17	23	11	16	11	16	9	9	8	2	6	8	5	6	4	6	3	3
49	24	6	20	27	14	16	13	18	10	9	9	3	8	10	6	6	4	7	3	3
48	26	9	26	34	19	17	15	22	12	9	10	5	10	12	8	6	5	8	3	3
47	31	16	38	48	28	18	18	26	14	7	12	7	14	17	11	6	6	10	4	2
46	36	25	54	68	41	18	25	36	19	6	14	11	19	23	16	5	8	13	6	2
45	19	4	25	36	16	18	26	36	20	10	7	3	9	12	6	5	8	13	6	3
44	19	2	20	28	12	18	20	29	16	11	7	2	7	10	5	5	7	10	4	3
43	19	2	17	25	11	17	17	25	13	11	7	2	7	9	5	6	6	9	4	3
42	20	2	17	24	10	17	16	23	12	11	7	2	6	9	5	6	5	8	4	3
41	20	2	17	24	11	17	15	22	12	11	7	2	7	9	5	6	5	8	3	3
40	21	3	19	26	12	17	16	22	12	11	8	2	7	9	5	6	5	8	3	3
39	22	5	22	30	15	17	17	24	13	10	8	3	8	11	6	6	5	9	4	3
38	29	14	36	46	26	18	19	28	15	8	11	6	13	16	10	5	6	10	4	2
37	38	28	59	73	45	18	26	38	20	5	15	12	21	25	17	5	9	14	6	2
36	21	7	30	41	20	18	27	38	21	10	8	4	11	14	8	5	9	14	6	3
35	22	6	27	36	18	18	22	32	17	10	8	3	9	13	7	5	7	12	5	3
34	22	6	25	34	17	18	20	29	16	10	8	3	9	12	7	5	7	10	4	3
33	23	6	25	34	17	18	19	28	15	10	8	4	9	12	7	5	6	10	4	3
32	23	7	26	35	18	18	19	27	15	10	9	4	9	12	7	6	6	10	4	3
31	24	8	28	38	20	18	20	28	15	9	9	4	10	13	8	5	6	10	4	3
30	26	11	32	43	23	18	21	31	16	9	10	5	11	15	9	5	7	11	5	3
29	33	20	47	60	36	18	25	35	19	7	13	9	17	21	13	5	8	13	5	2
28	41	34	70	87	54	16	32	46	25	4	16	14	24	30	20	5	10	17	7	1
27	24	13	42	55	29	16	33	47	25	8	9	6	14	19	11	5	11	17	7	2
26	25	12	37	50	26	17	28	40	22	8	9	5	13	17	10	5	9	15	6	3
25	25	11	35	47	25	18	26	36	20	9	10	5	12	16	10	5	8	13	6	3
24	26	12	35	46	25	18	24	35	19	9	10	5	12	16	9	5	8	13	5	3
23	26	12	36	47	25	18	24	34	18	8	10	6	13	16	10	5	8	12	5	3
22	28	14	38	50	28	18	25	35	19	8	10	6	13	17	11	5	8	13	5	2
21	29	16	42	55	31	18	27	38	20	7	11	7	15	19	12	5	9	14	6	2
20	30	18	46	60	34	17	29	41	22	7	11	8	16	20	13	5	9	15	6	2
19	42	36	73	91	57	16	33	47	26	3	17	15	25	31	21	5	11	17	7	1
18	29	21	54	70	40	15	36	52	28	6	11	9	19	24	15	5	12	19	8	2
17	29	19	49	64	36	16	33	47	25	6	11	8	17	22	13	5	11	17	7	2
16	29	18	47	61	35	17	31	43	23	7	11	8	16	21	13	5	10	16	7	2
15	30	19	47	61	35	17	30	42	23	7	12	8	17	21	13	5	10	15	7	2
14	31	20	49	63	37	17	30	42	23	6	12	8	17	22	14	5	10	15	7	2
13	32	22	53	67	39	17	31	44	24	6	12	9	18	23	15	5	10	16	7	2
12	33	23	56	72	42	16	33	48	26	5	13	10	19	24	16	5	11	17	7	2
11	32	24	58	74	43	16	35	50	27	5	13	10	20	25	16	5	11	18	8	2
10	44	41	84	104	66	14	39	56	30	2	18	17	29	36	24	4	13	20	9	1
9	34	30	70	89	53	13	43	62	33	3	14	12	24	30	19	4	14	22	10	1
8	35	30	69	87	52	14	41	59	32	3	14	12	24	30	19	4	13	21	9	1
7	35	29	67	85	51	14	39	56	30	4	14	12	23	29	19	4	13	20	9	1
6	35	29	66	83	50	15	38	54	29	4	14	12	23	28	18	5	12	19	8	1
5	36	29	65	83	49	15	37	52	28	4	14	12	23	28	18	5	12	19	8	1
4	36	29	65	83	50	15	36	52	28	4	14	12	23	28	18	5	12	19	8	1
3	36	30	66	84	50	15	36	52	28	4	14	12	23	29	19	5	12	19	8	1
2	41	37	77	96	59	15	38	54	29	3	16	15	27	33	22	5	12	19	8	1
1	50	47	89	110	71	16	34	49	26	1	20	19	31	38	26	5	11	18	8	0

Lower Variation

High Variation

Results from Table 4.1 also show that at each set change, the disks involved present an increase in the Variation, which shows that for lower temperatures, the impact of the method applied to the Remaining Life estimation is higher. A possible explanation for this result is the cooling fluid circulation. As explained before, in each set change the fluid is all forced to go through a outlet channel. Since the fluid comes from different zones (axial and radial) that present different temperatures, its mix causes a decrease of the temperature in the next disk and, consequently, a higher Variation.
Regardless of the inlet water concentration, Case 2 and 5 present the lower values of Variation along the winding, and Case 4 the highest variation, when compared to Case 6.

Finally, when compared to the same case variation, data proves that higher inlet concentrations provide a lower variation on the Remaining Life estimation. Again, this verifies the previous statement, the methodology approach presents a lower influence once the inlet water concentration gets higher.

To sum up, the methods applied to estimate the Remaining Life have more impact when the transformer operates with lower water concentration and temperatures. Since the most concerning set is exposed to the highest temperatures, which is the most concerning zone of the power transformer, none of the methods is quite distinctive except for Case 7. For these conditions, any of them could be valid, when compared to each other.

Table 4.2 describes the Variation when compared the estimation through solid or fluid temperatures, by Equation 4.2. For this analysis, Case 6 was not considered since the estimation of the Remaining Life uses both temperature profiles.

$$\text{Variation} = \text{RL}_{\text{fluid}} - \text{RL}_{\text{solid}} \quad (4.2)$$

As the position on the winding gets higher, Variation for all the cases is lower, which is expected. Along the winding, heat exchanges between the paper and the oil cause an increase in the fluid temperature and, consequently, a lower temperature gradient between the two temperature profiles. Since both temperatures get close to each other, the Remaining Life values obtained present lower Variation.

Through an overall analysis, Case 7, presents the lower variation along the winding, and it is followed by the cases exposed to $20\ \text{ppm}$ of inlet water concentration. Depending on the disk, Case 2 and Case 4 for $5\ \text{ppm}$ present the highest Variation for the Remaining Life estimation.

Finally, between each set, an increase of the variation is verified. Again, this outcome can be explained through the temperature of the fluid. In the set change, the fluid is all forced to pass the same inlet channel. Depending on the fluid position, its temperature is different, especially on the axial positions where it is lower since the mix leads to a decrease in the inlet temperature of the next set. Therefore, due to the higher temperature gradient between the solid of the next disk and the fluid, variation in each change set increases.

Table 4.2 - Variation of the Remaining Life along the winding to dry, 5 ppm and 20 ppm water concentration values, from Simulation 1

	dry	5 ppm					20 ppm				
Disk Number	Case 7	Case 1	Case 2	Case 3	Case 4	Case 5	Case 1	Case 2	Case 3	Case 4	Case 5
54	2	15	15	15	16	12	6	6	6	5	5
53	2	15	12	13	13	10	5	5	5	4	4
52	2	14	12	13	14	10	5	5	5	4	4
51	2	15	12	13	14	11	5	5	5	5	5
50	2	16	13	15	16	12	5	5	5	5	5
49	2	17	15	17	18	14	6	6	6	6	6
48	3	18	18	20	22	16	7	7	7	7	7
47	3	21	24	27	29	22	8	9	10	10	9
46	4	24	31	34	38	28	11	12	13	12	12
45	2	11	14	10	10	7	5	6	4	2	4
44	2	12	13	11	11	8	5	5	4	3	4
43	2	13	13	11	12	8	5	5	4	3	4
42	2	14	13	12	13	9	5	5	4	4	4
41	2	14	13	13	13	10	5	5	5	4	4
40	2	15	14	13	14	10	5	5	5	4	5
39	2	15	15	15	16	12	6	6	6	5	5
38	3	20	22	24	26	19	8	9	9	8	8
37	4	25	33	37	41	30	11	13	14	13	13
36	2	13	17	13	13	9	6	7	5	3	5
35	2	14	16	14	14	10	6	6	5	4	5
34	2	14	16	15	16	11	6	6	6	5	5
33	2	15	16	16	16	12	6	6	6	5	5
32	2	15	17	16	17	13	6	7	6	5	6
31	3	16	18	18	19	14	6	7	7	6	6
30	3	17	20	20	21	15	7	8	7	6	7
29	4	21	27	29	31	23	9	11	11	10	10
28	5	28	38	41	45	33	12	15	15	14	14
27	3	16	21	16	16	12	7	8	6	4	6
26	3	16	20	18	18	13	7	8	6	5	6
25	3	16	20	18	19	14	7	8	7	6	6
24	3	16	20	19	20	15	7	8	7	6	7
23	3	16	21	20	21	15	7	8	7	6	7
22	3	17	22	22	23	17	8	9	8	7	8
21	3	18	24	23	25	18	8	9	9	7	8
20	3	19	25	24	25	19	8	10	9	8	8
19	5	29	39	43	47	34	13	16	16	15	15
18	3	20	26	23	24	17	9	10	9	7	8
17	3	19	25	23	23	17	8	10	8	7	8
16	3	19	25	24	25	18	8	10	9	7	8
15	3	19	25	24	26	19	9	10	9	8	9
14	3	20	26	26	27	20	9	11	10	8	9
13	3	21	28	27	29	21	9	11	10	9	10
12	4	22	29	28	30	22	10	12	10	9	10
11	4	22	29	28	29	21	10	12	10	9	10
10	5	32	43	46	50	37	14	17	17	16	16
9	4	24	33	30	30	22	10	13	11	9	10
8	4	24	33	31	32	23	11	13	11	9	11
7	4	24	33	31	33	24	11	13	12	10	11
6	4	24	33	32	34	25	11	13	12	10	11
5	4	24	33	32	34	25	11	13	12	10	11
4	4	25	33	33	35	26	11	13	12	11	11
3	4	25	34	34	36	26	11	13	12	11	12
2	5	29	39	41	44	33	13	16	15	14	14
1	6	36	49	57	63	46	16	19	21	21	19

Lower Variation

High Variation

Figure 4.2 represents the data obtained for the Remaining Life regarding Simulation 2, where the inlet fluid velocity was changed to double.

In an overall analysis, the results presented show very similar behavior as the ones obtained in Simulation 1. Remaining Life estimation through fluid temperature profiles presents lower values when compared to the calculation through the solid temperature profiles, and its values tend to converge on the top of the winding.

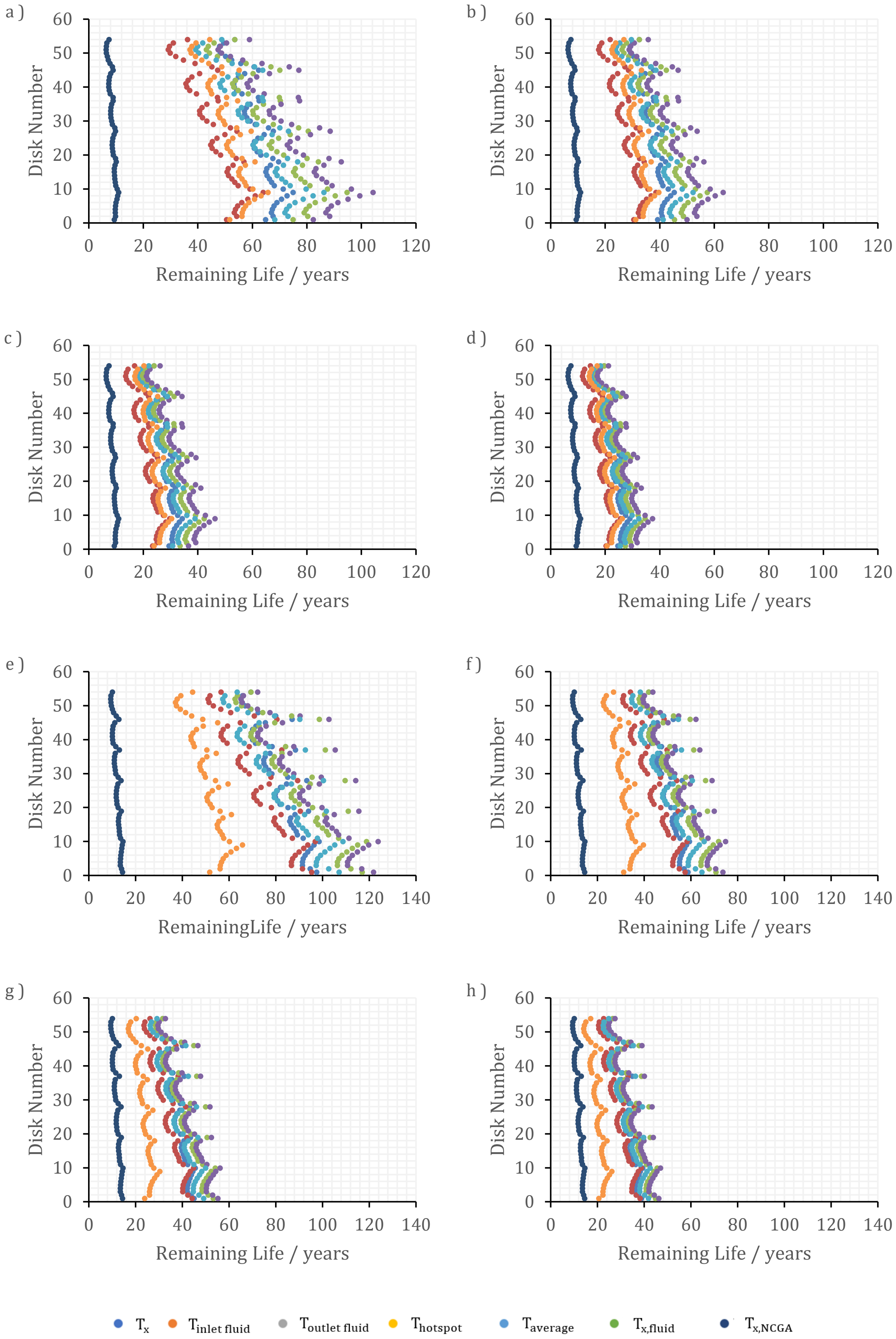


Figure 4.2 - Remaining Life estimation data from Simulation 2 from solid temperature profile: a) 5 ppm; b) 10 ppm; c) 15 ppm; d) 20 ppm; and fluid temperature profile: e) 5 ppm; f) 10 ppm; g) 15 ppm profile; h) 20 ppm.

Regarding the methodology applied to the Remaining Life estimation, the same as Simulation 1, Case 2 ($T_{inlet\ fluid}$) is the one that presents lower values of the Remaining Life estimation along the winding when used the solid temperature and Case 6 ($T_{x,fluid}$) for fluid temperature.

In almost all of the conditions performed, Case 3 ($T_{outlet\ fluid}$) and Case 4 ($T_{hotspot}$) show values very close to each other and highest values for the Remaining Life estimation, which can be due to the velocity increase. If the oil circulates faster, its temperature at the top will be lower. Therefore, since the simulation is performed on steady state and the heat exchange is the same, the temperature gradient between the two components will be lower, which contributes to a lower hot spot temperature as well as the last disk temperature.

As for the inlet water concentration, as Simulation 1, higher values lead to a lower Remaining Life of the power transformer. However, as the difference between the two simulations gets lower, water concentration gets higher. In other words, the results obtained present a higher difference for the $5\ \mathrm{ppm}$ than the $20\ \mathrm{ppm}$.

When the data from both simulations are compared, results demonstrate lower Remaining Life values for Simulation 2. Since temperature profiles from Simulation 2 are lower when compared to Simulation 1, these temperatures used in the estimation are lower, which leads to higher A-values and, consequently, lower Remaining Life results.

Through the same logic, in Simulation 1 the temperature profile is higher so its A-values are lower and, consequently, the Remaining Life results are higher. However, the temperature gradient obtained in the transformer winding is a very important parameter in this situation, according to Fourier’s Law. As the disk position gets closer to the top of the transformer winding, the temperatures of both profiles get closer to each other. Therefore, on the bottom of the transformer, the temperature profiles obtained for Simulation 1 are more distinct from the temperature profiles of Simulation 2. Consequently, even though its A-values are lower, the Remaining Life estimation presents lower results due to the high temperature used in Equation 2.8. In contrast, on the top of the winding, since the temperatures obtained for simulations present lower distinction, Remaining Life results are higher for Simulation 1 due to its lower A-values. In this region, the difference between the temperature profiles is not enough to hide the A-value weight. To sum up, for this particular case, the Remaining Life estimation results are smaller for regions with lower temperature.

Another fact retained is that results from Simulation 2 are more compressed. In other words, for the cases where moisture is considered, the results are contained in a smaller range than Simulation 1. Case 7 shows very similar behavior in both simulations.

In Appendix D is represented the Variation obtained for Simulation 2, towards Case 2 and Case 6, which once again present the worst results. From Table D.2, the results show a lower variation for all the cases, when compared to the ones obtained in Simulation 1. This outcome confirms that there is higher compaction of the results obtained in different cases.

Regarding the Variation between Remaining Life from solid and fluid profiles in each case, also exposed in Appendix C, all cases present a similar Variation when compared to data from Simulation 1, described in Table D.1.

Figure 4.3 represents the data obtained from Simulation 3, where the inlet temperature was increased by $10\ ^{\circ}\mathrm{C}$, comparatively with Simulation 1.

By analyzing the data, the focus is on the quite significant decrease of the Remaining Life of the power transformer. Regardless of the conditions to what they are exposed, all the values decrease to almost half of those obtained in Simulation 1. Since oil inlet temperature is higher, it leads to a reduction of the heat exchange between solid and fluid components, because the temperature gradient is smallest. Furthermore, another aspect observed in all the results is a slight change in the Remaining Life value’s behavior along the winding. A higher dispersion occurs in the bottom of the winding, regardless of the profile used, although it is more significant for lower water inlet concentrations.

Higher inlet water concentration leads to lower Remaining Life values. However, regarding the method’s applicability, one of the main conclusions withdrawn from Figure 4.3 is of higher proximity to Case 7. Even though this method does not consider the influence of moisture present on the winding, as the water inlet concentration increases, the results obtained from the other cases get close to the one obtained in Case 7, more than the ones in Simulations 1 and 2. In other words, all the cases’ results for inlet water concentration of $5\ \mathrm{ppm}$ for Simulation 3 are closest to the Case 7 than the case’s results in Simulation 1, which leads to conclude that for higher temperatures the inlet water concentration presents a lower impact.

In Appendix C is represented the Variation obtained for Simulation 3, through Table D.4 where, once again, Case 2 and Case 6 are used as standard cases. When the inlet water concentration increases, in this case for $20\ \mathrm{ppm}$, these two cases present very similar results, which lead to conclude that the use of any of these two methods, for high temperatures and extreme water conditions is the same, it does not present differences. Regarding the Remaining Life estimation along the winding, the same behavior is observed, even though the values obtained are significantly lower.

Regarding the Variation between the two profiles used in each case, it is represented in Table D.3, also described in Appendix D. Unlike the other assessments in this simulation data, it presents negative values. These results do not agree with what would be expected, which indicates that another factor is interfering with the Remaining Life estimation, since solid temperature profiles always show superior values to fluid temperature profiles, like the other

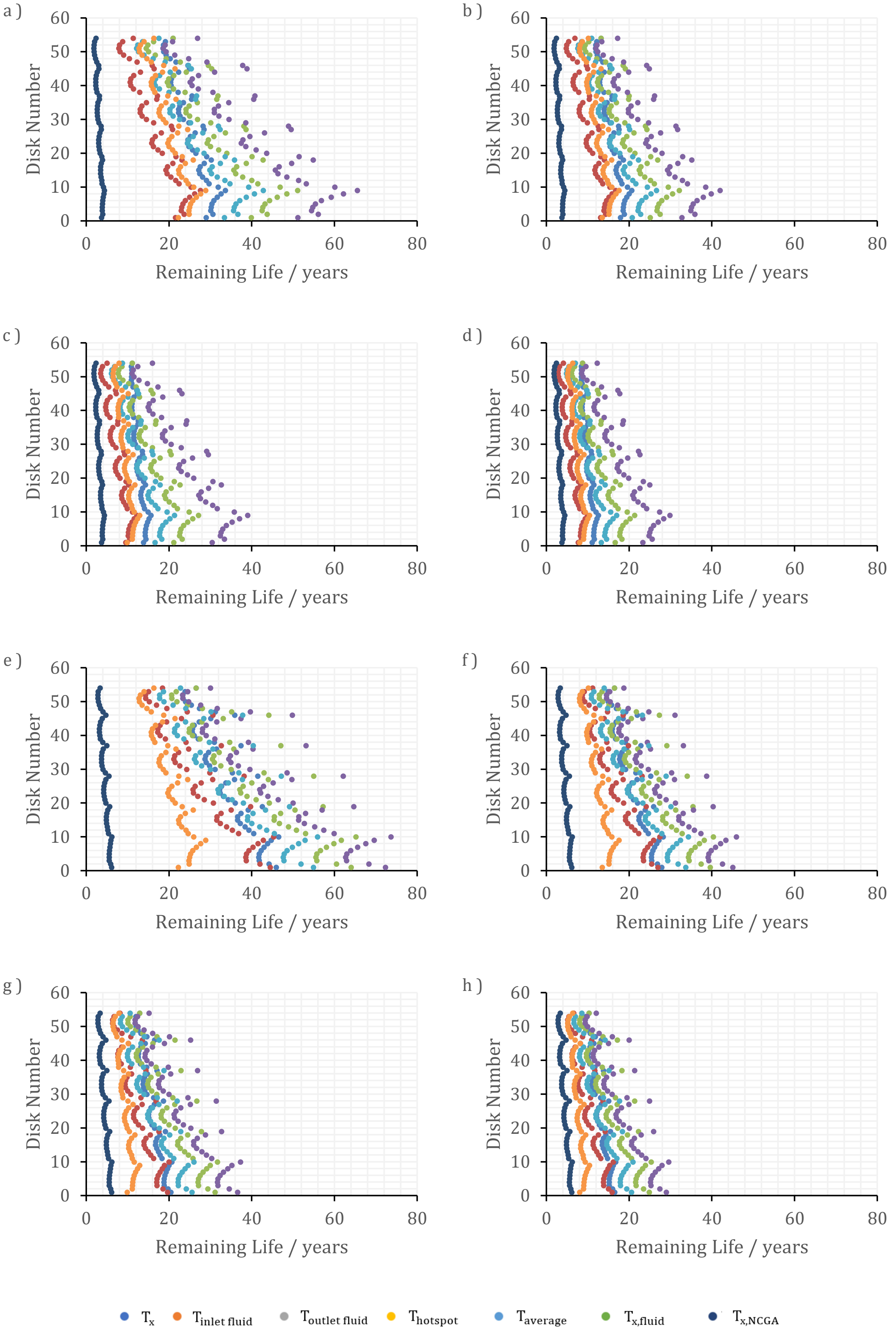


Figure 4.3 - Remaining Life estimation data from Simulation 3 from solid temperature profile: a) 5 ppm; b) 10 ppm; c) 15 ppm; d) 20 ppm; and fluid temperature profile: e) 5 ppm; f) 10 ppm; g) 15 ppm profile; h) 20 ppm.

simulations. A possible explanation could be through the Oommen's equilibrium curves, which are designed to describe the system between 0 and $100\ ^{\circ}\mathrm{C}$. Since in this simulation temperature along the winding exceed $100\ ^{\circ}\mathrm{C}$, by using extrapolation methods for higher temperatures, the results for the water content in paper estimation are not very accurate, which leads to uncertainty.

Finally, Figure 4.4 represents the data obtained from Simulation 4, where the disk's heat sources were double, comparatively with Simulation 1.

According to the temperature profiles, Simulation 4 presents the highest temperatures along the winding, which is acceptable due to the higher amount of heat generated. However, through the analysis of Figure 4.4, the Remaining Life values obtained are superior when compared with all the other simulations. This outcome does not match with the theory, since higher temperature leads to the degradation of cellulose insulation and, thus, a lower Remaining Life. Again, this could also be explained by the equilibrium curves, as in Simulation 3, even though for this scenario, it does not regard only one, but all the case's results.

Therefore, Simulation 4 presents an alternative panorama where the limitations of the method applied to the estimation of the Remaining Life are more exposed. If, on the one hand, the results present very high values, especially in Case 4, on the other hand, some case's results show results very close to the Case 7, which could indicate that, in these situations, the presence of moisture does not influence the calculations. In a way, this information may not be entirely wrong due to the correlation between moisture and temperature. Oommen's equilibrium curves demonstrate that the higher the temperature to which the system is exposed, the less amount of moisture is present. So, for this type of situation, maybe Case 7 could present an acceptable scenario. However, it is vital to keep in mind that at high temperatures, the main responsible for cellulose degradation is hydrolysis and, in some cases, pyrolysis reactions, in which water is one of its main products. So, for this type of situation, maybe Case 7 could not present an acceptable scenario. Therefore, there are two possible approaches to interpret the problem when the winding is exposed to these conditions, both valid even though they defend contradictory ideas.

As a final point for the assessment of the Remaining Life Estimation of a Power Transformer, the analysis of the winding condition was analyzed. Through the results obtained for all the simulations, it is possible to verify that the values obtained can present high deviation along the winding. This deviation presents a significant issue regarding a power transformer's condition assessment. In a real situation, when the transformer is stopped and opened, insulation paper samples are collected to analyze its degree of polymerization. However, data shows that depending on the position of where the sample is collected the Remaining Life, the estimation, can be very unreliable.

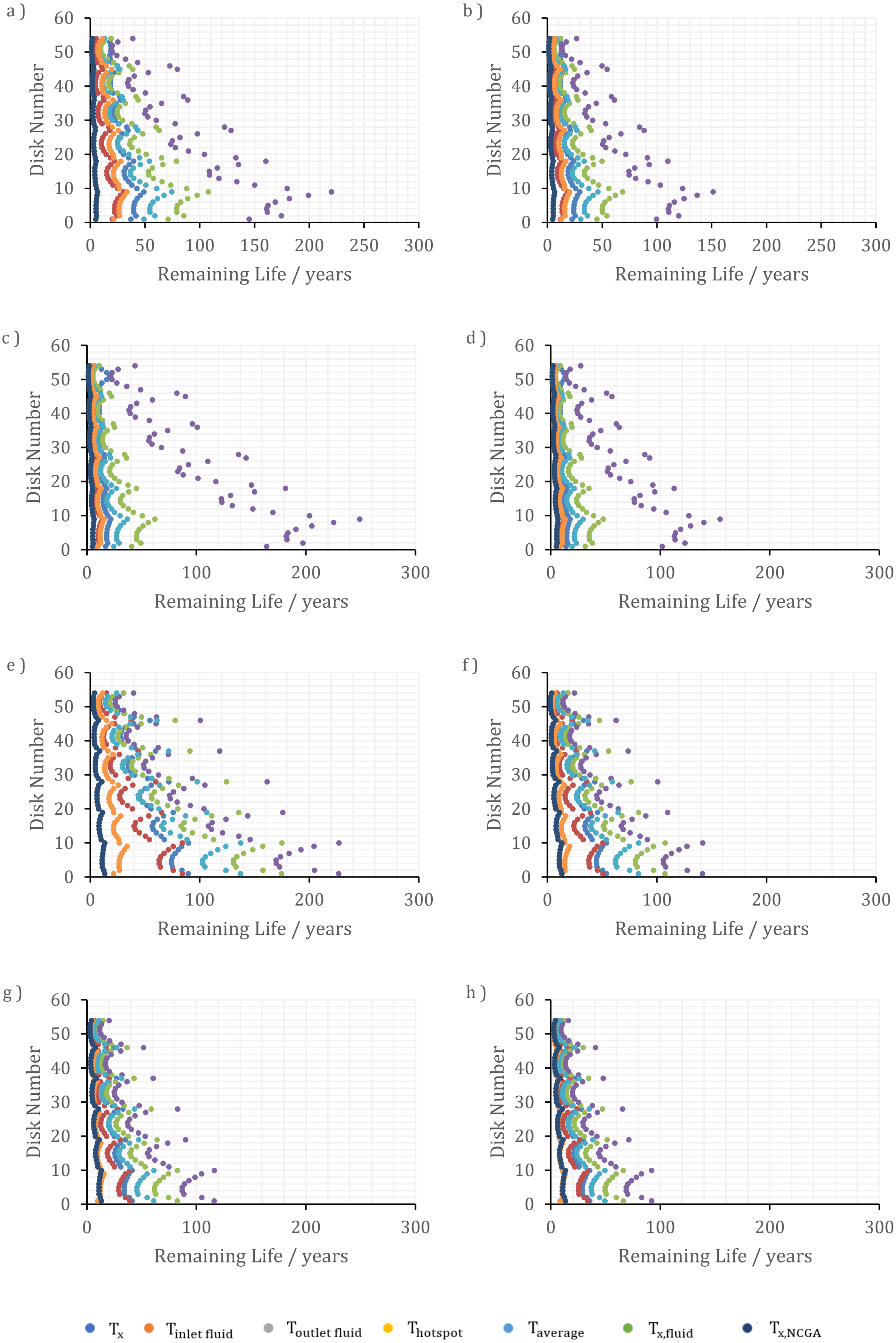


Figure 4.4 - Remaining Life estimation data from Simulation 4 from solid temperature profile: a) 5 ppm; b) 10 ppm; c) 15 ppm; d) 20 ppm; and fluid temperature profile: e) 5 ppm; f) 10 ppm; g) 15 ppm profile; h) 20 ppm.

In other words, the position from which the paper is collected in the winding can present very different cellulose degradation, since it is exposed to very different conditions, especially if the gathering is made in the lower part of the transformer. Therefore, it is important to collect insulation samples from different positions of the power transformer in order to decrease the error associated with the Remaining Life estimation.

4.2 Thermal Model vs. Non-Thermal Model

For all the simulations analyzed, the results for the Remaining Life estimation show that regardless of the conditions applied, the lower value for each case always corresponds to the hot spot of the winding. This outcome can be explained due to the conditions imposed during the simulation.

Exposed in Appendix D, Table D.1 presents the data collected for Case 1 regarding the Remaining Life and all the variables implicated on its estimation, such as the solid temperature profile, the water content in paper and, consequently, the A-value calculated for each disk. As exemplified, the lowest value for the Remaining Life is $30\ \mathrm{years}$, approximately, and it is obtained for the hot spot temperature achieved on the winding, $96.8\ ^{\circ}\mathrm{C}$.

In Table 4.3 is described the results obtained for Method A. Through an overall analysis, the results obtained show that a decrease of $5\ ^{\circ}\mathrm{C}$ lead to a significant increase in the water content in paper value when compared with the original. Consequently, the water concentration obtained in each disk presents very high values, when compared with $5\ \mathrm{ppm}$.

The lowest values of moisture in oil are obtained for the set exposed to the highest temperatures, in some cases close to the hot spot temperature. However, the water concentration values obtained are almost twice the value of the inlet water concentration assumed at the winding in the simulations performed. For the rest of the winding, the water concentration obtained in each disk is considerably higher and, thus presenting unrealistic results.

Table 4.3 - Data used in Method A to estimate the moisture in oil

Disk	T_{real} (°C)	T_{new} (°C)	wpc_{real} (%)	wpc_{new} (%)	moisture oil (ppm)
54	92.96	87.96	0.30	0.62	12.81
53	95.27	90.27	0.28	0.49	9.97
52	96.48	91.48	0.26	0.43	9.51
51	96.80	91.80	0.26	0.42	9.36
50	96.55	91.55	0.26	0.43	9.48
49	95.64	90.64	0.27	0.47	9.84
48	94.09	89.09	0.29	0.55	11.27
47	92.37	87.37	0.30	0.66	13.57
46	89.69	84.69	0.33	0.86	19.26
45	89.55	84.55	0.33	0.87	19.56
44	91.56	86.56	0.31	0.71	14.77
43	92.97	87.97	0.30	0.62	12.80
42	93.67	88.67	0.29	0.57	11.83
41	93.91	88.91	0.29	0.56	11.51
40	93.79	88.79	0.29	0.57	11.68
39	93.27	88.27	0.29	0.60	12.40
38	91.95	86.95	0.31	0.68	14.10
37	89.27	84.27	0.34	0.90	20.21
36	89.20	84.20	0.34	0.91	20.32
35	90.72	85.72	0.32	0.78	16.75
34	91.56	86.56	0.31	0.71	14.76
33	91.92	86.92	0.31	0.69	14.13
32	91.98	86.98	0.31	0.68	14.06
31	91.73	86.73	0.31	0.70	14.38
30	91.07	86.07	0.32	0.75	15.91
29	89.81	84.81	0.33	0.85	18.95
28	87.57	82.57	0.37	1.07	23.68
27	87.47	82.47	0.37	1.08	23.97
26	88.75	83.75	0.35	0.95	21.05
25	89.57	84.57	0.33	0.87	19.53
24	90.00	85.00	0.33	0.83	18.50
23	90.11	85.11	0.33	0.83	18.25
22	89.87	84.87	0.33	0.85	18.83
21	89.22	84.22	0.34	0.90	20.28
20	88.53	83.53	0.35	0.97	21.39
19	87.33	82.33	0.37	1.10	24.37
18	86.56	81.56	0.38	1.19	26.12
17	87.38	82.38	0.37	1.09	24.24
16	88.05	83.05	0.36	1.02	22.36
15	88.30	83.30	0.35	0.99	21.77
14	88.25	83.25	0.36	1.00	21.84
13	87.87	82.87	0.36	1.04	22.83
12	87.29	82.29	0.37	1.10	24.49
11	86.81	81.81	0.38	1.16	25.52
10	85.96	80.96	0.39	1.26	28.70
9	85.10	80.10	0.41	1.38	31.72
8	85.54	80.54	0.40	1.32	30.44
7	85.94	80.94	0.39	1.26	28.77
6	86.28	81.28	0.39	1.22	27.18
5	86.48	81.48	0.38	1.20	26.30
4	86.56	81.56	0.38	1.19	26.11
3	86.58	81.58	0.38	1.19	26.07
2	86.26	81.26	0.39	1.23	27.30
1	87.11	82.11	0.37	1.12	24.87

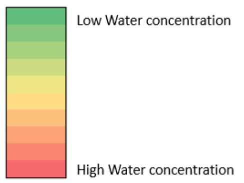
Low Water concentration

High Water concentration

Through the results obtained for Method B, which are presented in Table 4.4, it is possible to discuss some topics. To start, values of the water concentration along the entire winding are more acceptable, when compared results from the previous method. For temperatures close to the hot spot temperature, the water concentration obtained is very close to 5 ppm.

Table 4.4 - Data used in Method B to estimate the moisture in oil

Disk	T_{real} (°C)	wpc_{real} (%)	wpc_{new} (%)	moisture oil (ppm)
54	92.96	0.30	0.37	8.55
53	95.27	0.28	0.30	6.37
52	96.48	0.26	0.27	5.91
51	96.80	0.26	0.26	5.78
50	96.55	0.26	0.27	5.88
49	95.64	0.27	0.29	6.24
48	94.09	0.29	0.34	7.51
47	92.37	0.30	0.40	9.07
46	89.69	0.33	0.52	10.48
45	89.55	0.33	0.53	10.65
44	91.56	0.31	0.43	9.47
43	92.97	0.30	0.37	8.54
42	93.67	0.29	0.35	7.90
41	93.91	0.29	0.34	7.68
40	93.79	0.29	0.35	7.79
39	93.27	0.29	0.36	8.27
38	91.95	0.31	0.41	9.30
37	89.27	0.34	0.54	11.03
36	89.20	0.34	0.54	11.12
35	90.72	0.32	0.47	9.81
34	91.56	0.31	0.43	9.47
33	91.92	0.31	0.41	9.31
32	91.98	0.31	0.41	9.28
31	91.73	0.31	0.42	9.40
30	91.07	0.32	0.45	9.68
29	89.81	0.33	0.51	10.31
28	87.57	0.37	0.64	13.31
27	87.47	0.37	0.65	13.44
26	88.75	0.35	0.57	11.73
25	89.57	0.33	0.52	10.63
24	90.00	0.33	0.50	10.07
23	90.11	0.33	0.50	10.02
22	89.87	0.33	0.51	10.25
21	89.22	0.34	0.54	11.08
20	88.53	0.35	0.58	12.03
19	87.33	0.37	0.66	13.62
18	86.56	0.38	0.71	14.77
17	87.38	0.37	0.65	13.56
16	88.05	0.36	0.61	12.69
15	88.30	0.35	0.60	12.36
14	88.25	0.36	0.60	12.42
13	87.87	0.36	0.62	12.92
12	87.29	0.37	0.66	13.68
11	86.81	0.38	0.69	14.27
10	85.96	0.39	0.76	16.18
9	85.10	0.41	0.83	18.26
8	85.54	0.40	0.79	17.18
7	85.94	0.39	0.76	16.22
6	86.28	0.39	0.73	15.42
5	86.48	0.38	0.72	14.95
4	86.56	0.38	0.71	14.76
3	86.58	0.38	0.71	14.72
2	86.26	0.39	0.73	15.48
1	87.11	0.37	0.67	13.90



Through the data described in Table 4.4, it is verified that there is some inconsistency with what would be expected since in the hot spot temperature - which corresponds to disk 51 - the moisture in oil should be 5 ppm. However, the value is slightly higher. This can be explained by the methods of predicting water content on paper. The code used as an estimate shows some deviation from the original curve, represented in Figure 2.9, so the calculation through the code is slightly higher when compared with the results from the interpolation of the original curve.

Even though these results present some error due to the poor accuracy in the interpolation methods, the values obtained demonstrate that there is a proximity between the concentration of water obtained and the value used in the simulations. Therefore, the results allow for highlighting of a possible alternative calculation of the Remaining Life where it can be affected by the humidity along the winding. In other words, Method B demonstrates that zones with lower temperatures can present lower Remaining Life values when compared to the hot spot. Again, this outcome can be explained since higher temperatures lead to lower water concentration.

In spite of it regards temperatures close to the hot spot, Method B shows that a purely thermal method to estimate the Remaining Life of a Power Transformer does not present an exclusive result where all the concepts and theory are involved.

To conclude, it is essential, as future work, to understand the behavior of water in these systems and how it is possible to create zones with higher water concentration, depending on the temperature at which they are exposed.

5 Conclusions

Through numerical simulations Remaining Life estimation was obtained for Power Transformer winding exposed to several conditions. Different approaches were performed in order to study the impact of the two most concerning variables in paper insulation aging calculations, temperature, and oil moisture.

The methodologies approached in work developed show that regardless the conditions to which the cases are exposed, water content in paper estimation through inlet fluid temperature (Case 2) and combined temperature profiles (Case 6) present the worst scenarios. In contrast, the use of hot spot temperature (Case 4) presents the best scenario, followed by the outlet fluid temperature (Case 3). This outcome demonstrates that even though higher temperatures in the winding present a concerning situation for paper degradation, in Remaining Life estimation they show a good result when compared with the other methodologies.

Results from the different methodologies also allow verifying the impact of the temperatures profile used. Remaining Life estimation through fluid temperature profile presents higher values than through solid temperature profiles. However, the variation between the two values gets lower as a higher position is taken on the winding.

The distinction between the results from both profiles is higher for lower inlet water concentrations. In other words, results from $20\ \mathrm{ppm}$ are more compressed than results from $5\ \mathrm{ppm}$. To sum up, the methodologies show a stronger influence for lower inlet water concentrations, especially on the bottom of the winding.

For Case 7, where the moisture is not considered a variable, the variation between both temperature profiles is minimal when compared with the remain methodologies.

By comparing each methodology performed for the four simulations, the best Remaining Life estimation scenarios are from Simulation 1, followed by Simulation 2. As for the other simulations, even though Simulation 4 works with higher temperatures, Simulation 3 presents the lowest values of the Remaining Life of the Power Transformer. Due to the limitations of the Oommen's equilibrium curves Simulation 4 results do not present a valid scenario which leads to an A-value calculation poorly performed, and an incorrect Remaining Life estimation.

As for the inlet water concentration, regardless of the simulation and the methodology applied, higher values lead to lower Remaining Life estimation values.

Finally, the study of water behavior in the transform winding present more acceptable values for Method B since oil moisture values are closer to $5\,\mathrm{ppm}$, which is the inlet water concentration assumed in the simulations performed.

The idea of possible limitations of the thermal models used in the transformer assessment is considered, which emphasizes the need to deepen the knowledge on paper-oil-water systems, and the possible creation of regions with higher water concentrations on the winding.

6 Work Assessment

6.1 Purpose Achieved

Through the work developed, new perspectives to assess the Remaining Life of a Power Transformer were present. Even though the results are provided from simulation data, they allow to verify the limitations of current methodologies applied.

It also allowed to understand better how temperature and moisture can interfere simultaneously with paper degradation, and how important it is to acquire more knowledge on the paper-oil-water system present in this complex device.

6.2 Limitations and Future Work

All assumptions registered on the work development present limitations on the integration of the results into actual transformer condition assessment. Therefore, there is a high necessity to overcome these barriers.

To start, it is critical to analyze the transformer winding in a non-stationary state. The stabilization of the transformer is a process that can take about 8 hours and implies that it does not suffer any interference. By itself, these conditions compel that in real conditions, Power Transformers hardly operate in the steady state since its energy condition depends on market demand. Therefore, the next step should be to understand the winding behavior when performed in the transitional regime.

As mentioned before, the simulations performed only present the temperature as a variable along the winding.

However, to understand the limitations of thermal models, it is crucial to understand how temperature and moisture influence the Remaining Life estimation when both are presented as variables along the winding. It is necessary to define the water migration behavior within the paper-oil-water system when exposed to a considerable temperature gradient and to identify how the water concentration values may change.

Finally, an alternative method for the water content in paper estimation should be developed since equilibrium curves present higher limitations and errors in the Remaining Life estimation.

6.3 Other Work Performed

In orther to understand the ageing process of paper insulation in Power Transformers, several projects were adopted. However, due to some difficulties in the area of research, it was impossible to pursuit them.

To start, the work attempted to incorporate an aging analysis using oil analysis data recognized during transformer operation. The study consisted of an analysis of the concentration of certain gas compounds, which result from cellulose degradation for active transformers. However, the main problem is that the sample collection of the refrigerant oil to analyze is not always performed by the same company, so there is a lapse in the information over time. In addition, the transformer data did not provide any information on possible equipment treatments, especially the replacement of this insulating material.

After that, it was studied the methods applied for the collection of variables over time and how it would be possible to implement something different. The sensor technology presented some limitations, especially on the water content during the tansformer operation.

A study was made of the different technologies applied in digital solutions and their evolution over time. Consequently, after understanding all the parameters involved, a parametric study was carried out, aiming to understand the weight and influence of each variable involved in the Remaining Life estimation of Power Transformers.

Finally, a study was performed to assess the paper condition before the transformer become active. During the transformer's manufacture, tests were performed to analyse the degree of polymerization of the new paper insulation and the its possible degradation before incorporate the machine, mainly due to its environmental conditions during the different process manufacture steps.

6.4 Final Assessment

The Remaining Life of a Power Transformer is an elaborated and complexed factor to estimate, and it is related to several variables involved in the transformer operation. Furthermore, the variables reading presents limitations and considerable associated errors. Therefore, technological evolution is needed to unlock the development of this equipment performance.

Even though simulations can be performed with a detail description of the geometric dimensions of the transformer winding, there is still a significant distinction between these results and real-life cases.

To sum up, the Remaining Life is a very slow variable. The time required to verify this variable behavior is very long since paper degradation can take many years to present a lower degree of polymerization of cellulose insulation. In other words, the execution of works around this subject presents big limitations regarding the collection of real data to posterior analysis. The implementation of digital solutions that assess the Remaining Life of the transformer is the first step in a path that will take Efacec through monitoring, control, optimization and automation of the energy network with minimal risk and highest return.

At a more personal level, this work has allowed me to understand the industrial sector a little more. I realized that there are many hurdles and difficulties in developing and optimizing a product and that it is not easy to overcome them. It was important for personal development both technically and professionally, and I am thankful for the opportunity.

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9 Appendix

9.1 Appendix A – Operational Data

- Temperature

During the operation of a power transformer, the temperature is one of the most important variables take into consideration and thoroughly controlled. As one of the transformer main operational data, temperature is involved in several issues, for example, it provides an alert in case the machine is not operating correctly since the variation of temperature is directly related to the loading current. In other words, when the loading current increases, the temperature increases too. Usually, the temperature can be compartmentalized into three parameters: the outdoor temperature, the hot spot temperature, and the oil temperature.

Although it is not very usual to consider the ambient temperature in laboratory studies related to power transformers, this parameter has a significant influence on the operation device. Fourier's Laws defines that higher exterior temperatures cause a decrease in the temperature gradient and, consequently, more difficulty in heat exchange processes. These conditions lead to an increase in the oil temperature and, consequently, a higher rate of thermal degradation of the paper.

Regarding hot spot temperature, this is characterized as the higher temperature in the machine, and it is essential to control and monitor since it is the location where thermal degradation happens faster. Typically, hot spots are in the windings of the transformer since on the top of the transformer it is where the oil shows the highest temperature. However, the top oil temperature on the winding is not precisely located at the extreme of the windings as one could expect.[6 28]

- Insulation Oil Properties

Another insulation material present in power transformers is oil. However, unlike paper, this fluid is also in charge of the heat exchange process, once in transformer operation, high temperatures are achieved that can damage or destroy the machine. So, it is imperative to understand the physical and chemical properties of the cooling fluid, since they are influenced by temperature, which varies over time and space. Usually, periodic analysis is made to the oil, that is recovered during the operation, and it has evaluated its physical and chemical properties along with the gas analysis.

In the oil test, the standard procedure consists in the evaluation of the physical and chemical properties, and the analysis of dissolved gas. Oil properties can be assessed qualitatively, like the color, or quantitatively, as dielectric strength, acidity, water content measures, among others, described above. Regarding oil analysis, it is measured the concentration of different gases in the oil sample, products from chemical, thermal, and electrical degradation processes, such as paper aging and overloads.

Therefore, the result set allows an evaluation of the oil properties and provide an idea of how the transformer is operating. In the case of the results show alarming values, other analysis can be made since it could mean that the transformer needs maintenance or to be shut down.

Besides oil properties, another essential factor is the perform of the heat exchange process during transformer operation. Usually, there are three types of convection used: natural, forced, and directed. These models can be combined since oil and air do not need to be circulating under the same conditions.

- Gas

The most concerning processes during transformer's aging are electrical and thermal degradation. Each one of these leads to the formation of certain products, usually gases, which allows control of the machine state and to what conditions it was exposed.

Regarding thermal degradation, the gases involved are monoxide carbon (CO) and carbon dioxide (CO_2) due to the degradation of paper insulation, and ethylene (C_2H_4) and ethane (C_2H_6) from oil degradation. On the other hand, electrical degradation is related to hydrogen (H_2) and methane (CH_4) due to partial discharges and hydrogen and acetylene (C_2H_2) from power flashes (arcing electrical discharges). Other gases are also present in the oil samples, such as oxygen (O_2), nitrogen (N_2) and furan compounds.[5] [29] Except for CO_2, all compounds mentioned are combustible gases.

- Transformer Design

Depending on the purpose of a particular transformer, this machine presents a set of specifications and characteristics, in which one of them is the design. In general, the transformer design affects not only its dimensions, as the volumes of the materials, but also the material used in its manufacture, the processes involved and the ability to control and gather most of the variables described above.

The more crucial change is in the heat exchange activity. With higher volumes of oil and different arrangements in the crossing sections, the cooling system changes and, consequently, temperature distribution and hot spots location alter, which influence the thermal degradation of the insulation material.

Regarding the transformer structure, another crucial variation parameter is the oxygen levels. Typically, there are three types of transformers considering the presence or lack of the conservator, which is a secondary oil tank that can control oil expansion when the temperature rises. This conservatory can allow direct contact between the oil and the atmospheric air, or it can incorporate a protection layer that separates the oil and the outside air. If the transformer does not have a conservator, on the top of the cube is added a gas layer, mostly nitrogen, connected to a gas deposit, with specific concentrations.

Thus, a controlled atmosphere inside of the transformer is considered when the atmosphere air and oil do not contact with each other, and in this case, oxygen levels and water content is usually an important measured parameter. If there is contact between outside air and the cooling fluid, then the environment is considered non-controlled, and the oxygen levels are not taken into consideration since oxygen or any other compound diffusion process can happen from the air to the oil or vise-versa.[8 30]

9.2 Appendix B - Original Temperature Data of the transformer winding

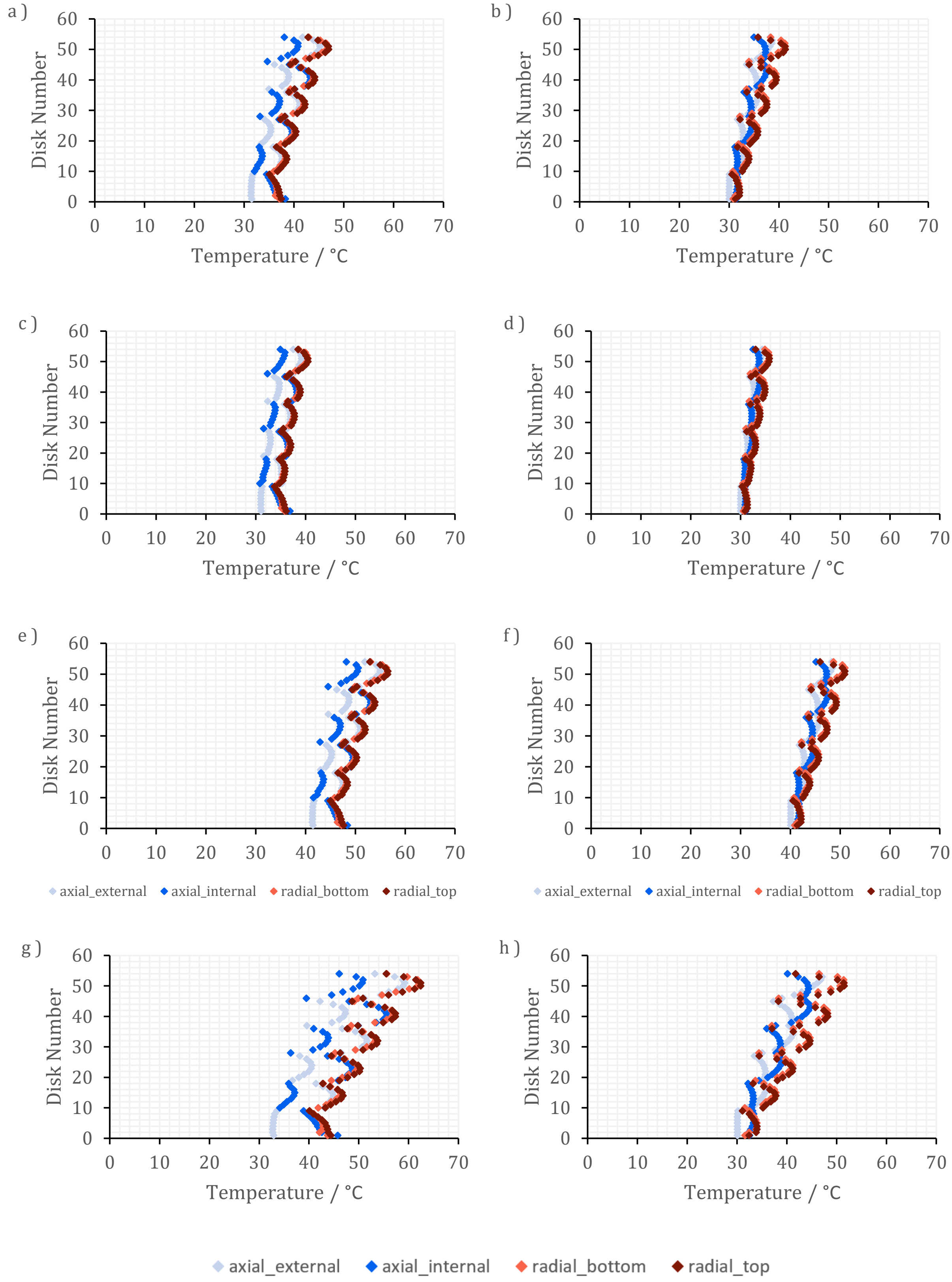

Figure B. 1 - Temperature distribution in the transformer winding for a) solid, simulation 1; b) fluid, simulation 1; c) solid, simulation 2; d) fluid, simulation 2; e) solid, simulation 3; f) fluid, simulation 3; g) solid, simulation 4; h) fluid, simulation 4.

Through the offset of 50 ℃ of the temperature along the winding represent above, in Figure 3.4, the hot spot temperature obtained in each profile for each simulation is represented in Table B.1.

Table B. 1 – Hot Spot temperatures obtained in each simulation performed, for both solid and fluid temperature profiles

Simulation	Hot spot Temperature of solid profiles	Hot spot Temperature of fluid profiles (°C)
1	97 ℃	91 ℃
2	90 ℃	86 ℃
3	107 ℃	101 ℃
4	112 ℃	102 ℃

9.3 Appendix C – Methodologies applied to the estimation of the Remaining Life of Power Transformers

Table C. 1 -Description of the Methodologies applied in each case

Case	Methodology
1	$\text{wcp} = f(\text{wco};\ T_{x,solid})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,solid})$
	$\text{wcp} = f(\text{wco};\ T_{x,fluid})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,fluid})$
2	$\text{wcp} = f(\text{wco};\ T_{inlet\ fluid})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,solid})$
	$\text{wcp} = f(\text{wco};\ T_{inlet\ fluid})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,fluid})$
3	$\text{wcp} = f(\text{wco};\ T_{outlet\ fluid})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,solid})$
	$\text{wcp} = f(\text{wco};\ T_{outlet\ fluid})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,fluid})$
4	$\text{wcp} = f(\text{wco};\ T_{hotspot})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,solid})$
	$\text{wcp} = f(\text{wco};\ T_{hotspot})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,fluid})$
5	$\text{wcp} = f(\text{wco};\ T_{average})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,solid})$
	$\text{wcp} = f(\text{wco};\ T_{average})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,fluid})$
6	$\text{wcp} = f(\text{wco};\ T_{x,fluid})\ ; A = f(\text{wcp})$ $\text{RL} = f(A; T_{x,solid})$
7	$A = const$ $\text{RL} = f(A; T_{x,solid})$
	$A = const$ $\text{RL} = f(A; T_{x,fluid})$

9.4 Appendix D – Data from the variation Analysis

Variation Data from Simulation 2

Table D. 1 - Variation of the Remaining Life along the winding to dry, 5 ppm and 20 ppm water concentration values, from Simulation 2

	dry	5 ppm					20 ppm				
Disk Number	Case 7	Case 1	Case 2	Case 3	Case 4	Case 5	Case 1	Case 2	Case 3	Case 4	Case 5
54	3	16	20	16	13	15	7	8	7	6	7
53	3	16	21	18	16	16	7	8	8	7	7
52	3	17	21	19	17	17	8	9	8	7	7
51	3	18	22	20	18	18	8	9	8	8	8
50	3	19	23	21	19	20	8	9	9	8	8
49	3	19	25	22	20	20	9	10	9	9	9
48	3	20	26	23	21	21	9	10	10	9	9
47	4	24	32	29	27	27	11	13	12	12	11
46	4	26	35	32	29	30	12	14	13	13	13
45	2	13	18	10	6	9	6	7	5	4	5
44	2	14	19	13	10	12	6	7	6	5	6
43	3	15	20	15	12	14	7	8	7	6	6
42	3	16	20	16	13	15	7	8	7	6	7
41	3	16	21	17	14	15	7	8	7	7	7
40	3	17	22	17	15	16	7	9	8	7	7
39	3	17	22	18	15	17	8	9	8	7	7
38	4	22	29	26	23	24	10	12	11	10	10
37	4	26	35	31	29	29	11	14	13	12	12
36	2	15	20	12	9	12	7	8	6	5	6
35	3	16	21	15	12	14	7	9	7	6	7
34	3	17	22	17	14	16	8	9	8	7	7
33	3	18	23	18	15	17	8	9	8	7	8
32	3	18	24	19	17	18	8	10	8	8	8
31	3	19	25	20	17	19	8	10	9	8	8
30	3	19	25	20	17	19	8	10	9	8	8
29	4	24	32	28	25	26	11	13	12	11	11
28	4	27	37	33	30	30	12	15	14	13	13
27	3	17	23	14	10	13	7	9	7	6	6
26	3	18	24	16	13	15	8	10	8	7	7
25	3	18	25	18	15	17	8	10	8	7	8
24	3	19	25	19	16	18	8	10	9	8	8
23	3	20	26	21	18	19	9	10	9	8	8
22	3	20	27	21	18	20	9	11	9	8	9
21	3	20	27	21	18	20	9	11	9	8	9
20	4	22	30	24	21	23	10	12	11	10	10
19	4	27	36	31	28	29	12	15	13	12	12
18	3	19	25	17	12	16	8	10	8	7	7
17	3	20	27	19	15	18	9	11	9	8	8
16	3	21	28	21	18	20	9	11	10	8	9
15	3	22	29	23	19	21	9	12	10	9	9
14	4	22	30	24	21	22	10	12	11	10	10
13	4	22	30	24	20	22	10	12	11	10	10
12	4	22	30	23	20	22	10	12	10	9	10
11	4	24	32	26	22	24	10	13	11	10	11
10	4	27	38	31	27	29	12	15	14	12	13
9	3	21	30	20	16	19	9	12	9	8	9
8	3	22	31	22	18	21	10	12	12	9	10
7	4	23	32	24	20	22	10	13	11	10	10
6	4	23	32	25	21	24	10	13	11	10	10
5	4	24	33	26	22	24	10	13	11	10	11
4	4	24	33	27	23	25	11	13	12	11	11
3	4	24	33	27	24	25	11	13	12	11	11
2	4	27	37	32	28	30	12	15	14	13	13
1	5	33	45	42	39	39	14	18	17	17	16

Table D. 2 - Variation of the Remaining Life along the winding to 5 ppm (right) and 20 ppm (left) for both solid and fluid temperature profiles, from Simulation 2

	5 ppm										20 ppm									
	Fluent					Solid					Fluent					Solid				
Disk Number	**Case 1 & 6**	**Case 2 & 6**	**Case 3 & 6**	**Case 4 & 6**	**Case 5 & 6**	**Case 1 & 2**	**Case 3 & 2**	**Case 4 & 2**	**Case 5 & 2**	**Case 6 & 2**	**Case 1 & 6**	**Case 2 & 6**	**Case 3 & 6**	**Case 4 & 6**	**Case 5 & 6**	**Case 1 & 2**	**Case 3 & 2**	**Case 4 & 2**	**Case 5 & 2**	**Case 6 & 2**
54	25	12	25	28	19	17	17	23	13	8	10	6	10	10	8	5	5	7	4	3
53	26	12	24	27	19	18	15	19	11	8	10	6	9	10	8	5	4	6	3	3
52	27	13	25	27	19	18	14	19	10	8	10	6	10	10	8	5	4	5	3	3
51	28	14	26	29	21	18	14	18	10	8	11	6	10	11	8	5	4	5	3	2
50	29	16	28	31	22	18	14	19	10	8	11	7	11	12	9	5	4	5	3	2
49	30	17	30	33	24	18	15	20	11	7	12	8	12	12	10	5	4	6	3	2
48	31	19	33	36	27	18	17	22	12	7	12	8	13	13	11	5	5	6	4	2
47	36	27	43	46	35	17	19	25	14	5	14	11	16	17	14	5	5	7	4	2
46	38	32	50	54	42	15	22	28	16	4	15	13	19	20	16	5	6	8	5	1
45	20	10	24	28	18	15	23	30	16	8	8	5	9	10	7	5	7	9	5	2
44	23	10	24	27	18	16	20	26	14	8	9	5	9	10	7	5	6	7	4	3
43	24	11	25	27	19	17	18	24	13	8	9	5	9	10	8	5	5	7	4	3
42	25	12	25	28	19	17	17	23	13	8	10	6	10	10	8	5	5	7	4	3
41	26	13	26	29	20	18	17	22	12	8	10	6	10	11	8	5	5	7	4	2
40	26	14	27	30	21	17	17	23	12	8	10	6	10	11	8	5	5	7	4	2
39	27	15	28	31	22	17	18	23	13	8	10	7	11	12	9	5	5	7	4	2
38	33	24	39	43	32	17	19	25	14	6	13	10	15	16	13	5	6	7	4	2
37	38	32	51	55	42	15	23	30	16	3	15	13	19	20	16	5	7	9	5	1
36	23	13	28	32	21	15	23	30	17	7	9	6	10	11	8	5	7	9	5	2
35	25	14	29	32	22	16	21	27	15	7	10	6	11	12	9	5	6	8	5	2
34	26	15	30	33	23	16	20	26	14	7	10	7	11	12	9	5	6	8	4	2
33	27	16	31	34	24	16	20	26	14	7	11	7	12	13	10	5	6	7	4	2
32	28	17	32	36	25	16	20	26	14	7	11	8	12	13	10	5	6	7	4	2
31	29	19	34	37	27	16	20	26	14	6	11	8	13	14	11	5	6	8	4	2
30	29	19	35	38	28	16	21	27	15	6	11	8	13	14	11	5	6	8	5	2
29	35	28	46	50	38	15	22	29	16	4	14	12	17	18	15	5	6	8	5	1
28	39	35	55	60	46	14	25	33	18	2	15	14	20	22	18	4	7	10	5	1
27	25	18	35	39	27	13	26	34	19	5	10	7	13	14	10	4	8	10	6	2
26	26	18	35	39	27	14	24	31	17	6	10	8	13	14	11	4	7	9	5	2
25	28	19	35	39	28	15	23	30	16	6	11	8	13	14	11	5	7	9	5	2
24	29	19	35	39	28	15	22	29	16	6	11	8	13	14	11	5	6	8	5	2
23	29	20	36	40	29	16	21	28	16	6	11	9	14	15	11	5	6	8	5	2
22	30	21	37	41	30	15	22	28	16	6	12	9	14	15	12	5	6	8	5	2
21	30	21	38	42	30	15	22	29	16	5	12	9	14	15	12	5	7	9	5	2
20	33	25	43	47	35	15	23	30	17	4	13	11	16	17	14	4	7	9	5	1
19	38	34	55	59	45	13	26	34	19	2	15	14	20	22	17	4	8	10	6	1
18	27	21	40	44	31	13	27	36	20	4	11	9	15	16	12	4	8	10	6	1
17	29	22	40	44	32	14	25	33	18	4	11	9	15	16	12	4	7	10	6	1
16	30	24	41	45	33	14	25	32	18	4	12	10	15	16	13	4	7	9	5	1
15	32	25	43	47	35	14	24	32	18	4	12	10	16	17	13	4	7	9	5	1
14	32	26	45	49	36	14	25	32	18	4	13	11	17	18	14	4	7	9	5	1
13	33	27	46	50	37	14	25	33	18	4	13	11	17	18	14	4	7	10	5	1
12	32	27	45	50	37	14	26	34	19	4	13	11	17	18	14	4	8	10	6	1
11	34	29	49	54	40	13	26	34	19	3	13	12	18	19	15	4	8	10	6	1
10	38	37	59	64	49	12	28	37	21	1	15	15	22	23	19	4	8	11	6	0
9	31	28	49	54	40	11	31	40	22	2	12	11	18	19	15	3	9	12	7	1
8	32	29	50	54	40	12	29	38	21	2	13	12	18	19	15	4	9	11	6	1
7	33	29	50	54	40	12	28	37	20	2	13	12	18	19	15	4	8	11	6	1
6	34	30	50	54	40	13	27	35	20	3	13	12	18	19	15	4	8	10	6	1
5	34	30	49	54	40	13	26	34	19	3	14	12	18	19	15	4	8	10	6	1
4	35	30	50	54	41	13	26	34	19	3	14	12	18	20	16	4	8	10	6	1
3	35	30	50	54	41	14	26	34	19	3	14	12	18	20	16	4	8	10	6	1
2	39	35	56	61	46	13	26	34	19	2	15	14	21	22	18	4	8	10	6	1
1	46	44	65	70	55	14	24	32	18	1	18	18	24	26	21	4	7	9	5	0

Variation Data from Simulation 3

Table D. 3 - Variation of the Remaining Life along the winding to dry, 5 ppm and 20 ppm water concentration values, from Simulation 3

	dry	5 ppm					20 ppm				
Disk Number	Case 7	Case 1	Case 2	Case 3	Case 4	Case 5	Case 1	Case 2	Case 3	Case 4	Case 5
54	3	16	20	16	13	15	7	8	7	6	7
53	3	16	21	18	16	16	7	8	8	7	7
52	3	17	21	19	17	17	8	9	8	7	7
51	3	18	22	20	18	18	8	9	8	8	8
50	3	19	23	21	19	20	8	9	9	8	8
49	3	19	25	22	20	20	9	10	9	9	9
48	3	20	26	23	21	21	9	10	10	9	9
47	4	24	32	29	27	27	11	13	12	12	11
46	4	26	35	32	29	30	12	14	13	13	13
45	2	13	18	10	6	9	6	7	5	4	5
44	2	14	19	13	10	12	6	7	6	5	6
43	3	15	20	15	12	14	7	8	7	6	6
42	3	16	20	16	13	15	7	8	7	6	7
41	3	16	21	17	14	15	7	8	7	7	7
40	3	17	22	17	15	16	7	9	8	7	7
39	3	17	22	18	15	17	8	9	8	7	7
38	4	22	29	26	23	24	10	12	11	10	10
37	4	26	35	31	29	29	11	14	13	12	12
36	2	15	20	12	9	12	7	8	6	5	6
35	3	16	21	15	12	14	7	9	7	6	7
34	3	17	22	17	14	16	8	9	8	7	7
33	3	18	23	18	15	17	8	9	8	7	8
32	3	18	24	19	17	18	8	10	8	8	8
31	3	19	25	20	17	19	8	10	9	8	8
30	3	19	25	20	17	19	8	10	9	8	8
29	4	24	32	28	25	26	11	13	12	11	11
28	4	27	37	33	30	30	12	15	14	13	13
27	3	17	23	14	10	13	7	9	7	6	6
26	3	18	24	16	13	15	8	10	8	7	7
25	3	18	25	18	15	17	8	10	8	7	8
24	3	19	25	19	16	18	8	10	9	8	8
23	3	20	26	21	18	19	9	10	9	8	8
22	3	20	27	21	18	20	9	11	9	8	9
21	3	20	27	21	18	20	9	11	9	8	9
20	4	22	30	24	21	23	10	12	11	10	10
19	4	27	36	31	28	29	12	15	13	12	12
18	3	19	25	17	12	16	8	10	8	7	7
17	3	20	27	19	15	18	9	11	9	8	8
16	3	21	28	21	18	20	9	11	10	8	9
15	3	22	29	23	19	21	9	12	10	9	9
14	4	22	30	24	21	22	10	12	11	10	10
13	4	22	30	24	20	22	10	12	11	10	10
12	4	22	30	23	20	22	10	12	10	9	10
11	4	24	32	26	22	24	10	13	11	10	11
10	4	27	38	31	27	29	12	15	14	12	13
9	3	21	30	20	16	19	9	12	9	8	9
8	3	22	31	22	18	21	10	12	12	9	10
7	4	23	32	24	20	22	10	13	11	10	10
6	4	23	32	25	21	24	10	13	11	10	10
5	4	24	33	26	22	24	10	13	11	10	11
4	4	24	33	27	23	25	11	13	12	11	11
3	4	24	33	27	24	25	11	13	12	11	11
2	4	27	37	32	28	30	12	15	14	13	13
1	5	33	45	42	39	39	14	18	17	17	16

Table D. 4 - Variation of the Remaining Life along the winding to 5 ppm (right) and 20 ppm (left) for both solid and fluid temperature profiles, from Simulation 3

	5 ppm										20 ppm									
	Fluent					Solid					Fluent					Solid				
Disk Number	Case 1 & 6	Case 2 & 6	Case 3 & 6	Case 4 & 6	Case 5 & 6	Case 1 & 2	Case 3 & 2	Case 4 & 2	Case 5 & 2	Case 6 & 2	Case 1 & 6	Case 2 & 6	Case 3 & 6	Case 4 & 6	Case 5 & 6	Case 1 & 2	Case 3 & 2	Case 4 & 2	Case 5 & 2	Case 6 & 2
54	10	2	10	14	6	10	10	16	6	5	4	0	4	6	2	5	5	8	3	2
53	10	1	8	11	5	10	7	12	5	5	4	0	3	4	1	5	4	6	2	2
52	10	1	8	10	5	11	7	11	4	5	4	0	3	4	1	6	3	6	2	2
51	11	2	8	11	5	11	7	11	4	5	4	0	3	4	2	6	3	6	2	2
50	11	2	9	12	6	11	7	11	4	5	4	0	3	5	2	6	3	6	2	2
49	12	3	11	14	7	10	8	12	5	4	5	1	4	6	3	5	4	7	2	2
48	13	5	13	17	9	10	9	14	6	4	5	1	5	7	3	5	4	8	3	2
47	15	9	19	24	14	9	10	17	7	3	6	3	8	10	5	5	5	9	3	2
46	17	12	25	31	19	9	14	22	9	3	6	4	10	13	7	4	7	12	4	1
45	9	2	12	16	7	9	14	22	9	5	3	0	5	7	2	4	7	12	4	2
44	9	1	10	13	6	9	11	18	7	5	3	0	4	6	2	4	5	9	3	2
43	9	1	9	12	5	10	10	16	6	5	4	0	3	5	2	5	5	8	3	2
42	10	1	9	12	5	10	9	15	6	5	4	0	3	5	2	5	4	8	3	2
41	10	2	9	12	6	10	9	15	6	5	4	0	4	5	2	5	4	8	3	2
40	10	2	10	13	6	10	9	15	6	5	4	0	4	5	2	5	4	8	3	2
39	11	3	11	15	7	10	10	16	6	5	4	1	4	6	3	5	5	8	3	2
38	14	8	18	23	13	9	11	18	7	4	5	2	7	9	5	4	5	9	3	2
37	18	13	27	33	21	8	15	24	9	3	7	4	11	14	8	4	7	12	4	1
36	10	3	14	19	9	8	14	23	9	5	4	1	6	8	3	4	7	12	4	2
35	10	3	13	17	8	9	12	20	8	5	4	1	5	7	3	4	6	11	4	2
34	11	3	13	17	8	9	11	18	7	5	4	1	5	7	3	4	6	10	3	2
33	11	3	13	17	8	9	11	18	7	5	4	1	5	7	3	4	5	9	3	2
32	11	4	13	17	9	9	11	18	7	5	4	1	5	7	3	4	5	9	3	2
31	12	5	15	19	10	9	11	19	7	4	5	1	6	8	4	4	6	10	3	2
30	13	6	16	21	11	9	12	20	8	4	5	2	7	9	4	4	6	11	4	2
29	16	11	24	29	18	9	14	22	9	3	6	4	10	12	7	4	7	12	4	1
28	19	16	33	40	25	8	18	28	11	2	7	6	13	17	10	3	9	15	5	1
27	11	6	19	25	13	8	18	29	11	4	4	2	8	11	5	3	9	15	5	2
26	12	6	18	23	12	8	15	25	10	4	4	2	7	10	5	4	8	13	5	2
25	12	6	17	22	12	8	14	23	9	4	4	2	7	9	4	4	7	12	4	2
24	12	6	17	22	12	9	14	22	9	4	5	2	7	9	4	4	7	12	4	2
23	13	6	18	22	12	9	13	22	9	4	5	2	7	10	5	4	7	11	4	2
22	13	7	19	24	13	9	14	22	9	4	5	2	8	10	5	4	7	12	4	2
21	13	8	20	26	14	8	15	24	10	4	5	2	8	11	5	4	7	13	4	2
20	14	9	23	28	16	8	16	25	10	3	5	3	9	12	6	4	8	13	5	1
19	19	17	34	41	26	7	18	30	12	2	7	6	14	18	10	3	9	16	6	1
18	13	9	25	31	17	7	20	32	13	3	5	3	10	13	7	3	10	17	6	1
17	13	9	23	29	16	8	18	29	12	3	5	3	9	12	6	3	9	15	5	1
16	14	9	23	29	16	8	17	27	11	3	5	3	9	12	6	4	8	14	5	1
15	14	9	23	29	17	8	16	26	11	3	5	3	9	12	6	4	8	14	5	1
14	15	10	24	30	18	8	17	27	11	3	5	3	10	13	7	4	8	14	5	1
13	15	11	26	32	19	8	17	28	11	3	6	4	11	14	7	3	8	15	5	1
12	15	11	27	33	19	7	18	30	12	2	6	4	11	14	7	3	9	16	6	1
11	16	12	28	35	21	7	19	31	12	2	6	4	12	15	8	3	9	16	6	1
10	20	19	39	48	30	7	22	35	14	1	7	7	16	20	12	3	10	18	6	0
9	16	14	33	41	24	6	23	38	15	1	6	5	14	17	9	3	11	20	7	1
8	16	14	32	40	24	6	22	36	14	1	6	5	13	17	9	3	11	19	7	1
7	16	14	31	39	23	7	21	34	14	2	6	5	13	17	9	3	10	18	6	1
6	17	14	31	38	23	7	20	33	13	2	6	5	13	16	9	3	10	17	6	1
5	17	13	31	38	23	7	20	32	13	2	6	5	12	16	9	3	10	17	6	1
4	17	14	31	38	23	7	20	32	13	2	6	5	12	16	9	3	10	17	6	1
3	17	14	31	38	23	7	20	32	13	2	6	5	13	16	9	3	9	17	6	1
2	19	17	36	43	27	7	20	32	13	1	7	6	14	18	10	3	10	17	6	1
1	24	22	42	50	33	7	18	30	12	1	9	8	17	21	13	3	9	16	6	0

9.5 Appendix E – Simulation Data

Table E. 1 - Data collected from Case 1 of Simulation 1

Disk Number	Treal (°C)	wpc (%)	A-value	Remaining Life
54	92.96	0.30	2.23E+10	39.10
53	95.27	0.28	2.02E+10	33.06
52	96.48	0.26	1.92E+10	30.44
51	96.80	0.26	1.89E+10	29.79
50	96.55	0.26	1.91E+10	30.29
49	95.64	0.27	1.99E+10	32.23
48	94.09	0.29	2.13E+10	35.97
47	92.37	0.30	2.28E+10	40.88
46	89.69	0.33	2.54E+10	50.16
45	89.55	0.33	2.56E+10	50.56
44	91.56	0.31	2.35E+10	43.51
43	92.97	0.30	2.23E+10	39.08
42	93.67	0.29	2.17E+10	37.08
41	93.91	0.29	2.15E+10	36.45
40	93.79	0.29	2.16E+10	36.77
39	93.27	0.29	2.20E+10	38.21
38	91.95	0.31	2.32E+10	42.20
37	89.27	0.34	2.60E+10	51.44
36	89.20	0.34	2.61E+10	51.64
35	90.72	0.32	2.43E+10	46.49
34	91.56	0.31	2.35E+10	43.50
33	91.92	0.31	2.32E+10	42.30
32	91.98	0.31	2.32E+10	42.11
31	91.73	0.31	2.34E+10	42.95
30	91.07	0.32	2.40E+10	45.20
29	89.81	0.33	2.52E+10	49.78
28	87.57	0.37	2.85E+10	57.30
27	87.47	0.37	2.87E+10	57.69
26	88.75	0.35	2.68E+10	53.12
25	89.57	0.33	2.56E+10	50.51
24	90.00	0.33	2.49E+10	49.23
23	90.11	0.33	2.48E+10	48.82
22	89.87	0.33	2.51E+10	49.63
21	89.22	0.34	2.61E+10	51.57
20	88.53	0.35	2.71E+10	53.84
19	87.33	0.37	2.89E+10	58.22
18	86.56	0.38	3.00E+10	61.38
17	87.38	0.37	2.88E+10	58.04
16	88.05	0.36	2.78E+10	55.53
15	88.30	0.35	2.74E+10	54.64
14	88.25	0.36	2.75E+10	54.80
13	87.87	0.36	2.81E+10	56.16
12	87.29	0.37	2.89E+10	58.40
11	86.81	0.38	2.96E+10	60.31
10	85.96	0.39	3.09E+10	64.03
9	85.10	0.41	3.22E+10	68.12
8	85.54	0.40	3.15E+10	65.99
7	85.94	0.39	3.09E+10	64.09
6	86.28	0.39	3.04E+10	62.58
5	86.48	0.38	3.01E+10	61.70
4	86.56	0.38	3.00E+10	61.37
3	86.58	0.38	3.00E+10	61.29
2	86.26	0.39	3.05E+10	62.69
1	87.11	0.37	2.92E+10	59.11

Annex A - Data information of the Simulations performed

Table AA. 1 - Distribution of the heights of the radial channel along the winding, adapted [27]

Radial Channel	Channel Height / mm					
	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5	Pass 6
10	3	3	3	3	3	3
9	3	3	3	3	3	4
8	3	3	3	3	3	4
7	3	3	3	3	3	4
6	3	3	3	3	3	4
5	3	3	3	3	3	4
4	3	3	3	3	3	4
3	3	3	3	3	3	4
2	4	3	3	4	4	4
1	3	3	3	3	3	3

Table AA. 2 - Heat source released on each disk used in the simulations [27]

Pass	Disc number	Set 1 W m^{-3}	Set 2 W m^{-3}	Pass	Disc number	Set 1 W m^{-3}	Set 2 W m^{-3}
	1	215 051.0	430 102.0		28	166 375.3	332 750.5
	2	185 127.4	370 254.8		29	165 976.3	331 952.6
	3	173 158.0	346 315.9		30	165 976.3	331 952.6
	4	167 971.2	335 942.4		31	166 375.3	332 750.5
1	5	165 976.3	331 952.6	4	32	165 976.3	331 952.6
	6	165 577.3	331 154.6		33	165 976.3	331 952.6
	7	165 577.3	331 154.6		34	165 976.3	331 952.6
	8	166 375.3	332 750.5		35	165 976.3	331 952.6
	9	167 173.2	334 346.5		36	165 976.3	331 952.6
	10	165 577.3	331 154.6		37	167 572.2	335 144.4
	11	165 577.3	331 154.6		38	166 774.3	333 548.5
	12	165 976.3	331 952.6		39	166 774.3	333 548.5
	13	165 976.3	331 952.6		40	166 375.3	332 750.5
2	14	166 375.3	332 750.5	5	41	166 375.3	332 750.5
	15	166 375.3	332 750.5		42	165 976.3	331 952.6
	16	166 774.3	333 548.5		43	165 976.3	331 952.6
	17	167 173.2	334 346.5		44	165 577.3	331 154.6
	18	167 971.2	335 942.4		45	165 976.3	331 952.6
	19	165 976.3	331 952.6		46	167 173.2	334 346.5
	20	165 976.3	331 952.6		47	166 375.3	332 750.5
	21	165 976.3	331 952.6		48	165 577.3	331 154.6
	22	166 375.3	332 750.5		49	165 577.3	331 154.6
3	23	166 375.3	332 750.5	6	50	166 375.3	332 750.5
	24	166 375.3	332 750.5		51	168 370.2	336 740.4
	25	166 375.3	332 750.5		52	173 158.0	346 315.9
	26	166 375.3	332 750.5		53	185 127.4	370 254.8
	27	166 375.3	332 750.5		54	215 849.0	431 698.0