CFD study of the impact of the deviation on the mass flow inlet on winding hot-spot temperature of a power transformer using mineral and ester oils

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***Abstract*— This work presents a study where a deviation on the mass flow rate in adjacent sectors of the winding is considered. A CFD model was developed for this study, where heat transfer between sectors is enabled due to the lack of thermal symmetry, and the goal of this study is to determine whether this effect can be neglected or not. To carry out this study, a Low Voltage Winding of a 100 MVA power transformer was selected. This transformer has been manufactured and tested by BEST Transformers, and the results obtained from the heat run test were used to validate the CFD model. The study also considered an alternative dielectric liquid, natural ester, in order to estimate if the different thermal and hydraulic conditions can affect to the relevance of the studied effect. The CFD simulations have been carried out with ANSYS Fluent. The results showed a deviation of 3-4% of the heat dissipated due to the non-symmetric conditions with a 10% of mass flow deviation, which is the heat transfer between the adjacent sectors. This effect is identical when considering mineral oil or natural ester. The results shows there is a small impact of the winding temperatures due to this effect, and that it can be considered negligible.**

Keywords—CFD, Power transformer, Ester oils, Thermal modelling

I. INTRODUCTION

Oil-immersed power transformers are one of the most expensive and critical components of an electrical system. Despite being highly efficient machines, a small fraction of the transferred power is lost in the form of heat (mainly in the windings), which must be removed. A heat-carrier dielectric fluid, generally a mineral oil, is used to remove the generated heat, and simultaneously provide electrical insulation. This liquid circulates around and through the windings cooling them, and thus preventing hot spots that negatively affects to the transformer lifetime. The dimensions of these cooling channels depend on the dielectric fluid properties, as well as the structural and electrical requirements, [1].

One of the most extended techniques for the thermal modelling of power transformers is the Computational Fluid Dynamics (CFD). In CFD, the governing principles of both fluid flow and heat transfer are written in the form of partial differential equations that are then replaced by algebraic equations and solved at discrete elements in time and space. During the last two decades, several authors have reported the CFD technique as a relevant tool to investigate and improve the thermal performance of power transformers windings. In the first decade, the main purpose of CFD was to determine the velocity and temperature profiles of a 2-D winding immersed in a mineral oil, [2–7]. More recently, the improvement of computational resources has enabled the use of 3-D models to conduct numerical investigations, allowing to capture three-dimensional phenomena that are impossible to find in 2-D models, [8-12]. These works model fluids and solids in the transformer, using the Conjugate Heat Transfer (CHT) model for the fluid-solid interface coupling.

More recent studies have been carried out using both 2-D and 3-D models to better understand and characterize the thermal-hydraulic performance of the insulation systems (oil and paper) with ester-based oils, [13, 14], as well as to evaluate the cooling efficiency of several alternative liquids, [15–18].

The hot-spot temperature is directly related with the aging of the transformer insulation. In this topic, studies have determined that natural ester reduces the aging rate of the insulation paper. To carry out these studies, accelerated aging test where performed and the degree of polymerization and tensile strength were tested when immersed in mineral oil and natural ester [14], [19–24].

The lower aging rate of the dielectric paper immersed in esters is offset by the higher temperature that appears in its windings, due to the higher viscosity of these liquids, compared to mineral oil. Notwithstanding the higher temperature in the windings, there are multiple experiences in which transformers designed for mineral oil were filled with biodegradable esters [16, 19], for overload requirements, environmental reasons or to increase fire safety in the substation. In addition, the retrofilling of transformers with esters is outlined in the standards that deal with these fluids [20, 21].

Traditionally, thermal winding models considers identical winding sectors, limited by sticks and spacers inside the winding, with identical behavior i.e. same hydraulic resistance, mass flow rate and heat generated per section. However, real life constructions can lead to slightly differences among the sections which can lead to deviations on the total hydraulic resistance and the mass flow rate

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between sectors. This effect breaks the identical behavior of the sections and enables the heat transfer between two adjacent sections. This work tries to assess this effect considering a power transformer winding and the goal is to estimate the impact of these mass flow deviations in adjacent sectors of the winding.

II. MODEL DESCRIPTION

This section describes the model used for the CFD simulations carried out in this study. The model corresponds to a 100 MVA power transformer Low-Voltage Winding (LVW) working under heat-run test conditions.

A. Geometry

As previously mentioned, the geometry considered for this work corresponds to a LVW of a 100 MVA power transformer that is currently manufactured and tested by BEST Transformers. The studied winding consists of an inner insulation cardboard cylinder of 784 mm of diameter and five conductor layers, which are 16 mm width. The spacers placed between layers form axial cooling ducts of 6mm width. 80 spacers are placed on the tangential direction, leading to 80 sectors of 4.5 degrees each, which have identical behavior under normal conditions. The winding is formed by Continuously Transposed Conductor (CTC) with 16 mm radial dimension and 15mm in axial dimension. The total height of the winding is 1634 mm.

For this study, the heat transfer between sections is considered and analyzed. This heat transfer mechanism is provoked by a deviation on the mass flow rate at the inlet of each section. This deviation can derive from differences in the manufacturing process or tolerances on the construction, leading to different hydraulic resistances. This will end up in adjacent sections working under different thermal conditions and thus allowing the heat transfer between sections. For this study, deviations up to 10% are considered to study the impact of this effect over the heat transfer in the winding.

B. Governing equations

Regarding the CFD simulations, the solid and fluid interfaces inside the transformer winding are modelled using the Conjugate Heat Transfer model. Thus, different equations are considered for the fluid and solid domains.

In the fluid domain, mass, momentum and energy conservation equations are considered. To model the buoyancy forces, the Boussinesq approach has been used in the model. For this approach, fluid properties are considered constant and calculated at the reference temperature. This model leads to the equations (1-3).

$$\nabla \boldsymbol{u} = 0 \tag{1}$$

$$\rho \cdot \frac{\partial \boldsymbol{u}}{\partial t} + \rho \cdot (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla p + \mu(\nabla^2 \boldsymbol{u}) + \rho_{ref} \cdot \boldsymbol{g} \cdot \beta \cdot (T - T_{ref}) \tag{2}$$

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} + \rho \cdot c_p \cdot \nabla \cdot (\boldsymbol{u}\, T) = k \cdot \nabla^2 T \tag{3}$$

Where ρ is the fluid density, u is the velocity field, p is the pressure field, μ is the fluid viscosity, g is the gravity vector, β is the thermal expansion coefficient, c_p is the specific heat of the fluid, k is the thermal conductivity of the fluid and T is the temperature field.

Equations (1-3) describe a non-isothermal incompressible flow for a Newtonian fluid, where the viscous friction and pressure contribution to the energy equation are negligible. In this case, these equations describe the oil flow through the winding channels. Since the flow is thermally driven and the fluid viscosity is high, no high Reynolds number are expected, so laminar flow model is chosen for the case.

In the solid domain, the temperature follows a diffusion equation. Equation (4) describes the behavior of the temperature field inside the solid domain.

$$\rho\, c_p \frac{\partial T}{\partial t} = k \cdot \nabla^2 T + q_s \tag{4}$$

Equation (4) represents the equation of a transient 3D diffusion process with a source term that represents the power losses on the conductor layers of the winding.

The governing equations are solved using the Finite Volume Method (FMV) using the commercial software ANSYS Fluent and considering a steady-state study. For this problem, a structured hexahedral mesh is used for the FVM. Second Order Linear Upwind scheme is selected for the derivatives approach in a pressure-velocity coupled scheme of a pressure-based solver. The normalized residuals are set to be lower than 10^{-5}, except for the energy equation residuals, that is set to be lower than 10^{-8}. The model uses a structured hexahedral mesh of 14M elements for the CFD analysis. Mesh independence test and validation of the CFD model have been carried out a previous work of the authors [24].

C. Boundary conditions

The boundary conditions selected for this case are a uniform velocity and uniform temperature at the inlet, that represents the mass flow rate through each section and the bottom oil temperature of the transformer, which is the inlet temperature of the winding. These values are obtained from the geometrical aspects of the transformer and from the heat run test results, by performing a thermal and hydraulic balance of the transformer cooling circuit. At the outlet, a zero gauge pressure condition was set. External walls of the domain are considered as static walls with no-slip condition and adiabatic, since the thermal conductivity of the insulation cylinder is very low. Solid-fluid interface boundaries, such as disc walls, are considered as no-slip walls with thermal coupling (considered in the CHT model). For the heat losses, a volumetric heat source is considered in the conductor domain, which represents the losses under heat-run test conditions.

D. Materials

The oils considered for this work are a mineral oil and a natural ester as cooling fluids. Since Boussinesq approach is considered, properties of the oil are calculated at a reference temperature, which is the bottom oil temperature. The properties from these fluids are shown in Table I. Thermal properties of dielectric fluids.

	Mineral oil	**Natural ester**
Ref T (K)	337.9	329
Density (kg/m3)	832.1	894.4
Viscosity (Pa·s)	3.98e-3	1.93e-2
Specific heat (J/kgK)	2392	1915
Thermal Conductivity (W/mK)	0.129	0.172
Thermal expansion coefficient	6.26e-4	5.89e-4

The conductor material is considered as a uniform material with cylindrical orthotropic thermal conductivity that represents the combination of materials in a CTC conductor.

III. RESULTS AND DISCUSSION

In this section, the results obtained from the simulations proposed in this work are presented. Three different cases are considered, apart from the reference case. In all of them, there are two inlets of two adjacent sections when considering a 10% deviation of the mass flow rate as well as the reference value of the oil flow rate at the inlet. Those values are presented in Table II. The inlet temperature corresponds to the reference temperature shown in Table I.

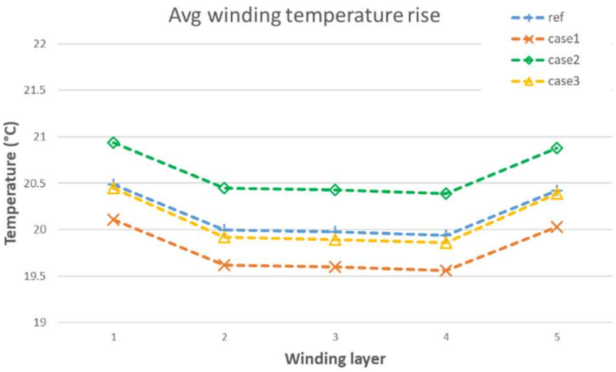
A. *Mineral oil*

The results from all the cases considered show that there exists a little heat transfer between adjacent sections under the conditions considered in the study. With a 10% mass flow deviation, the section with higher mass flow rate dissipates a 3-4% more heat than the generated in that section. In the case of temperature distributions and hot spot temperatures, having a mass flow deviation in those sections does not produce any different average or maximum temperature deviation between them. Average and maximum temperature in both layers are the same.

When comparing the thermal behavior between the cases, similar results have been obtained, as seen in Fig 1. Case 2 is the most unfavorable case, leading to higher temperatures, whereas case 1 leads to the lower temperatures. In both case 1 and 2, the total mass flow rate is lower and higher than the reference case, respectively. This effect takes part on leading to lower or higher temperatures, although there are slightly temperature differences among them. Case 3 has the same total mass flow rate as the reference case and the temperatures obtained in this case are very similar, which means there is no big impact on the heat transfer between sections for a CFD study in this case.

TABLE I. MASS FLOW RATE FOR THE CASES CONSIDERED

	Mineral oil		**Natural ester**	
	Inlet 1 (kg/s)	***Inlet 2 (kg/s)***	***Inlet 1 (kg/s)***	***Inlet 2 (kg/s)***
Reference case	8.94e-3	-	4.87e-3	-
Case 1	8.94e-3	9.83e-3	4.87e-3	5.36e-3
Case 2	8.94e-3	8.04e-3	4.87e-3	4.38e-3
Case 3	8.45e-3	9.38e-3	4.63e-3	5.11e-3



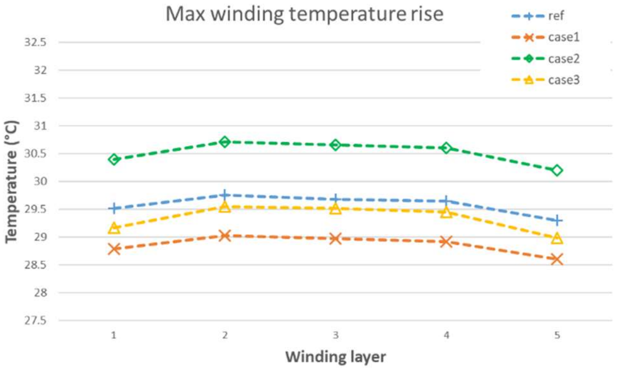


Fig. 1. Average and maximum winding temperature rise for mineral oil

B. *Natural ester*

Considering the natural ester case, a different temperature distribution is observed. This is mainly caused by the lower mass flow rate through the windings, leading to a different Reynolds number and a different hydraulic behavior. As in the mineral oil, a 4% increase on the heat dissipation is observed in the section with higher mass flow rate. Regarding the temperature distribution no temperature difference is observed between the sections in terms of average and maximum temperature.

With natural ester, as well as mineral oil, case 2 predicts the higher temperatures, where the mass flow rate of the second section is reduced in a 10%, as shown in Fig. 2. The maximum deviation observed among the cases is 6-8% of the average temperature and maximum winding temperature. Comparing the obtained results with mineral oil, natural ester presents higher temperature rise values than mineral oil, being those of 20ºC and 30ºC for average and maximum winding temperature with mineral oil and 30ºC and 50ºC in the natural ester case.

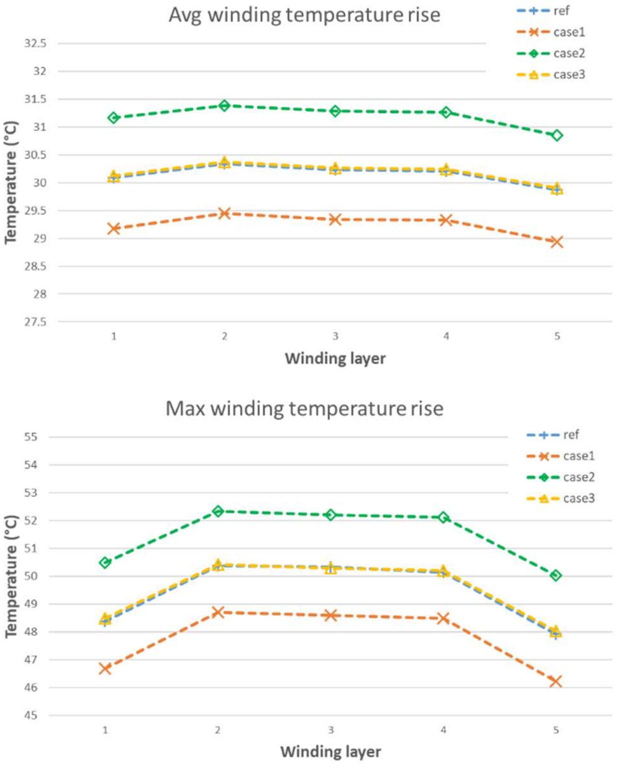


Fig. 2. Average and maximum winding temperature rise for natural ester

IV. CONCLUSIONS

In this work, the possible impact of mass flow deviations in the winding sections and their impact on the temperature distribution has been analyzed. The results show that this effect has low impact on the winding temperatures as well as on the hot-spot temperature. In addition, no big difference has been observed between sections, which implies that the tangential heat transfer between adjacent sections has negligible impact on the temperature field when there exists mass flow deviations lower than 10%. This effect has been also tested with an alternative fluid, natural ester, and the results showed the same behavior of mineral oil.

Regarding the temperature distributions for both fluids, the results showed higher temperature rise values for the natural ester case. This is mainly caused by lower mass flow rates through the winding due to the higher viscosity of the ester, which affects negatively in an ON cooling system. The predicted mass flow of the ester is a 55% of the mineral oil flow, which leads to higher average and hot spot temperatures in the winding. However, under this different inlet conditions, the temperature field is variated, but the effect of the deviation in adjacent sectors is still negligible.

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REFERENCES

[1] "Electrical Insulating Oils," in ASTM Special Technical Publication, 1988.

[2] J. M. Mufuta and E. Van Den Bulck, "Modelling of the mixed convection in the windings of a disc-type power transformer," Appl. Therm. Eng., vol. 20, no. 5, pp. 417–437, 2000.

[3] N. El Wakil, N.-C. Chereches, and J. Padet, "Numerical study of heat transfer and fluid flow in a power transformer," Int. J. Therm. Sci., vol. 45, no. 6, pp. 615–626, 2006.

[4] E. Rahimpour, M. Barati, and M. Schäfer, "An investigation of parameters affecting the temperature rise in windings with zigzag cooling flow path," Appl. Therm. Eng., vol. 27, no. 11–12, pp. 1923–1930, 2007.

[5] J. Smolka, O. Bíró, and A. J. Nowak, "Numerical simulation and experimental validation of coupled flow, heat transfer and electromagnetic problems in electrical transformers," Arch. Comput. Methods Eng., vol. 16, no. 3, pp. 319–355, 2009.

[6] F. Torriano, M. Chaaban, and P. Picher, "Numerical study of parameters affecting the temperature distribution in a disc-type transformer winding," Appl. Therm. Eng., vol. 30, no. 14–15, pp. 2034–2044, 2010.

[7] A. Skillen, A. Revell, H. Iacovides, and W. Wu, "Numerical prediction of local hot-spot phenomena in transformer windings," Appl. Therm. Eng., vol. 36, no. 1, pp. 96–105, 2012.

[8] M. E. Rosillo, C. A. Herrera, and G. Jaramillo, "Advanced thermal modeling and experimental performance of oil distribution transformers," IEEE Trans. Power Deliv., vol. 27, no. 4, pp. 1710–1717, 2012.

[9] F. Torriano, P. Picher, and M. Chaaban, "Numerical investigation of 3D flow and thermal effects in a disc-type transformer winding," Appl. Therm. Eng., vol. 40, pp. 121–131, 2012.

[10] Nogueira, G. C., et al. "Thermal Analysis of Power Transformers with Different Cooling Systems using Computational Fluid Dynamics." Journal of Control, Automation and Electrical Systems, vol. 33, no. 1, 2022, pp. 359-368.

[11] F. Torriano, H. Campelo, M. Quintela, P. Labbé, and P. Picher, "Numerical and experimental thermofluid investigation of different disc-type power transformer winding arrangements," Int. J. Heat Fluid Flow, vol. 69, no. November 2017, pp. 62–72, 2018.

[12] M. Quintela, H. Campelo, F. Torriano, P. Labbé, and P. Picher, "Assumptions and Numerical Parameters Influencing the Accuracy of Thermal Models for Core-Type Power Transformer," no. August 2017.

[13] R. Lecuna, F. Delgado, A. Ortiz, P. B. Castro, I. Fernandez, and C. J. Renedo, "Thermal-fluid characterization of alternative liquids of power transformers: A numerical approach," IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 5, pp. 2522–2529, 2015.

[14] I. Fernández et al., "Thermal degradation assessment of Kraft paper in power transformers insulated with natural esters," Appl. Therm. Eng., vol. 104, 2016.

[15] Stebel M et al., "Thermal analysis of 8.5 MVA disk-type power transformer cooled by biodegradable ester oil working in ONAN mode by using advanced EMAG–CFD–CFD coupling." Int J Electr Power Energy Syst 2022;136..

[16] R. C. Breazeal, A. Sbravati and D. M. Robalino, "Evaluation of Natural Ester Retrofilled Transformers After One Year of Continuous Overload," 2019 IEEE Electrical Insulation Conference (EIC), Calgary, AB, Canada, 2019, pp. 115-119, doi: 10.1109/EIC43217.2019.9046617.

[17] A. Santisteban, A. Piquero, F. Ortiz, F. Delgado, and A. Ortiz, "Thermal Modelling of a Power Transformer Disc Type Winding Immersed in Mineral and Ester-Based Oils Using Network Models and CFD," IEEE Access, vol. 7, pp. 174651–174661, 2019.

[18] X. Zhang, Z. Wang, Q. Liu, M. Negro, A. Gyore, and P. W. R. Smith, "Numerical investigation of influences of liquid types on flow distribution and temperature distribution in disc type ON cooled transformers," 2017 IEEE 19th Int. Conf. Dielectr. Liq. ICDL 2017, vol. 2017–Janua, no. Icdl, pp. 1–4, 2017.

[19] B. Wei, Y. Wang, S. Ren, R. Wang and Y. Xu, "Overload Investigation on Retrofilling Mineral Oil Distribution Transformer with Soybean-Based Natural Ester," 2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE), Beijing, 2020, pp. 1-4, doi: 10.1109/ICHVE49031.2020.9279714.

[20] IEEE Guide for Acceptance and Maintenance of Natural Ester Insulating Liquid in Transformers, IEEE Standard IEEE Std C57.147, 2018.

[21] IEC Natural esters - Guidelines for maintenance and use in electrical equipment, IEC Standard 62975, 2021.

[22] A. A. Abdelmalik, J. C. Fothergill, and S. J. Dodd, "Aging of Kraft paper insulation in natural ester dielectric fluid," Proc. IEEE Int. Conf. Solid Dielectr. ICSD, pp. 541–544, 2013.

[23] R. Liao, S. Liang, C. Sun, L. Yang, and H. Sun, "A comparative study of thermal aging of transformer insulation paper impregnated in natural ester and in mineral oil," Eur. Trans. Electr. Power, vol. 20, no. April 2009.

[24] R. Altay et al., "Use of Alternative Fluids in Very High-Power Transformers: Experimental and Numerical Thermal Studies," in IEEE Access, vol. 8, pp. 207054-207062, 2020, doi: 10.1109/ACCESS.2020.3037672.