

Performance analysis of natural, synthetic and mineral oil in a 100 MVA power transformer

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Abstract- The power transformer lifespan depends on the dielectric capacity of its insulation system, mainly of the paper. Integrity of this material depends significantly on the cooling capacity of the oil used to cool it. Currently, ester-based fluids are being researched with the intention to substitute the traditional cooling liquid in power transformers, the mineral oil. Here, cooling capacity of two different ester-based fluids, a synthetic and anatural esters, is compared with that of a mineral oil. To carry out this task, CFD results of a low voltage winding of a 100 MVA power transformer jointly with the experimental ones get from a heat-run test done in this transformer are used. This winding has an axial cooling system in ON regime. As a result of this study, it can be inferred that alternative liquids could be used with high load levels (rated power or higher) since no significant changes in the temperatures distribution of the winding cooled with these fluids in comparison with that get with mineral oil are appreciated.

I. INTRODUCTION

High power transformers are one of the most expensive equipments of the Transmission Systems (TS). Also, the reliability of these systems depends importantly on these equipment's working correctly. For that reason, any improvement applied to these machines must be very tested before their final implementation.

The transformer fleets of the TS use habitually mineral oil as a coolant due to its proven reliability from the dielectric and cooling standpoint, [1]. However, the replacement of this type of liquid by others with better environmental and fire safety properties is currently being studied. In fact, several studies can be found in the scientific literature analyzing different aspects of these new dielectric ester-based liquids. For instance, dielectric behavior of these fluids has been studied, [2], [3].

Regarding the cooling studies, the use of numerical techniques based on finite element method, i.e. CFD, has spread in the last two decades. In last two decades, many authors have used both commercial and non-commercial codes to study the thermal-hydraulic behavior of the fluid considering different type of winding geometries. However, all of them used mineral oil as dielectric liquid. Very recently, several authors have used this technique to analyze the cooling performance of the new liquids in transformers. For instance, in 2015, Park et al. and Lecuna et al. compared the temperatures get with different alternative liquids in the numerical models of several types of power transformers with those get with mineral oil. In both cases, the main conclusion was that the use of alternative fluids

worsens the cooling of the windings [4], [5]. Finally, in 2017, Santisteban et al. published a work in which, in contrast with the previous results, those obtained in this work showed that the hot-spot temperature was lower for the vegetal oils if mineral oil cooling system design was considered, [6].

Summarizing, these few works use different types of model to analyze transformers with different rated power and different type of cooling systems. Last but not least, the results of these works are not conclusive: in some cooling systems, the temperatures obtained with alternative liquids are higher than those obtained with mineral oil, [4] [5], and in the other case is the opposite, [6]. In conclusion, more studies are needed to better understand the thermal-hydraulic behavior of the ester-based dielectric liquids in power transformers.

This work tries to contribute to this topic by presenting the experimental results of a heat-run test of 100 MVA power transformer immersed in a mineral oil flowing through axial channels. Then, a CFD model of the transformer was developed and also validated using these experimental results. Finally, the cooling performance comparison of two alternative liquids (synthetic and natural esters) with mineral oil was carried out using this model. To the best knowledge of the authors, this type of study has not yet carried out in transformers of this rated power and with this type of cooling system.

II. EXPERIMENTAL SETUP

A temperature-rise test has been carried out according [7] to get the temperatures inside the Low Voltage Windig (LVW) of a phase of a three-phase power transformer (100 MVA, 170/36 kV, ONAN/ONAF). As can be seen in Figure 1, these temperatures were measured using several fiber optic sensors located in the fourth layer, inside the fourth cooling channel, at approximately 100 mm. of the top of the winding. Ambient temperature was also measured using thermocouples placed around the transformer. Finally, temperatures at the top and at the bottom of the transformer and also in the inlet and in the outlet of the oil cooler were measured using thermometers.

Short-circuit method was used to determine whether the coolant (a traditional mineral oil) and winding temperatures were in accordance with the specifications of the standard when the total losses are supplied. Following this standard, the temperature registration was done regularly (elapsed time between registers of 60 minutes) until reaching permanent regime.

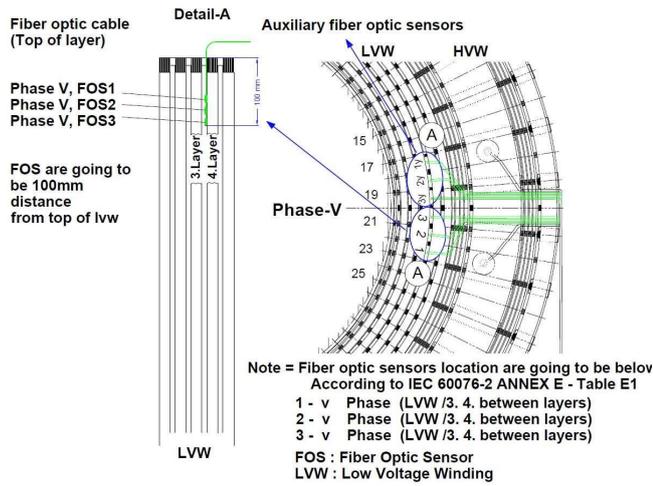


Fig. 1. Fiber optic sensors location inside the LVW.

III. NUMERICAL MODEL

Here, the description of the numerical model developed to compare the thermal behavior of the ester-based fluids with that of the mineral oil inside the channels of the LVW in steady-state regime is presented.

A. Computational domain and mesh

As can be seen in Figure 2, 1/80 (4.5 degrees) of the LVW of a phase has been considered. This simplification can be done due to all the winding can be made by replication of this section. In this model, five layers of copper conductors and six vertical cooling ducts are only considered. Neither cardboards nor sticks have been really taken into account in this model due to their very low thermal conductivity.

Regarding the mesh, all the volume has been divided using hexahedral elements. After performing a mesh independence test, a mesh with approximately 38 million of elements has been

chosen to get the temperatures. Finally, the average values of the aspect ratio, orthogonal quality and skewness of this mesh are 6.18, 0.99 and 0.007, respectively.

B. Governing Equations

Navier–Stokes equations which state the conservation of mass, momentum and energy for a fluid flow are solved using *Ansys Fluent vers. 19*. For an incompressible fluid (oils can be considered this way), the equations that state mass, momentum and energy conservation are (1)-(3). On the other hand, for the solid domains, the equation that state energy conservation is (4).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \mu (\nabla^2 \mathbf{u}) + \mathbf{g}(\rho - \rho_{ref}) \quad (2)$$

$$\frac{\partial (\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p \mathbf{u} T) = \nabla \cdot (k \nabla T) + q \quad (3)$$

$$\frac{\partial (\rho c_p T)}{\partial t} = \nabla \cdot (k \nabla T) + q_s \quad (4)$$

Where ρ , ρ_{ref} , \mathbf{u} , p , μ , \mathbf{g} , c_p , T , k and q_s of (1)-(4) are density, density of reference, velocity vector, pressure, dynamic viscosity, gravity, specific heat capacity, temperature, thermal conductivity, and heat source, respectively.

The right-hand terms of (2) are the pressure force, the viscous force and the buoyancy force, respectively. The latter represents the force that drives the flow in natural convection regime and it is related to density gradients in the fluid. Also, the right-hand second term of (4) represents the heat source (in this case, the heat losses in the 3D section of the LVW considered, 0.275 kW).

C. Material properties

Physical properties of the three commercial oils tested in this study are presented in Table I by means of mathematical expressions depending temperature expressed in Kelvin.

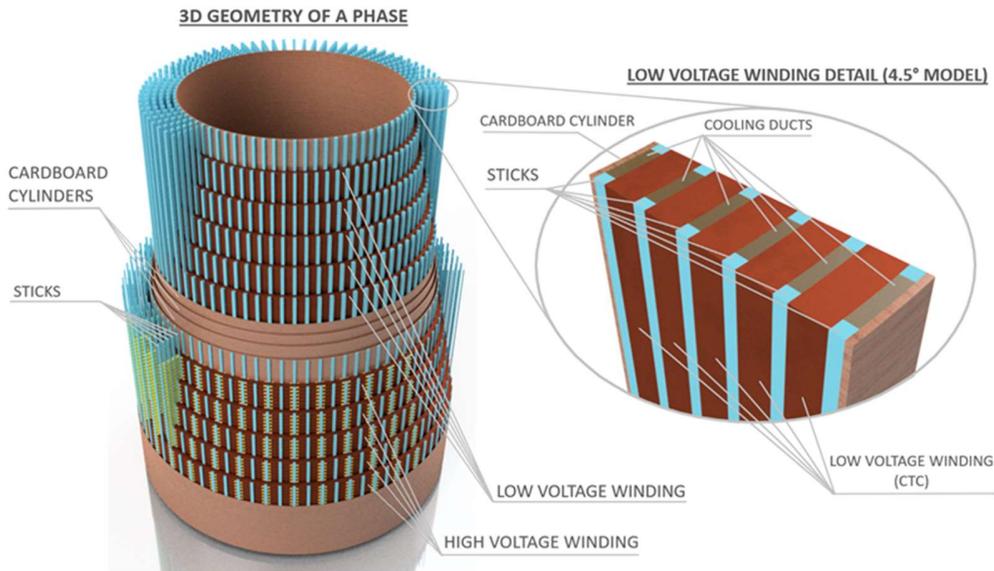


Figure 2. 3D drawing of a phase and detail of the LVW

Table I. Physical properties of the oils

| | Mineral oil | Natural ester | Synthetic ester |
|--------------------------------|--|---|---|
| ρ (kg/m ³) | 1055-0.660*T[K] | 1108-0.666*T | 1185-0.7333*T |
| C_p (J/(kg·K)) | 1172.7+3.6097*T | 1088+2.98*T | 1242.4+2.198*T |
| K (W/(m·K)) | 0.1529-6.95E-5*T | 0.1979-9.648E-5*T | 9.71E-2+3.74E-4*T-7.2503E-7*T ² |
| μ (Pa·s) | 6.8715-7.6222E-2*T+3.1820E-4*T ² -5.9186E-7*T ³ +4.1355E-10*T ⁴ | 1.3645-7.4087E-3*T+1.0119E-5*T ² | 0.2565-1.2963E-3*T+1.6761E-6*T ² |

On the other hand, the turns of the winding layers are made of Continuously Transposed Conductors (CTC). This type of conductor is made with several copper plates that are wrapped all of them with an insulation paper, [8]. The thermal conductivity of this CTC is modelled with an equivalent value that consider the same heat transfer behavior than the copper and paper arrangement, [9]. Also, this equivalent thermal conductivity of the conductor is orthotropic in cylindrical coordinates, with a radial, axial and tangential conductivity of 1.5, 1.1 and 385 W/(m K), respectively. Finally, the other two thermal properties are considered with constant values: 381 J/(kg·K) for specific heat and 8978 kg/m³ for density.

D. Boundary conditions

Equation (5), in which \mathbf{n} is the normal vector to the boundary surface, establishes that the contact surfaces between cellulosic materials with the fluids and with the electrical conductors are considered as adiabatic walls. This way, as mentioned above, this type of solid material can be eliminated of the numerical model. This boundary condition is also applied on external surfaces belonging to the copper conductors.

$$-\mathbf{n} \cdot (-k\nabla T) = 0 \quad (5)$$

Equation (6) set no-slip condition in all the walls of the cooling channels.

$$\mathbf{u} = 0 \quad (6)$$

Pressure null has been considered at the outlets of the channels, (7).

$$p_{outlet} = 0 \quad (7)$$

Equations (8)-(9) define the inlet temperature and also the inlet velocity at the bottom of the model.

$$u_{inlet} = 0.00266 \left(\frac{m}{s} \right) \quad (8)$$

$$T_{inlet} = 337 \text{ (K)} \quad (9)$$

E. Computational aspects

A second-order discretization was chosen to avoid diffusion errors and the solver was set with double precision in a coupled scheme. The convergence residuals accepted were 1e-3 for continuity and momentum equations and 1e-6 for energy equation.

The approximate solution of the PDEs showed in subsection B were solved using the commercial solver ANSYS Fluent® v2019 R2.1. This software was run in a Dell PowerEdge R730 server using 36 processors at 2.30 GHz and 500 GB of RAM.

IV. RESULTS

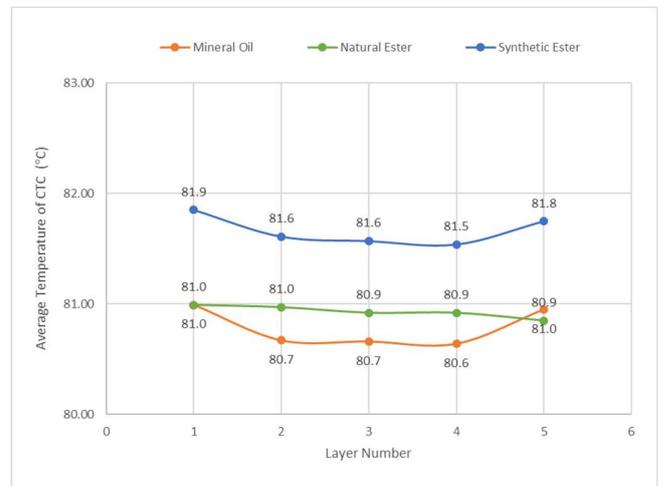
A. Model validation

In order to verify the accuracy of the CFD model, the temperature calculated at 100 mm of the top of the winding in this model is compared with the average temperature of the five probes used in the heat-run test. Thus, the numerical result is 89.3 °C, value that is very close to real temperature, 89.0 °C (mean value of 88.5, 88.5 85.3, 89.5 and 93.1 °C). Then, the numerical model can be used to determine the temperature distribution in the winding both with mineral and vegetal oils.

B. Temperature distributions: Vegetal oil vs. mineral oil

First, as can be seen in Figure 3, those windings cooled with ester-based liquids have the hottest temperature distributions, with the highest temperatures close to the top of the coils. Thus, the highest hot-spot (the hottest temperature of winding conductors in contact with solid insulation or insulating liquid, [7]) belongs to synthetic ester (91.9 °C) and is located in the second layer from the inner part of the winding, at 23.8 mm of the top. The other two hot-spots are practically at the same height in the same part of the volume. Nonetheless, the difference between the hottest spot and the coldest one (mineral oil) is pretty small, 2 °C.

More information about temperatures in the LVW is shown in Fig. 4. Here, mean temperatures of the five layers of the winding can be seen. Again, the winding cooled by the synthetic ester supports the highest temperatures. However, as mentioned above, the highest gradients, between extreme cases, do not exceed two degrees.



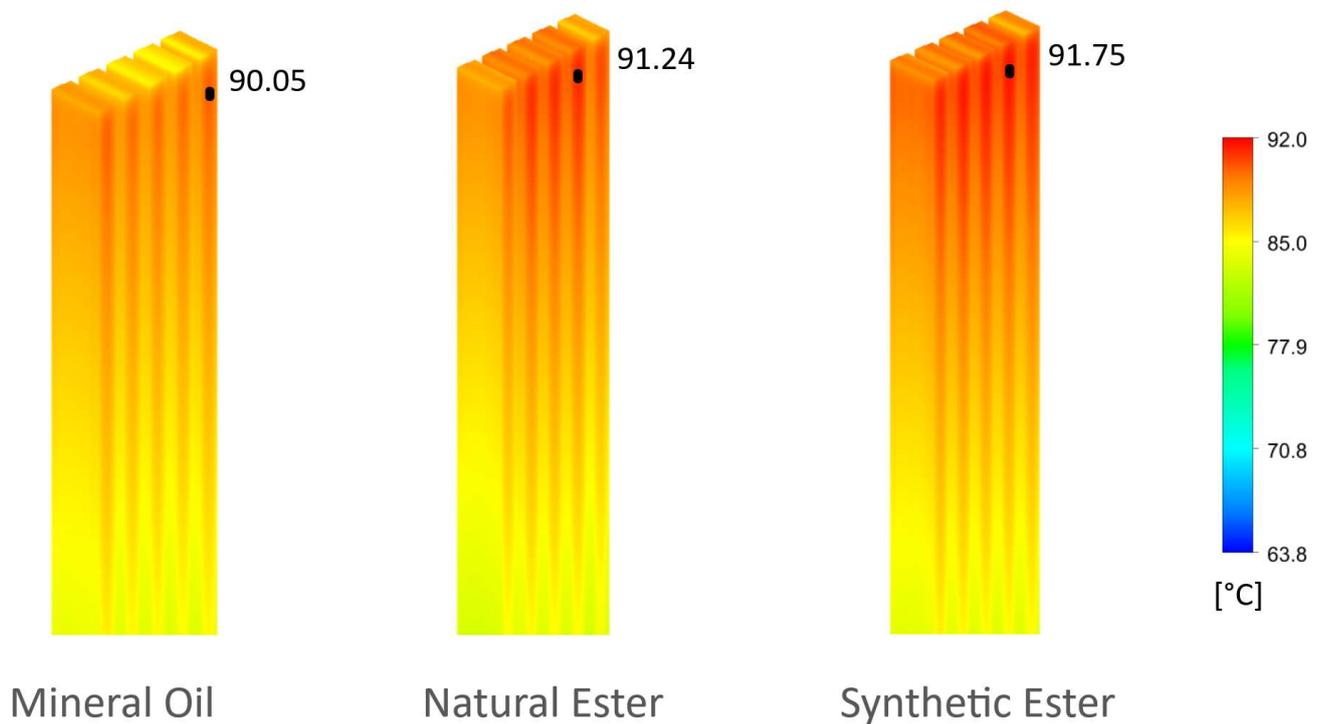


Fig. 3. Temperature distributions, hot-spot values and their location

IV. CONCLUSIONS

According to the results previously presented, the temperature increases get with the ester-based fluids in an axial cooling system of a power transformer LVW in ON regime are pretty small. Then, the affectation to the structural integrity of the cellulose-based insulation (paper) due to these increments could be considered scarce.

Summarizing, in principle, high power transformers with axial cooling system in ON regime could be cooled with these new alternative liquids based on esters.

ACKNOWLEDGMENT

The authors of this research wish to thank for its financial support:

- The European Union by means of the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 823969. This grant fund the European project *Biotrafo: raising knowledge and developing technology for the design and deployment of high performance power transformers immersed in biodegradable fluids*; European Commission, h2020-mscarise-2018- 823969; 2019-21
- The Spanish Ministry of Science, Innovation and Universities by means of the National Research Project *Improvement of Insulation Systems of Transformers through Dielectric Nanofluids* (DPI2015-71219-C2 1-R).
- The Universities and Reseach Council of the Government of Cantabria by means of the grant *Fluidos*

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