IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received September 11, 2020, accepted November 5, 2020, date of publication November 16, 2020, date of current version November 27, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3037672

Use of Alternative Fluids in Very High-Power Transformers: Experimental and Numerical Thermal Studies

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Part of the work was performed during secondments between BEST Transformers and the University of Cantabria executed in the framework of the BIOTRAFO project "Raising knowledge and developing technology for the design and deployment of high performance power transformers immersed in biodegradable fluids", H2020-MSCARISE-2018- 823969, 2019-21. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 823969. Also, we acknowledge the support of the Spanish Ministry of Science and Innovation by means of the National Research Project "Asset management of biodegradable-fluid-based transformers" (PID2019-107126RB-C22) and the Universities and Research Council of the Government of Cantabria by means of the grant "Biodegradable fluids in electrical power transformers: solid dielectric impregnation and thermal modeling with THNM", VP32, 2019-2.

ABSTRACT The very high-power transformer lifespan depends mainly on the temperature that cellulose insulation reaches during its operation. Traditionally, its cooling has been carried out using mineral oil as coolant. Nowadays, alternative ester-based liquids are under study as substitutes due to their better environmental and fire-safety properties. This paper compares the cooling capacity of two ester-based fluids with that of a mineral oil using a 3D numerical model of a 100 MVA low voltage winding of a power transformer with axial cooling system and ONAN cooling mode. Heat-run test results with mineral oil have been used to validate this model. As a first approximation, according to the comparison developed, ester-based fluids could replace mineral oils in this type of transformers when they are going to work in a range of powers close to the rated one.

INDEX TERMS Computational fluid dynamics, ester-based liquids, experimental setup, mineral oil, power transformers, thermal modeling.

I. INTRODUCTION

High power transformers (HPT) are one of the most expensive equipment of electricity Transmission Systems (TS). Also, the reliability of these systems depends importantly on HPT's suitable performance, [1]. For that reason, any proposed improvement of these electrical machines that could affect to these evaluation criteria (cost and reliability) must be deeply tested before their final implementation.

These static electrical machines are usually cooled by mineral oil. In fact, the HPT fleets of TS use this liquid due to its proven reliability from the dielectric and cooling standpoint, [2]. However, the replacement of this type of liquid by others with better environmental and fire safety properties is currently being studied. These alternative liquids are ester-based and are produced from harvest products such as soybean, palm, rapeseed, sunflower..., [3]. In fact, several studies can be found in the scientific literature analyzing different aspects of these new dielectric liquids. For instance, several authors have analyzed the impact of these liquids on the aging of winding insulation paper since the transformer lifetime strongly depends on it, [4]–[7]. Also, the dielectric behavior of these fluids has been also studied by other researchers, [7]–[9]. Finally, their cooling capacity is currently under study.

Regarding the latter topic, the use of numerical techniques based on finite element method, e.g. Computational Fluid Dynamics (CFD), has spread in the 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. For instance, several authors used a vertical cooling channel configuration to ensure both the cooling and dielectric insulation, [10]–[12]. By contrast, other works present

The associate editor coordinating the review of this manuscript and approving it for publication was Gang Mei.

a zig-zag oil channel configuration in the winding cooling system, [13]–[19].

However, all these works previously cited used mineral oil as dielectric liquid. More 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*. compared the temperatures got in two 2D numerical models of two different 3-phase windings (power transformer of 66 kV, 16.5 MVA, with zig-zag cooling system and a distribution transformer of 22 kV, 2.3 MVA with axial-radial cooling system) cooled with two types of ester-based alternative liquids with those get with mineral oil. The considered cooling method was ON. The main conclusion of this work was that the use of ester-based liquids highly increases the hotspot temperatures in the windings, [20]. In the same year, *Lecuna et al*. carried out the same type of study using a 3D model of a power transformer of 66/6.3 kV, 14 MVA and ONAN cooling in axial channels, reaching similar conclusions to those got in the previous work, [21]. Finally, in 2017, *Santisteban et al*. published a work in which a 2D axisymmetric model of 25/26.4 kV, 66 MVA, ONAN/ONAF transmission transformer with zig-zag cooling, [22]. 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. Further simulations seemed to confirm these results, not only by CFD, also by Thermal Hydraulic Network Models (THNM) [23].

In short, few works about the cooling performance of the alternative liquids in HPTs can be found. Also, these works use different types of numerical models 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, [20], [21], and in the other case is the opposite, [22], [23]. Therefore, more studies are needed to better understand the thermal-hydraulic behavior of the ester-based dielectric liquids in HPTs.

Following the above, this work presents the results of an experimental thermal test and, also, a numerical study, allowing the cooling performance comparison of two alternative liquids (synthetic and natural esters) with mineral oil. This comparison has been done in the axial cooling system of the Low Voltage Winding (LVW) of a 100 MVA HPT. For this purpose, a 3D CFD model of this LVW has been developed. The heat-run test of this transformer with mineral oil was used to validate the CFD model. Then, this model was used to compare the thermal-hydraulic behavior of the ester-based oils with that of the mineral oil at rated power. As far as this research group know, this type of study has not yet carried out in transformers of this power rating and with this type of cooling system.

Next sections present the experimental setup and the numerical model developed to carry out the study. Then, the model validation is carried out. Later, the numerical results of the alternative liquids are compared with those of the mineral oil. Finally, some conclusions are inferred.

In the other hand, a mesh independence test has been carried out to check that the number of the elements does not have influence in the results. A mesh with approximately $38{\cdot}10^6$ hexahedral elements was finally used. Also, as can be seen in Fig. 6, a boundary layers-type mesh with inflation was used close to the walls of the cooling ducts to capture the temperature and velocity gradients that occur in these parts. Finally, the average values of the aspect ratio, orthogonal quality and skewness are obtained to measure the mesh element quality. These values are 6.18, 0.99, and $7{\cdot}10^{-3}$, respectively.

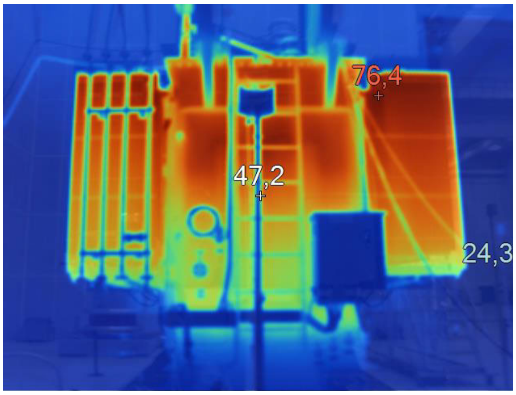


FIGURE 1. Thermographic photo of the transformer during the test (temperature in °C). Source: [24].

II. EXPERIMENTAL SETUP

A heat-run test has been carried in the three-phase power transformer of 170/36 kV, 100 MVA, ONAN/ONAF shown in Fig. 1.

A. GEOMETRICAL DESCRIPTION

Fig. 2 shows the two main windings of a phase: LVW in the inner part and High Voltage Winding (HVW) in the outer part of the figure.

Regarding the LVW, as can be seen in Fig. 2 and Fig. 3, it is composed of an internal cardboard cylinder (3 mm thick and 792 mm of inner diameter) surrounded by 5 concentric layers with 25 copper turns by layer. Each turn has 4 parallel plates (plate dimensions: 15.95 mm x 14.95 mm) that are wrapped with a dielectric paper of 0.8 mm width. The copper layers are separated by means of 80 wooden sticks of 6 mm thick. This way, 80 ducts of 3.1 degrees of amplitude are created between internal cylinder and first layer, another 80 cooling channels between the first layer and the second layer, and so on. Finally, the total height of the LVW is 1.634 mm.

As can be seen in the Fig. 4, the monitoring of the temperatures inside the LVW was performed using Fiber Optic Sensors (FOSs) located in the inner part of the fourth layer of both phases V and W (numbering from the inside part of the winding), at approximately 100 mm of the top of the winding.

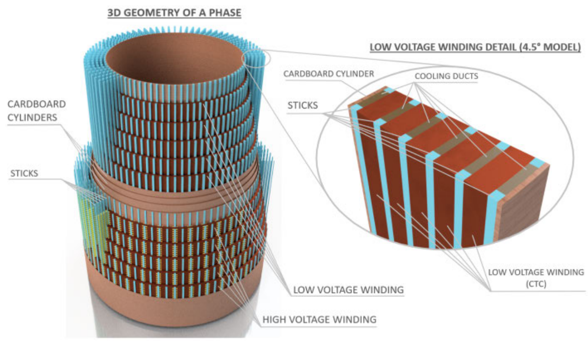


FIGURE 2. 3D drawing of a phase and detail of the LVW.

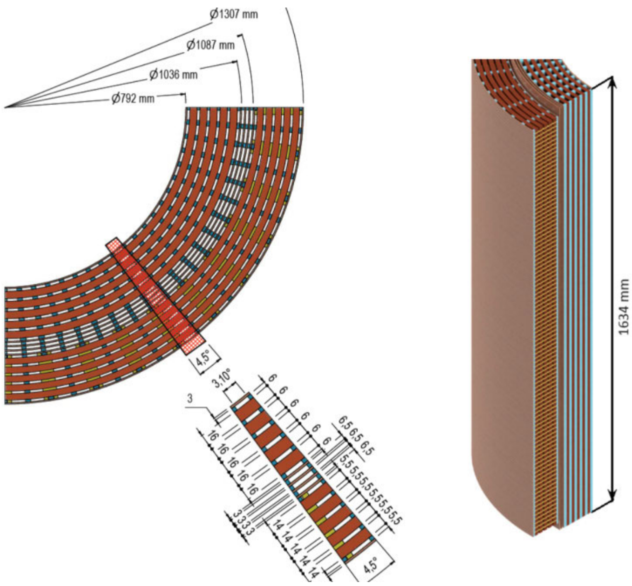
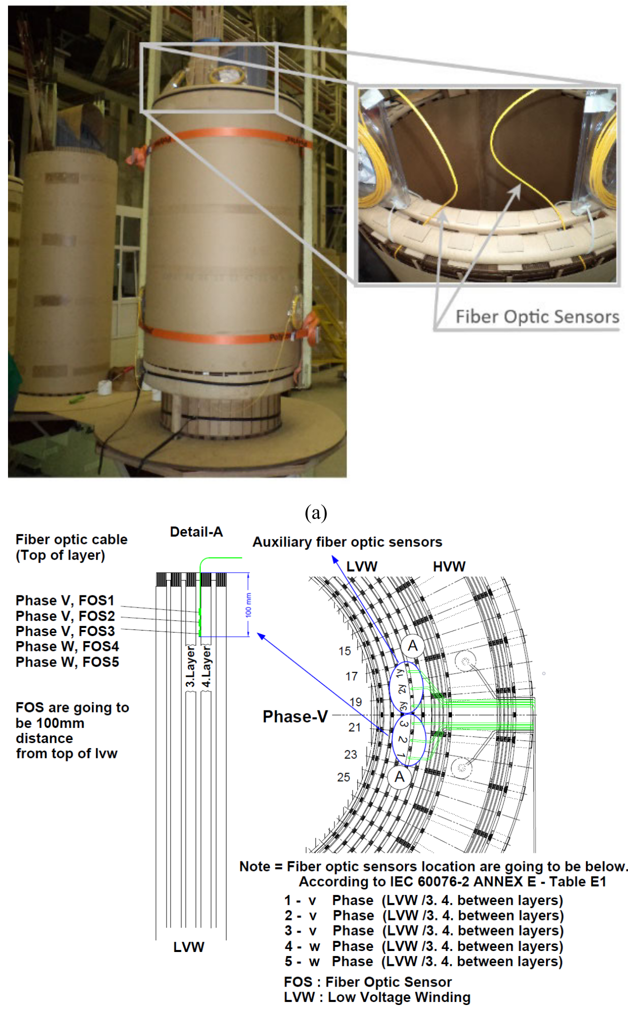


FIGURE 3. Geometrical information of the phase.



(b)

FIGURE 4. a) Fiber optics sensors installation. b) Plant drawing with the fiber optic sensors location.

The accuracy of these sensors is ±1 °C. Also, according the IEC Standard 60076-2 [25], the ambient temperature was measured using 4 thermocouple sensors located all around the transformer (one in front each face of the tank, two meters away from its perimeter and from the cooling surfaces) at about halfway height up the cooling surfaces. Finally, thermometers are placed in the thermometer pockets located in the transformer cover but also in the inlet and outlet of the transformer oil cooler. The temperature measurements were recorded by a commercial datalogger. In addition, a commercial transformer Loss Measuring System was used.

B. EXPERIMENTAL TEST PROCEDURE

As mentioned previously, a heat-run test has been carried out using the previously described experimental setup, ONAN cooling and a commercial mineral oil. Short-circuit method is used to determine whether the oil and winding temperatures are in accordance with the standard specifications, [25]. Before starting the test (cold transformer), the sensors temperatures were measured and recorded. Then, the test was performed in two steps. The first one was carried out supplying the total losses (highest losses of the transformer). According to [25], the temperature registration was done regularly with an elapsed time between each measure (in this case, 60 minutes) until reaching steady-state condition. This condition has been fulfilled when the rate of change of top-liquid temperature rise has fallen below 1 K/h and has remained there for a period of 3 h. Then, in the second step, the transformer is loaded with the rated current of the test tap position for one hour. Meanwhile, all temperatures continued to be measured. The total test duration was 14 hours.

III. NUMERICAL MODEL

This section presents the description of the numerical model that allows to study the heat transfer and fluid mechanics phenomena that occur in the LVW of the transformer during its operation. A 3D section of the LVW of a phase of this transformer is used in the CFD model since the highest temperatures usually appears in this winding due to its highest electric currents and its location in the inner part of the phase. This way, the computational domain considered, the mesh

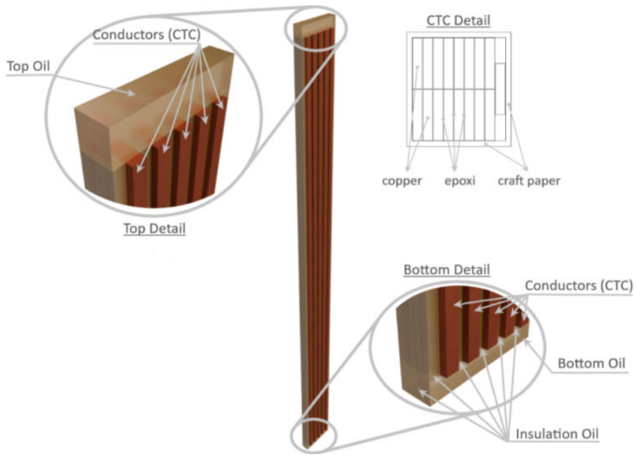


FIGURE 5. **3D computational domain and CTC section.**

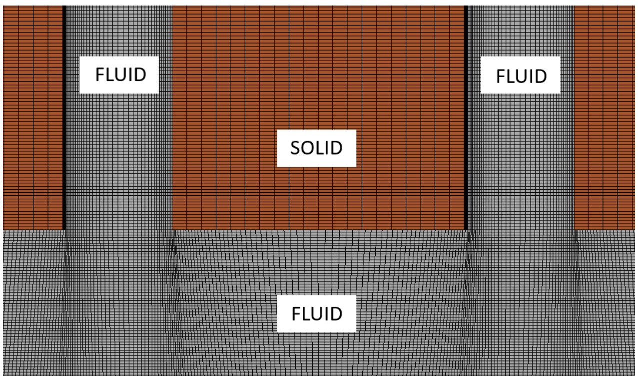


FIGURE 6. **Meshing detail.**

defined, the governing equations involved, and the boundary conditions applied in a steady state study of this model are presented. Also, material properties and computational requirements are shown.

A. COMPUTATIONAL DOMAIN AND MESH

The computational domain considers both the oil and solid parts of the 1/80 (4.5 degrees) of the LVW of a phase. This simplification is based on the replicability of this section allowing the drawing all the winding. As can be seen in Fig. 5, five layers of copper conductors and six cooling ducts are only considered. Also, bottom and top oil parts are shown in the same figure. Finally, the cellulosic materials (cardboard and sticks) are not considered due to their very low thermal conductivity.

On the other hand, a mesh independence test has been carried out to check that the number of the elements does not have influence in the results. A mesh with approximately $38{\cdot}10^6$ hexahedral elements was finally used. Also, as can be seen in Fig. 6, a boundary layers-type mesh with inflation was used close to the walls of the cooling ducts to capture the temperature and velocity gradients that occur in these parts. Finally, the average values of the aspect ratio, orthogonal quality and skewness are obtained to measure the mesh

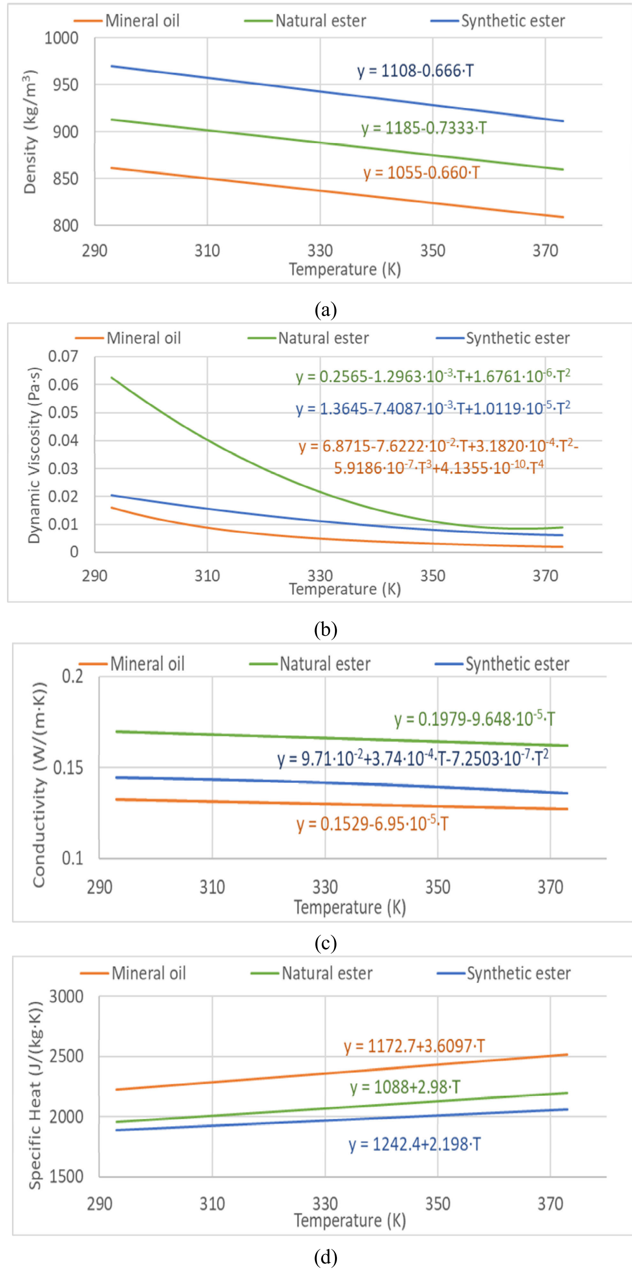


FIGURE 7. **Physical properties of the three dielectric oils. Density (a), dynamic viscosity (b), Thermal conductivity (c) and Specific heat (d).**

element quality. These values are 6.18, 0.99, and $7{\cdot}10^{-3}$, respectively.

B. GOVERNING EQUATIONS

The finite volume-based numerical method solves the Navier–Stokes equations, which state the conservation of mass, momentum and energy for a fluid flow. 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 domain, the equation that state energy conservation is (4).

$$\nabla\cdot(\rho u) = 0 \tag{1}$$

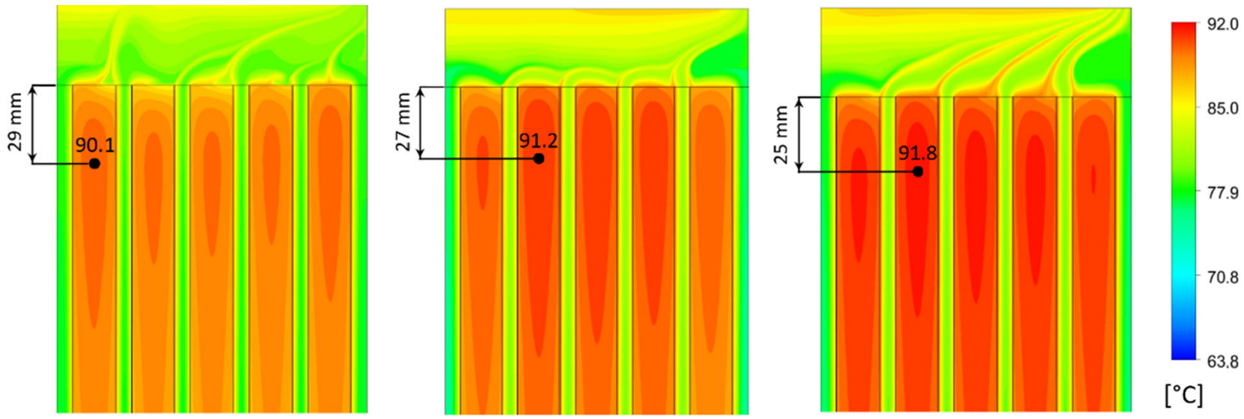


FIGURE 8. Hot-spots location and their values in the CFD models simulated with mineral oil (90.1 °C), natural (91.2 °C) and synthetic (91.8 °C) esters.

$$(u\cdot\nabla)\rho u = -\nabla p + \mu(\nabla^2 u) + g\rho \quad (2)$$

$$\nabla\cdot(\rho C_p u T) = \nabla\cdot(k\nabla T) + q_s \quad (3)$$

$$0 = \nabla\cdot(k\cdot\nabla T) + q_s \quad (4)$$

where ρ, ρ_{ref}, u, p, μ, 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).

Following the assumptions of other authors, [14]–[16], [22], since the oil velocities in the channels are low (bulk velocity in the hydraulic circuit smaller than 100 mm/s), it is considered a laminar flow to solve (1-3).

C. SIMULATION PARAMETER

This subsection presents the material properties involved in the model and boundary conditions considered.

1) MATERIAL PROPERTIES

The physical properties of the oils considered in the model solved are presented in Fig. 7 with their mathematical expressions. These expressions depend on the temperature expressed in Kelvin and are calculated using data that are available in public datasheets since all the liquids are commercial oils.

On the other hand, as shown in Fig. 5, 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, [26]. 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, [27]. 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/m^3 for density.

2) BOUNDARY CONDITIONS

In this subsection, the boundary conditions used in the model are presented. First of all, the contact surfaces of the cellulosic materials (sticks and cardboard cylinders) with the fluids and with the electrical conductors are considered as adiabatic due to the very low thermal conductivity of these components. In fact, they have been eliminated from the model. This way, the heat flux to the outside of the winding is avoided, leading to a more conservative scenario, [13]. No-slip condition is used in the fluid domain walls. A conjugate heat transfer model has been considered for the fluid-solid interface to enable the heat flux from the winding conductors to the dielectric liquid. This way, the solvers couple the solid and fluid domains from a thermal point of view. The heat generated in the LVW is modeled as a heat source in the conductors as it was explained in the previous section.

Regarding the fluid inlet and outlet conditions, following other works in this knowledge area, [14]–[16], an inlet velocity and an outlet pressure have been fixed in order to give good numerical stability to the solver. To get the first value (0.00266 m/s), CFD and experimental results carried out by Özben Kaymaz were used, [28]. This value was applied at the bottom surface of the model. Regarding the second value, a zero-gauge pressure was applied at the oil volume outlet located 30 mm from the top of the conductors of the LVW, at the upper right side. The exit location is based on the assumption that most of the oil flows up following this path. Finally, an oil inlet temperature was considered, 337 K. This temperature was obtained at the bottom of the transformer in the heat-run test.

D. 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

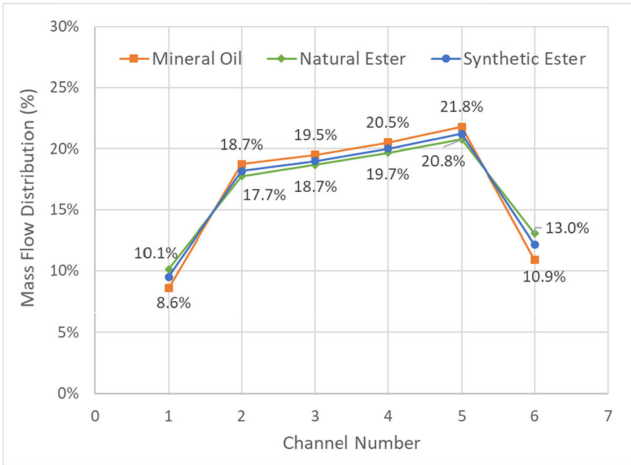


FIGURE 9. Mass flow rate distribution in the axial ducts.

10^{-3} for continuity and momentum equations and 10^{-6} for energy equation.

The approximate solution of the partial differential equations showed in subsection 3.2 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

Experimental and numerical results are presented in this section. In a first step, the first ones are used to verify the validity of the numerical model. Then, once this validation has been done, thermal-hydraulic behavior of the three dielectric liquids are compared using the numerical results.

A. MODEL VALIDATION

The validity of the CFD model developed was carried out by comparison of the average temperatures measured by the FOSs in the test with that obtained in the same position of the model with mineral oil. The temperature calculated on the CFD model was 89.3 °C, whereas the average temperature obtained experimentally in steady state during the heat-run test was 89 °C. This way, the CFD model is validated and it will be used to compare the thermal-hydraulic behavior of the mineral oil with those of the ester-based oils.

B. MINERAL OIL VS. ESTER OILS TEMPERATURES AND VELOCITIES

As can be seen in Fig. 8, the hot spots (the hottest temperature of winding conductors in contact with solid insulation or insulating liquid, [25]) location of the three liquids is well above the position of the FOSs in the real transformer. That is, the FOSs are not positioned where the hot spots appear. However, the temperature differences between both locations are not significance.

Regarding the layer in which hot spots are located, they are in the second layer in alternative liquids whereas in the case of the mineral oil is in the innermost layer. This different location can be explained using Reynolds (Re) number: both types of liquids have different Re numbers due to higher viscosity of ester-based oils, leading to different mass flow rate distribution through the axial ducts, as can be seen in Fig. 9.

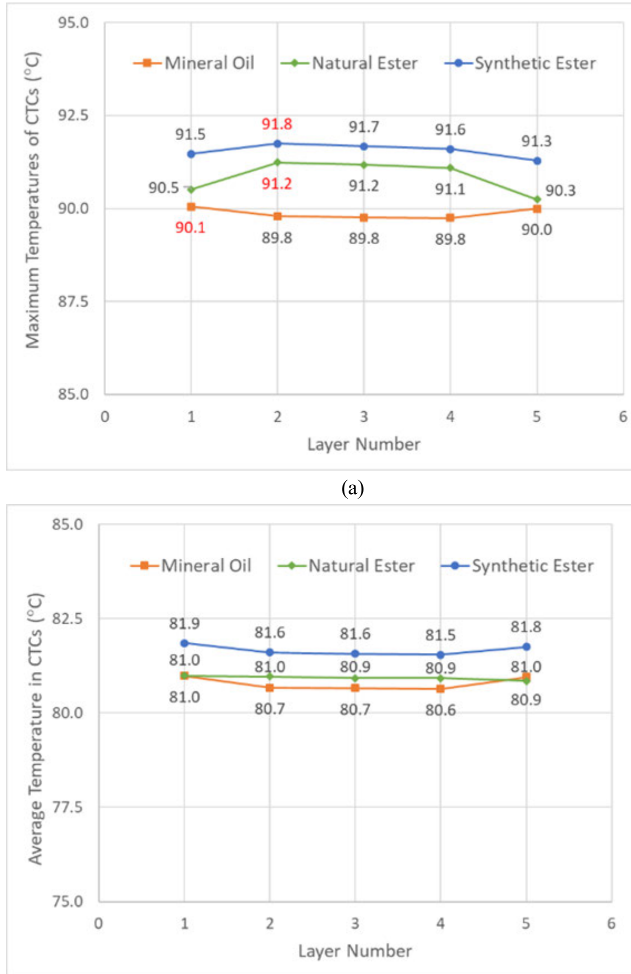


FIGURE 10. Maximum (a) and Average (b) temperatures in CTCs' layers.

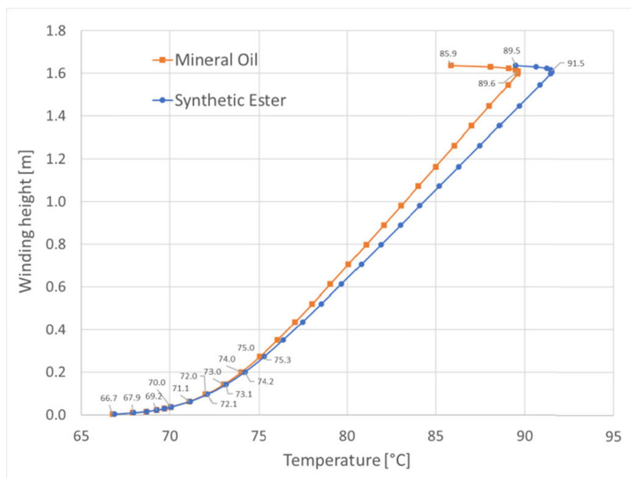


FIGURE 11. Temperature evolution with height in 3rd CTC layer.

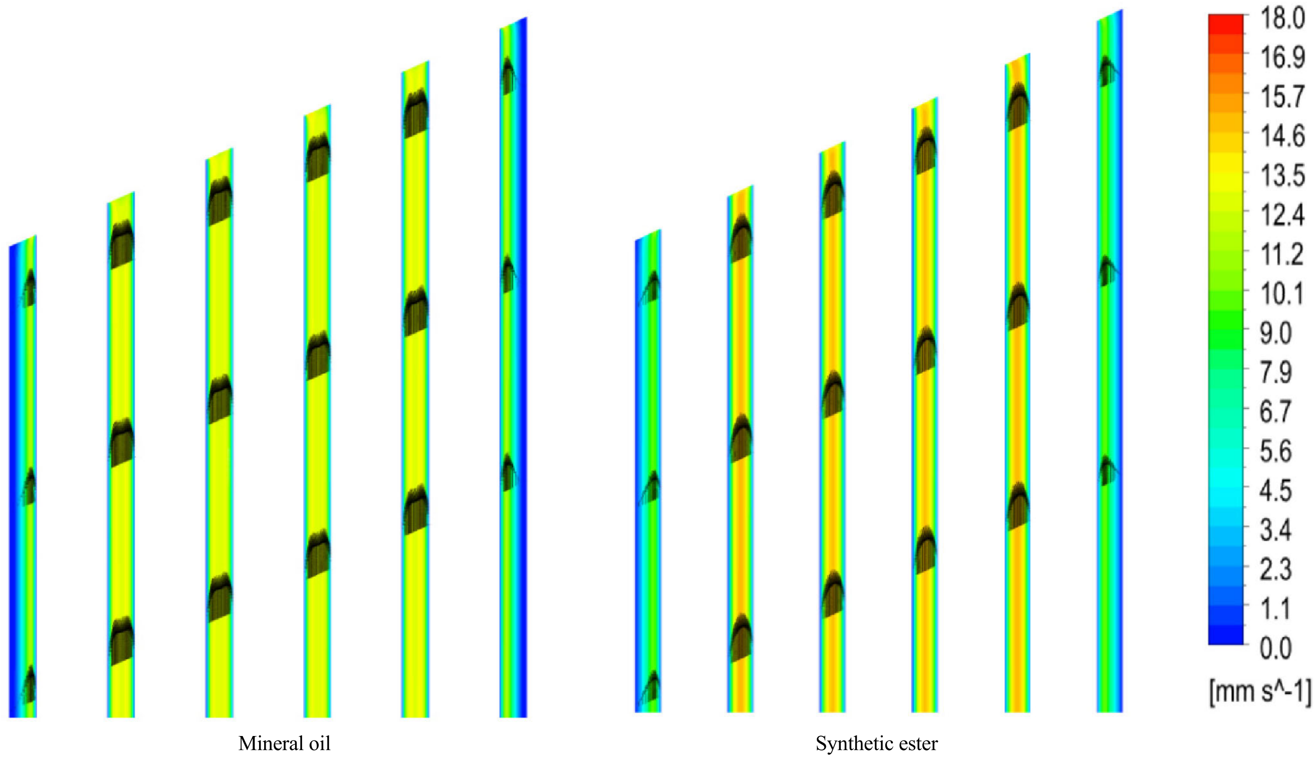


FIGURE 12. Velocity profiles at the top of the winding.

As a result, hot spot locations changes for the alternative liquids.

On that same topic, Fig. 10 presents maximum and average temperatures in CTCs's layers. The highest hot spots, showed in Fig. 8 and Fig. 10.a, are those belonging to ester-based liquids, 91.2 and 91.8 °C. Nonetheless, there is not a significant difference between the hottest hot spot (synthetic ester) and the coldest one (mineral oil), less than 2 °C. On the other hand, considering each liquid individually, the variation of the layers maximum temperatures is pretty small. That is, if it is considered the worst case, natural ester, a maximum difference of 0.9 °C can be seen between layers. In the opposite case, mineral oil, this difference is not significant, 0.3 °C. This fact can be also seen even more pronounced when the average temperatures of the layers are considered, in Fig. 10.b. In fact, there is a slight variation of the mean temperatures with the layer for each liquid. That is, regardless the dielectric liquid considered, the cooling system of the winding leads to uniform cooling of the layers, i.e. there is no bad cooling in one individual layer.

More thermal information is provided in Fig. 11, in which the temperature evolution with height in the third layer of the winding cooled by the best and worst coolant is shown. It is needed to point out that the temperature evolution in the rest of the layers presents the same pattern. Three parts can be clearly distinguished in the curves. The first one is that in which the flow is thermally developing and the temperature of the CTC layer increase rapidly with height since the fluid thermal layer is being developed and heat exchange between solid and fluid is bad. The second one (constant slope) is that in which the thermal layer of the flow has been developed. As a result, the temperature increases linearly with height in this part of the winding. Another point to highlight of this part is that the alternative oil curve slope is smaller than that of the mineral oil, thus leading to higher temperatures. Finally, the third one shows the temperature decrease due to the cooling effect of the top oil.

Fig. 12 presents the comparison of the velocity profiles of both fluids, mineral oil and synthetic ester, at the top of the winding. It can be appreciated that in both-side heated channels the velocity profiles at the end of the duct shows a fully developed behavior.

V. CONCLUSION

In the present work, the cooling performance of three dielectric liquids (a mineral oil and two ester-based fluids) in a 100 MVA HPT with axial cooling system and ONAN cooling mode has been studied using a 3D CFD model of its LVW. This model was successfully validated by comparing with the experimental results of the transformer heat-run test.

Numerical results show that all fluids keep the winding layers cooling uniformly although mineral oil is a slightly better coolant at rated power. This in due to the higher viscosity of biodegradable liquids, which negatively affects their cooling capabilities. However, the temperature increments in the winding using alternative liquids regarding mineral oil are pretty small.

In accordance with the foregoing, ester-based liquids could be used as substitute liquids of the mineral oils in this type of HPT when they are going to work in a range of powers close to the rated one.

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