11140 Session 2022
SC A2 – POWER TRANSFORMERS AND REACTORS
PS 2 – BEYOND THE MINERAL OIL-IMMERSED TRANSFORMER AND REACTORS

Analysis of new dielectric fluid alternatives using the design of a thermal distribution test platform model and CFD methods.

Pedro Jose QUINTANILLA CAVIA*
University of Cantabria[1]
Spain
quintanillap@unican.es

Agustin SANTISTEBAN DIAZ
University of Cantabria[1]
Spain
agustin.santisteban@unican.es

Ramazan ALTAY
BEST Transformer[2]
Turkey
ramazan.altay@besttransformer.com

Alfredo ORTIZ FERNANDEZ
University of Cantabria[1]
Spain
alfredo.ortiz@unican.es

SUMMARY

The inclusion and implementation of new alternative dielectric fluids in electrical power transformers is taking place and it requires in-depth knowledge and understanding of new liquids' performance. One factor that can improve the progress of their application is the use of CFD technology to predict their behaviour in systems of different complexities, achieving unprecedented knowledge, open to the creativity and technique of each author and based on a prior parameterisation of the fluid.

From the above point, this work proposes the development of a test platform for these dielectrics, which can be used to understand their performance and compare them with each other, including the mineral oil used to date as a reference.

Considering this objective, a 2D model has been proposed for an analysis based on computational fluid dynamics. This allows us to observe how various fluids behave in a closed cooling and insulation system. The fluid is heated by a variable heat source and cooled by means of a radiator whose geometry is adjusted to obtain a high level of heat dissipation. Once the model is completed, a comparison is made between fluids with diverse origins.

KEYWORDS

CFD, dielectric fluid, ester, fluid behaviour, mineral oil, power transformer, test platform, thermal analysis.

INTRODUCTION

In view of the growing demand for electrical energy, it is necessary to adapt the distribution, transmission and generation systems of this energy while maintaining the safety and reliability of the whole. One of the key elements to face this problem is the electrical transformer, which requires an evolution to cope with the continuous power increases that are happening [1]. Taking into account that the capacity of this element is limited by the temperature it reaches during its operation, which is given by the power at it works, the current use of this equipment must be significantly improved by pursuing the cooling and insulation systems to control it.

A key point in the design and use of the electrical transformer is the operation of this cooling system, which is carried out in such a way that this element does not reach dangerous temperatures for a calculated operation. In the case of very high temperatures, the insulation, composed of paper and a dielectric fluid, would age faster than expected, causing its deterioration. The correct performance and design of the cooling system will prevent or at least reduce system failures caused by breakdowns with their respective high cost.

Throughout the history of power transformers, mineral oil has been used as a dielectric coolant to ensure the correct operation of this electrical switchgear. The high increase in energy demand that is occurring and is expected to continue, makes it necessary to seek new alternatives that reduce current problems such as risk of fire or environmental damage in the waste and in its procurement. Mineral oil offers conditions that meet the basic needs; however, new alternative dielectric fluids are making their way into the market thanks to the study, analysis and application in power transformers. These studies reveal their higher flash point, which allows more compact designs, better cooling qualities at high operating regimes and less damage to the environment [2-5]. Research on the aging of the winding insulation paper and on the dielectric behaviour of these new alternatives can be found [6-10].

Comparations with new alternatives started in the 1990s with the study of different dielectric fluids to mineral oil. This topic, which is still current today, focuses in most of its studies on the form. The main aim of these studies is on the way in which temperature alters different properties of the suggested fluids, among which palm oil, corn oil or canola oil can be highlighted [11-12]. All the new liquids can be classified into two types currently used as an alternative to mineral oil: natural esters, obtained from different vegetable seeds, and biodegradable liquid synthetic esters.

Knowing the importance of the thermal distribution of the winding in the parameters mentioned above, it is important to highlight the simulation using CFD methods. This way of calculating preliminary results is very useful for the design of electrical transformers. The preparation of a good analysis is important to accurately estimate the real behaviour of the different fluids. In [13-20], this type of analysis of transformers or parts of them can be observed, although most of them are focused on the study of mineral oil.

With the latter dielectric, a few studies have been carried out on test platforms that allow the thermal response of power transformer windings to be studied [21-26]. Thus, the study prepared has a basis on which to build the analysis using natural ester as an alternative and leaving the possibility of continuing with similar analyses using other alternatives.

At this point, the present study analyses the behaviour of these fluids by means of a testing platform that allows to obtain the temperature distribution of a winding from the calculated heat losses. This paper tries to study a platform that, pursuing the resemblance to an accurate real model, takes the winding reference of a 170/36 kV, 100 MVA transformer in ONAN regime.

A CFD methodology is used from a design applied to a 2D model in order to reduce the computational power required. The above design emulates a basic regeneration circuit based on the section of the real transformer model described. In this way, only a first approximation is proposed that only includes a heater, a radiator that acts as a cooling component and a circuit that allows the circulation of fluids according to their natural forces, thus representing the ONAN configuration mentioned above.

DESIGN

In order to obtain a valid 2D model, part of the radial section of the low-voltage winding of the real transformer model is made to obtain the heater design. From it, a prismatic geometry with the same length as the perimeter of the original model is established. Two cardboards are added on the sides of the heater in parallel in order to study homogeneous channels representing the cellulose insulation of the winding, complying with the distances measured in the transformer, and the assembly is incorporated into a tank that will form the key part of the circuit. Thus, the heater has dimensions of 16 mm thickness in the five sections that represent the winding losses while having a separation between them of 6 mm. The heigh is 1634 mm in function of the original transformer.

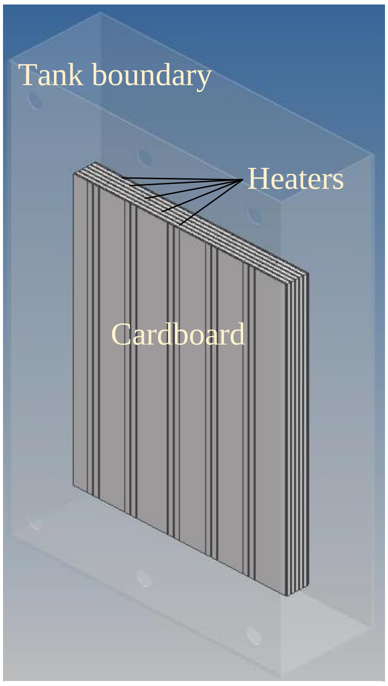


Figure 1: 3D Heater design.

On the other hand, a radiator model is established with an exchange surface proportional to the losses estimated in a previous analysis.

This study will allow to check the adequacy of the sizing established according to the results obtained since the usual operating range of refrigerants of transformers of these characteristics is known. Considering the governing equations developed below and knowing the nature of the radiator based on aluminium, the showed surface area is obtained taking into account the sole action of convection as a form of heat exchange.

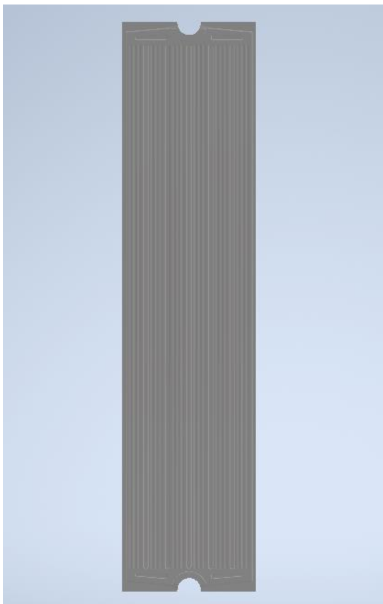


Figure 2: Radiator design.

Radiator fins are made up of six identical regions through which the fluid will flow. Each one of them is composed of two thick channels (6.70 mm) and three narrow channels (4.70 mm) so that the heat exchange is sufficiently high allowing a quick identification of the cooling zone.

The pipes connecting these two main regions have a maximum length of 1050 mm. This measurement has been used as the greatest possible distance between the tank and the furthest radiator in a three-dimensional model. The calculation is given by the maximum number of radiators in parallel required for the maximum power that could be dissipated by a platform with the described geometry.

NUMERICAL MODEL

The CFD analysis is based on the heat transfer and fluid mechanics phenomena that occur in this test platform in response to the performance of the elements that emulate the operation of the chosen low-voltage winding. The finite volume method solves the Navier-Stokes equations the state of the conservation of mass, momentum and energy for the fluid flow. The governing equations (1-5) have been adapted to the specific model.

$$\frac{\partial \rho}{\partial t} + \nabla(\rho\, \vec{v}) = 0 \tag{1}$$

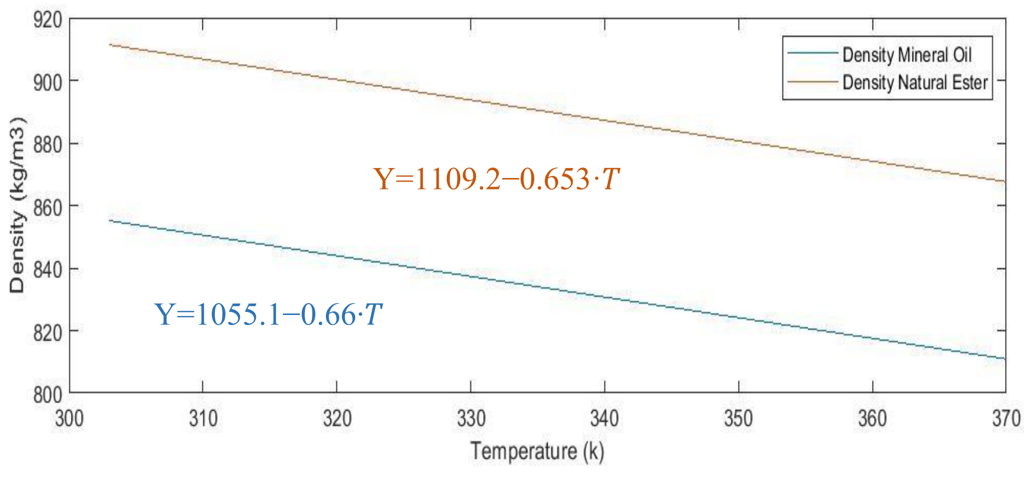
$$\frac{\partial}{\partial t}(\rho\, \vec{v}) + (\vec{v} \cdot \nabla) \cdot (\rho\, \vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho\, \vec{g} + \vec{F} \tag{2}$$

$$\bar{\bar{\tau}} = \mu \cdot \nabla^2\, \vec{v} \tag{3}$$

$$\frac{\partial}{\partial t}(\rho\, CpT) + \nabla(\rho\, CpuT) = \nabla \cdot (k\nabla T) + S_h \tag{4}$$

$$\nabla \cdot (k \cdot \nabla T) + S_h = \frac{\partial}{\partial t}(\rho\, CpT) \tag{5}$$

Where ρ, $\vec{v}$, μ, g, Cp, T, k, and S_h density, velocity vector, dynamic viscosity, gravity, specific heat capacity, temperature, thermal conductivity and heat source, respectively. From previous analyses by other authors with the base transformer [13], a heat source of 275 W (S_h) is established. In addition, laminar flow is assumed due to the operating regime (ONAN) and the parameters of the fluids studied, highlighting their high viscosity.



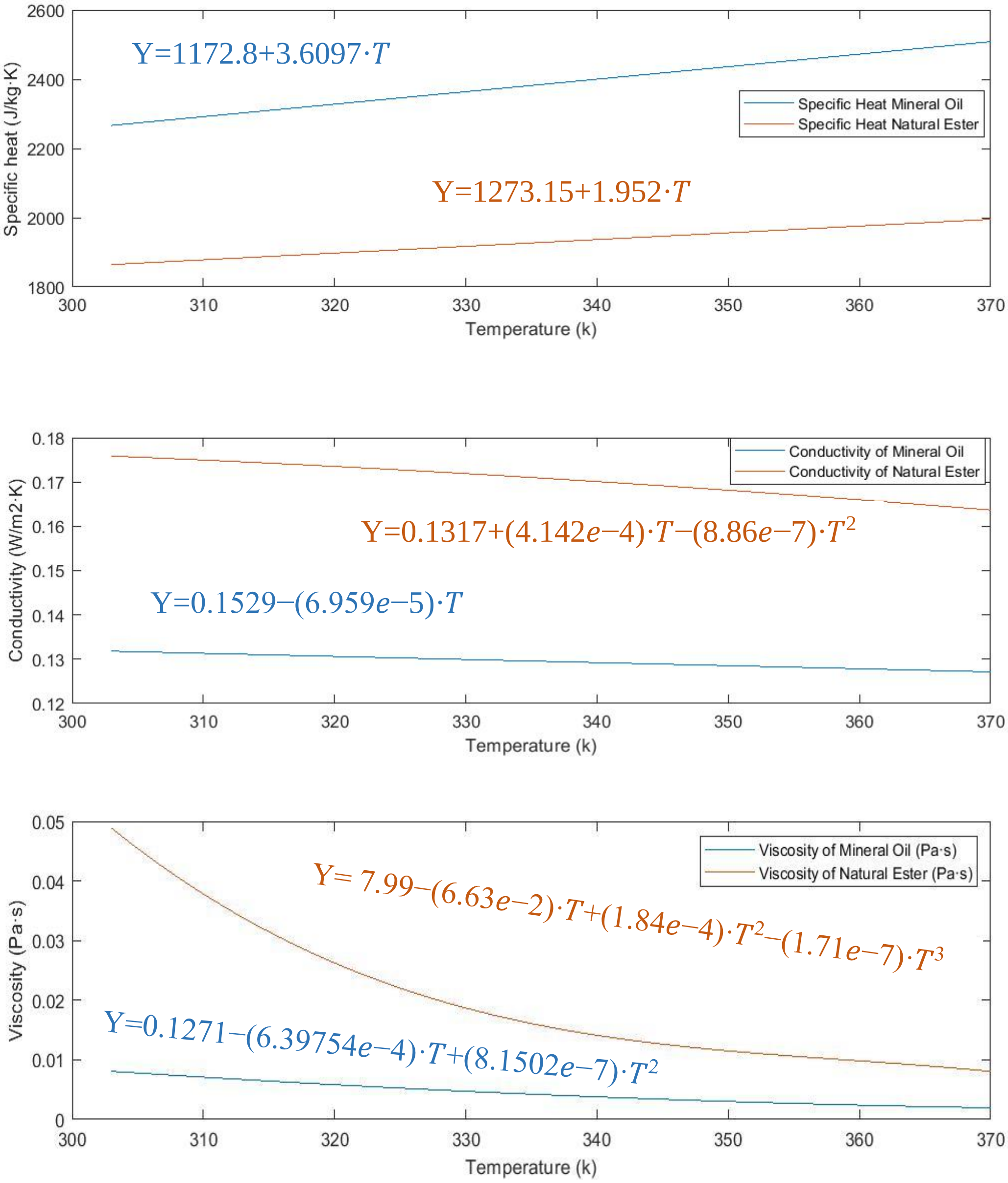


Figure 3: Parameter values for simulations.

From the values of each of the key parameters established in Figure 3, the CFD analysis is developed.

About contact surfaces of the cellulosic materials (sticks and cardboard surface) with the fluids and with the electrical conductors are considered as adiabatic due to the very low thermal conductivity of these type of elements. Only the energy exchange at the surface of the heater and the radiator has been considered, taking the rest of the contact boundaries as adiabatic due to their relative unimportance with respect to the main components.

Assuming aluminium for radiator fins, steel for the tank and copper as main material of the heaters, the thermal coefficients corresponding to each material have been established taking into account that the environment is air at nominal conditions.

By generating a heat flow from the data obtained from the heaters, the analysis has been carried out for mineral oil and natural ester and their behaviour in ordinary operation has been observed.

The solution of the partial differential equations were obtained using the commercial solver ANSYS Fluent v2020.R1. This software was run in a HP ProDesk 600 G3 MT system model using 8 processors at 3.6 GHz and 32 GB of RAM.

RESULTS

This section shows the results obtained from the CFD simulation for the 2D circuit model that allows to observe the values to be expected from the test platform to be built in the future once the present analysis and the previous ones developed in 3D have been validated.

Pending the construction and experimental verification of the model, the current validation methodology is the comparison with previous studies performed on real transformers [13] or already built platforms that allow to see the relationship between this type of adaptation and commercial transformers [26].

This analysis shows the behaviour of the two fluids proposed above with respect to the heat generated by the thermal source and the heat dissipation that occurs in the radiator. In this way, the differences between the two fluids are tested in specific operating regimes.

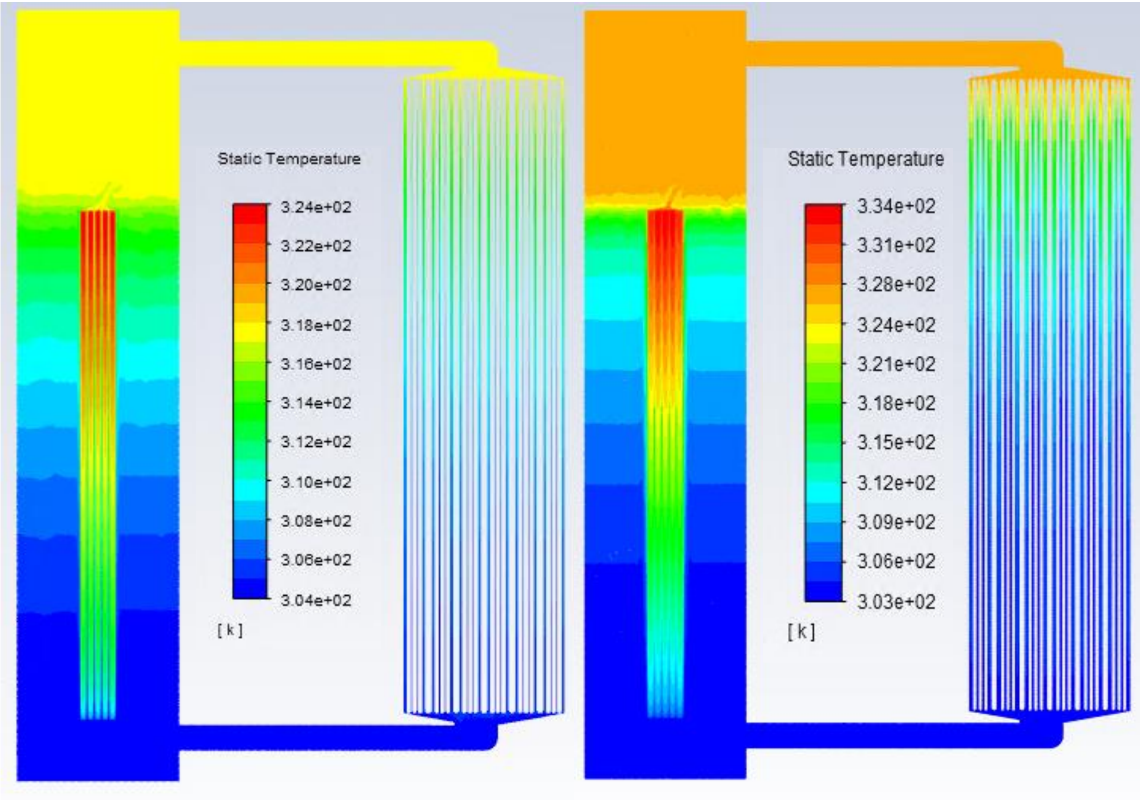


Figure 4: Results of 2D test platform for rated conditions a) Mineral Oil b) Natural Ester.

Firstly, having a thermal source of nominal value for the dimensions, the temperatures in both cases are very low compared to similar studies. In the case of mineral oil, the maximum temperature in the heater is close to 51ºC, which indicates an oversizing of the cooling circuit.

This data, considering previous studies [27], predicts worse conditions for the natural ester, which is confirmed in the results, offering a maximum temperature of 61ºC.

Another important point is the thermal distribution along the cooling circuit. In this case, the analysis clearly favours mineral oil, since the viscosity of both fluids at relatively low temperatures produces a poor distribution of the ester when observing its temperature, with very hot parts remaining in the upper part of the circuit due to the low velocity that appears naturally.

From the equations illustrated in Figure 3, better performance of the ester can be expected under high temperature conditions. Repeating the analysis for the previous model based on the original transformer, considering an overrated load (1.15pu), the results are presented to see if thermal values obtained between the two dielectric fluids are close.

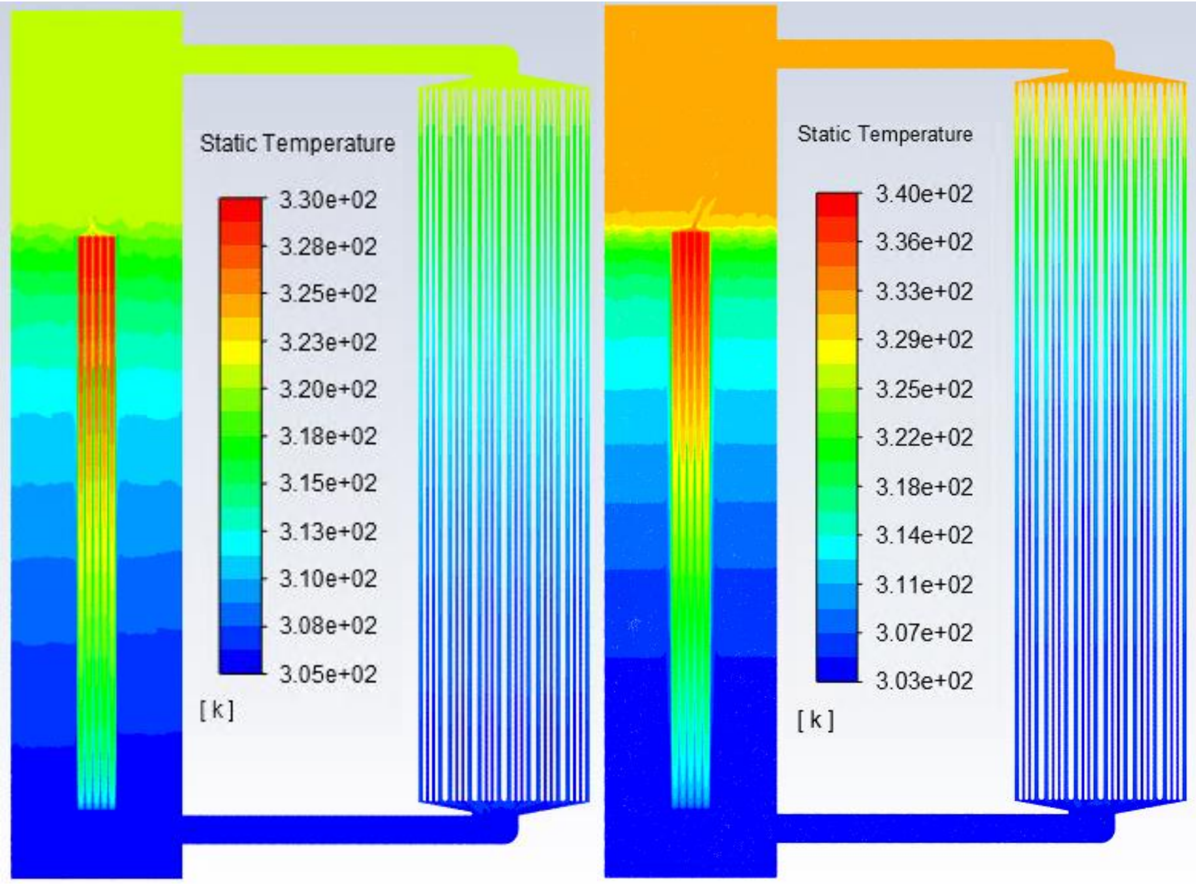


Figure 5: Results of 2D test platform for 1.15pu overrated conditions a) Mineral Oil b) Natural Ester.

In this way, it is observed that both fluids act better as a coolant at temperatures closer to normal design operation.

The oversizing of the cooling for the 2D geometric adaptation of the real transformer can be confirmed with this analysis. If it is proposed to make a platform that is useful for various geometries and transferred energy, the need to correct the suitability for this specific case is determined by analysis.

The thermal difference is maintained so that the best performance of the ester or an increase in the similarity between the behaviour of both fluids cannot be determined. However, the increase in the cooling speed, the greater dissipation and the qualitative improvement of the ester can be mentioned.

This fact leaves the possibility of continuing the research in the future with conditions in which more approximate results occur between both dielectrics.

The possibility of reducing costs and being able to validate results with confidence and speed in this field of study through a testing platform has not proven to be a case of simple application. However, the possibilities that reaching this milestone would offer and the first preliminary results provoke the pursuit of this aim.

CONCLUSION

With this work, the authors have presented the preliminary design of a 2D test platform to check and obtain validation for transformer designs without big expenses. This one has been used to compare the traditional mineral oil and a natural ester as coolant in an immersed oil type of power transformer. The validation of the model couldn’t be determined perfectly due to the deviation produced in the calculation step from a 3D model to a 2D one to reduce computational power given the outstanding cooling circuit for 2D models. However, it has been possible to observe the comparison between the behaviour of both dielectrics at low operating regimes from their parametric equations.

Numerical results show both of them keep the layers cooling uniformly although mineral oil is better coolant at rated power.

The next tests which will be carried out from the of a 100 MVA transformer must be suitable for values that allow normal thermal distributions, otherwise resources will be wasted.

BIBLIOGRAPHY

[1] Ferreiro, A. y Nigro, No. (2011) “Ensayo numérico del calentamiento en un transformador eléctrico”. Revista Iberoamericana de Ingeniería Mecánica. Vol. 15, n. 2, 2011, p. 15-28. ISSN 1137-2729

[2] Lewand, L. (2004). Laboratory testing of natural ester dielectric liquids. Neta World, 1-4.

[3] U. Mohan Rao, I. Fofana, T. Jaya, E. M. Rodriguez-Celis, J. Jalbert and P. Picher, “Alternative Dielectric Fluids for Transformer Insulation System: Progress, Challenges, and Future Prospects,” in IEEE Access, vol. 7, pp. 184552-184571, 2019, doi: 10.1109/ACCESS.2019.2960020.

[4] SM, Bashi, et al. Use of natural vegetable oils as alternative dielectric transformer coolants. 2006.

[5] I. Fernández, A. Ortiz, F. Delgado, C. Renedo, S.Pérez. “Comparative evaluation of alternative fluids for power transformers, Electric Power Systems Research”, Volume 98,2013, Pages 58-69, ISSN 0378-7796.

[6] I. Fernández, F. Delgado, F. Ortiz, A. Ortiz, C. Fernández, C. J. Renedo, and A. Santisteban, “Thermal degradation assessment of kraft paper in power transformers insulated with natural esters,” Appl. Thermal Eng., vol. 104, pp. 129-138, Jul. 2016.

[7] P. Trnka, J. Hornak, P. Prosr, O. Michal, and F. Wang, “Various aging processes in a paper-natural ester insulation system in the presence of copper and moisture”, IEEE Access, vol. 8, pp. 61989-61998, 2020.

[8] T. Mariprasath and V. Kirubakaran, “Thermal degradation analysis of pongamia pinnata oil as alternative liquid dielectric for distribution transformer,” Sãdhanã, vol. 41, no. 9, pp. 933-938, Sep. 2016.

[9] J.-I. Jeong, J.-S. An, and C.-S. Huh, “Accelerated aging effects of mineral and vegetable transformer oils on medium voltage power transformers”, IEEE Trans. Dielectrics Electr. Insul., vol. 19, no. 1, pp. 156-161, Feb. 2012.

[10] C. Thirumurugan, G. B. Kumbhar, and R. Oruganti, “Effects of impurities on surface discharges at synthetic ester/cellulose board,” IEEE Trans. Dielectrics Electr. Insul., vol. 26, no. 1, pp. 64-71, Feb. 2019.
[11] M. Meira, R. Álvarez, L. Catalano, C. Ruschetti, and C. Verucchi, “Comparación de Aceites Dieléctricos Minerales y Vegetales en Relación a la Producción de Gases,” [Online]. Available: http://sedici.unlp.edu.ar/handle/10915/77711.
[12] M. H. A. Hamid; M. T. Ishak; M. F. Md. Din; N. S. Suhaimi; N. I. A. Katim, “Dielectric properties of natural ester oils used for transformer application under temperature.
[13] Altay, R., Santisteban, A., Olmo, C., Renedo, C. J., Fernández, A. O., Ortiz, F., & Delgado, F. (2020). “Use of Alternative Fluids in Very High-Power Transformers: Experimental and Numerical Thermal Studies.”, IEEE Access, 8, 207054-207062.
[14] M. E. Rosillo, C. A. Herrera, and G. Jaramillo, “Advanced thermal modelling and experimental performance of oil distribution transformers”, IEEE Trans. Power Del., vol. 27, no. 4, pp. 1710-1717, Oct. 2012.
[15] S. Khandan, S. Tenbohlen, C. Breuer, and R. Lebreton, “CFD study of fluid flow and temperature distributions in a power transformer winding,” in Proc. IEEE 19th Int. Conf. Dielectric Liquids (ICDL), Jun. 2017, pp. 1-4.
[16] X. Zhang, Z. Wang, Q. Liu, P. Jarman, and M. Negro, “Numerical investigation of oil flow and temperature distributions for ON transformer windings”, Appl. Thermal Eng., vol. 130, pp. 1-9, Feb. 2018.
[17] G. Liu, Z. Zheng, X. Ma, S. Rong, W. Wu, and L. Li, “Numerical and experimental investigation of temperature distribution for oil-immersed transformer winding based on dimensionless least-squares and upwind finite element method,” IEEE Access, vol. 7, pp. 119110-119120, 2019.
[18] Nogueira, G. C., Medeiros, L. H., Oliveira, M. M., Barth, N. D., Bender, V. C., Marchesan, T. B., & Falcão, C. E. (2021). Thermal Analysis of Power Transformers with Different Cooling Systems Using Computational Fluid Dynamics. Journal of Control, Automation and Electrical Systems, 1-10.
[19] Raeisian, L., Werle, P., Niazmand, H., & Ebrahimnia-Bajestan, E. (2018, November). Prediction of Oil Hotspot Temperature in a Distribution Transformer by CFD Method. In VDE High Voltage Technology 2018; ETG-Symposium (pp. 1-6). VDE.
[20] Daghrah, M., Zhang, X., Wang, Z., Liu, Q., Jarman, P., & Walker, D. (2020). Flow and temperature distributions in a disc type winding-part I: Forced and directed cooling modes. Applied Thermal Engineering, 165, 114653.
[21] M. Daghrah, Z. D. Wang, Q. Liu, D. Walker, C. Krause, and G. Wilson, “Experimental investigation of hot spot factor for assessing hot spot temperature in transformers,” C. 2016 - Int. Conf. Cond. Monit. Diagnosis, pp. 948–951, 2016, doi: 10.1109/CMD.2016.7757981.
[22] S. Tenbohlen, N. Schmidt, C. Breuer, S. Khandan, and R. Lebreton, “Investigation of Thermal Behavior of an Oil-Directed Cooled Transformer Winding,” IEEE Trans. Power Deliv., vol. 33, no. 3, pp. 1091–1098, 2018, doi: 10.1109/TPWRD.2017.2711786.
[23] 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, doi: 10.1016/j.ijheatfluidflow.2017.11.007.
[24] S. Khandan, S. Tenbohlen, C. Breuer, and R. Lebreton, “CFD study of fluid flow and temperature distributions in a power transformer winding,” 2017 IEEE 19th Int. Conf. Dielectr. Liq. ICDL 2017, vol. 2017-Janua, no. Icdl, pp. 1–4, 2017, doi: 10.1109/ICDL.2017.8124674.
[25] M. Daghrah, Z. D. Wang, Q. Liu, D. Walker, P. W. R. Smith, and P. Mavrommatis, “Design of experimenal setup to study factors affecting hot spot temperature in disc type winding transformers,” IET Conf. Publ., vol. 2015, no. CP668, pp. 3–8, 2015, doi: 10.1049/cp.2015.0899.
[26] G. R. Rodriguez, L. Garelli, M. Storti, D. Granata, M. Amadei, and M. Rossetti, “Numerical and experimental thermo-fluid dynamic analysis of a power transformer working in ONAN mode,” Appl. Therm. Eng., vol. 112, pp. 1271–1280, 2017, doi: 10.1016/j.applthermaleng.2016.08.171.
[27] A. Santisteban, F. O. Fernández, I. F. F. Delgado, A. Ortiz and C. J. Renedo, “Thermal analysis of natural esters in a low-voltage disc-type winding of a power transformer,” 2017 IEEE 19th

International Conference on Dielectric Liquids (ICDL), 2017, pp. 1-4, doi: 10.1109/ICDL.2017.8124698.