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Thermal Modeling of a Power Transformer with Different Dielectric Liquids

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ABSTRACT

In order to improve the transformers performance, dielectric oils are used as cooling fluids. Therefore, the characteristics of these fluids have great influence on the useful life of these machines.

In this study, the cooling performance of two vegetable oils will be analyzed; the results will be compared with those of a mineral, which is the oil typically used in electrical transformers.

This comparison will be carry out in a power transformer with zigzag cooling channels. The model of this transformer will be 2D asymmetric, and will be tested using a software based on finite elements method, COMSOL Multiphysics.

The temperature of the hot spot or the hot spot factor reached with the three dielectric fluids will be compared. In addition, the influence of increasing number of cooling steps on the hot spot temperature will be studied for all liquids. The conclusions obtained in this study show that vegetable oils ensure that the temperature of the hot spot is lower than that reached with mineral oil.

The values of the hot spot factor indicate that a greater number of steps leads to more efficient cooling circuits due to the increase in pressure drop, although the hot spot temperature decreases. It is also observed that an increase in the number of steps affects more positively when considering mineral oil.

Power transformer; Thermal modelling; Conjugate Heat Transfer; Alternative dielectric liquid, Hot-spot temperature;

1. Introduction

Electric power transformers are one of the most important machines in electric power distribution systems [1-3]. These machines must operate at a point where the losses are minimal and the performance maximum.

Low efficiency means power losses that translate into heat, and therefore an increase in the working temperature inside the machine. This increase in temperature means that the degradation of the components is favored. In particular, it is the dielectric paper the component that suffers higher deterioration with the increase of temperature. And it is the winding in the low voltage part the point more critical, since it reaches the highest temperature. This is because these conductors are those where more losses are generated, thanks to the high value of current flowing through this winding.

Therefore it is very important to try to work with the lowest temperatures to improve their performance, lengthen life and protect from possible failures in the transformers. Today the most widespread way to perform the refrigeration is by mineral oils, having as properties high thermal conductivity, high dielectric breakdown voltage, low viscosity, low ignition point, low freezing temperature and low dielectric losses.

Some research works have had as a consequence the appearance of new dielectric liquids [4] that try to improve certain properties of mineral oils. These are vegetable oils that have higher ignition and combustion points, higher than 300ºC and 350ºC respectively, which allow having a higher level of safety in electrical substations. Due to their composition of natural origin, these have a high biodegradability what means that at the end of their useful life can be recycled and reused. Another property that is improved is the dielectric rigidity, since they have a high water saturation point.

To study the cooling capacity of these new dielectric liquids, computational fluid dynamics (CFD) techniques have been used. Some authors, as Torriano et al. [5-6], have used this technique. They performed simulations in a low voltage winding (LVW) of a power transformer with zigzag cooling. The objective was to determine the temperature distribution for different 2D and 3D models based on the CFD analysis of the heat transfer processes. In 2009, Taghikhani et al. [7] used a 2D heat transfer model of a power transformer to predict the value and location of the hot spot, including the influence of the directed oil flow (DOF) and the non-directed oil flow settings (NDOF)).

In 2010, Sorgic and Radakovic [8] carried out a 2D simulation of a transformer submerged in mineral oil to compare the cooling system with the oil-driven and forced oil configuration. In 2012, Tsili et al. established a methodology to develop a 3D model and to predict the temperature of the hot spot [9]. In this year, Skillen et al. conducted a CFD simulation of an asymmetric non-isothermal flow 2D model to characterize the oil flow in a transformer winding with zigzag cooling [10]. In 2014, Yatsevsky carried out a 2D simulation of a transformer submerged in oil with natural convection including the core, the tank and the radiator, to predict hot spots. The developed model showed a good performance that was verified by experiments [11]. Recently, Torriano et al. developed the 3D heat transfer model in a scale disk-type power transformer with natural convection cooling (ON) [12].

The objective of this study is to perform a 2D thermohydraulic simulation of a power transformer with zigzag cooling, considering two vegetable oils and a mineral oil. This would serve as a reference of a LVW. In addition, an analysis of the influence of the number of passes on the temperature of the hot spot for each dielectric liquid is discussed.

2. Material and methods

Figure 1 shows the properties of the two vegetable oils and the mineral oil considered as coolant of this transformer. The properties of the mineral oil were obtained from [5] and the natural esters have been obtained from the data of the manufacturers of these fluids. It is observed that the specific heat has similar values for all the fluids, while density, thermal conductivity and kinematic viscosity of the mineral oil is lower than that of vegetable oils. On the other hand, the thermal properties of vegetable oils are better than those of mineral oils. All properties except specific heat decrease with temperature. The dynamic viscosity takes lower values for mineral oil with respect to vegetable oils.

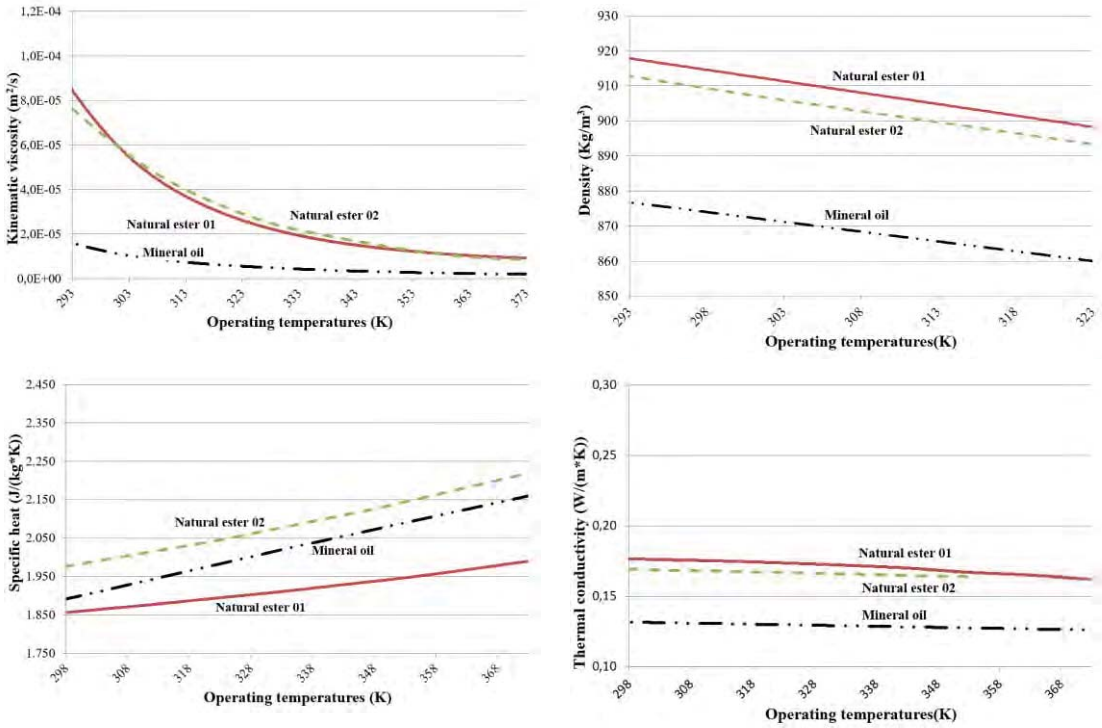


Figure 1.- Properties of the oils considered

The geometry of the study corresponds to an LVW of a 66 MVA power transformer. To reduce the computational requirements, some simplifications have been made, obtaining an asymmetric two-dimensional model of the winding that is fully described in [5].

The winding of the transformer is shown in Figure 2, which is composed of an input section of two disks and four passes of 19 disks separated by flow guides that make a total of 78 disks. Each disc of the winding is 50.8 mm wide and 15 mm high, and is composed of 18 copper conductors individually wrapped with a layer of 0.4 mm thick insulating paper. The disks are separated by horizontal conduits of 4.1 mm high.

The present study combines the physical principles of fluid dynamics and heat transfer. For the fluid domain, the Navier-Stokes equations, mass conservation, moment conservation and energy conservation, are considered.

The CHT module of COMSOL Multiphysics v5.2 was used in the cooling channels and the winding discs to reach a stationary solution through FEM. The simulations were carried out on a Dell Precision T5500 workstation, with two processors at 2.66 GHz and 72 GB of RAM, which took between 7 and 9 hours to reach a solution for each case.

A simulation of one-step of the transformer was prepared to validate the developed model, comparing results with those presented in [5] with the complete CHT model.

In order to validate the developed model and estimate its accuracy, a simulation of a single step from the transformer was performed, and the results of the average temperature of the disk T_w, location of the hot spot T_h and distribution of the oil speed were obtained, comparing with those presented in [5].

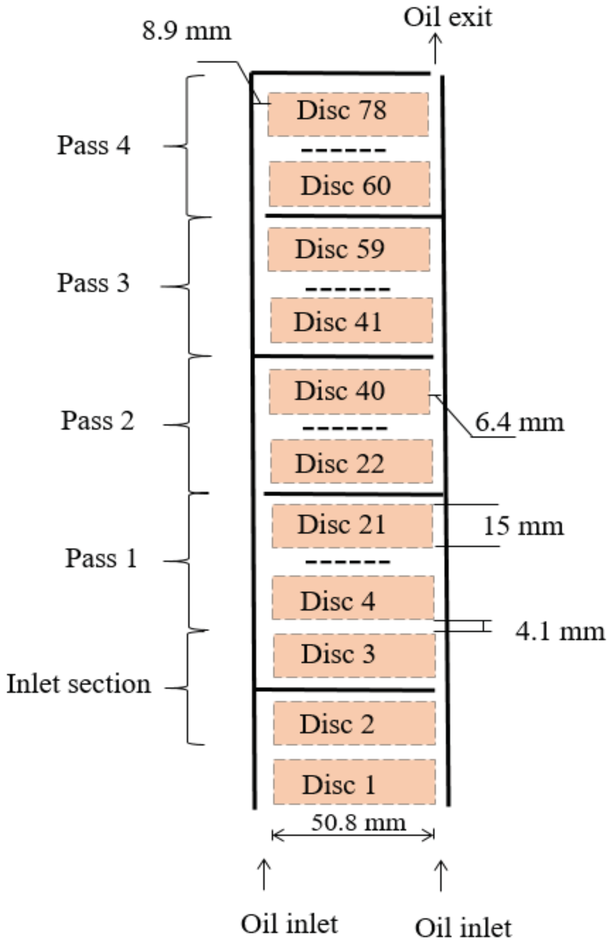


Figure 2. LVW geometry

Figure 3 shows the average temperature of the disks obtained from the simulation and from [5]. It can be seen that similar values are obtained since the maximum error is 0.7% in the average temperature and the average discrepancy is 0.44%.

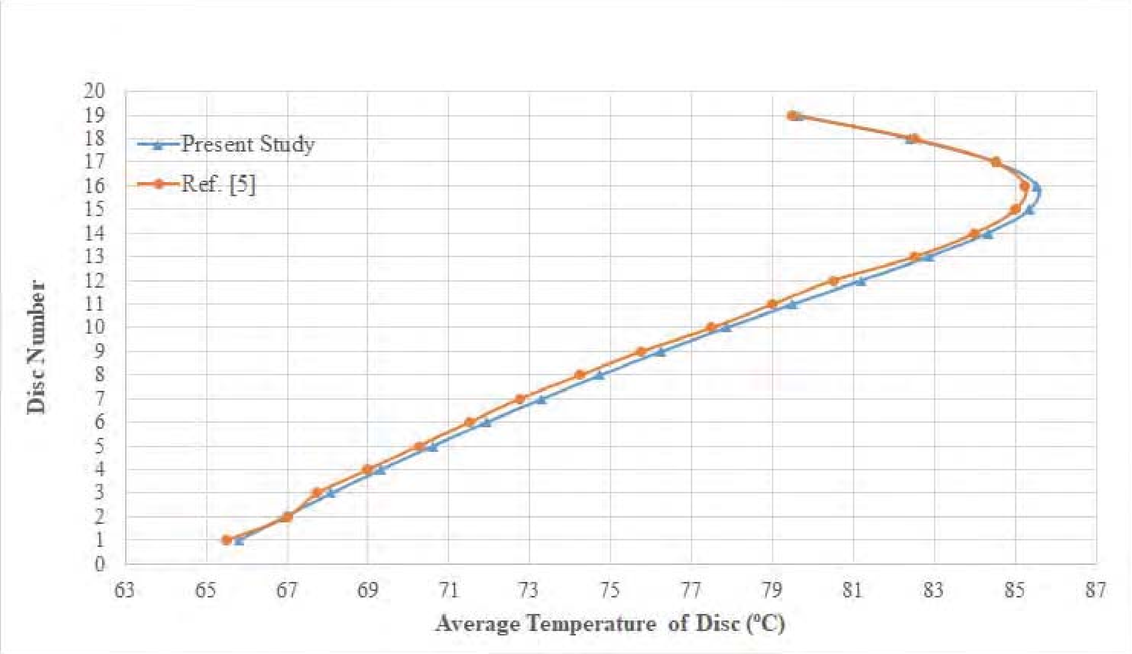


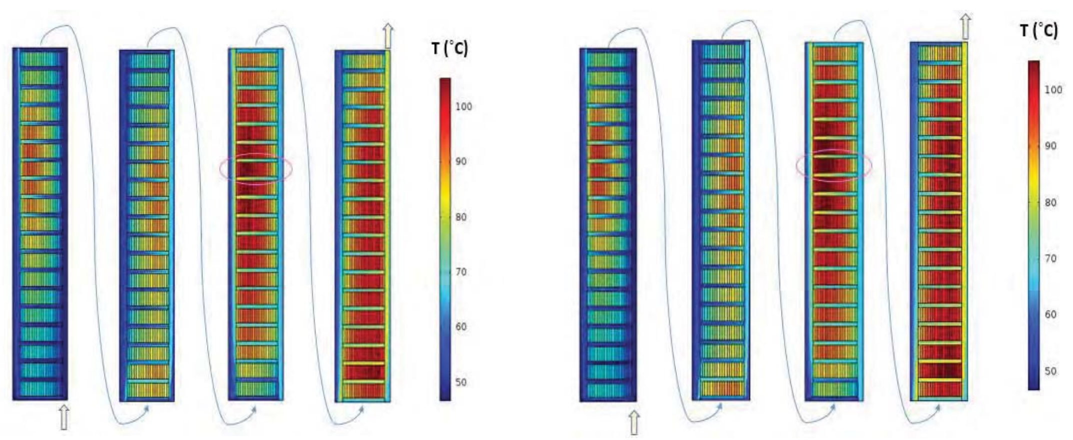
Figure 3. Average disc temperature in comparison with Ref. [5]

3. Results and discussion

The conditions of the study have been established so that the mass flow at the entrance is the same, to establish the comparison from the thermal point of view.

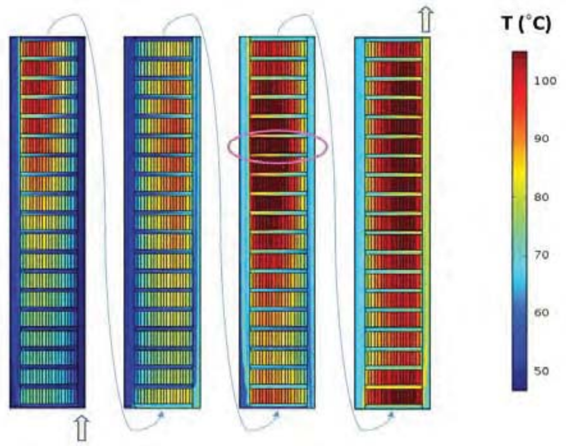
The load losses that occur in the winding are greater in the case of natural esters.

Figure 4 shows the evolution of the temperatures in the windings in their four steps for the three dielectric liquids studied. It can be seen that the refrigeration achieved with vegetable oils is similar, and better than that of mineral oil; this is mainly due to the different densities and viscosities of the fluids.



Vegetal oil 1

Vegetal oil 2



Mineral oil
Figure 4 Temperature and HSL

The appearance of hot veins in the initial discs of the second and fourth passes, makes the temperature of these discs higher than those of the discs that follow them. These hot veins pass from one axial conduit to another through the first horizontal channels of the mentioned passage, which increases the temperature of the oil on the surface of these discs.

Figure 5 represents the temperature of the oil obtained for each liquid, and it can be seen the appearance of hot veins in the oil. For the mineral oil it is observed that in the third pass a cold line appears between the third and fifth channels, which is formed at the end of the second pass. A second cold line appears in the oil at the end of the fourth pass.

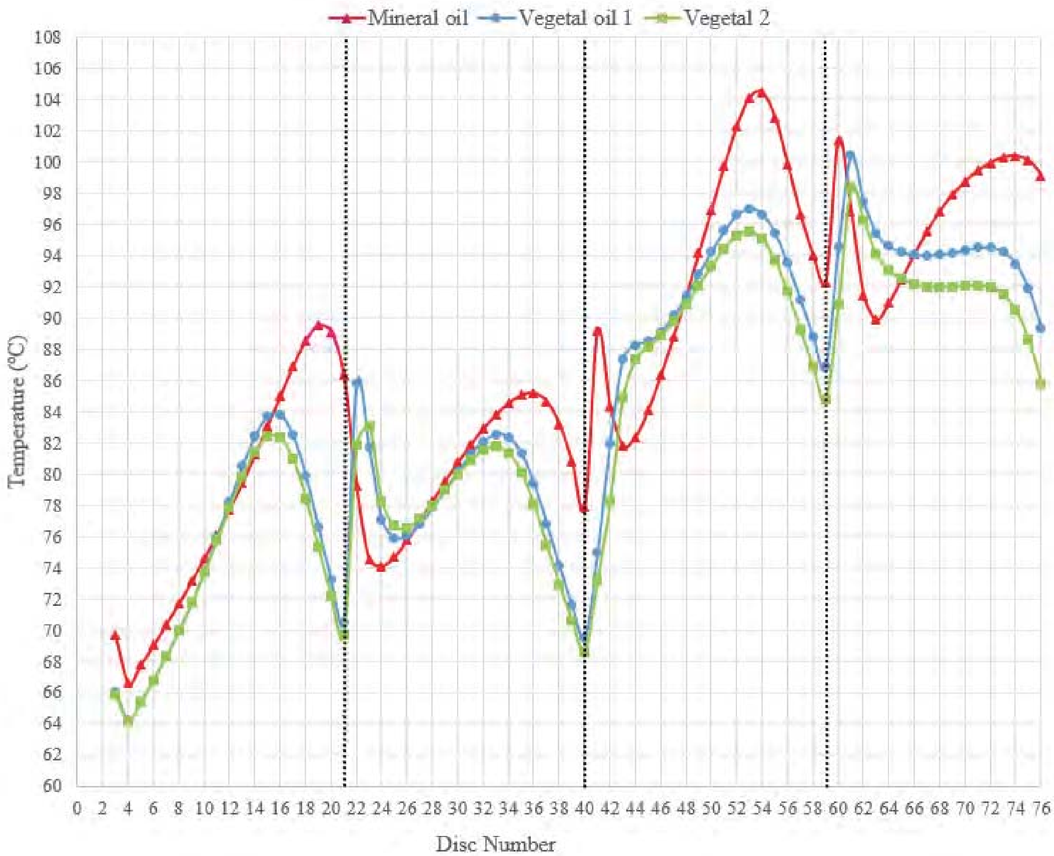


Figure 5 Temperature and HSL

Table 1 includes the data of top oil temperature, T_o, the average winding temperature, T_w, hot spot temperature, T_h and the point at which the hot spot is located (HSL) for each of the three oils. It should be emphasized that the temperature of the hot spot with the mineral oil is about 10ºC superior to the one obtained when vegetable oils are used.

Table 1 Temperature obtained in each pass

	To (ºC)	Tw (ºC)	Th (ºC)	HSL
Mineral oil	79.0	86.7	114.7	Disc 54
Vegetal oil 1	78.5	83.8	105.3	Disc 53
Vegetal oil 2	75.4	82.6	103.5	Disc 53

An analysis of the influence of the number of passes on the hot spot temperature of the cooling circuit was carried out for the three oils. The number of passes increase is achieved by the addition of new washers in different positions without altering the dimensions of the elements that make up the cooling circuit (height of the horizontal channels and width of the vertical ducts). As a result of the number of passes growth, the liquid must cover a longer path, and the speeds in the horizontal channels are augmented, since increasing the number of passes reduces the number of channels. The oil entry conditions (oil mass flow rate and temperature) and the same boundary conditions have not been modified. The analyzed cases have been:

- • 5 steps with 15 discs per step and 3 lower discs
- • 6 steps with 13 discs per step
- • 7 steps with 11 discs per step and 1 lower disc
- • 8 steps with 9 discs per step and 6 lower discs
- • 11 steps with 7 discs per step and 1 lower disc

Figure 6 shows the evolution of the hot spot temperature for the different cases analyzed. It can be seen that there is better heat exchange with the increase in the number of steps; this is due to the increase of the speeds in the horizontal channels, since by increasing the number of steps the number of channels is reduced. This can reduce T_h 15ºC. In the mineral oil a greater reduction is appreciated with the increase of the steps. In addition, it can be observed that with a greater number of passes, the value of T_h of the three liquids is similar. This is due to the fact that the hydraulic properties of the mineral oil (viscosity and density) balance its worst thermal properties with respect to vegetable oils. With vegetable oils the influence of the number of steps is much smaller, so that with a large step number the T_h value of the three liquids is similar.

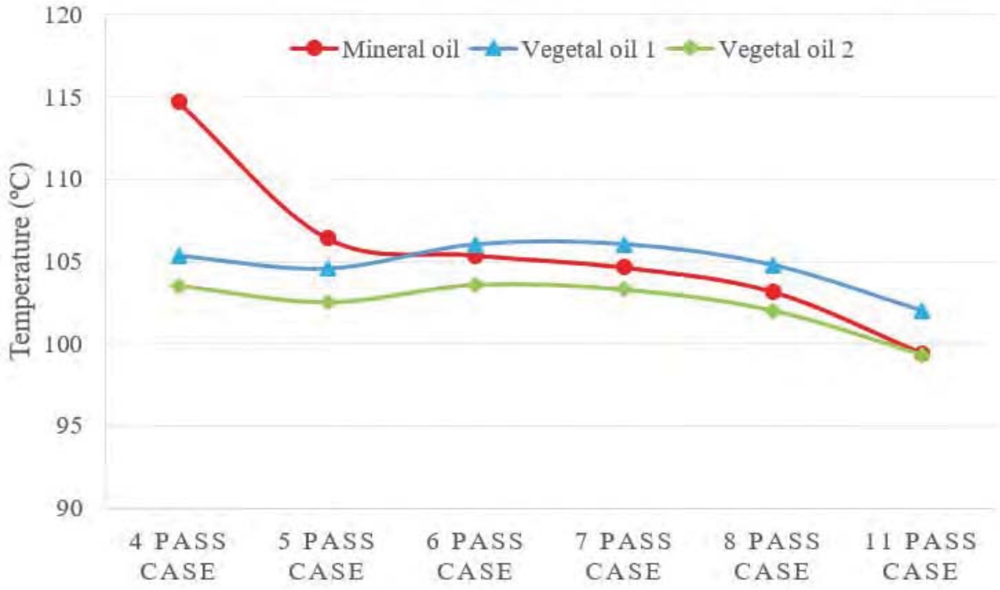


Figure 6 Hot spot temperature

4. Conclusions

In the results obtained it can be seen that the mineral oil has a hot spot temperature higher than vegetable oils, which shows that vegetable oils have better thermal properties for their use as a dielectric liquid.

The increase of the steps produces an appreciable improvement in the hot spot temperature in the mineral oil, while the vegetable oils influence in the number of steps is very slight. Therefore, the substitution of mineral oil by another vegetable in transformers can represent a great advantage in the refrigeration of the machines when the number of steps is reduced, however, it may have no effect in the case the number of steps is high.

In the case of new transformers in which the use of vegetable oil is planned, it must be considered that the number of steps does not seem to have a great influence on the refrigeration, so that its design and construction can be simplified.

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