Simulation of a distribution transformer

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Abstract: - Within transformer industry, one of the thermal design key parameters in this type of devices is the determination of the transformer cooling oil temperature. Several researchers, including manufacturers and people from professional associations like IEEE, have proposed thermal models ranging from the simplified analytical to the computational of concentrated parameters which predict the oil temperature within the transformer cooling ducts of the high and low voltage windings of this type of energy conversion device. In this work, a computational thermal model that predicts the oil temperature distribution in winding ducts of a 1000 kVA one-phase transformeris proposed. This model was developed based on the finite volume technique that is used in Fluent ™. It was found that the temperature distribution obtained from the model agrees well with experimental data for a transformer with the same power capacity.

Keywords: distribution transformer, thermal model, windings, temperature, duct, finite element

1 Introduction

Distribution transformers are used to convert electrical energy from a high to a low voltage. In Mexico these levels of voltage vary from 13.2 to 34.5 kV in the higher level to 0.12 to 13.6 kV in the lower level.

Nowadays several designs of electrical distribution transformers can be found which are differentiated due to its electrical construction, new magnetic materials used in the core, etc. Therefore, its electrical design has almost not changed since its first design more than a century ago. However, during the last 50 years an increasing interest towards the thermal design of power and distribution transformers has evolved. According to C57.91 from IEEE [2], thermal design is carried out by using an empirical method which is based on a calculation of the top oil and top winding temperatures. This method involves extrapolating thermal data with empirical equations to calculate the top oil and top winding temperatures. Nearly all the power and distribution transformers manufacturers use this method as well as thermal tests known as heat run tests.

Here detailed numerical modelsusing finite volumetechniques solve for the temperature distribution and velocities of oil in inner parts of power and distribution transformers. Thesenumerical methods although more precise in the calculation of oil and windings temperatures have been considered as a complementary calculation to the empirical or thermal test [3, 4, 5]. L. W. Pierce has developed a network model which produces a set of algebraic equations based on a heat balance performed in every node considered in the region of interest. The thermal convective coefficients are considered from standard correlations found in the literature. Later this set of finite difference equations are solved for the temperatures using standard algorithms for solution of the resulting matrices. Other researchers have used a less traditional approach by means of the heat conduction equation and its solution through advanced mathematical techniques [9].

El-Wakil et al [10], propose a numerical model which is solved by using the Fluent® program for a 100 kV/ 22.5 kV power transformer. He analyses some interesting geometries composed of top and bottom barriers within the low and high voltage windings which yield different oil velocities.

Olsson [11] analyses a disc type winding of a power transformer to determine the influence of oil streams coming out from the horizontal oil ducts which are believed to modify the oil velocity. The analysis is performed in a two dimensional model of a disc composed of eighth conductors. The momentum and energy equations are solved by the Fluent™ program.

Haritha [12] proposes a numerical model and solves it with NISA™ program for a 500 KVA one-phase transformer.

Hereby a numerical thermal model which involves the use of Fluent™ program is proposed for a 1000 KVA distribution transformer. Numerical results obtained are consistent with experimental values obtained from tests performed by other authors.

2 Modeling of the distribution transformer

The internal structure of a transformer is complex and it does not fit any known geometry. Therefore, the internal geometry for a 1000 kVA distribution transformer is composed of rectangular sections. Corresponding core and high and low voltage windings are equally rectangular shaped. Refer to Fig. 1 to visualize the mentioned internal structure.

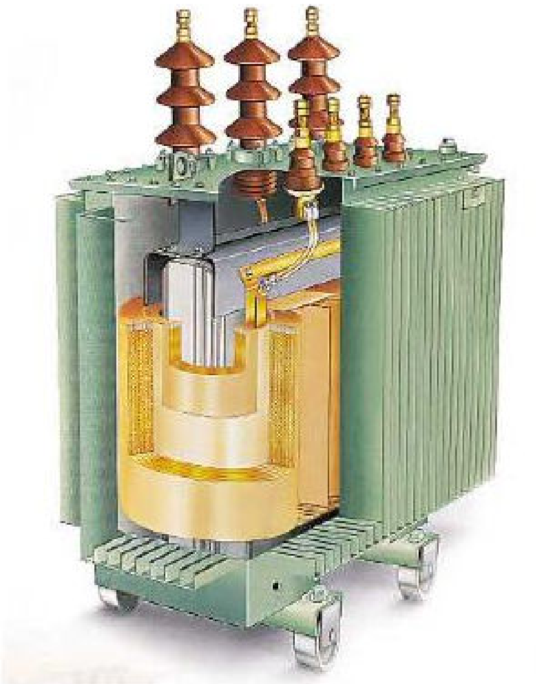

Figure 1 Internal geometry of a transformer

Besides, the windings are made of layers of copper or aluminum and among them a layer of insulating NOMEX paper to electrically isolate every turn of copper or aluminum layer.

The 2D model proposed is taken as a rectangular slice of the transformer, composed of the corresponding section of core, high and low voltage windings, oil ducts and radiator ducts and tank, see Fig. 2.

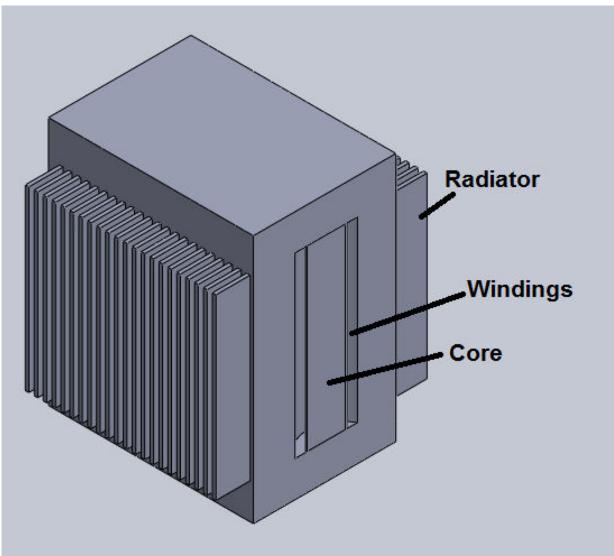

Figure 2 Slice model

Based on the fact that we have a symmetry along the centreline of the transformer which passes through the transversal section composed of the core, high/low windings and fins of the radiator, a slice model could be used as representative on the bulk system. This slice model is shown complete in Fig. 3 with the physical dimensions which were taken from the actual dimensions of a 1000 kVA distribution transformer.

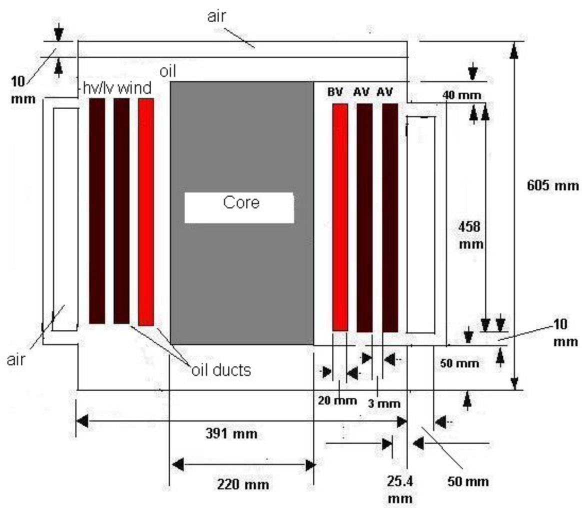

Figure 3 Complete slice model

Initially, the whole system was considered at the atmospheric temperature (24 °C) in order to simulate the initial condition of the transformer and to observe the evolution of the system. However, since the evolution time was not too big in comparison with the time the transformer reaches its steady state operation, the final condition was considered as a steady state condition.

Boundaries for this analysis are composed of the internal boundaries conformed by the HV/LV windings and core, and external boundaries which are composed of the tank walls and radiator fins. This is shown in Fig. 4.

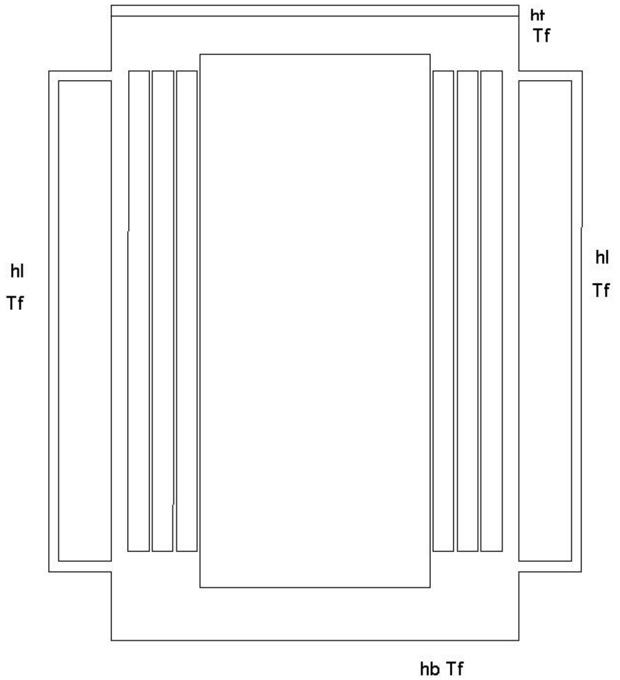

Figure 4 Boundaries of the slice model

It was considered that the total heat generated in the HV/LV windings and core is dissipatedin the oil and in turn it is transferred to the surrounding air. Values of temperature corresponding to the boundaries composed of HV/LV windings and core were taken from a heat run test previously performed in a three phase power transformer 1000 KVA capacity.

The other boundaries composed by the tank walls and radiator fins were included by adding heat transfer convection coefficients h_t, h_b and h_l formulated according to standard empirical correlations published in textbooks for the corresponding geometry.

The model is constituted of the following equations which are valid for laminar flow occurring in the inner parts of the transformer. This is due to the high Prandtl number of the oil and corresponding Raleigh number encountered in the winding and radiator cooling ducts. The equations are composed of the continuity equation (1), the momentum equation (2) and the energy equation (3).

$$\nabla \cdot u_j = 0$$

$$(1) - \nabla p + \mu \nabla^2 u_j + (\rho - \rho_{ref}) g = \rho \frac{Du_j}{Dt}$$

(2)

$$[k]\nabla T + A(t) q'' = \rho c \frac{DT}{Dt} \qquad (3)$$

The corresponding boundary conditions shown in Table 1 and depicted bellow.

Table 1

Region	Boundary conditions		
	Time	Velocities	Thermal
Core	0	$u=v=0$	Equation (4)
HV/LV windings	0	$u=v=0$	Equations (5) and (6)
Lid	0	$u=v=0$	Equation (7)
Base	0	$u=v=0$	Equation (8)
Vertical(tank walls)	0	$u=v=0$	Equation (9)
Vertical(fins)	0	$u=v=0$	Equation (10)

Temperatures in the LV and HV windings and core were obtained in a heat run test in a 1000 KVA transformer, which are given bellow:

$$T = 0.0062y^2 + 1.3y + 32 \qquad (4)$$

$$T = 0.00011y^3 - 0.0023y^2 + 1.9y + 19 \qquad (5)$$

$$T = 3.6x10^3 y^4 - 3.6x10^3 y^3 + 1.1x10^3 y^2 - 72y + 49 \quad (6)$$

y is in millimeters.

The above mentioned temperature profiles (equations 4,5 and 6) were obtained as a set of results from a heat run test. During this test a constant heat flux composed of the winding and core losses was considered while developing the heat run test. All other boundary conditions were taken exactly as the ones used during the heat run test.

For the regions named lid, base and vertical tank and radiator fins, the corresponding equations are:

$$k_w \frac{\partial T}{\partial y} = h_t \left(T_{y=605mm} - T_f\right) \quad (7)$$

$$k_w \frac{\partial T}{\partial y} = h_b \left(T_{y=0mm} - T_f\right) \quad (8)$$

$$k_w \frac{\partial T}{\partial y} = h_l \left(T_{x=\pm 195.5mm} - T_f\right) \quad (9)$$

$$k_w \frac{\partial T}{\partial y} = h_l \left(T_{x=\pm 245.5mm} - T_f\right) \quad (10)$$

Heat transfer coefficients were obtained using the following correlations:

For the lid and base:

$$Nu_{base} = 0.27 Ra_L^{0.25} all \quad Ra_L \quad (11)$$

$$Nu_{lid} = 0.27 Ra_L^{0.25} if \quad Ra_L > 10^7$$
$$Nu_{lid} = 0.865 Ra_L^{0.333} if \quad Ra_L < 10^7 \quad (12)$$

For vertical fins:

$$Nu_y = 0.59 Ra_y^{0.25} for \quad Ra_y 10^4 - 10^7$$
$$Nu_y = 0.1 Ra_y^{0.333} for \quad Ra_y 10^9 - 10^{13} \quad (13)$$

Where:

$$Ra_L = \frac{g\beta(T_s - T_f)L^3 \Pr}{\nu^2}$$

$$Ra_y = \frac{g\beta(T_s - T_f)y^3 \Pr}{\nu^2}$$

$T_s$is obtained based on an average considered for the tank and radiator walls. All properties were calculated at T_f.

The final values obtained were:

Table 2

T_s , °C	60
T_f, °C	30
h_t, W/m^2°C	11.7
h_b, W/m^2°C	1.1
h_l, W/m^2°C	9.9

Properties for oil were taken as:

$$\rho(T) = 1098.7 - 0.72T$$
$$k(T) = 0.1509 - 7.1x10^{-5} T$$
$$c_p(T) = 807.1 + 3.58T$$
$$\mu(T) = 0.08467 - 0.0004T + 5x10^{-7} T^2$$
$$T \quad in \quad Kelvin \quad (14)$$
$$\rho \quad in \quad kg/m^3$$
$$k \quad in \quad W/m\,K$$
$$c_p \quad in \quad J/kg\,K$$
$$\mu \quad in \quad kg/m\,s$$

For the layer of air above oil the corresponding correlation for ideal gases was taken.

The boundarybetween air and oil was taken according to the Ramaswamy and Jue correlation [13]:

$$\frac{\partial u}{\partial y} = -\frac{1}{\mu}\frac{\partial \sigma_i}{\partial T}\frac{\partial T}{\partial x} \qquad (15)$$

Superficial tension σ varies linearly with temperature with a value of slope of 1.7x10^{-4} N/m^2.

3. Problem solution

The mathematical model is based on a system of four partial differential equations (1), (2) and (3) along with boundary conditions (4)-(10). These governing equations were discretized in Fluent™ V6.3.26 and were solved by the computational segregated-iterative method. The non-linear governing equations were linearized using the implicit approach in combination with the volume of fluid method (VOF) to define sharp interfaces. The discretization was performed using the first-order upwinding scheme. The PRESTO scheme was used for pressure interpolation; this scheme computes the cell-face pressure by assuming that the normal gradient of the difference between pressure and body forces is constant. The algorithm used for pressure-velocity is the one known as SIMPLE developed by Patankar [14].

The finite control volume has the advantage over the finite element method, if the physical domain is highly irregular and complicated,as many arbitrary volumes can be used to subdivide the physical domain. Also if the equations are solved directly in a physical domain, no coordinate transform is needed. Another advantage of the finite control volume is that mass, momentum and energy are conserved automatically.

The domain was subdivided by means of a non uniform mesh composed of tetrahedral elements and refined in areas where was needed as in the cooling winding and radiator ducts, tank walls and in the oil-air interface to accomplish a higher degree of detail in the simulation to be performed in these areas. For the discretization process the PRESTO facility (Pressure Staggering Option) was used. The final mesh had 126,000 nodes and its distribution in the upper section of the tank is shown in Fig. 5.

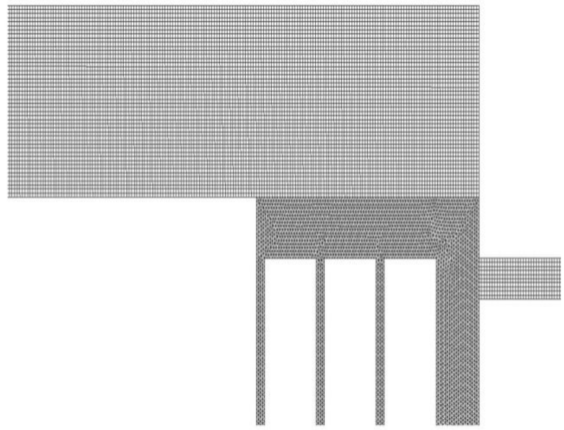

Figure 5 Mesh detail

For the simulation the time step used was 0.01 seconds. The relaxation factors used were: pressure, 0.3, density, 1, body forces, 1, momentum, 0.7, VOF, 0.2, energy, 0.8. The total simulation elapsed time was 3 hours and 20 minutes.

The convergence criteriawasachieved when the residual reached values equal or smaller than:

$$1x10^{-3}\ for\quad velocities\quad and\quad pressure$$

$$1x10^{-6}\quad for\quad energy$$

After the simulation the figures obtained for residuals were:

$$1x10^{-4}\ for\quad velocities\quad and\quad pressure$$

$$1x10^{-7}\quad for\quad energy$$

3.1 Result analysis

The analysis was focused on the oil movement through the windings and core assembly. Although the thermal behavior of the transformer is the main concern for the manufacturer, it is the oil movement which determines the regions of heat concentration and therefore first it is presented the fluid dynamics results. Later the thermal results are presented.

Fig 6 shows a velocities diagram of the region at the top part of the tank. Oil velocities observed in the cooling ducts are clearly low, 10^{-3} m/s order of magnitude (see Figs 6 and 7), which matches to the natural convection of oil within the transformer. Similar low values of velocity of 10^{-3} order of magnitude were measured by J.J. Kunes [15] in his study on characteristics of thermosyphon flow in distribution transformers. It is also shown that there are some regions where oil is being recirculated in a swirling pattern.

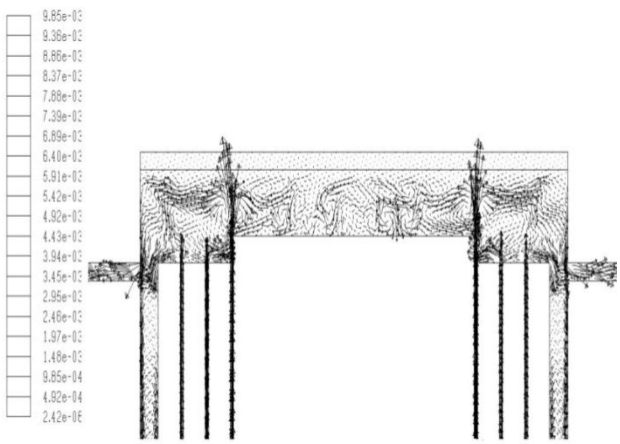

Figure 6 Detail of the oil velocities at the top of the tank

Figure 7 shows the bottom part of the transformer that oil is coming up through the winding cooling ducts and it is returning through the radiator fins and inner wall of the tank. There are two regions of swirling flow which can be caused by the position of the core in reference to the windings. Therefore, this oil velocity distribution brings less dense oil into the oil flow movement pattern. This might help the designer while locating the windings in reference to the core within the transformer tank.

The cooling oil temperature distribution obtained from the numerical simulation is shown in Fig. 8. In this figure it can be seen that there are two regions, one high temperature area located at the top part and one low temperature area located at the bottom part of the tank. Besides, oil temperatures are varying from 59.8 °C to 81.6 °C. The radiator fins which are not hollow provide a different path to the hot oil coming up, oil temperatures are varying from 59.8 °C to 69.6 °C.

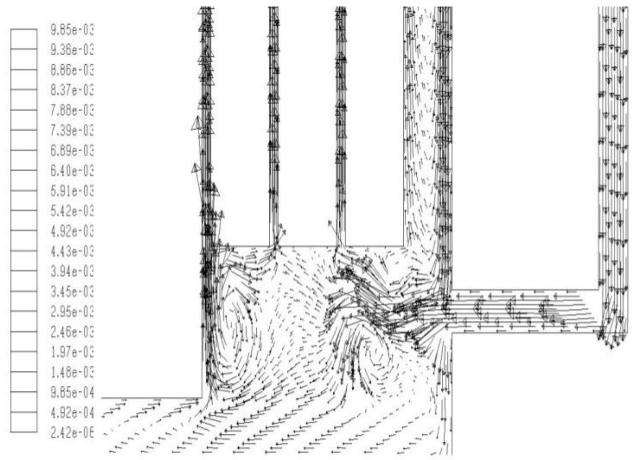

Figure 7 Oil velocities distribution at bottom part of the tank

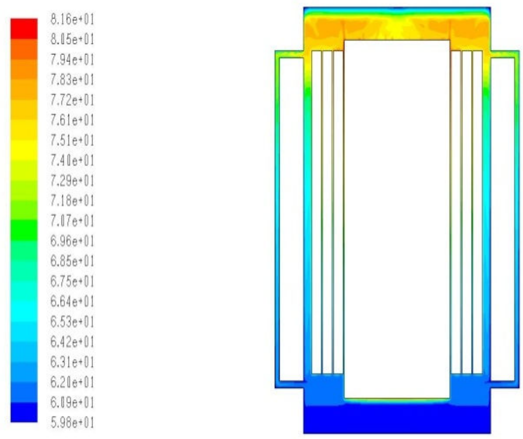

Figure 8 Oil temperature distribution

To study in more detail the regions where the temperature shows the biggest changes, three detailed figures were included as follows.

In Fig. 9 it is shown a sub region of maximum temperature near the inner top part of the core and low voltage winding. Such area reached a temperature of 81° C. The layer of air located above the oil has a temperature which varies from 69.6 °C to 59.8 °C.

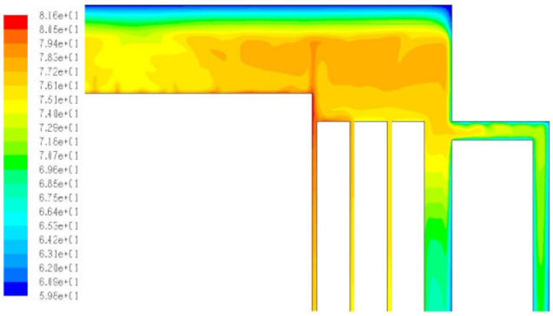

Figure 9Detail of oil temperature at top of the tank

Figs. 9 and 10 show the oil temperature at the central part and bottom of the windings. Fig. 9 shows that the inner cooling duct oil has a higher temperature than the outer cooling duct. This is expected since the inner duct is the most confined one and the region where the cooling almost does not have effect. In addition, less heat flux is emerging in the fins section. This figure shows that the oil temperature in the radiator descend more rapidly than the one found in the winding cooling ducts. This reflects the thermal efficiency of having the radiator fins in contact with the surrounding air. The beforehand mentioned heat transfer convection coefficient, h_l, given to the radiator fins provide the thermal efficiency.

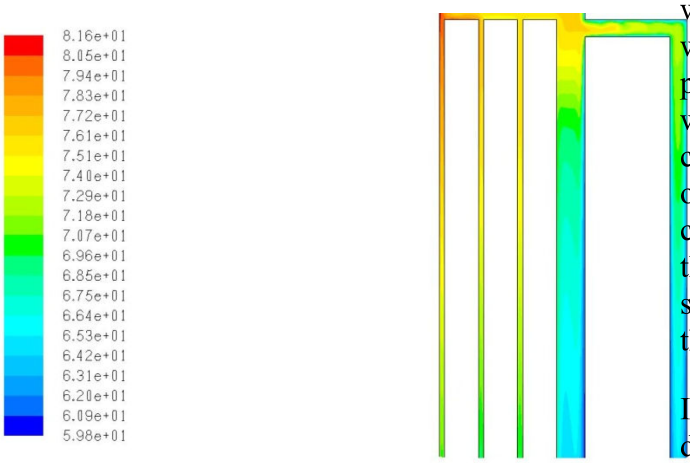

Figure 10 Detail of oil temperature at the central part of the tank and radiator.

Since density of oil depends on its temperature, it is anticipated that the cooler oil moves downward to the tank bottom. Figure 11 shows at the bottom of the tank a region of oil which has a low temperature (59.8 °C). Also, it can be noticed that a region of high oil temperatures can be found at the bottom part of the core. This reflects the fact that oil is being entrapped in this region (see Fig. 11) providing high temperature oilat the bottom of the core.

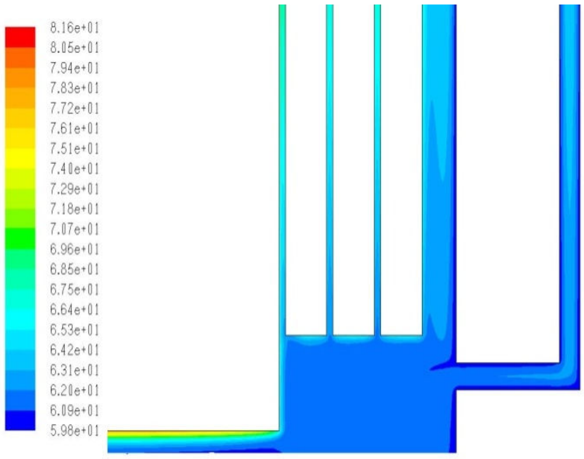

Figure11Detail of oil temperature at the bottom of the tank and radiator

The widest cross sections at the cooling channel, close to the tank wall constitute a downcomer and riser for the circulating oil. This is due to the effect hot oil going upwards while cold oil going downwards in the same wide cooling channel and the difference in pressure established by the thermosyphoning which seems to depend on the position of the core-windings as well as the cross section area of the cooling duct. In the case of the narrow cross section cooling ducts which are in theinner cooling ducts oil is going up which suggest that the hot oil is directing to the top of the transformer tank.

In regards to the radiator cooling fins the oil is directing downwards which also shows that the cold oil flow is governed by the thermosyphon phenomena.

In order to validate and support this work, a comparison between numerical and experimental data is presented. Fig. 12 shows a comparison of numerical and experimental results (provided by a national transformer manufacturer). This oil temperature obtained from the numerical procedure was the oil temperature profile for the inner cooling duct. Similarly, the experimental oil temperature was obtained for the corresponding inner cooling duct. Clearly, the comparison shows that there is good agreement between the numerical and experimental results. The highest experimental oil temperature was 78.5 ˚C which occurred in the inner part of the cooling duct close to the core.

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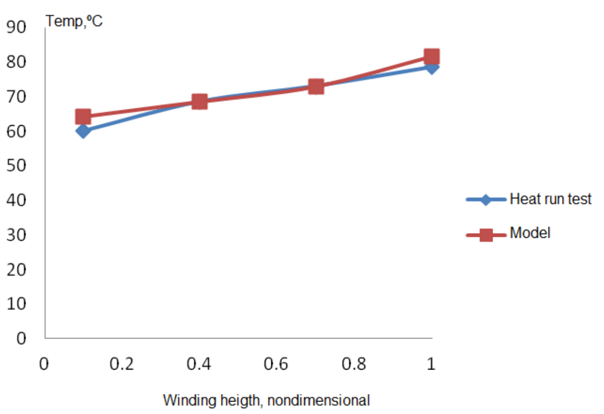

Figure 12Comparison between numerical and experimental oil temperatures

Conditions of heat run test[16] are shown in Table 1.

Table 1

Capacity	1000 kVA
Number of turns, low voltage winding	8
Number of layers, high voltage	8
Number of turns per layer, high voltage	115
Weigth, windings	454 kg
Weigth, core	1138 kg
No load loss	1298 W
Load loss	11 825 W
Ambient Temperature	30°C

4. Conclusions and future work

We can conclude that the computational model predictsthe measured oil temperature distribution and it can be thereby concluded that the oil dynamics within the distribution transformer is also modeled well. Besides, this constitutes a great valuable piece of information on how oil is moving inside the transformer tank and radiator.There are very different dynamics in different positions of the windings-core assembly thatsubsequently give temperature distribution. Also, here it was presented the interaction between the air layer and the oil within the transformer. It was shown that the air layer presents an air expansion due to heating which in this case was negligible. The numerical results do not show appreciably the thermal expansion of the oil. Air temperature distribution was quite uniform but posses a heat reservoir for the heated oil within the transformer. A comparison between the experimental data and the numerical data from the obtained simulation showed good agreement. Also, the model agrees with other published data. The convergence criteria figures obtained for the model was satisfactory.

Future work suggests that the optimization of the internal geometry (vertical position of the core-windings as well as cooling duct width) should be investigated. This would benefit the national transformers manufacturers by including valuable modifications to their actual designs of distribution transformers.

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