

# A Thermal Simulation of a Power Transformer Using 2D and 3D Models

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**Abstract** - In this work, 2D and 3D models are compared for the thermal simulation of a power transformer. The experimental work from a heat run test of a national manufacturer is used to validate the models. The continuity, Navier-Stokes, and energy equations were used to simulate oil flow within the windings and core of the power transformer. A commercial CFD software was used to solve the numerical equations resulting from the discretization of the domains of the 2D and 3D models. The 3D model provides a better description of the oil flow inside the windings and the core of the power transformer, and it shows a zone of almost stagnant oil flow in the vertical cooling channels and also it shows an area of high temperature of oil in the winding located farthest from the oil inlet.

**Keywords:** CFD, Power transformer, Oil flow, cooling channels, thermal simulation.

## I. INTRODUCTION

The power transformers industry is a significant asset in any public or private installation. The efficiency of such devices has been linked to the conversion of electrical power from one voltage to another at a different voltage. Besides this, electrical behavior depends on the thermal behavior of elements such as coils and core in the power transformer. Researchers have focused their effort on studying these elements and their cooling using oil. In the past and present [1], 2D Computational Fluid Dynamics (CFD) models have been constructed to identify the so-called hot spot or highest temperature in the windings due to possible entrapment of oil in the cooling ducts. This model shows good results by taking one-fourth of a winding as a representative geometry of the whole transformer, considering an initial windings temperature, and conducting a transient thermal simulation. Another research work [2] considers a 2D and 3D one-fourth duct model to simplify the analysis and reduce computational time. This work considers forced oil convection through the windings and compares the results with temperature measurements, obtaining good agreement between temperature measurements and CFD results. Also, 2D and 3D

one-fourth cooling duct models have been proposed [3] to investigate oil behavior in a directed oil power transformer, obtaining oil flow dynamics, which showed the eddies formation at the entrance of horizontal cooling ducts. Although the authors say that the position of the hot spot is between discs 3 and 4 of pass 1, they indicated that the obtained position does not coincide with the common belief that the hot spot is generally located at the top of the winding because the 3D model showed that there is a no uniform oil flow in the horizontal cooling ducts.

A previous paper [4] analyzed a power transformer's mixed oil flow in windings. The considered model was a 2D cad geometry of the power transformer's winding, tank, and core. It was found that oil flow is non-uniform in the horizontal cooling channels giving rise to a different location of the hot spot in the last top inner low voltage cooling windings. Other researchers have studied the thermal behavior of the windings and cooling channels [5] using a 2D and 3D model of a section of a cooling oil duct operating in different natural convection modes. Also, they have performed experimental work on half of a section of a winding, considering the symmetry of a cylindrical winding concerning oil flow distribution. They found similar behavior in the oil flow in horizontal cooling ducts, and their no uniform flow. Also, this reverse oil flow overestimated temperatures and the necessity of using a 3D model. It was pointed out that there is a tendency for significantly bigger temperatures compared to measurements at different cooling ducts and windings because there might be reverse flows at some horizontal cooling ducts and the formation of hot streaks of oil coming out from some cooling ducts, which increase temperatures.

In this sense, manufacturers report an average increase in oil temperature in windings when performing a heat run test in the power transformer [6]. Still, they have no idea of oil behavior within cooling ducts. Almost none of the researchers have completed a 3D simulation of the whole power transformer operating in mixed convection because of the grid's inherent complexity required for the thermal simulation. Also, the CPU time increases with the complexity of the 3D model [7,8].

Therefore, this work uses the simulation's 3D cad geometry of the whole power transformer. The results in oil flows in cooling channels in windings and core are compared with the previous results [4] of the 2D cad geometry.

## II. CFD GEOMETRY OF THE POWER TRANSFORMER

The geometry of the power transformer was used, including the windings, core, and enclosure. The windings were solid cylinders made of copper, and the core body was considered a solid rectangular frame made of iron. The cooling channels were the ones that are usually located in the vertical interspace among the HV (high voltage) and LV (low voltage) windings and core yokes. The power transformer considered can be observed in Figure 1.

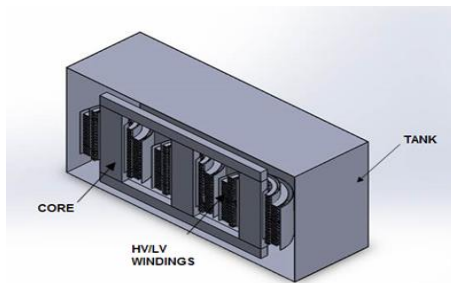


Figure 1: Power transformer

The internal supports of the windings and core were not considered to focus on the primary heat-generating windings and core. Figures 2 and 3 shows a sectional view of the power transformer where the windings, core, and oil inlet and outlet are depicted. The radiator was removed in the geometry considered for the CFD analysis, see Figure 3.

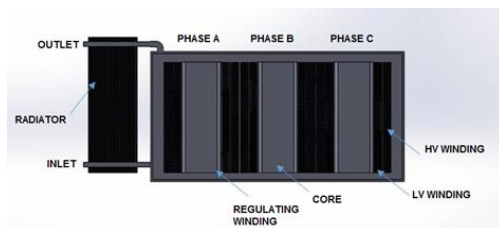


Figure 2: A sectional view of the power transformer

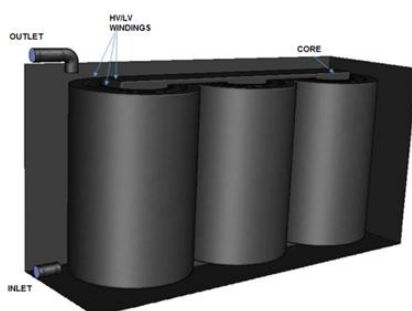


Figure 3: Inner view of the power transformer

### 2.1 2D Model

The 2D model used for the CFD analysis is shown in Figure 4. In this model the radiator was removed to simplify the analysis. Only the oil flow was considered within the windings and core.

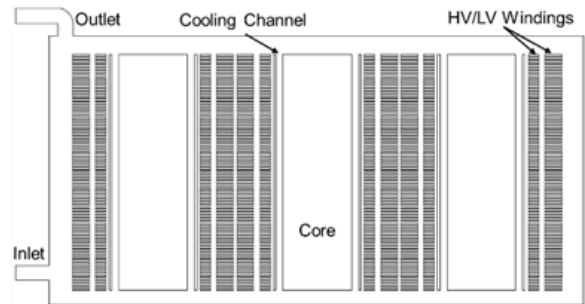


Figure 3: 2D Model sectional view

### 2.2 3D Model

The 3D model considered for CFD analysis is shown in Figure 5. The windings were considered solid cylinders and the radiator was removed for the CFD analysis.

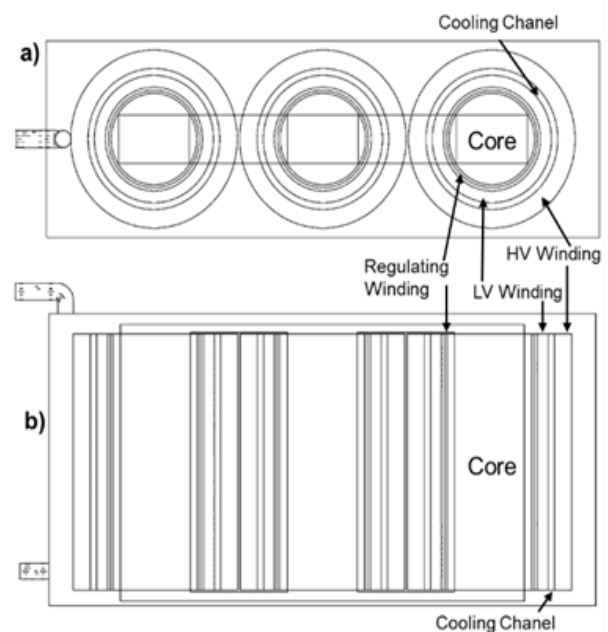


Figure 5: 3D Model, a) Upper view, b) Lateral view

## III. SOLUTION OF THE PROBLEM

The models were analyzed using the solution of the Navier-Stokes equations and continuity equation and heat equation and the buoyancy Boussinesq approximation. They are shown in the following:

Continuity equation:

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

Momentum equation:

$$\frac{\partial(\rho u)}{\partial t} + \nabla(\rho uu) = -\nabla P + (\mu + \mu_t)\nabla^2(u) + \rho g + F \quad (2)$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho E) + \nabla(u(\rho E + p)) = \nabla(k\nabla T) + Se \quad (3)$$

The equations were applied to the discretized domain obtained from ANSYS-Fluent® software. This software uses the volume element approach to establish a set of algebraic equations regarding oil velocities and temperatures. The program setup includes defining a time step and solving the equations iteratively; the final values of the oil velocities and temperatures are obtained.

The boundary conditions were defined according to the following:

- Walls of the model (tank, windings and core) have non-slip condition.
- Outlet is set up as a zero pressure condition.
- Inlet is set up as velocity-inlet condition (0.002, 0.05 and 0.1 m/s).
- Inlet oil temperature is 298 K.
- Fixed heat generation are: 7.87 W/m<sup>2</sup> for core, 5.18W/m<sup>2</sup> for low voltage winding, 1.94 W/m<sup>2</sup> for high voltage winding, and 2.94 W/m<sup>2</sup> for regulating winding. These values were obtained based on the power dissipation for each of the windings and core and the total area of each of the windings and core. The power dissipation values were obtained from a local power transformer manufacturer.

### 3.1 Meshing and test for independence

#### 3.1.1 2D model

For the 2D model, the boundary conditions are the same as described before. The grid was constituted of triangles and quadrilateral elements being 2 million cells number. In the region of horizontal cooling channels, a refinement in the mesh was considered to consider the laminar boundary layer formed when the oil flows. Similarly, the same scheme was considered for the vertical cooling channels. The grid is shown in Figure 6. The time spent on the solution of the 2D model was two days for each case.

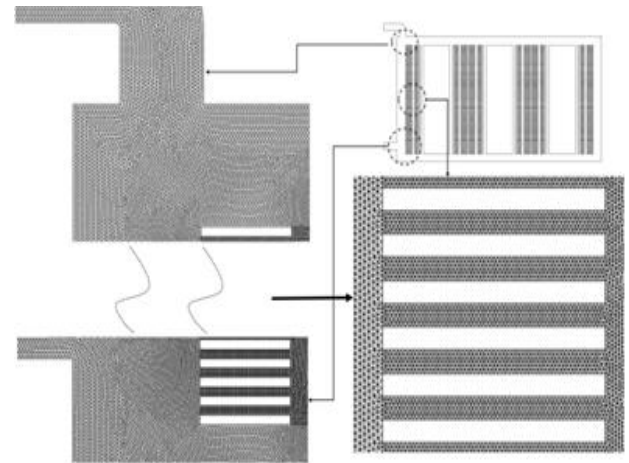


Figure 6: Grid for 2D Model

The ANSYS-Fluent gambit tool was used to produce a high-quality structured grid. The grid was refined using the same device and had an excellent grid in regions of high velocities as in the cooling channels where the fluid stretches. Also, in the areas attached to solid parts, a refinement was made to include the effect of velocity change in the limit layer. Table 1 shows the refinement made and the values of oil temperature obtained for the case of 0.05 m/s oil inlet velocity.

Table 1: Grid independence and verification for 2D model

Case	Cell Number x10 <sup>6</sup>	Oil Temperature Location in Phase C	Oil Temperature, K
A	0.5	Top Centered in the cooling channel	323.32
B	1	Top Centered in the cooling channel	323.56
C	2	Top Centered in the cooling channel	323.69

#### 3.1.2 3D Model

The grid for the 3D model is shown in Figures 7, 8, 9, and 10. It is formed with triangles and quadrilateral elements. It was decided to go for a finer grid in regions where the distances were small. This was because the complexity of the grid was enormous, and the computational time increased. Also, for the 3D model, it was decided to analyze the oil flow through the windings and core without any transversal cooling channels. It took, for each case, about two days to obtain a converged solution for the 2D Model and one week for the 3D Model in an upgraded twenty-parallel processor computer. The convergence criteria were set to accept minimum residuals in continuity and pressures in 10E-07. The number of cells was 4 and 9 million for the 3D model with solid windings.

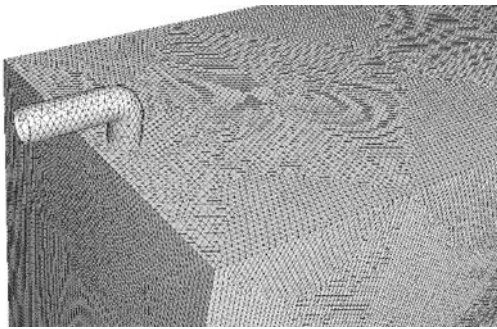


Figure 7: Outer view, 4 million cells for 3D Model

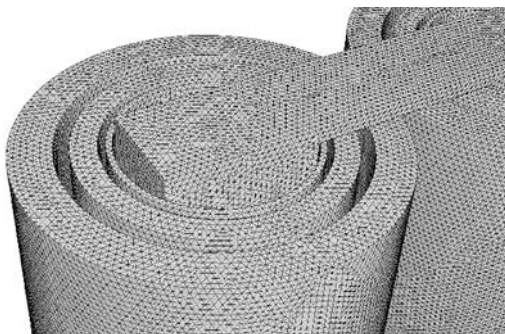


Figure 8: Inner view, 4 million cells for 3D Model

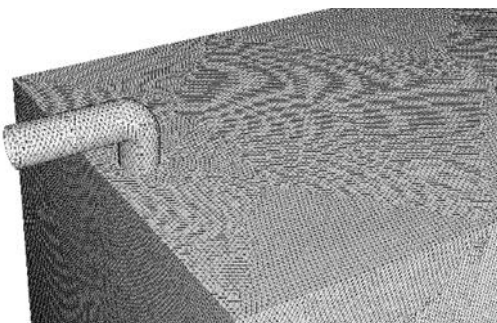


Figure 9: Outer view, 9 million cells for 3D Model



Figure 10: Inner view, 9 million cells for 3D Model

In the case of the 3D model, the grid was refined in the cooling channels where the oil velocities are reduced due to the effect of the solid walls of the windings. Also, a three-dimensional grid was used to notice the effects in the axial, tangential, and circumferential oil velocities and temperatures. Table 2 shows the refinement in the grid and the values

obtained in the oil cooling channels for the 0.05 m/s oil velocity.

Table 2: Grid independence and verification for 3D model

Case	Cell Number x 10 <sup>6</sup>	Oil Temp. Location in Phase C	Oil Temp. K
A	4	Top Centered in the cooling channel	323.56
B	9	Top Centered in the cooling channel	323.69

The power transformer was tested in a heat run [6], which consisted of performing a dynamic test of the power transformer with a known load and taking the oil, windings, and ambient temperatures from zero to full load. The load consists of a simulation of inductive and resistive loads. Temperatures are recorded every five seconds with a data acquisition system. A set of fiber optic sensors measure the temperatures and are positioned using special insulation components. The location of the temperature probes is shown in Figure 11.



Figure 11: Location of temperature probes

Temperatures obtained in the three phases of the power transformer were recorded as an average, and the data is presented as an average of the oil temperature rise and winding temperature rise. These temperatures must comply with the maximum values indicated in the ANSI/IEEE Loading Guide for Mineral Oil Immersed Power Transformers, C57.91-2011.

The obtained values were:

HV Upper location: oil temperature 342 K, Winding temperature 359 K

HV Lower location: oil temperature 316 K, winding temperature 326 K

LV Upper location: oil temperature 342 K, winding temperature 374 K

LV Lower location: oil temperature 316 K, winding temperature 326 K

Taking the average of the experimental values obtained for the oil temperature at the upper location, which is 329 K, there is a good agreement with the numerical value obtained for the 2D and 3D models, 323 K. The probable error accounts for 1.82%. This may be attributed to uncertainties in the temperature probe readings and location of the sensors within the HV and LV cooling ducts.

#### IV. RESULTS AND DISCUSSION

In the case of  $V=0.002$  m/s for the inlet oil velocity, the 3D model of the 9 million cells simulation shows similar behavior for the oil velocities developed within the oil cooling ducts and windings of the power transformer. This is shown in Figure 12. Slight differences are shown in oil velocities in cooling channels and oil inlet. The oil velocities encountered in such zones are  $2 \times 10^{-4}$  m/s. Most of the high oil velocities are shown in phase C vertical cooling ducts and phase A vertical cooling oil located near the oil inlet. At the farthest phase C oil cooling duct regions of high and low oil velocities are shown. It appears that in some regions in the cooling duct oil decelerates and accelerates in others. In the inner phase C cooling duct near the core oil is circulating at the same velocity in the whole vertical cooling duct indicating that the oil is almost entrapped. In the other cooling vertical ducts oil is almost stagnant. The plane considered for the oil velocity vectors field is shown in Figures 13, this is at  $z=0$  and it is shown at the lateral view center of the HV and LV windings. Also, the maximum oil velocity shown in the scale in figures is not the maximum oil inlet velocity for each case simulated. This is just for clarity in the contrast of maximum and minimum oil velocities encountered in the simulations.

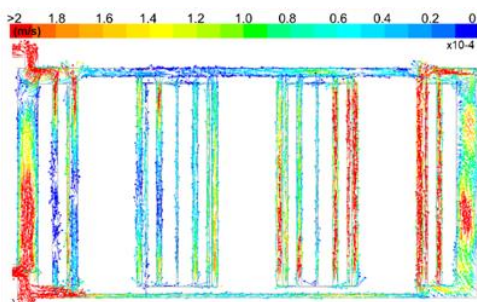


Figure 12: Oil velocity vectors at the central symmetrical plane, for 9 million cells 3D Model, lateral view,  $V=0.002$  m/s

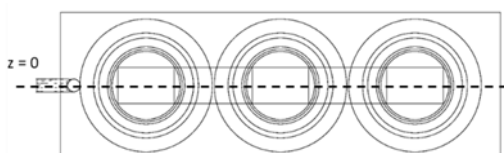


Figure 13: Central symmetrical plane position in z, in m

Considering the oil dynamics from Figure 12, much of the oil flow goes up through the cooling duct that goes directly to the outlet, which is named short-circuit, the rest of the oil is distributed through each winding cooling duct. To observe how the oil flow reaches the transformer upper section, velocity vectors were calculated in a horizontal plane (see Figure 14) located at  $y = 1.6$  m at the top LV and HV windings (see Figure 15 for location of plane). The oil flow being directed to the cooling duct located nearer to the inlet following the less hydraulic resistance path. The mixed convection derived from the changes of density and low-velocity oil flow is then forcing oil through the windings.

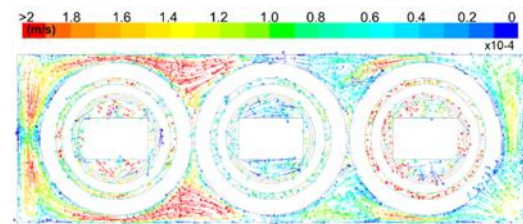


Figure 14: Oil velocity vectors at a horizontal plane, for 9 million cells 3D Model, top view,  $V=0.002$  m/s

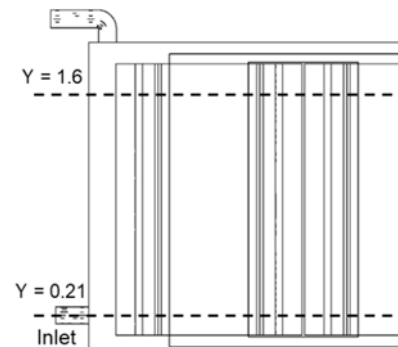


Figure 15: Scheme for horizontal plane position ( $y = 1.6$  m)

The oil temperature contours, calculated at the central symmetrical plane of the transformer, also show a slight difference in values, from 329 to 330 K, in the same oil cooling and inlet zones see Figure 16. The obtained values were between 320 and 334 K at the inlet and top of HV and LV windings. The difference concerning experimental matters might be because one oil inlet is considered in the power transformer simulation, while two lateral oil inlets are used in other designs of the power transformer. This means that oil cooling is not so efficient in this case. Oil hydraulics plays a fundamental role in the oil movement through windings because buoyancy forces are developed according to the oil temperatures. In this oil forced convection the oil velocities are pretty low which is low compared to the possible changes in density due to changes in oil temperatures between the top and bottom of the power transformer.

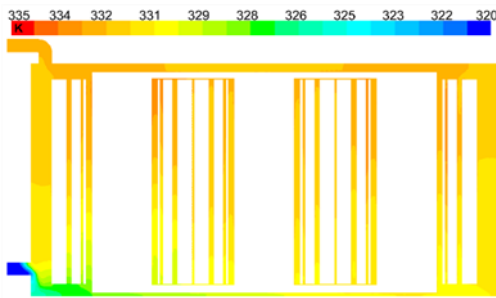


Figure 16: Oil temperature contour at the central symmetrical plane, for 9 million cells 3D Model, lateral view,  $V=0.002$  m/s

In the case of  $V=0.05$  m/s, the oil velocity vectors are shown in Figures 17 and 18. The same locations of the planes considered previously apply. In this case, a significant amount of flow is observed and oil is distributed in a more optimum way through the windings, allowing the oil temperature not to rise as much as in the previous case. This is because changes in oil temperature and less buoyancy of oil through the windings are occurring and more convective flow through them. As in the previous case, the maximum oil velocity shown in the scale in the figures is not the maximum oil inlet velocity for each case simulated. This is just for clarity in the contrast of maximum and minimum oil velocities encountered in the simulations.

In the case presented for oil velocity of 0.05 m/s in Figure 17, the flow moves mainly in a similar way to the previous cases but more oil is reaching the farthest winding from the oil inlet. Furthermore, oil is almost stagnant in phase A, B and C. Less oil is circulating through the oil hydraulic short circuit.

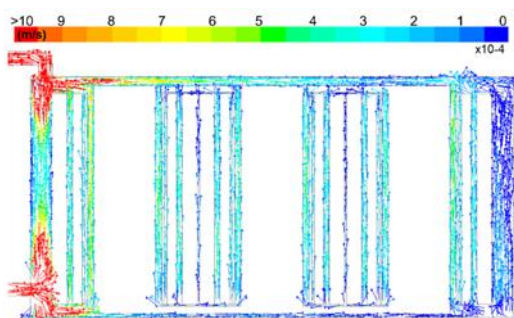


Figure 17: Oil velocity vectors at the central symmetrical plane, for 9 million cells 3D Model, lateral view,  $V=0.05$  m/s

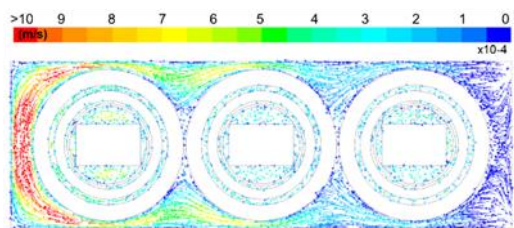


Figure 18: Oil velocity vectors at a horizontal plane, for 9 million cells 3D Model, top view,  $V=0.05$  m/s

The oil temperatures are depicted in Figure 19 for the case of 0.05 m/s oil velocity. The same location of the plane considered previously applies.

Figure 19 shows that the oil temperature at the top was 321 K and 320 K at the bottom. The slight difference in oil temperature between the top and bottom of the power transformer might be attributed to the fact that, in this case, the oil velocity is high, and forced convection is ruling the process of heat transfer between windings and core and the circulating cooling oil.

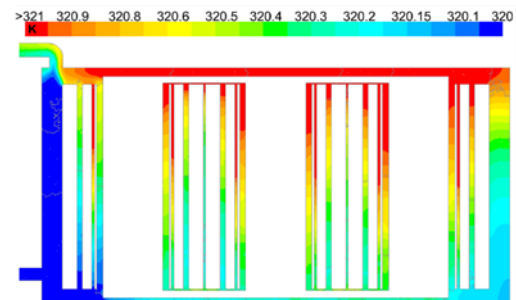


Figure 19: Oil temperature contours at the central symmetrical plane, for 9 million cells 3D Model, lateral view,  $V=0.05$  m/s

In the case of  $V=0.1$  m/s, the oil velocity vectors are shown in Figures 20 and 21. The same locations of the planes considered previously apply. As in the previous case, the maximum oil velocity shown in the scale in the figures is not the maximum oil inlet velocity for each case simulated. This is just for clarity in the contrast of maximum and minimum oil velocities encountered in the simulations.

Oil is reaching more easily the farthest winding from the oil inlet and a more efficient oil distribution is achieved through the windings. In this case as oil velocity is bigger than the one encountered in the previous cases, more oil is reaching the farthest winding named phase C. When comparing Figures 19 and 22 it looks like almost the same cooling is achieved and a region of high oil temperatures are located at the top of the whole windings. Although higher oil velocities are reached in the three phases of the windings, the pattern of almost stagnant oil flow is presented in this case.

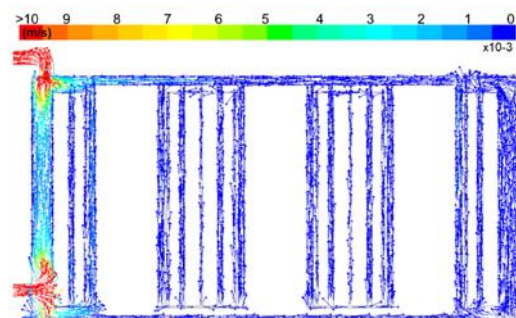


Figure 20: Oil velocity vectors at the central symmetrical plane, for 9 million cells 3D Model, lateral view,  $V=0.1$  m/s

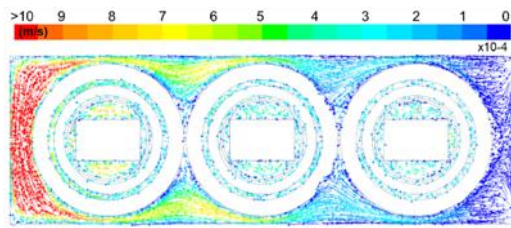


Figure 21: Oil velocity vectors at a horizontal plane, for 9 million cells 3D Model, lateral view,  $V=0.1$  m/s

Oil temperatures are depicted in Figure 22. The same location of the plane considered previously applies. The maximum oil temperature is 321 K at the top of the windings and core arrangement. As in the previous case of  $V=0.05$  m/s oil velocity, the difference between top and bottom oil temperatures is slight. The forced oil inlet flow dominates the mixed convection.

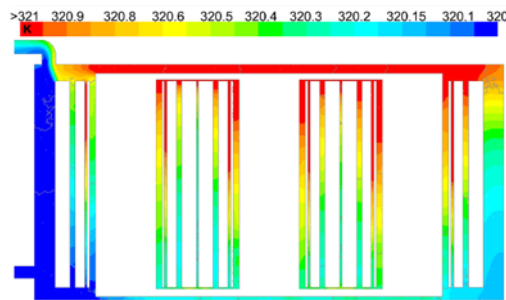


Figure 22: Oil temperature contour at the central symmetrical plane, for 9 million cells 3D Model, lateral view,  $V=0.1$  m/s

## V. CONCLUSION

Although 2D and 3D models have been developed in the past for the study of oil flows in cooling ducts and the location of hot spots in power transformers operating in forced, natural, and mixed oil flow configurations, the need for a 3D model simulation of a whole power transformer has been addressed due to the oil dynamics determines the possibility of oil hot streaks formation and reverse flows in vertical and horizontal cooling ducts.

A comparison between a previously 2D Model and a 3D Model for a whole power transformer is presented. In the 3D Model simulations, three oil inlet velocities were used, and the corresponding oil velocity vectors and temperatures were obtained. Also, a heat run test is included in the study and its average top and bottom oil measurements.

The accuracy of the simulations was determined by the analysis of the independence of the grid. It was satisfactory that the oil temperatures showed a good agreement between the 1, 4, and 9 million cells simulations.

The oil velocities encountered in the simulations were reasonably good when using the 9 million cells 3D model. Also, when increasing the oil velocity, the differences were minor. The same pattern was observed with the oil temperatures.

Although the oil temperature difference between the top and bottom of the power transformer was reduced by increasing oil inlet velocity, a reasonable explanation was obtained based on the natural and forced convection created in the oil entering the windings and core. Another difference in respect to the number of oil inlets was addressed. This is a possible reason for the difference between the oil temperatures obtained from the simulations and those obtained in the heat run test. Furthermore, the whole cooling of the windings and core of the transformer depends on the oil flow being established among the cooling ducts. This means that when one lateral oil inlet is used and the winding geometry is providing a wide vertical cooling duct next to the inlet a closed hydraulics oil circuit is created and most of the oil is diverted to the exit leaving most of the oil ducts without enough oil to cool down the windings located farthest from the oil inlet. This explains why the hot spot is located at the top of the phase C. It is concluded that further simulations are necessary to include the effect of the number of oil inlets being used as well as a study of the variation of the cooling oil circulation in relation to the elimination of possible oil hydraulics short circuits within the power transformer.

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#### AUTHORS BIOGRAPHY



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