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Thermal Simulation of A Mixed Convection Cooled Power Transformer And its Analysis of the Variations of Thermal Design Parameters

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ABSTRACT: *The Power transformer is a high capital cost machinery that composes the electrical grid in every industry. Therefore, the CFD study of thermal behavior under different conditions is interesting for the power transformer owner and the designer. In this work,a real disc type ON cooled power transformer, three-phase 33.6 MVA, 115/34.5 kV is consideredand temperature values from the heat run test were compared with the ones found with the numerical study.Mixedconvectiondissipation of oil is considered in vertical and horizontal cooling ducts. The outcome of the CFD study is an evaluation of thermal behavior regarding critical temperature points when varying design parameters in the construction of a disc type power transformer such as high voltage cooling duct width, number of discs and winding power. The results show that the value of hot spot and location varies when the number of discs for each winding is changed. Also, in the case of heat dissipation increase for each winding, the hot spot value increases and its location is at the last upper discs within the HV winding. Finally, the outer HV cooling duct width modification leads to a decrease in temperature value of the hot spot. The Richardson number is employed to analyze the dominance of the buoyancy and forced convection processes found in circulating oil. There is a dominance of natural convection in the oil circulating in HV and LV ducts.*

Keywords: *Power transformer, thermal model, mixed convection, critical temperature points*

I. INTRODUCTION

Electrical transformers are key parts of an electrical grid in a power generation station or in a domestic/industrial distribution system. These devices transform primary energy at one level of voltage to secondary energy at another level of voltage. In this sense they can be step up or down voltage devices. The levels of transformation vary from extra high level above 115 kV, high level above 34/69 kV, medium level above from 220/440 V to 34/69 kV and low level below 220/440 V. Basically these devices operate at different loading conditions to satisfy different electrical needs. As such the power transformer is composed of a primary circuit which consists of turns of electrical cooper or aluminum wires or sheets wrapped around a core made of iron. Usually the primary circuit is connectedto a source of voltage which might be low or high and by means of an electromagnetic circuit created by the core and wires, connection is transformed into a voltage which might be used as a source for an electrical load in a secondary circuit. The low and high voltage wires and core assembly is enclosed in a mineral oil-filled steel tank. The electrical design of the transformer includes the use of paper isolators around each wire (conductor) as well as cardboard isolators to separate electrically each turn of conductors. Then theelectrical designs vary as wound wires or sheets core type power transformers to disc type (sets of conductors) power transformers.

The windings (high or low voltage conductors) produce heat due to the circulation of electrical currents through these wires,which in turn has to be dissipated by means of the circulation of the mineral oil within the tank and then by means of the tank walls and a set of an additional plate heat exchanger named the radiator. All this heat transfer surfaces and its analysis of the heat dissipation constitutes the thermal design of the power transformer.The determination of the location and value of the hot spot (maximum temperature in the windings) is of crucial importance due to the fact that it determines the degradation of the electrical isolators, which in turn limits the power transformer life. In this regard the power transformers are classified as ONAN (oil natural, air natural), OFAN (oil forced, air natural) or OFAF (oil forced air forced) thermal systems.

At the beginning researchers focus their efforts towards the study of the heat dissipation from the windings or core to the mineral oil, and the heat dissipation from the mineral oil to the tank walls and radiator, mainly known as natural or forced convection [1,2]. These investigations used experimental techniques in order to evaluate the performance of low and medium voltage power transformers in reference to the windings critical temperatures (hot spot) and some interesting features of oil flow when varying the position of the core. Later, as the numerical techniques became available, researchers focused their attention to investigating the hot spot location in power transformers [3, 4,5,6,7 and 8] by using thermal and hydraulic networks. These researchers have proposed variations of heat loss, number of washers, height of radiators and channel geometry. They have found a strong effect when varying the height of the radiator system. Other variations show weak effect in respect to variation of temperature rise.Also, computational techniquesas well as experimental techniques[9, 10, 11 and 12] were used to develop methods based on the numerical solution of the governing equations of heat transfer and fluid mechanics and physical models, in order to determine details of mass flowdistributionand temperature in a section of a disc type winding. The IEEE standards [13,14 and 15] have proposed a methodology of calculating the top oil temperature and hot spot based on a heat run test for power transformers. They also included a section for considering the temperature dependent properties of the cooling oil. Manufacturers normally use these standards as rule for calculating the top oil temperature and hot spot. Other researchers have proposed the use of mathematical analytical methods to determine the hot spot and its location in disc type power transformers [16]. They have proposed a cylindrical windings assembly and a Hankel and Fourier transform method for solving the heat conduction equation with convective boundaries.

The presentCFD study is focused on the thermal design parameters such as cooling duct width, number of discs and disc heat dissipationthat affects the thermal performance of disc type ON cooled power transformers. From the point of view of the designer and manufacturers,these parameters seem to affect the determination of the hot spot value and its location.Validation of the thermal model is performed by means of a basic case which considers 82 and 102 discs for the HV and LV windings and its comparison of the upper windings and oil temperatures with the ones found in the heat run test of a real 33.6 MVA disc type ON cooled power transformer.

II. CFD THERMAL MODEL OF A POWER TRANSFORMER

The real 33.6 MVA transformer is a three-phase transformer with a set of radiators attached to it. In Fig. 1showsthe internal geometry.

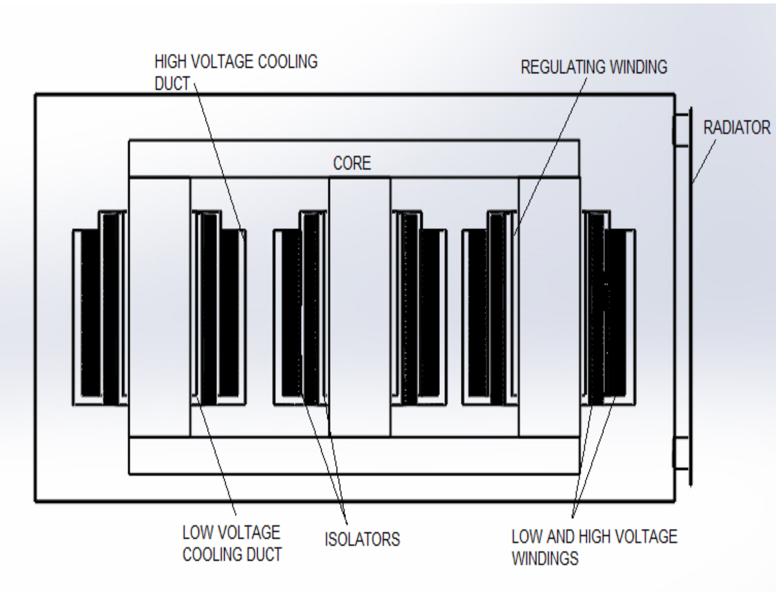

Figure 1 Geometry of the transformer

The transformer is a core type transformer which comprises of a magnetic core surrounded by cylindrical coaxial windings being the most common the disc type. The discs can be separated by washers but in this design, there are only vertical ducts,mainly in order to direct the cooling oil. Each phase of the transformer is comprised of a high voltage winding (HV), a low voltage winding (LV) and a regulating winding (Reg). A section of the windings is depicted in Fig. 2.

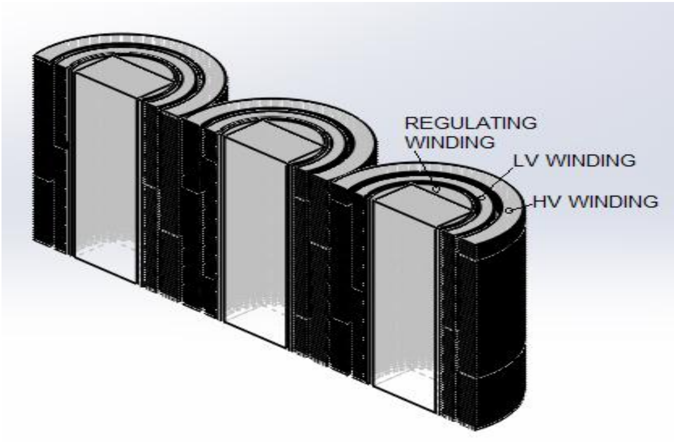

Figure 2 Internal windings of the transformer

Initially the model considered was analyzed on the basis of a 2D section of the real transformer without the radiators. This is depicted in Fig. 3. The geometry considered for the CFD model is a 2D model based on the symmetry of the transformer regarding each phase composed primarily of a low, high voltage, regulating windings and core.

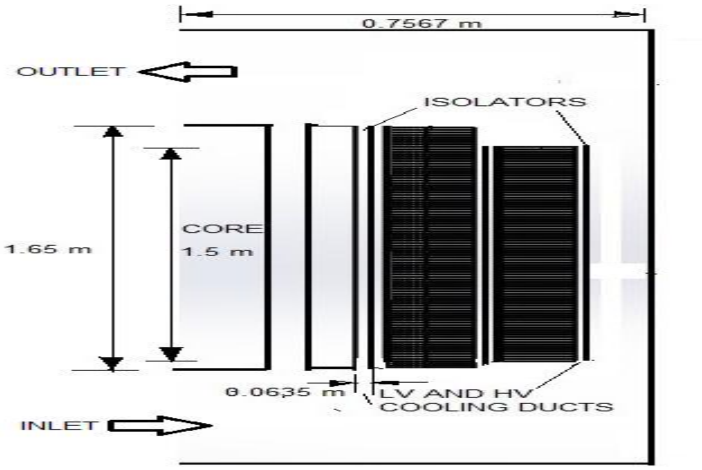

Figure 3 2D Section analyzed

In order to dissipate the heat that is being generated by the windings(discs) and core, a set of vertical cooling ducts are provided. The discs also contain horizontal cooling ducts. The dimensions of the verticalcooling ducts are shown in Fig. 4.

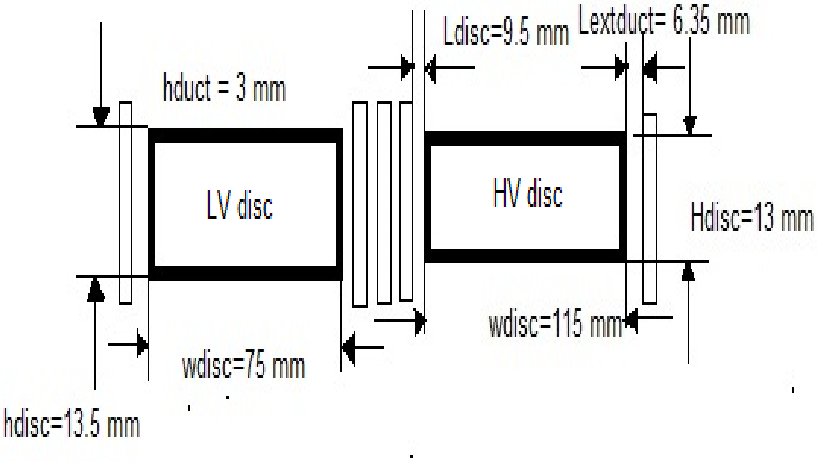

Figure 4 Dimensions of discs and cooling ducts

The LV and HV windings are composed of sections of discs(conductors). Each disc is composed of copper conductors surrounded by paper as the dielectric isolator. The HV, LV and regulating windings are surrounded by the iron core. The complete windings and core arrangement is contained in a steel tank and filled with oil.

The model does not consider the radiator section and only the inlet and outlet for cooling oil are provided. The velocity and temperature of the cold oil at the inlet are considered.

The model only considers the discs made out of copper. The paper insulation of each disc is not considered. The thickness of the insulating paper is relatively thin (less than a few mm), so the temperature variation across the paper may be ignored. The calculation of the convection coefficient is performed during the calculations taking into account the following:

$$h = \frac{q}{\Delta T_{oil}} = \frac{q}{T_{oil} - T_{solid}} \qquad (1)$$

Lid, base and walls of the tank are considered as adiabatic.

III. GOVERNING EQUATIONS

The governing equations regarding the conservation of mass, momentum and heat for the fluid are:

$$\nabla \cdot (\rho U) = 0 \qquad (2)$$

$$\nabla \cdot (\rho U \times U) = -\nabla p + \mu(\nabla^2 U) + \rho g \beta (\Delta T) \qquad (3)$$

$$\nabla \cdot \left(\rho c_p U T\right) = \nabla \cdot (k \nabla T) + S_E \qquad (4)$$

The source term S_E can be replaced by the losses of the windings Q.

The variation of density with temperature is included with the Boussinesq equation as follows:

$$\rho = \rho_0 (1 - \beta \Delta T) \qquad (5)$$

The set of equations mentioned above are solved by using the algorithm proposed by Patankar [17].

The variation of the oil properties with temperature are considered as follows [12].

$$\rho(T) = 1098.72 - 0.72T$$

$$k(T) = 0.1509 - 7.101E - 05T$$

$$c_p(T) = 807.163 + 3.58T \qquad (6)$$

$$\mu'(T) = 0.08467 - 0.0004T + 5E - 7T^2$$

T in K

The boundary conditions for the 2d model are shown in Table 1.

Table 1 Boundary conditions

Core loss	14500W
HV loss(3 Phases)	67300 W, 22433 W/per phase
LV loss (3 Phases)	75510 W, 25170 W/per phase
Regulatingwindingloss	5439 W per phase
Tank (lateral wall)	adiabatic
Upper and lower walls	adiabatic
Inlet oil temperature	320 K
Inlet oil velocity	0.002 m/s
Outlet pressure	0 kPa

The oil velocity was taken as 0.002 m/s at the inlet which gives a Reynolds number of 3.48 (based on the oil inlet velocity and the outer HV cooling duct width) and 5.75 (based on the oil inlet velocity and outer LV cooling duct) which is typically the case of laminar flow.

The grid considered was composed of 44,304 cells. The independency test was performed with the final grid of 269,310 cells.

IV. HEAT RUN TEST IN A REAL POWER TRANSFORMER

The heat run testof areal 33.6 MVA power transformer was performed at the transformers manufacturer. This test was done in order to verify the acceptance criteria established by the IEEE loading guide [12] concerning the calculated oil and windings temperature rises. It is also designed to verify possible hot spots inside or outside transformer windings. In this heat run test, the values obtained were compared to the values of the CFD model.In this test, a set of fiber optic probes were set as shown in Fig. 4a. The physical setting of the probes is shown in Fig. 4b. The averages of the temperatures recorded by the probes were obtained.

Figure 4a Location of probes in the power transformer

The heat run test was performed for ONAN (oil natural, air natural) and ONAF (oil natural, air forced) cooling modes. The purpose of the heat run test is to verify the thermal capability of the transformer. It is performed by using the short circuit loading method whereby one winding is short circuited and sufficient current is circulated in the windings to generate a loss equivalent to the core loss plus load loss. The transformer is connected at its maximum loss position. Thermocoupleswith an accuracy of ± 0.1℃ and resolution of 0.05°Care used to monitor the top oil temperature in the transformer and the air ambient temperature. The transformer is operated at this loading until the increase in oil temperature over ambient does not change more than 2.5% or 1 °C in three hours. It can take up to 12 hr. for temperature stabilization.

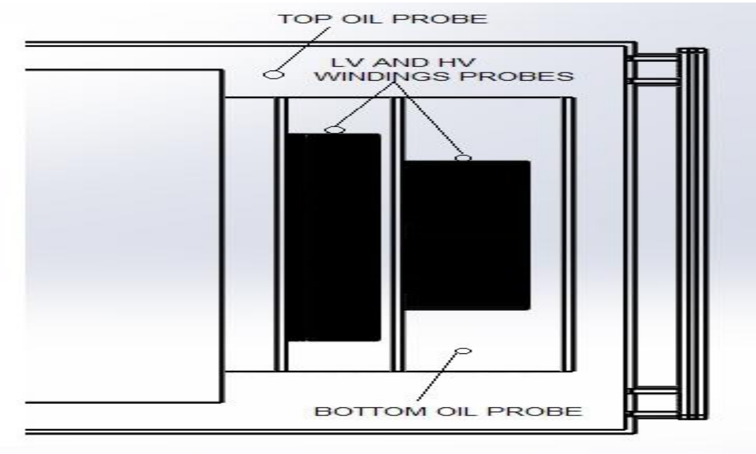

Figure 4b Location of probes in the power transformer

Additional to normal test instrumentation such as the thermocouples previously mentioned, a fiber optical monitor was installed in order to monitor winding temperatures. Gallium Arsenide − GaAs (SCBG) technology (OTG series optical sensors) were used. These sensors have dimension of 0.170 mm OD, offering a fast response time of less than 10ms; with an accuracy of ± 0.3°C and resolution of 0.05°C. According to the uncertainty analysis, the standard deviation of the readings for the oil temperature at the upper and lower positions was 2.32 and 1.66 respectively.The calculated typical error for those measurements was 0.7 and 0.5 respectively.

The temperatures of windings and oil obtained by means of the probes are shown in Table 2.

Table 2 Experimental results

Probe position	Winding Temperature	Oil temperature
Upper part HV winding	86°C (359 K)	69°C(342 K)
Upper part LV winding	101°C(374 K)	69°C(342 K)
Lower part HV winding	53°C(326 K)	43°C(316 K)
Lower part LV winding	53°C(326 K)	43°C(316 K)

V. RESULTS AND DISCUSSION

1. Basic Case

The results that were obtained with the simulations are presented as temperature and velocity contours. The case considered first was the one with 82 discs and102 discs for the HV and LV windings (basic case). The regulating winding was simulated as solid copper winding. Oil is distributed from its inlet through a set of vertical and horizontal cooling ducts.The temperature contour is depicted in Fig. 5.

This Fig. 5 depicts regions of high temperature in the LV and HV windings. The value reached is 87 °C(360 K) at the last HV discs and 103 °C(376 K) at the last LV discs. Oil is increasing its temperature from 43 °C (316 K) to 80 °C (353 K).

The Rayleigh number, $Ra = Gr \times Pr$, found in the outer HV cooling channel is 1.64×10^6 and in the outer LV cooling duct channel is 7.5×10^5 based on the cooling duct width. This parameter gives the relationship between the thermal forces and the dissipative forces in the fluid. The parameterGr / Re^2characterizes the mixed convection whether it is dominated by the forced or natural convection. In the outer HV cooling channel the mentioned parameter (Richardson number) is5.7×10^2 and in the outer LV cooling channel is 9.68×10^1. This indicates that the natural convection is dominating the flow in both channels.

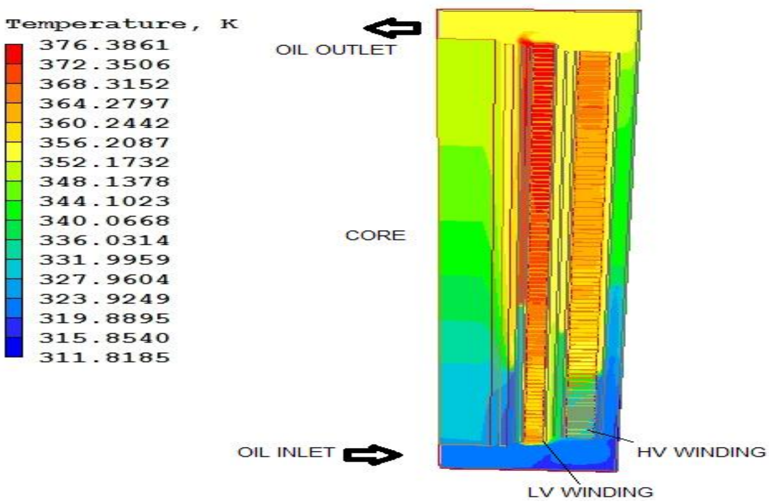

Figure 5 Temperature contour (basic case: 82 and102 discs for the HV and LV windings)

A comparison of the windings temperatures for this numerical basic case and the heat run test mentioned are shown in the following Table 3.

Table 3 Comparison of windings temperatures

Section	Heat run test	Numeric
Upper part HV winding	86°C (359 K)	87 °C(360 K)
Upper part LV winding	101°C(374 K)	103 °C (376 K)
Lower part HV winding	49°C(322 K)	55°C (328 K)
Lower part LV winding	53°C(349 K)	51 °C (324 K)

As a remark, it is deduced that the winding upperLV temperature value of 103 °C (376 K) for the basic case for HV and LV windings differs from the heat run test value of 101 °C (374 K) with 101 and 82 discs for the HV and LV windings. This is about 1.98% ofdifference.

The modifications to thermal design parameters will be presented in the next results, starting with the number of discs for the HV and LV windings. Later a modification of 10, 20 and 30% of heat dissipation in the HV and LV windings will be addressed and finally the modification of the inner HV cooling duct width will be presented.

2. Modification of number of discs

The number of discs in the HV and LV windings was modified and the corresponding winding and oil temperatures are depicted in the following Figs. 6, 7, 8 and 9.

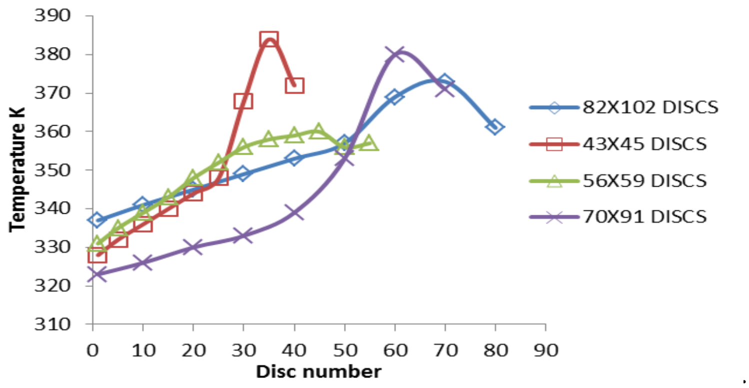

Figure 6 High Voltage winding temperature

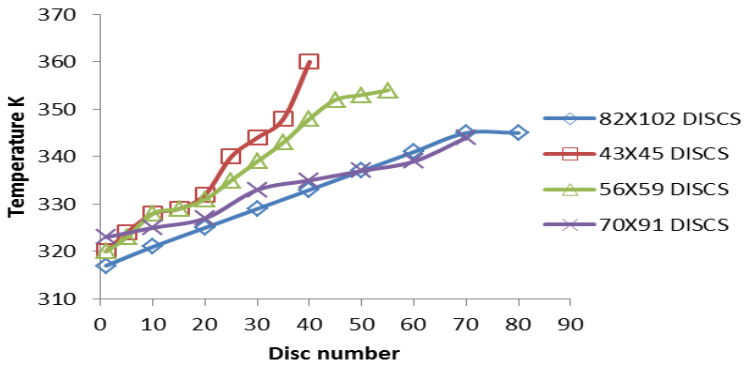

Figure 7 High voltage oil temperatures.

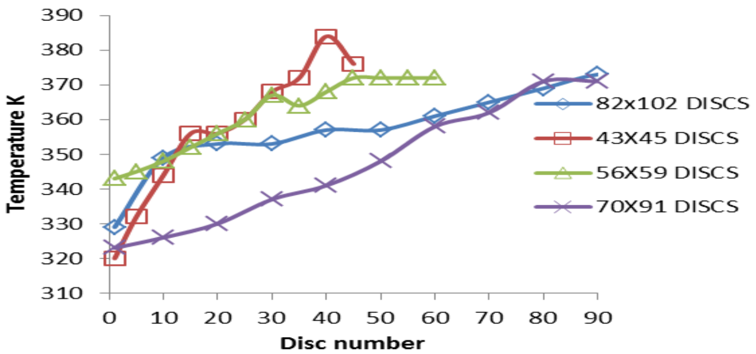

Figure 8 Low voltage winding temperature.

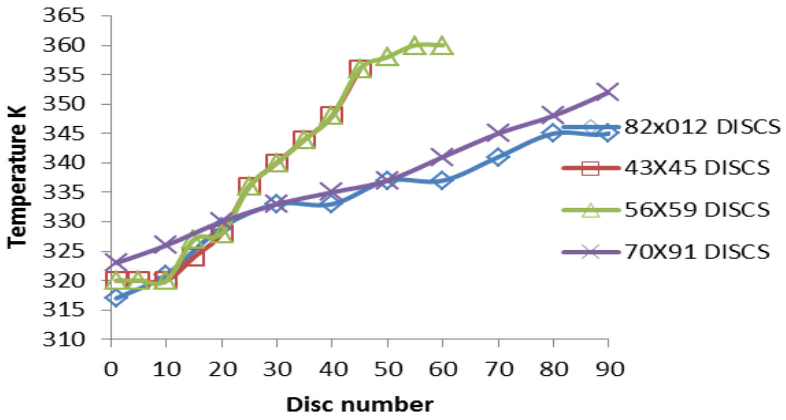

Figure 9 Low voltage oil temperatures.

From Figs. 6 and 8, it is observed that there is a peak of temperature for the HV winding with configuration of 43x45, 56x59 and 82x102 discs and for LV winding with configuration of 43x45 discs only. From Figs. 7 and 9, a linear increment in temperature is clearly observed as the height is increased.

Fig. 10 depicts the Richardson number for the configurations of 43x45, 56x59, 70x91 and 82x102 discsfor the HV winding. The buoyancy effect dominates the flow of oil in the HV channel as the Richardson number varies from $1.6x10^2$ to $5.19x10^3$ for the 70x91 discs configuration. This effect also takes place in the other configurations but it seems a little bit diminished in the Richardson number obtained. Figure 10 also shows an increasing Richardson number from discs 20 to 40 for 56x59 and 70x91 discs configurations reaching a maximum and then decreasing at the last HV disc. This emphasizes that the buoyancy effect is dominating from discs 20 to 40 and 60 respectively for the configurations mentioned and then decreases as oil is approaching the final discs. For the configuration 43x45, the buoyancy effect is dominant in the whole height of the configuration. For the 82x102 discs configuration, it increases from disc 20 to disc 40 and then tends to decrease from disc 40 to disc 50 and continue then increasing up to disc 70 and decreases up to disc 82.

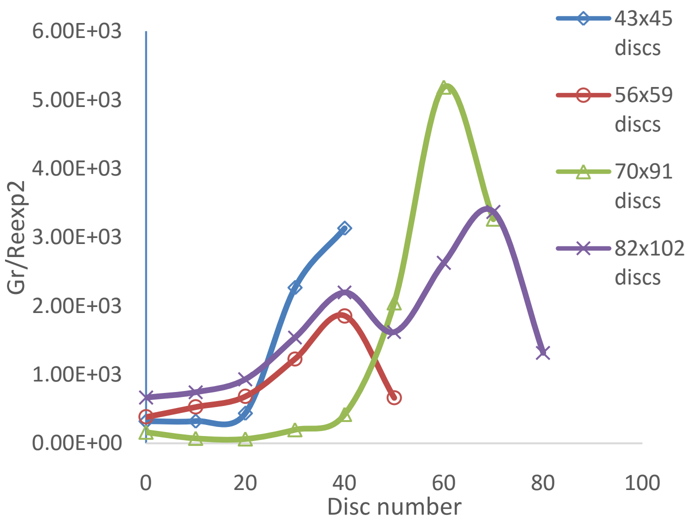

Figure 10 High voltage winding Richardson number

3. Modification of the windings heat dissipation

Then the heat dissipation varied from the original HV and LV windings heat dissipation to 10, 20 and 30% more. The temperature profiles for oil and windings are presented in Figs. 11, 12,13 and 14.

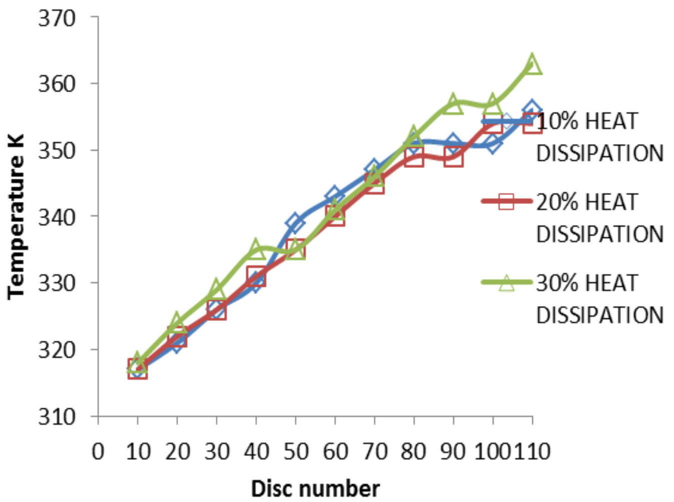

Figure 11 High voltage winding temperature

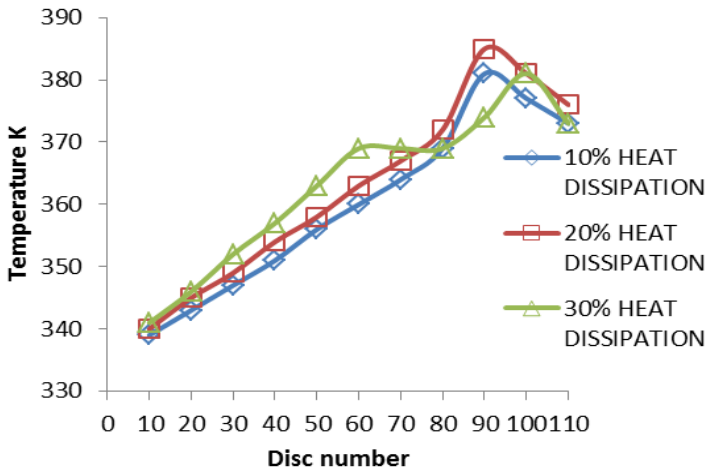

Figure 12 High voltage oil temperature

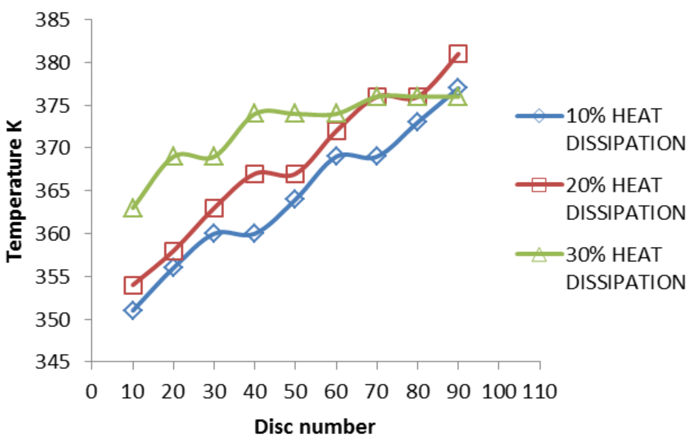

Figure 13 Low voltage winding temperature

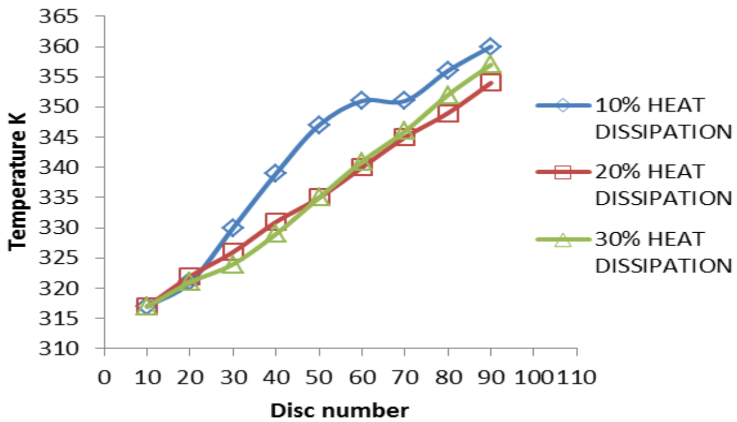

Figure 14 Low voltage oil temperature

Fig. 11 clearly shows that there is a linear trend along the height of the HV winding with a peak value found at the last upper discs of the winding.The maximum value depends on the percentage of heat dissipation considered. Figs. 12,13 and 14 presents a linear trend in temperature also.

Fig. 15 shows the Richardson number found for this 10, 20 and 30 % variation in heat dissipation. There is an increase in the Richardson number at the last upper discs of the HV winding. The heat dissipation variation shows a clear trend in its behavior in reference to an increase of the Richardson number, then a constant zone from discs 40 to 80 and another increase from disc 80 to reach a maximum value at disc 95 and a final decrease from discs 95 to disc 102. This suggest that the natural convection is dominating from disc 10 to disc 40, then there is a region where practically the natural convection is as important as the forced convection and finally natural convection keep increasing up to a point where forced convection is driving the oil in the HV duct. For the 30 % heat dissipation, this figure below depicts that the natural convection is dominating the flow of oil for a region between disc 10 to disc 40. Then, this effect keeps constant for discs 40 to 80 and continues growing up to disc 90, where it starts to reduce for the rest of the HV height.

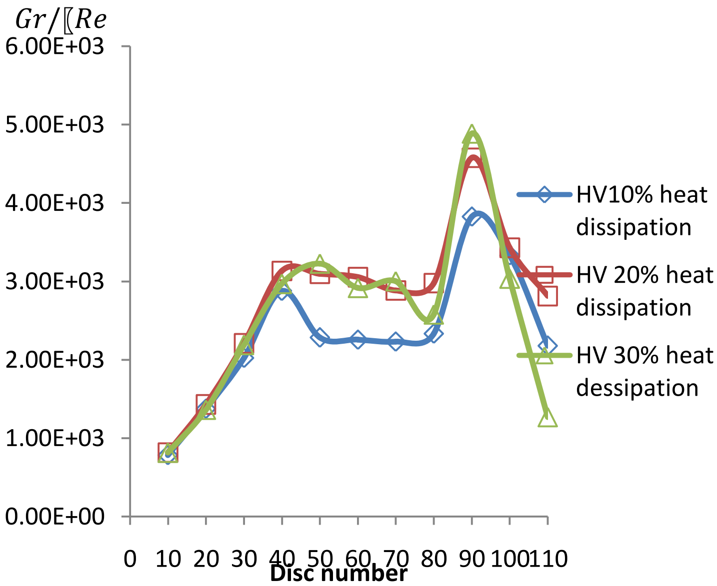

Figure 15 High Voltage winding Richardson number

4. Modification of outer HV cooling duct width

The HV outer and LV inner cooling ducts width were then varied to4, 6, 8 and 12 mm (0.1575, 0.2362, 0.315 and 0.472 inches) for the 82x102 discs configuration.Figs. 16 and 17 shows HV and LV windings temperature profiles.

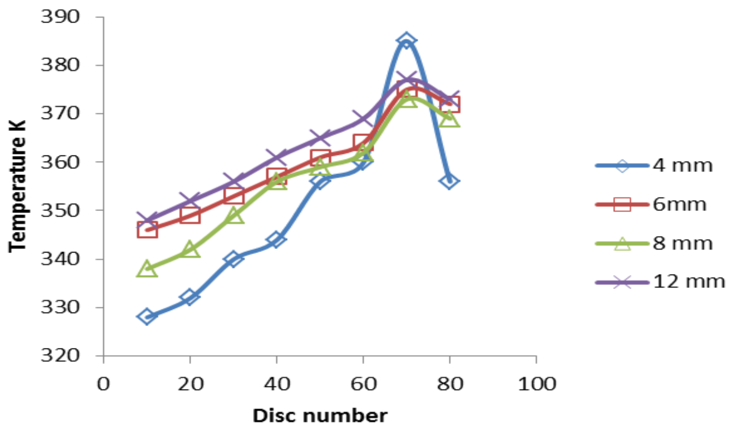

Figure 16 High voltage winding temperature

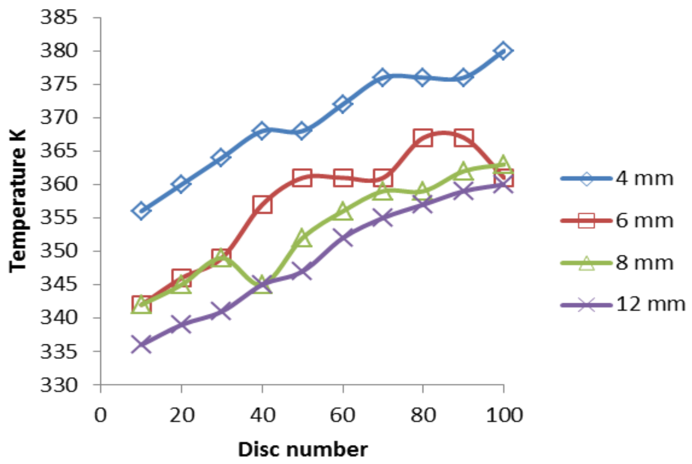

Figure 17 Low voltage winding temperature

When the HVwinding cooling ductwidth was modified from 12 mm to 4 mm, the maximum value of temperature in the HV winding varied from 104 °C (377 K)to 91°C (364K). In the case of the LV winding cooling duct, the value of high temperature varied from 87 °C (360 K) to 104 °C (377 K)for the modification in HV winding cooling duct width from 12mm to 4 mm. Fig. 18 depicts a close-up of the windings temperature for the 4 mm HV duct width where oil movement is shown in the horizontal and vertical cooling ducts.

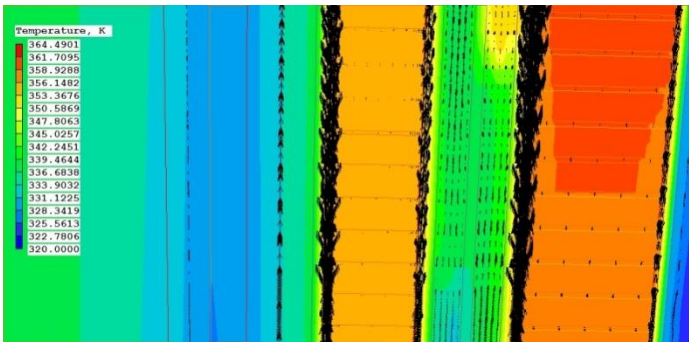

Figure 18 Closeup of winding temperature for the 4 mm HV duct width

The Richardson number variation is depicted in Figure 19 for the HV winding. It shows that there is an increase in the Richardson number along the height of the winding and suddenly there is a localized decrease at the disc 60 and continues growing to the previous value found for disc 50 and finally it decreases at disc 82.

From the cases investigated, clearly there is a trend in the Richardson number between discs 50 and 70. This downwards variation while reaching disc 60 confirms the dominance of viscous effects in this region which gives rise to some forced convection dominance. Then after disc 60, the natural convection effect takes over and finally after disc 65, the forced convection effect continues dominating the heat transfer process in the oil. .

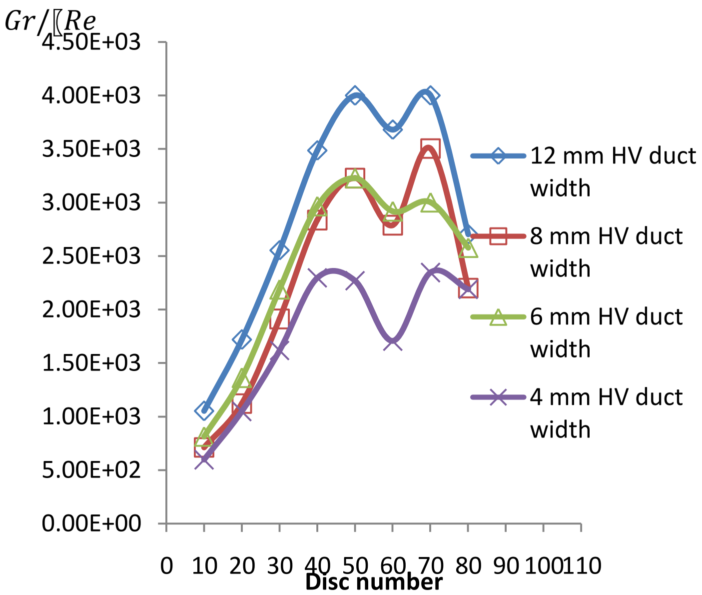

Figure 19 High voltage winding Richardson number

conclusions and future work

A basic windings, regulating coil and core design was used to obtain a CFD model(82x102 discs configuration). A comparison of winding temperatures from CFD model and the ones for the heat run test of real power transformer was performed. LV winding temperature of 103°C (376 K) for the case of 82x102 discs differs from the heat run test value of 101 °C (373 K). This is about 1.98 % of difference.

Some thermal parameters in the design of a disc type power transformer were analyzed. In respect to the change of number of discs,it is observed that there is a definite trend towards the definition of maximum winding temperature at the top of winding. Also, the location of the hot spot varies from HV to LV winding, being defined for HV and LV winding at almost the upper part, and varying its value from 380 to 360 K depending on the arrangement of discs selected.

When heat dissipation from the windings was increased by 10%, 20 % and 30%, the LV winding maximumtemperature increased from 381 K to 385 K and then decreased to 381 K respectively. Also,the location of high winding temperatures varied from the top of LV winding to the top of HV winding for 30 % heat dissipation.

When HV cooling duct width was changed, the value of the hot spot changed from 87 °C (360 K) to 112 °C (385 K) and its location was at the top of HV winding. This emphasizes the fact that cooling ducts width should be sized carefully in order to limit the value of the hot spot.

The different variations in number of discs show that configuration of 70x91 discs produces more buoyancy force of the oil which tends to increase the hot spot value in the HV winding, however, the 82x102 discs configuration although produces less buoyancy force tends to reduce the hot spot value in the HV winding.

The variation in heat dissipation shows that although the 30 % heat dissipation produces more buoyancy force, it tends to reduce the hot spot value found in the HV winding.

The variation in the outer HV duct width produces more buoyancy force for the 12 mm duct width when compared to the 6 mm duct width. The hot spot value in HV winding similarly reduces for the 12 mm duct width when compared to the 6 mm duct width.

As future work it isconsidered,this experimental work regarding these proposed variations of geometrical features should be done in order to do a comparison between the temperature values found for the variations outlined herein.

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Nomenclature:
$\boldsymbol{c_p}$**:** Specific heat (J/kg K)
E: energy (J/kg)
g: Gravity acceleration (=9.8 m/s^2)
k: Thermal conductivity(W/m K)
P: pressure (Pa)
S: source term (W/m^3)
T: temperature (℃ $or\ K$)
U: velociycomponent (m/s)

Abbreviations:
HV: high voltage
LV: low voltage

Greek symbols:
$\boldsymbol{\rho}$**:** density of oil(kg/m^3)
Δ**:** difference
$\boldsymbol{\beta}$**:** expansión coefficient of oil (K^{-1})
$\boldsymbol{\mu}$**:** absolute viscosity of oil ($Pa \cdot s$)

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