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Research Article

Thermal Investigation and Heat Flux Analysis of a Cascaded Transformer in the Tropics

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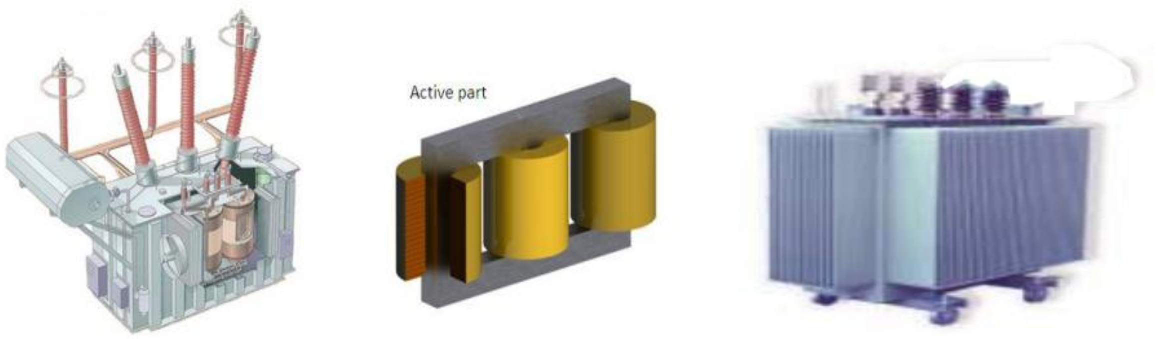
Abstract: The tropics is characterized with high temperature but in recent time with the advent of global warming that had shot the world temperature so high ,cascaded transformers failure is imminent due to excessive heat stored in the windings that could not be dispensed equitably. Understanding the thermal behavior of the windings in cascaded transformers is complicated, it is difficult to predict the location and strength of the hottest temperature in the winding (i.e. hotspot temperature). To initiate an improved understanding of the thermal behavior, a thermal analysis (steady and transient), numerical should be done. A model of cascaded transformer is made using Creo Element and built with Ansys Work Bench to analyze. The steady and transient thermal analysis with maximum -temperature distribution of 96.325°C ,and total heat flux $1.9463 \times 10^6 \; W/m\;C$ on a steady analysis and maximum temperature of 114.62C and toatal heat flux of $1.7172 \times 10^6 \; W/m\;C.$

Keywords: Thermal investigation, Temperature Distribution, Carbon Steel AISI 1905, Transformer Cascade.

INTRODUCTION

A transformer is the electrical device which is used to change the voltage of AC in power transmission system. The first transformer in the world was invented in 1840s. Modern large and medium power transformers consist of oil tank with oil filling in it, the cooling equipment on the tank wall and the active part inside the tank. As the key part of a transformer, the active part consists of 2 main components: the set of coils or windings (at least comprising a low voltage, high voltage and a regulating winding) and the iron core, as Figure 1.



A **b.**

Fig-1: cascaded oil cooled transformers and internal structure

Transformers can be classified by many standards, such as structures, applications, number of phases, cooling types, etc. According to the number of phases, we have single-phase transformers and poly-phase transformers; according to the cooling methods, there are dry type cooling transformers and oil immersed cooling transformers; and on the application purpose, there are constant voltage transformers, variable voltage transformers, current transformers and constant-current transformers. In this paper the model created is mainly on oil immersed cooling type of power transformers which are widely used in high voltage power transmission using Creo Element and built with Ansys Work Bench

The transformer life is limited by the age of insulation materials inside the transformer, such as insulation paper wrapping around the windings. The insulation materials, such as cellulose, will be destroyed if the transformer keeps working in the environment with high temperature. It is said from experience that when the hotspot temperature is in the range 80-140 C, the transformer life will be halved for every 6 degree increase [1]. Therefor, measures must be taken to avoid high temperature inside the transformer by removing the heat generated in the core and windings effectively. As described above, according to the size and capacity of the transformer, different methods are applied to achieve the cooling targets. The life of a power transformer is mostly governed by its hot-spot temperature. The winding hot spot temperature is the main factor limiting the loadability of a power transformer. Higher winding hot spot temperature causes degradation of the insulating materials and results in the formation of gas bubbles which facilitates the deterioration of transformer oil. The insulating oil changes its chemical properties and causes dissociation of oil, increased pressure in the tank because of the gases formed during the supposed chemical reactions which enhances the chances of tank explosion and fire hazards. The change in the electric and magnetic properties of the core and coil again result in increased losses and increased heat generation and accelerate the above discussed effects. With temperature and time, the cellulose insulation undergoes a depolymerization process. Eventually the paper become brittle and is not capable of withstanding short circuit forces and even normal vibrations that are part of transformer life. This situation characterizes the end of life of the solid insulation. Since it is not reversible, it also defines the transformer end of life.

In power technology community that transformers are crucial to the overall health and progress of the power system. Challenge to utilities in the US: managing aging substation transformers installed in the1960s and 1970s. (Approaching beyond their original life expectancy.) Cost of Replacement has forced many to keep transformers operating beyond their recommended life span. The main factors responsible for transformer aging are Temperature , Oxygen and Moisture. Controlling these variables can maximize the life of a transformer .“Small (~1°C) reductions in winding temperatures can significantly extended Transformer longevity”

HEAT ENERGY GENERATION AND THERMAL COOLING

The main losses come from the winding resistance thermal loss, the eddy current loss and the hysteresis loss. [2] in a real case scenario. In an ideal situation, no energy lost. Windings consist of wound wires made of copper or other conductors. Even though the resistance is low, the current through the wire coil can still cause resistive heat. In a high frequencies and high temperature in a transformer, the resistance will be increased. Eddy currents are circulating through the core and windings and the coupling effects of the frequency and material thickness could also lead to resistive heat loss. The hysteresis loss is mainly happening in the core which is a coupling effect from frequency and material properties [3].

The cooling method applied depend on size and purpose of the transformer. For dry type cooling method, the windings and cores inside the transformer are exposed in the air. The cooling effects can be achieved by natural convection of the air around the windings and cores or the air blast from the blower. The radiation from other parts of the transformer also adds the cooling effects. Due to the relative low cooling efficiency, this cooling method is usually applied for small size and low capacity transformer. For liquid immersed transformer, the active part including cores and windings is immersed in some insulating liquid, usually the transformer oil, filling in the transformer. The heat generated by windings and cores will be transferred to the transformer wall by convection.

Then, the heat will dissipate into the environment by radiation and convection. Usually, for some large transformers, fins and radiators are applied for improving the cooling capability. Atypical example of the liquid immersed transformers is the large oil immersed transformer in which a blower is installed forcing the circulating air to enhance the cooling effects.

Another cooling method is gas-vapor cooling transformers. This method applies a vaporizable liquid as the coolant. The liquid coolant is pumped to the top of the windings and cores then vapors while absorbing the heat generated, the hot vapor gas with heavy density than normal air would go down to the bottom circulating tubes. The vapor would be cooled into liquid in the cooler and back to the pump for the next circulation. This cooling method is usually used for large transformer.

OIL IMMERSION METHOD

Oil inside the transformer is incompressible fluid and acting as both the insulation material and the coolant for inner parts of transformer. transformer oil is that it is good insulator and has good property for transferring heat from active parts to the cooling parts. However, as a kind of oil, it usually has high viscosity and high Prantl number, which may decrease natural convection capability the problem that cause its deterioration are oxidation and moisture that must be guarded. Oil immersed cooling methods is applied in large capacity transformer .In the recent time, the oil immersed transformer can be divided into different types according to the cooling modes. There are three main cooling modes inside the oil tank:

i. ON (Oil Natural),

ii. OF (Oil Forced) and

iii. OD (Oil Directed) as well as three main cooling modes for the outside radiator: AN (Air Natural), AF (Air Force) and WF (Water Force). Principle of the typical cooling mode ONAN is described below

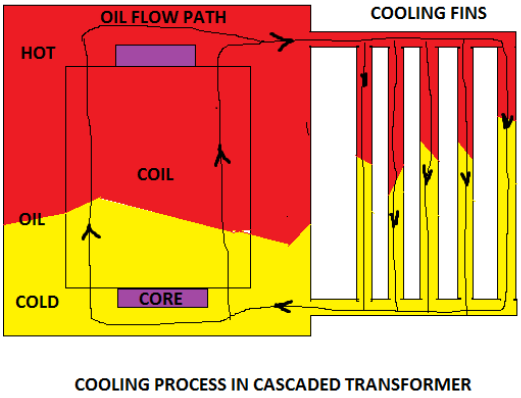
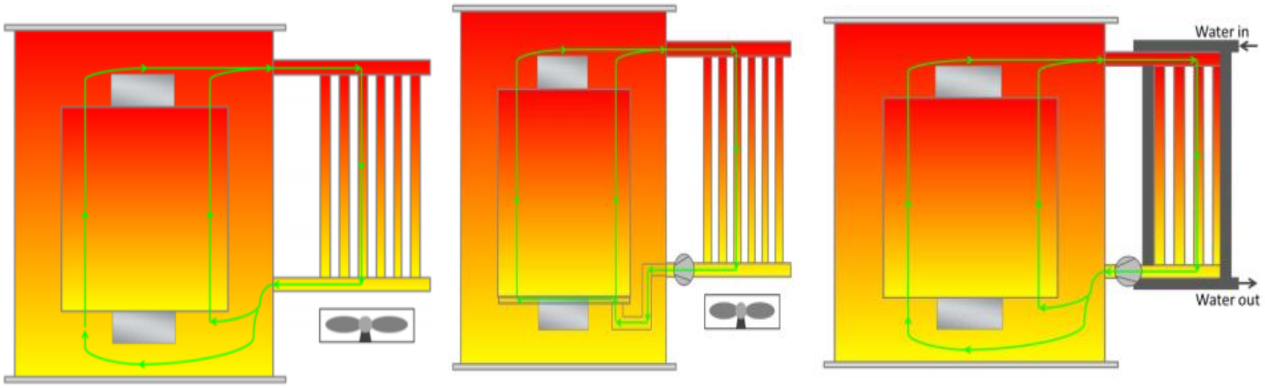


Fig-2: ONAN cooling circulation

This transformer consists of oil tank, cores, windings, and radiator. Transformer oil is filling inside the oil tank and radiator. In a steady state, cold oil comes in the tank from radiator. Oil is heated inside the transformer and hot oil will go up to the top and then go out of tank into radiator. Oil inside radiator will be cooled by natural convection of the air and the radiation in the environment. Oil flow inside the entire oil tank is actually buoyancy driven flow. When passing through windings and core, it is being heated and the density would be changed as well. Then, a buoyancy force is generated to drive the flow up. As Figure 2 shows, the line indicates the circulation direction of the oil. In this cooling circulation, the natural convection of the oil plays the key role for cooling the disc winding and the core. This cooling mode is called ON (Oil natural) cooling. If the oil inside the radiator is cooled by natural convection of air in surroundings, this cooling mode can be called ONAN cooling mode.



A. AF (Air Force) **B. Oil Directed Air forced** **C .Oil Directed WF (Water Force)**

Fig-3 : Different cooling modes for oil immersed transformer

Other cooling modes for large transformer include ONAF, OFAF, OFWF, ODAF, ODWF. In the tropics especially the African countries ,with the high rise in the world temperature the transformers need improved cooling system to improve the life span and functionality of the transformers. Africa with availability of water the water cooling system from and evaporative cooler should be encouraged but with proper seal and insulation.

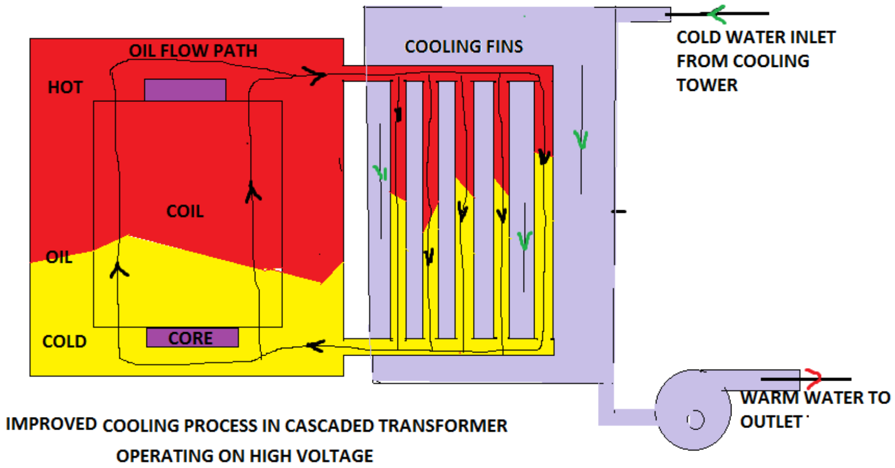


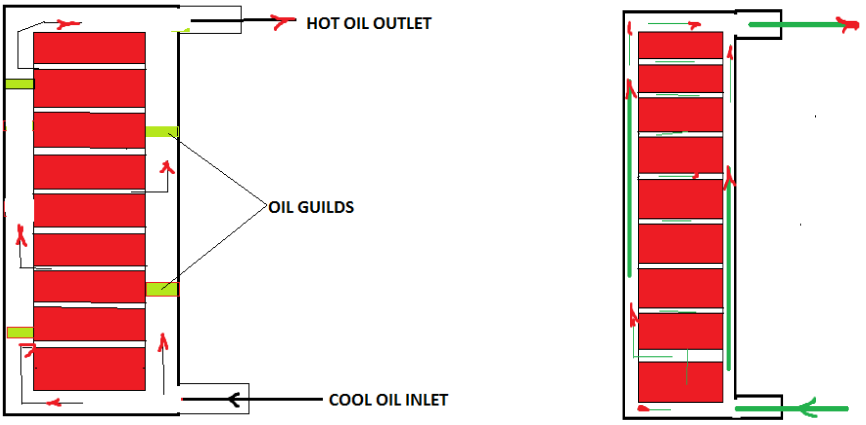
Fig-4: A Schematic Of Cooling System Suitable For Transformers Suggested Used In Trapics

This is because using convective air from a blower or fan may not have significant effect because the air is a product of the ambient hence same temperature within a short time.

WINDINGS

There are Oil guided and non-oil guided windings especially in disc windings transformers and active path between winding and core, Low Voltage windings and High Voltage windings, and windings and outer casing, there are insulation board layers, this gives closed space formed for each layer of windings. The purpose of setting oil guides is to improve the natural convection capability of the oil flow by avoiding the stagnation of the oil inside ducts. cold oil come in the windings from the bottom and the go through the vertical and horizontal ducts, the oil guides would change the oil flow direction and make the global oil distribution even. This enhances the global heat transfer coefficient .Transformer paper plays a pivotal role in the insulating and filtering mechanisms of a transformer coil.

Fig-5: Pictoral view of coil with insulation paper



OIL PATHS WITH OIL GUILDS IN DISC WINDINGS

OIL PATH IN DISC WINDINGS WITHOUT OIL GUILD

Fig-6: cross-sectional images of disc windings

THERMO-HYDRAULIC MODEL OF THE COOLING PROCESS

Assumption : Temperature of the strands is a uniform steady state condition.

The total temperature gradient from stands to the steady-state oil flow is ΔT the temperature gradient from the strands to insulation layers due to heat conductivity is ΔT_C and the gradient from insulation layers to the oil flow due to the natural convection is ΔT_{ac}

$$\Delta T = \Delta T_C + \Delta T_{ac} \qquad (1)$$

The hydraulic model describing the flow of the oil is analyzed using dimensionless numbers

i. Reynolds number, Re, :This identifies the regime of the flow, laminar, transition, or turbulent. It indicates the ratio of inertial forces to viscous forces. At very high, Re higher than 2000, the inertial force is much higher than the viscous force, then, the inertial force becomes the dominant force, which leads to turbulent flow; when Re is low, the viscous force would be the dominant force, which would lead to laminar flow.

$$Re = \frac{\rho v L}{\mu} \quad (2)$$

$$L = \frac{4A}{P} \quad (3)$$

$$A = wl \quad (4)$$

$$P = 2(w + l) \quad (5)$$

l is the characteristic length, v is the characteristic velocity, A is the cross-sectional area, P is the wetted perimeter, w is the width of the vertical duct and cl is the mean circumference of the disc windings. The properties of the oil and geometry of windings determines the flow

ii.Grashof Number

Grashof Number, Gr, in this case is mainly used to indicate the behavior of the transformer oil under a certain temperature. It can be expressed as the ratio of buoyancy to the viscous force. Thus, it is applied to describe this natural convection of the oil. Oil flow is driven by the buoyancy generated due to the density variation as a function of the temperature. In this case, transformer oil is one kind of fluid with high viscosity, the coupling effects of gravity and viscous force of the fluid become resistance to the buoyancy. Usually, a high Grashof Number of fluid indicates a high capability of natural convection while a small Grashof Number shows the low capability of natural convection. The oil flow between different disc windings can be regard as the oil flow passing through the plates, then, the empirical calculation method of the local Grashof Number

$$Gr = \frac{g\beta\Delta T L^3}{v^2} \quad (6)$$

where β the volumetric thermal expansion coefficient, ΔT is the temperature between surface temperature and the buld temperature (K) when $Gr > 10^8$, the boundary layer of the convection is laminar, $10^8 < Gr > 10^9$, it is the transition stage from laminar to turbulent. $Gr > 10^9$the boundary layer is turbulent. In this case, according to the properties of the transformer oil and the geometry dimensions,

$$Gr = \frac{g\beta\Delta T L^3 \mu^2}{\rho^2} \quad (7)$$

iii.Prandtl Number

Prantl Number, Pr, is the ratio of fluid viscosity and thermal diffusivity. It shows the relation between the hydraulic property and the thermal property of the fluid. Transformer oil is high Prantl Number fluid. That means the viscosity of the oil will impacts a lot on the thermal diffusivity. The Prantl Number of the transformer oil is generally lager than 50.

$$Pr = \frac{C_P \mu}{K} \quad (8)$$

C_P is specific heat (J/(kg.k)), k is thermal conductivity (w/mk).

iv. Rayleigh Number

Rayleigh number is the relation between the Grashof Number and the Prantl Number and as an indication of the heat transfer mode. At a certain buoyancy driven flow, there is a critical value, that when the local Rayleigh Number is below this value, the conduction is dominant, and when the local Rayleigh Number is higher than this value the convection heat transformer is dominant. In most situations, the value of Rayleigh is around 10^6 *and* 10^8

$$Ra = Gr.Pr = \frac{g\beta\Delta TL^3}{v\alpha} (9)$$

v. NUSSELT NUMBER

Nusselt Number, Nu, is the ratio of convective heat transfer to conductive heat transfer at the boundary in a fluid close to a wall. for a laminar flow, the value of Nu is close to 1, while a higher Nu means more active convection, such as turbulent heat transfer,h is the convective heat transfer coefficient, L is the characteristic length and k is the conductive heat transfer coefficient.

$$Nu = f(Ra, Pr) \quad (10)$$

$$Nu = f(Re, Pr) \quad (11)$$

THERMAL ANALYSIS

The power handling ability of a ferrite transformer is limited by either the saturation of the core material or, more commonly, the temperature rise. Temperature rise is important for overall circuit reliability, and staying below a given temperature insures that wire insulation is valid. On the other hand, as core temperature rises, core losses can rise and the maximum saturation flux density decreases commonly. R-type material is adopted in our design transformer, which attempt to mitigate this problem by being tailored to have decreasing losses to temperature of 100 ℃.One of the two major factors effecting temperature rise is core loss, which is a function of the operating flux density P

$$P_{core} = af^cB_m^d \quad (12)$$

Where Pcore is the loss density (mW/cm3), a, c, and d is the factors (a= 0.074, c= 1.43, d= 2.85 if R-type material is adopted, and f < 100kHz), fis the operating frequency (Hz), Bmis the maximum core flux density (kG, 10kG = 1T). So Bm is calculated by

$$B_m = \frac{E}{4A_cN_1f10^{-8}} \quad (13)$$

where E is the applied voltage of primary windings (V), Ac is the core area (cm^2), N$_1$ is the number of turns of primary windings, f is the operating frequency (Hz).

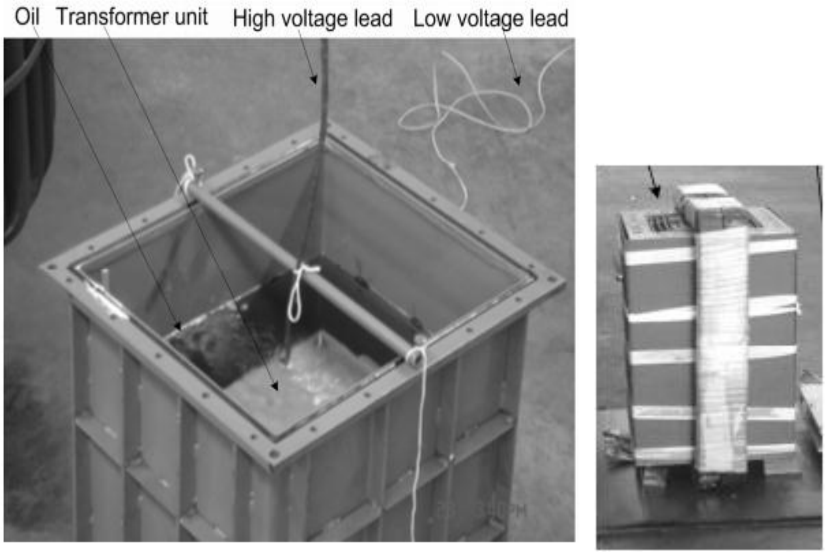


Fig-7: pictorial view of an oil filled cascaded transformer

In a steady state, the heat losses generated in discs is taken away by oil flow. An energy Balance

$$Q = mC_p\Delta T \quad (13)$$

Volume per disc winding:

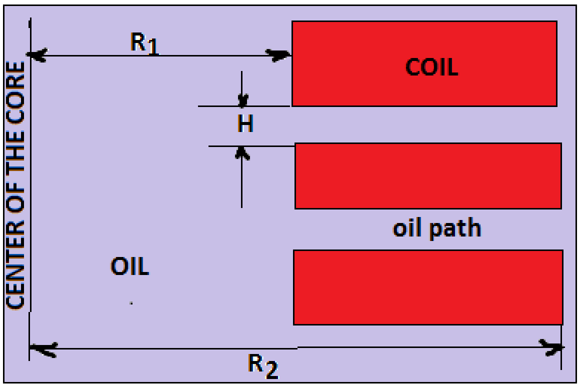


Fig-8 : A Schematic Diagram Of Disc Windings In Oil Data Calculation

$$V_i = \pi(R_2^2 - R_1^2)H \quad (14)$$

Volume of total disc winding:

$$V_T = N\pi(R_2^2 - R_1^2)H \quad (15)$$

N is numbers of windings /(disc), H distance between discs

SIMULATION

Material

The material selected for the cascade is a carbon steel AISI 1095

Table 1: thermal properties of carbon steel AISI 1095

S/N	PROPERTIES	VALUE
1	Thermal conductivity$(W/m\,C)$	52
2	Specific heat capacity$(J/Kg\,C)$	480
3	Maximum service temperature C	336

Culled from CES EDUPARK 2011(Granta)

Boundary Condition

Ambient temperature $T_{am} = 34\ C$

Temperature of the fluid going out of the windings $T_{cL} = 89C$

a. Steady state thermal analysis

Absumption

It is assumed that the air is still

Model

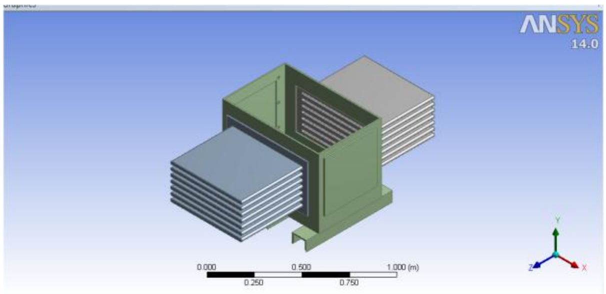
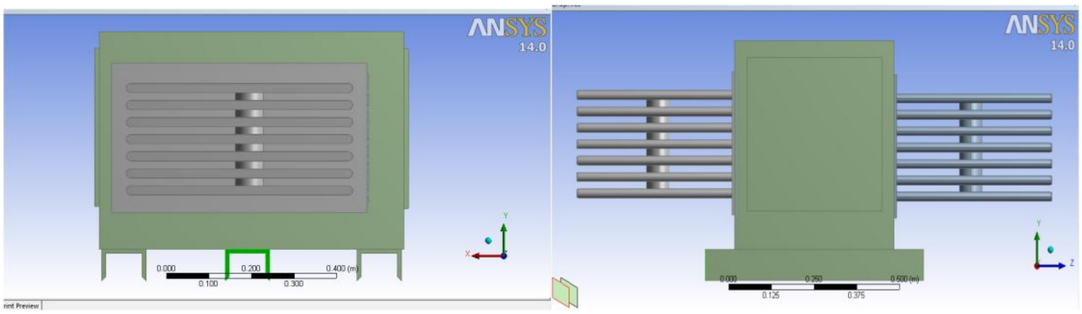


Fig-9: 3-D Model Of A Cascade



A **B**

Fig-10: Side Views Of The Cascade

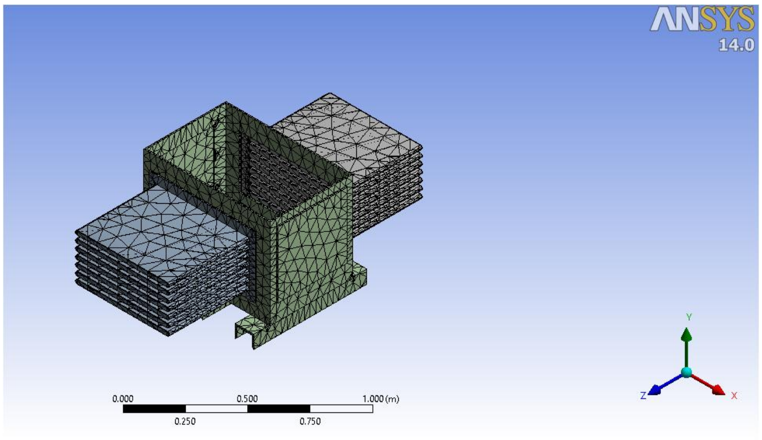
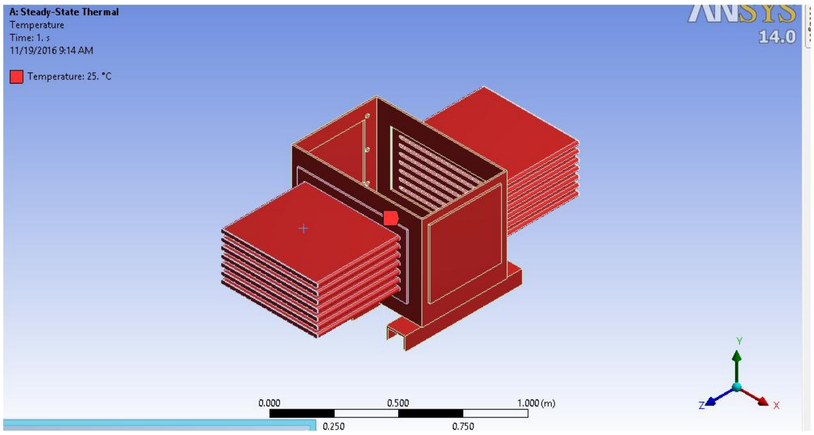


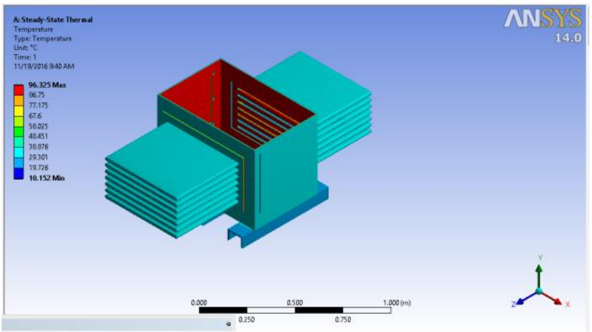
Fig-11: 3-D Mesh Form Of The Cascade Model



A: Steady-State Thermal
Temperature
Time: 1. s
11/19/2016 9:14 AM

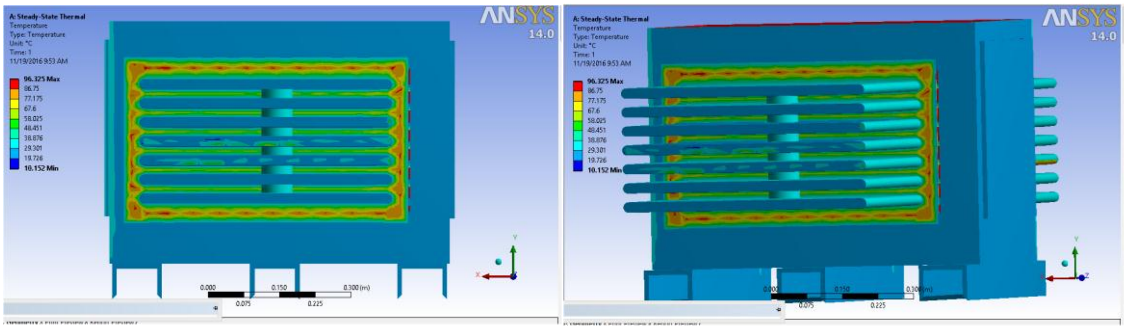
🟥 Temperature: 25. °C

Fig-12: Temperature load on the model



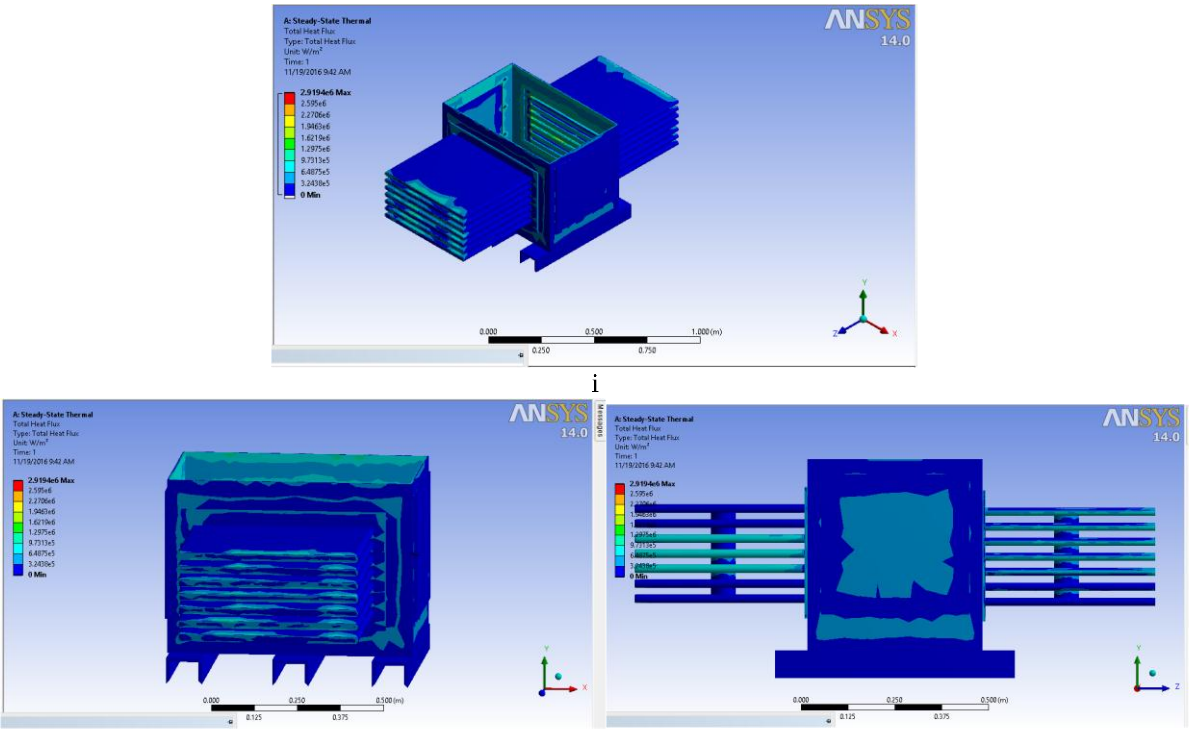
A: Steady-State Thermal
Temperature
Type: Temperature
Unit: °C
Time: 1
11/19/2016 9:40 AM

A



B **C**

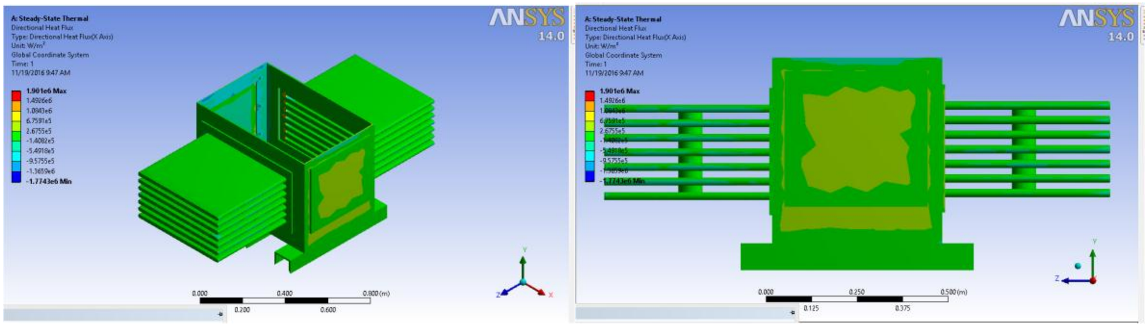
Fig-13: Temperature distribution in the model



i

ii iii

Fig-14: Total heat flux distribution

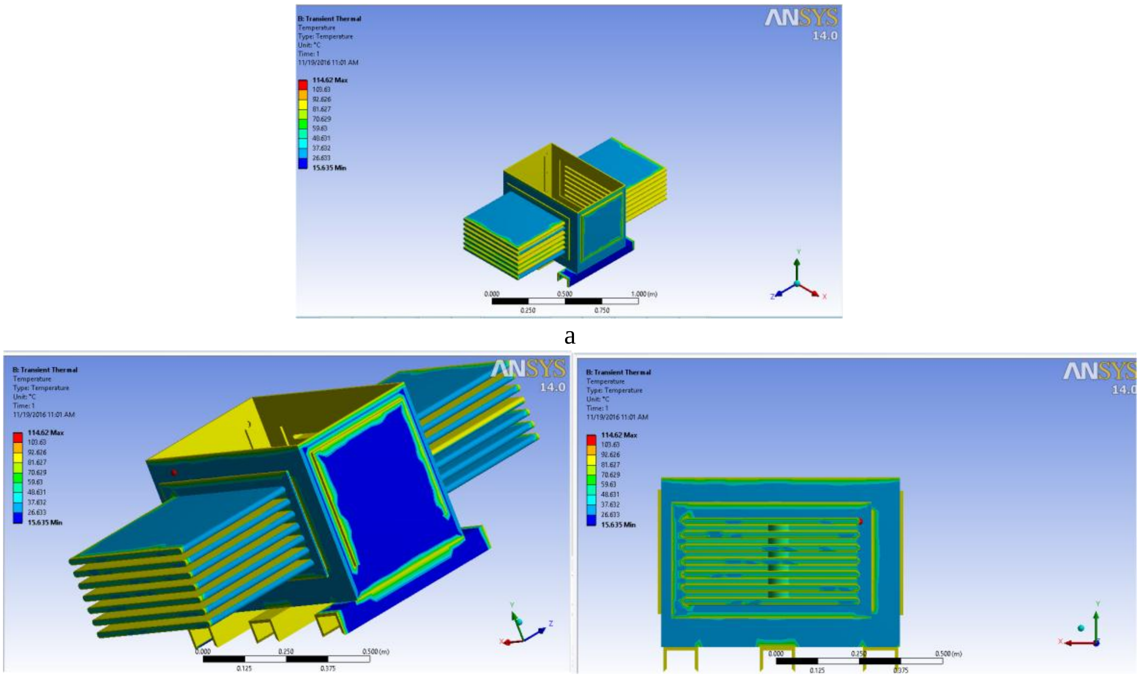


A **B**

Fig-15: Directional heat flux distribution

b. Transient Thermal Analysis

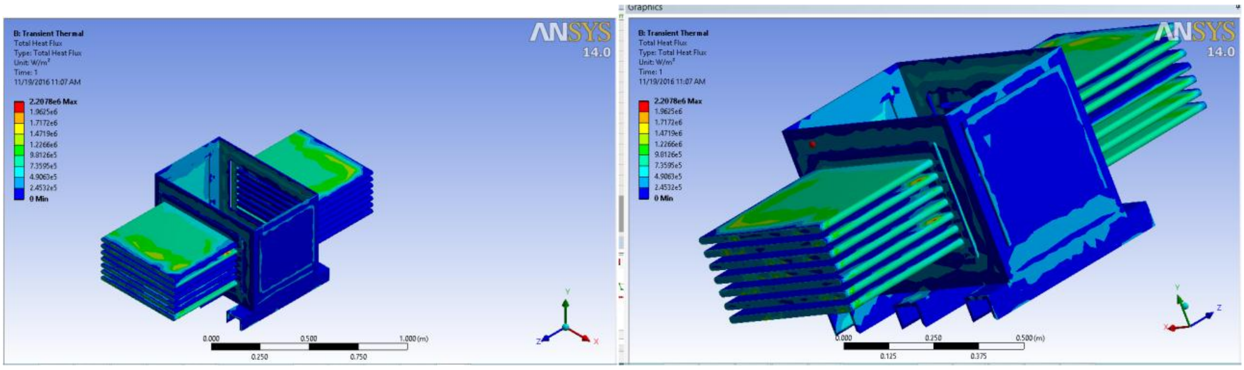
The same boundary conditions were used.



a

B C

Fig-16: 3-D view of Temperature distribution in the cascade



i ii

Fig-17:Total heat flux distribution in the cascade showing heat desipation

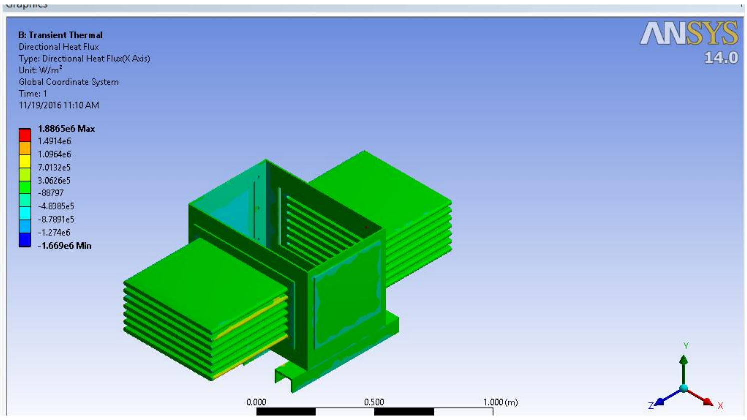


Fig-18: Directiona heat flux distribution

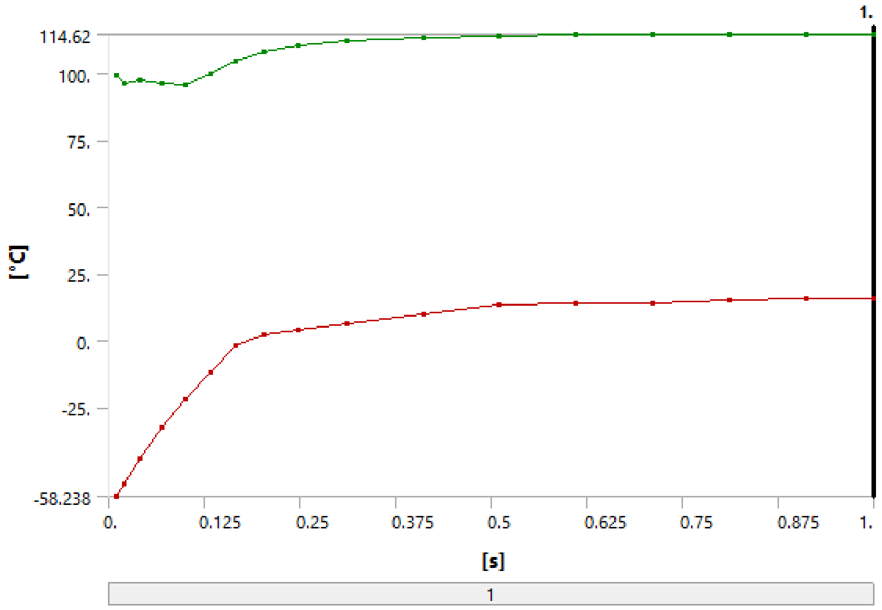


Fig-19: minimum and maximum temperature distribution in the cascade

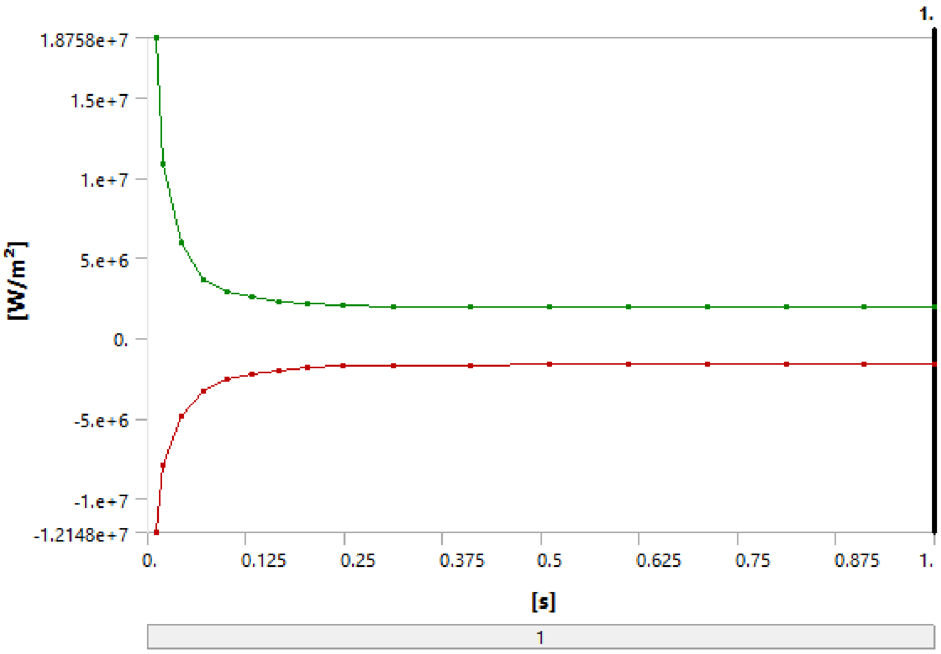


Fig-20: directional heat flux distribution as a function of minimum and maximum temperature

OBSERVATION

Although, a lot of parametric factors are found influencing the cooling process - radial disc width, inlet mass flow rate, horizontal duct height, vertical duct width and the inlet/outlet configurations. Orientation of cooling fins to the prevailing wind, air speed . the thermal performance of the transformer is determined by the hotspot temperature, the location of the hotspot and the number of oil flow patterns, material and thickness of the cascade and fins, the prevailing ambient temperature but this work shows the material effect on the heat conduction and dissipation which is principal means and boundary through which the great deal of heat generated by the windings transmitted by the oil is expelled to the environment. The steady and transient thermal analysis with maximum -temperature distribution of 96.325^{o}C ,and total heat flux $\mathbf{1.9463\times10^{6}}\ \boldsymbol{W/m\,C}$ on a steady analysis and maximum temperature of 114.62C and total heat flux of $\mathbf{1.7172\times10^{6}}\ \boldsymbol{W/m\,C}$. The graphical results in fig shows the temperature distribution as maximum temperature spreading outside to the external surface as an indication of flow of heat energy and the minimum temperature increasing in value as more heat is dissipated.

CONCLUSION AND RECOMMENDATIONS

The thermal work done in this work reveals that material selection is a factor that can be considered in building a cascade but the structural benefit of the mild steel cannot be undermined. This present surge in the world temperature demands a thermally efficient material that can improve heat transfer. A part from the main frame, the cooling fins assembly should be made of aluminum or its alloy because of its high thermal conductivity and diffusivity.

FUTURE WORK

Future work will be the investigation of the flow rate of the transformer, material thickness of the cascade , heat effect on the insulation paper, effect of different coiling modes ,and use of other oil and nano fluids as transformer oil

REFERENCES

1. Mufuta JM, Van den Bulck E. Modelling of the mixed convection in the windings of a disc-type power transformer. Applied Thermal Engineering. 2000 Apr 1;20(5):417-37.
2. Hosseini R, Nourolahi M, Gharehpetian GB. Determination of OD cooling system parameters based on thermal modeling of power transformer winding. Simulation Modelling Practice and Theory. 2008 Jul 31;16(6):585-96.
3. Torriano F, Chaaban M, Picher P. Numerical study of parameters affecting the temperature distribution in a disc-type transformer winding. Applied Thermal Engineering. 2010 Oct 31;30(14):2034-44.