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Comparative Thermal Analysis of Aluminum Alloy and Mild Steel for the Development of the Cascade of a Transformer

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Abstract: This work investigates thermal evaluation between two materials-aluminum alloy and mild steel for the development and fabrication of the cascade of a transformer. The ingenuity behind this comparative analysis on thermal performance of these two materials is saddled on the reoccurrence of transformers failures in the recent times especially in the tropics. A fair normal ambient temperature is favourable because it acts as heat sink but a scenario where the ambient temperature and the transformer temperatures are too close, it become dangerous to the operating conditions of this electrical device. A fast heat dissipation medium is needed to optimize cooling for the coils of the transformer. A model of cascaded transformer is developed using Creo Element and built with Ansys Work Bench to analyze aluminiun alloy and carbon steel AISI 1095. Properties of these material were carefully selected using a material reasource base software- Granta 2011©. The steady and transient thermal analysis for carbon steel AISI 1095 with maximum -temperature distribution of 96.325^{o}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 $1.7172 \times 10^{6}\ W/m\ C$ and cast aluminum alloy with maximum -temperature distribution of 96.344^{o}C ,and total heat flux $8.9827 \times 10^{6}\ W/m\ C$ on a steady analysis and maximum temperature of 114.65C and toatal heat flux of $6.793 \times 10^{6}\ W/m\ C$. Comparatively, aluminum alloy will perform better than carbon steel AISI 1095.
Keywords: Eddy heat generation, High ambient temperatures, thermal performace, aluminum alloy, Carbon Steel AISI 1905, Transformer Cascade

INTRODUCTION

Enhancement of transformer cooling encourage longevity, performance (e.g., increase in load limit) reliability, and, safety concerns. The formation of hotspots generated as a result of local heating of the coil due to eddy voltage in the power transformers is one of the major threats for the life of the transformer. Therefore, the hot spot temperature value is determining parameter governing the life expectancy of a power transformer. Power transformers are the most vital and costly investment in a power system. 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. Among these consequences, insulation deterioration is economically important. Insulation being very costly, its deterioration is undesirable as it is the main factor of transformer aging.

Fig-1: Cascaded transformer

With temperature and time, the cellulose insulation undergoes a depolymerization process. As the cellulose chain gets shorter, the mechanical property of paper such as tensile strength and elasticity degrades. 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. Hence, sustained efforts have been made to monitor the hot spot temperature to take advantage of cool ambient temperature, extend the transformer life while providing emergency overloading capabilities and taking advantage of market opportunities. It is also recognized that a sudden increase in load current may cause an unexpected high peak in the winding hot-spot temperature and hence the above method of estimation is inadequate. Also, these approaches do not take in to account, the winding eddy losses and stray loss in other structured parts of transformer. As a result, the direct measurement of winding temperature using fiber optic probes is always found to be greater than the estimated values. Attempts have been made by several researchers to estimate the hot spot temperature accurately [3-6]. The stray loss evaluation is an essential aspect to calculate hot spot temperature. The stray losses in transformer is caused by the time variable leakage flux which induces emf & circulates eddy currents in the winding conductors and in the other conducting parts of transformer like tank wall, core, clamps etc [7-9]. Evaluation of stray losses can be done more accurately by FEM. Hot spot temperature estimation for a dry type transformer [6] and for a ONAN power transformer [10], is also done in by a similar approach by thermal electrical analogy explained in IEC loading guides. This paper presents a new approach to calculate the hot spot temperature taking in to account the losses distributed across the transformer geometry.

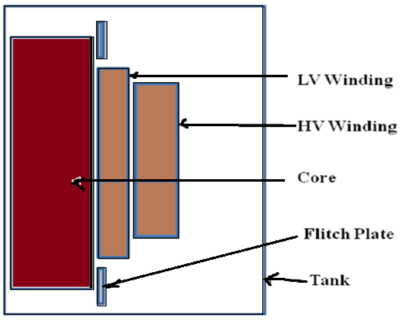


Fig-2: dimensional transformer cross section showing essential parts

DESIGN METHODOLOGY ANALYSIS

The model for the analysis is designed with a CAE software tool – Solid Works 2013©) .the two material properties are built in the models differently and subjected to the same boundary conditions using Ansys workbench for the analysis. Each material properties used in this work is not based on previous researches rather properties are culled from material based software –Granta 2011©. Thermanalysis conducted comprises steady and transient analyses for both aluminum alloy model and carbon steel AISI 1095 model.

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.

$P_{core} = af^c B_m^d$ (1)

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-

$B_m = \frac{E}{4A_c N_1 f 10^{-8}}$ (2)

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).

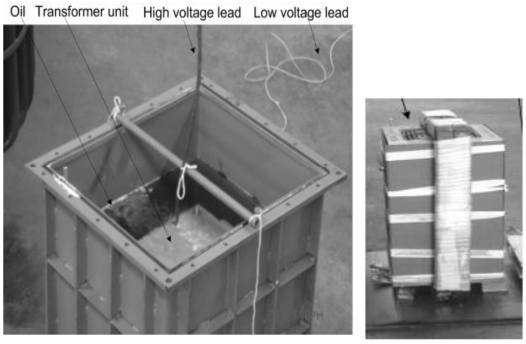


Fig-3: pictorial view of an oil filled cascaded transformer

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

$Q = mC_p \Delta T$ (3)

Volume per disc winding:
$V_i = \pi(R_2^2 - R_1^2)H$ (4)

Volume of total disc winding:
$V_T = N\pi(R_2^2 - R_1^2)H$ (5)

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

The thermal model of the transformer is formed from the equivalent electrical circuit simulating the thermal behavior of each element. Electrical equivalents are built for each element and they are used to develop the thermal model using thermal electrical analogy [2, 3].

A thermal process is defined by energy balance equation

$q = C_{th} \times \frac{d\theta}{dt} + \frac{\theta - \theta_{amb}}{R_{th}}$ (6)

where,
q is the heat generation,
Cth is the thermal capacitance,
θ is temperature,
Rth is the thermal resistance,
θ_{amb} is the ambient temperature.

A simple electrical RC circuit yields a similar equation based on Kirchoff's law,

$q = C_{el} \times \frac{du}{dt} + \frac{u}{R_{el}}$ (7)

where
i is the electrical current,
C_{el} is the electrical capacitance,
R_{el} is the electrical resistance,
u is the electrical voltage

The loss in the winding, copper loss given by I2R is calculated using the value of current and resistance in each section. The loss in the core is calculated using the formulae-

$P = K_h f B^{1.6} + K_e (sfB)^2$ (8)
is the core loss
Ke and Kh are material constants
f is the frequency of the alternating flux,
B is the maximum value of operating flux density,
s is the space factor

The heat dissipation by elements is represented by connecting resistors horizontally and vertically. Capacitors represent the storage of heat. The values of resistances and capacitances are calculated using the following formulae

$R_{th} = {}^{\Delta\theta_{Oil-rated}}/_{q}$ (9)
R_{th} *is* Thermal resistance
$\Delta\theta_{Oil-rated}$ *is* The rated top of oil temperature

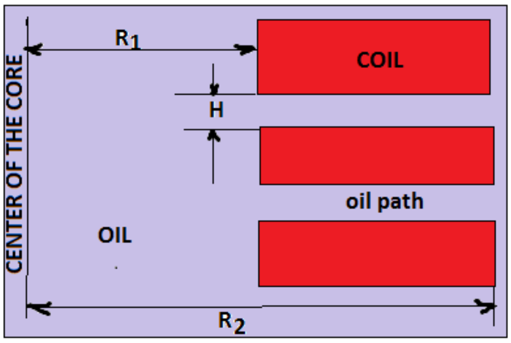


Fig-4: A Schematic Diagram of Disc Windings in Oil Data Calculation

SIMULATION

Material

Material needed for this analysis are shown with their thermal properties

Table 1: Thermal Properties Aluminums Alloy(Cast Aluminum Alloy)

s/n	property	unit	value
1	Maximum service temperature	^{0}C	220
2	Thermal conductivity	$W/m\,0C$	80-160
3	Specific heat capacity	$J/Kg\,0C$	900-995
4	Initial temperature	^{0}C	34
5	Final temperature	^{0}C	89

Granta CES edu pack (2011)

Table 2: 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

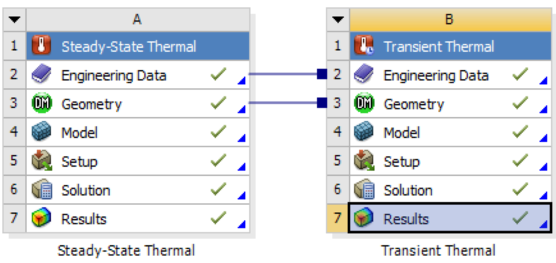


Fig-5: Analysis tree

Model

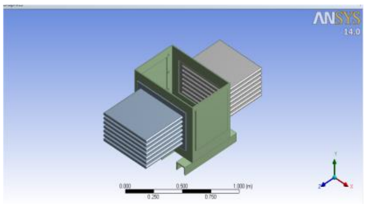


Fig-6: 3-D Model of a Cascade

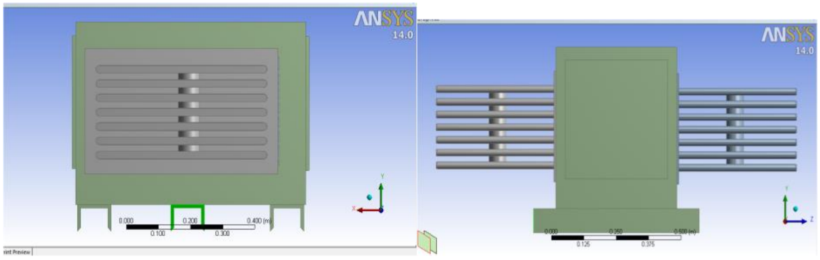


Fig-7: Side Views of the Cascade

Table 3: Mesh Details

Statistics			
Nodes	35002	34998	14400
Elements	18647	18659	7176
Mesh Metric	None		

RESULTS

Results of Aluminum Alloy

A. Steady State

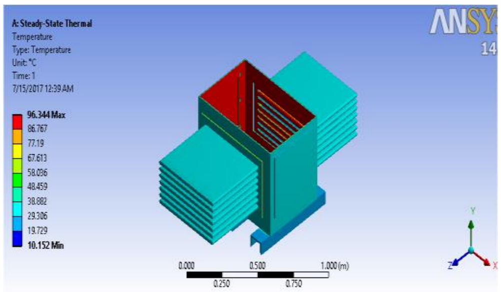


Fig-8: Temperature Distribution

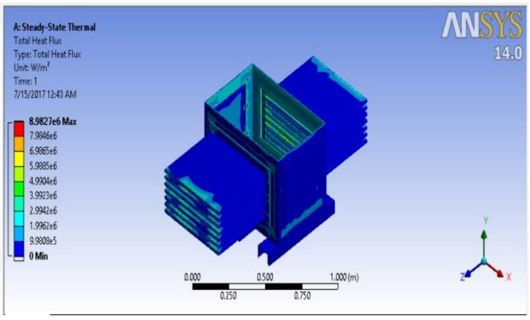


Fig-9: Heat flux distribution

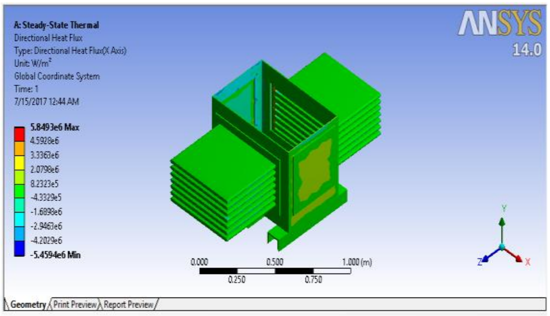


Fig-10: Directional heat distribution

B. Transient Analysis

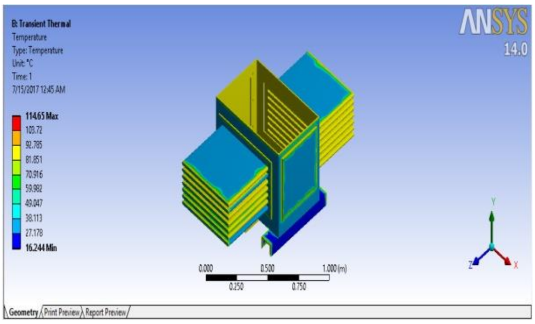


Fig-11: Temperature distribution

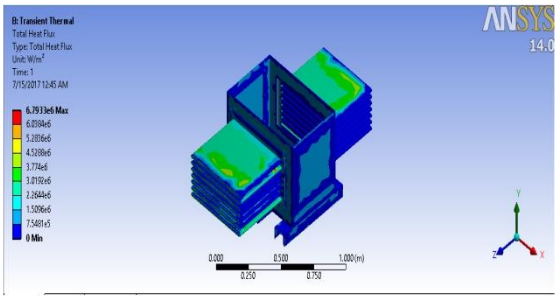


Fig-12: Total heat flux

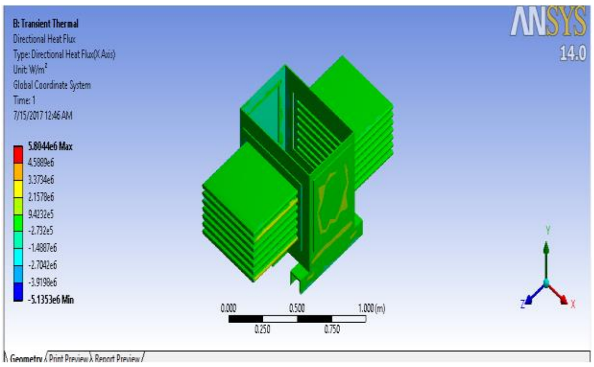


Fig-13: Directional heat flux

Results of Carbon Steel Aisi 1095

I. Steady State Analysis

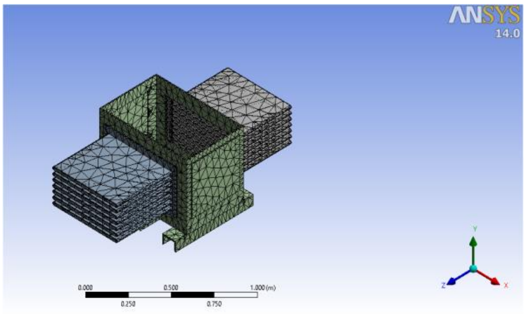


Fig-14: 3-D Mesh Form of the Cascade Model

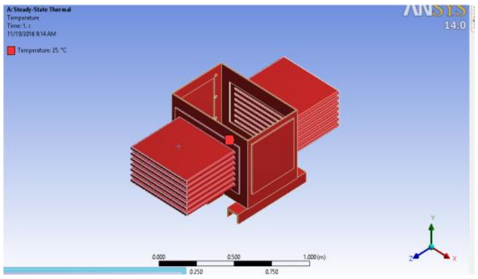


Fig-15: Temperature load on the model

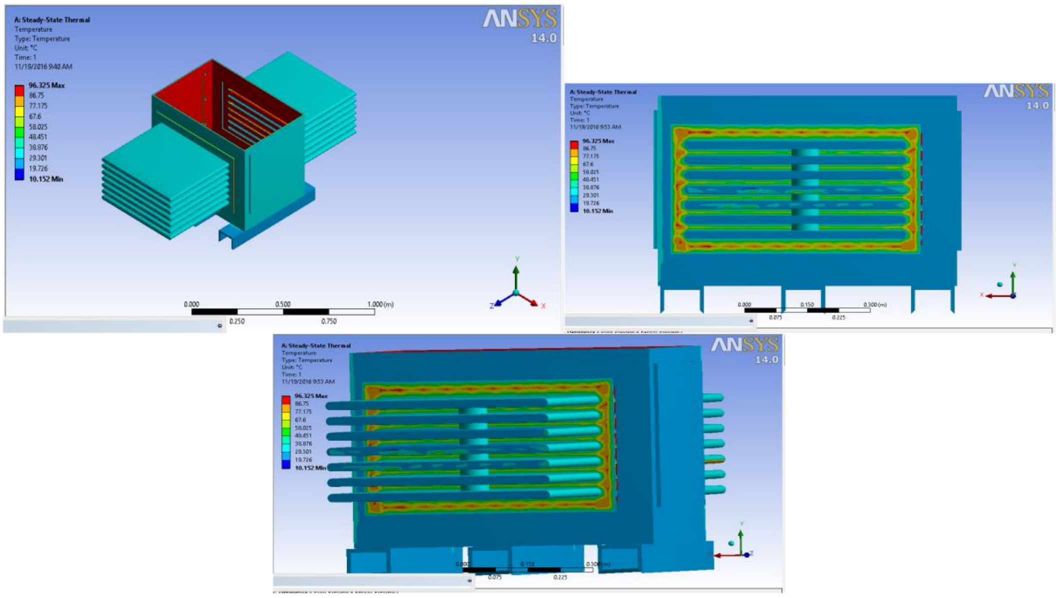


Fig-16: Temperature distribution in the model

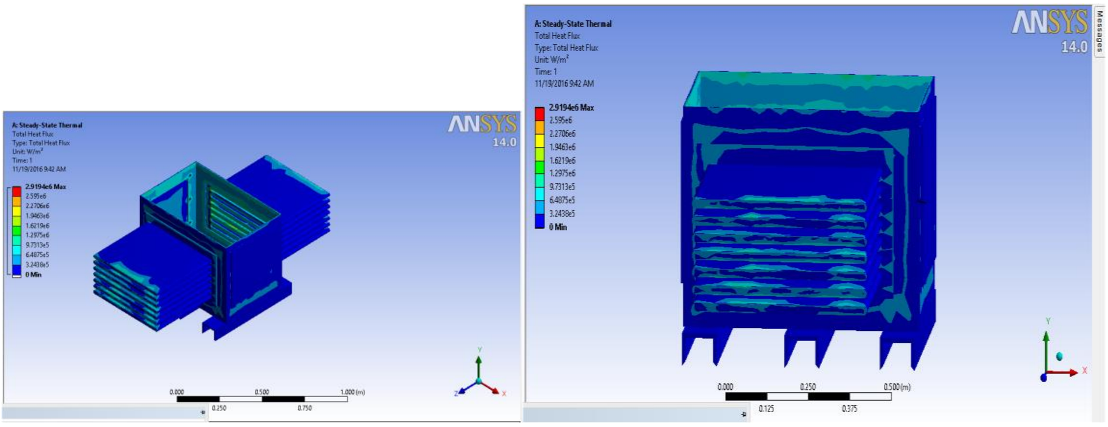


Fig-17: Total heat flux distribution

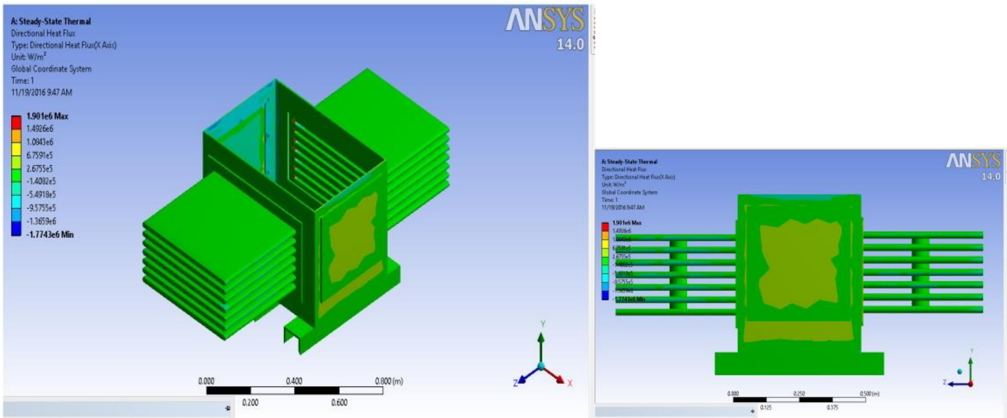
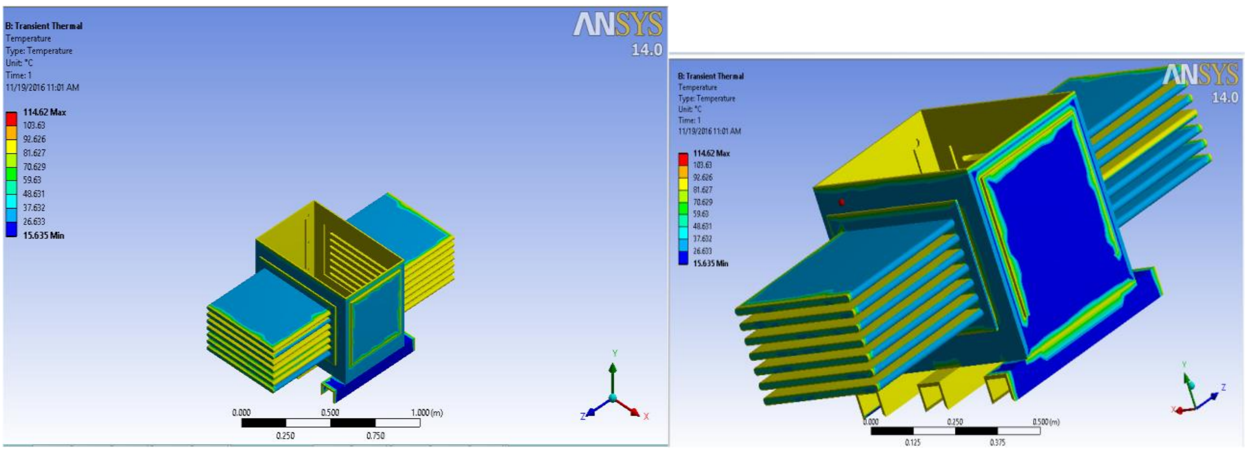


Fig-18: Directional heat flux distribution

II.Transient Thermal Analysis

The same boundary conditions were used.



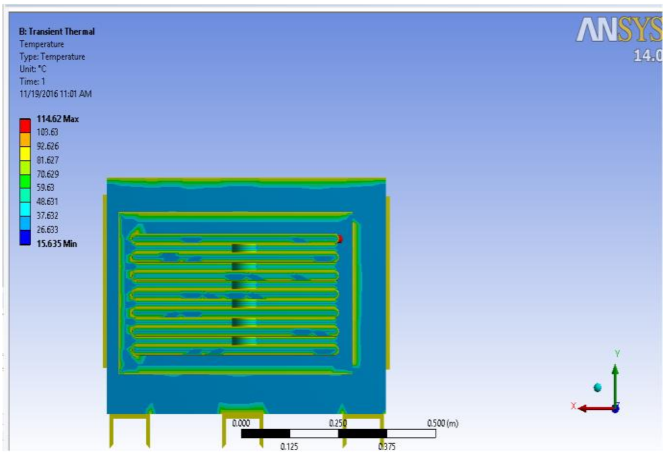


Fig-19: 3-D view of Temperature distribution in the cascade

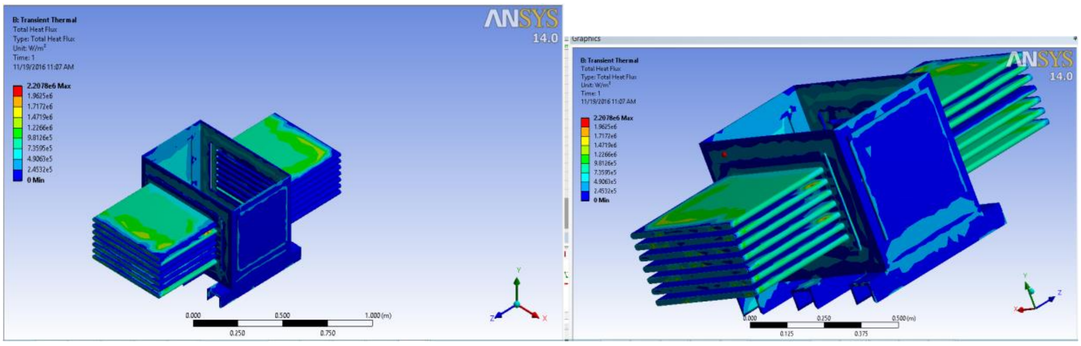


Fig-20: Total heat flux distribution in the cascade showing heat desipation

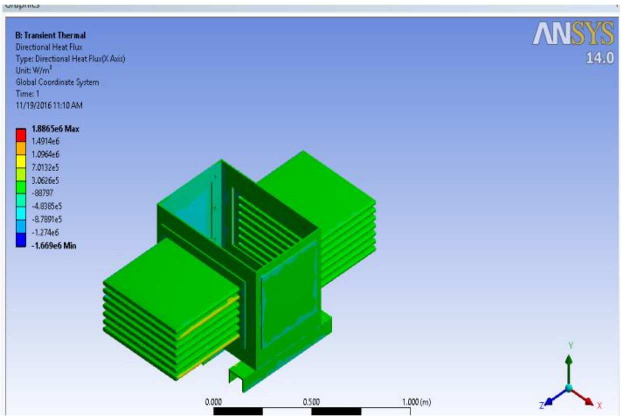


Fig-21: Direction a heat flux distribution

Graphical Representation in Aluminum Alloy Transient Thermal Analysis

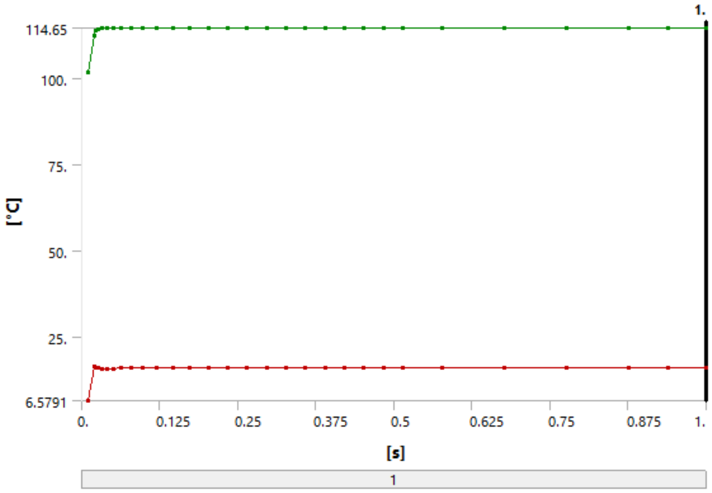


Fig-22: Temperature Distribution

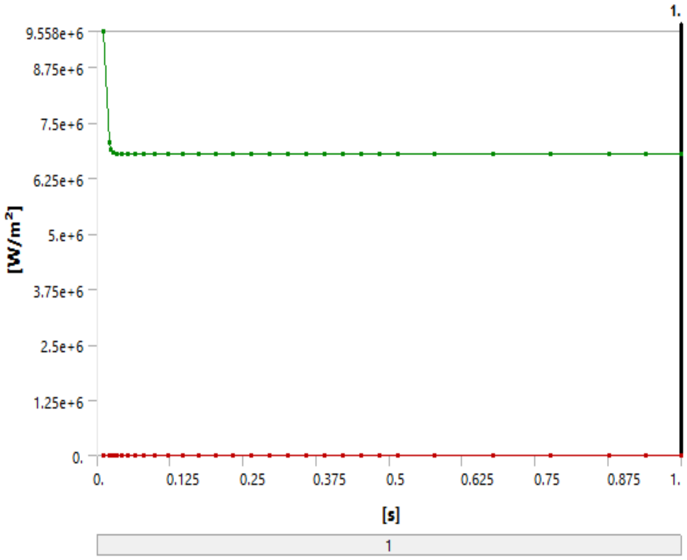


Fig-23: Total heat flux

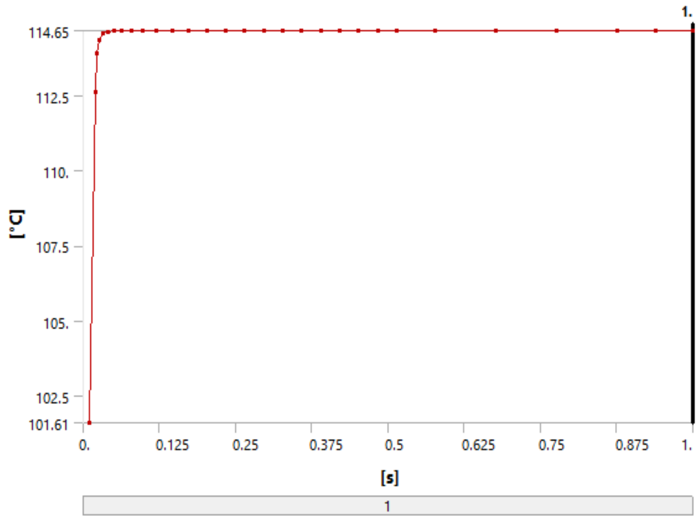


Fig-24: Temperature global maximum

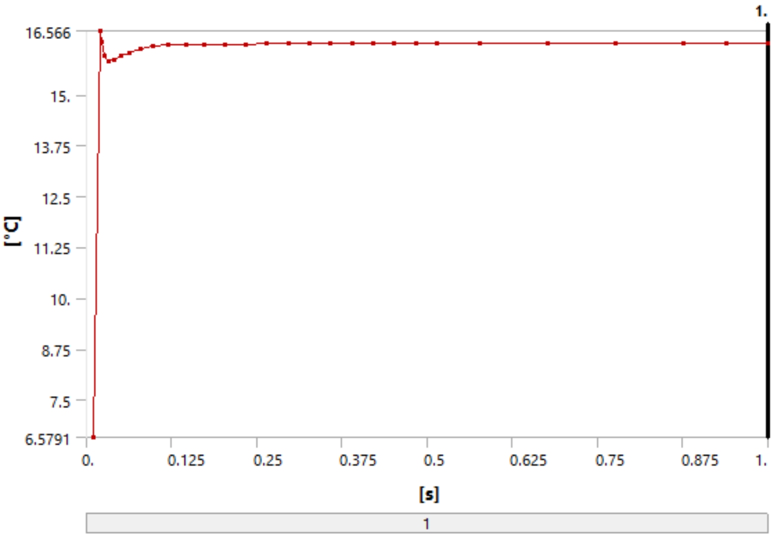


Fig-25: Temperature global minimum

Graphical Results of Transient Carbon Steel Aisi 1095

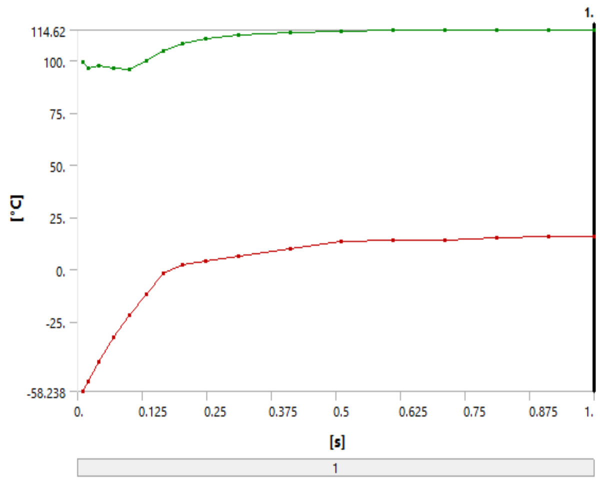


Fig-26: Minimum and maximum temperature distribution in the cascade

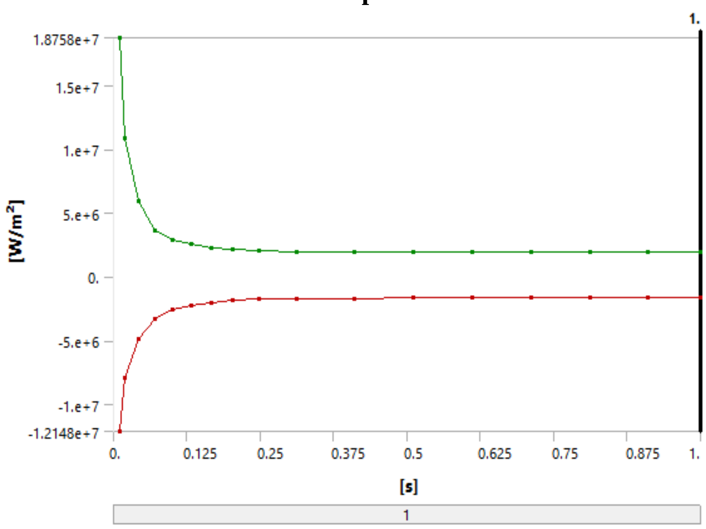


Fig-27: Directional Heat Flux Distribution as a Function of Minimum and Maximum Temperature

OBSERVATION

Having seen the results generated from the simulation, aluminum alloy will perform better than the steel material owing to its high thermal conductivity and thermal diffusivity. Besides lesser weight and its high resistance to corrosion ,as an alloy it has structural stability for absorbing thermal stress and the cooling process of the transformer can be affected by - 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. This paper work x-rayed the effect material selection on heat conduction and dissipation as a principal means through which great deal of heat generated by the windings transmitted by the oil is expelled to the environment. The cost of surface treatment and maintenance if carbon steel AISI 1095 is used is enormous .Such protective coating may affect heat dissipation. The result generated using Ansys workbench reveals a steady and transient thermal analysis for carbon steel AISI 1095 with maximum -temperature distribution of 96.325^{o}C ,and total heat flux $1.9463 \times 10^{6}\, W/m\, C$ on a steady analysis and maximum temperature of 114.62C and total heat flux of $1.7172 \times 10^{6}\, W/m\, C$ and cast aluminum alloy with maximum -temperature distribution of 96.344^{o}C ,and total heat flux $8.9827 \times 10^{6}\, W/m\, C$ on a steady analysis and maximum temperature of 114.65C and toatal heat flux of $6.793 \times 10^{6}\, W/m\, C$. Comparatively, aluminum alloy will perform better than carbon steel AISI 1095.

CONCLUSION AND RECOMMENDATIONS

The thermal analysis done in this paper shows that material selection is a factor that can be considered in building a cascade of a power transformer but the structural benefit of the mild steel cannot be undermined and selecting aluminum alloy is good approach to solving problem of thermal and structural performance. This present surge in the world temperature needs a thermally efficient material that can improve heat dissipation. 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 which are the most valuable properties on which choosing aluminum alloy is based.

FUTURE WORK

Future research work should be based on effect of surface coating on mild steel cascade, the investigation of the flow rate of the transformer, material thickness of the cascade , heat effect on the insulation paper, effect of transformer oil type on cooling ,effect of different coiling modes ,and use of other oil and nano fluids as transformer oil .

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