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Performance Analysis and Optimisation of an Oil Natural Air Natural Power Transformer Radiator

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Abstract

In Power transformers are inevitable components in alternating current generation, transmission, distribution and utilization systems. Lifespan and performance of power transformer are dependent on cooling system employed for dissipation of heat generated during its operation. In this paper numerical simulation of an oil natural air natural power transformer radiator was performed to determine its cooling capacity. In addition, optimum spacing between sections and optimum length of sections of radiator were also determined. An optimised radiator design was proposed and was simulated to determine its cooling capacity. The proposed radiator design was found to 14% more efficient than existing design in terms of cooling capacity for same material cost. The control volume method has been used to resolve the continuity, the momentum and the energy equations in steady state.

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Keywords: Power transformer; radiator; oil natural air natural; cooling capacity.

1. Introduction

Power transformer is a stationary electric device that employs Faraday's laws of induction to transform electrical energy from one circuit to another without changing the frequency of AC.

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AC is generated at low voltage level and transmission of large amount of power to load centres incurs huge power loss (I^2R loss) in transmission lines. Also cross sectional area of transmission lines should be large to accommodate high current and this increases cost involved many folds to transmit a given amount of power. High voltage power transmission is the solution to avoid power loss and to reduce cost involved in transmission. Power transformers are used at power generating stations to step up AC voltage before transmission and at load centres to step down its voltage to safe and suitable value.

Transformers are associated with primary copper loss, secondary copper loss, iron loss, dielectric loss and stray loss. These losses are proportional to size and weight of transformer and therefore are large for power transformers. Losses are transformed into heat which rise winding temperature and hot spot temperature within transformer. The hot spot temperature and winding temperature should be within prescribed limits so as to ensure life and reliability of transformer. In power transformers, the cooling is provided by circulation of oil between heated parts and radiators outside transformer tank. The simplest power transformer cooling system is oil natural air natural. In this method, heat generated within transformer core and winding is transformed to oil. The oil flows from transformer to radiator and back to transformer due to thermo-syphon effect. The heat from the oil will be dissipated in atmosphere due to natural convection of air around the radiator.

In literature, limited works related to transformer radiator cooling performance are available. In preceding works the focus was on thermal modelling of transformer and prediction of hot spot and top oil temperature.

Amoiralis et al. [1] numerically studied optimum design of ONAN transformer cooling system. They applied MNLP and BB technique to overall design optimization. Cha et al. [2] numerically simulated improvements in heat transfer in power transformer by varying difference in elevation between the center of the coils and center of radiators. Stefan et al. [3] performed dimensional optimization of frontal radiators of 630 kVA 20/0.4kV power transformer. Fdhila et al. [4] developed a model to study the effect of radiator design parameters like fan position, fan size and oil flow rate on the cooling capacity of radiators. They choose porous medium approach to model the radiators on a fine numerical grid, coupled with a turbulent heat transfer model on a much coarser grid for the heat and mass transport in the air surrounding the radiators. Sefidgaran et al. [5] developed a reliability model of power transformer with ONAF cooling. Kim et al. [6] predicted and evaluated the cooling performance of radiators used in oil-filled power transformer applications with non-direct and direct-oil-forced flow. They found the temperature difference between the top and bottom oil of radiator decreased according to increase in flow rate, cooling capacity increased at high flow rates due to its high volume flow rate. Paramane et al. [7] studied thermal performance of radiators in a power transformer in two parts: effect of blowing direction and offset of fans. Their studies showed that horizontal blowing to be more efficient than vertical blowing configuration, as the sideways leakage of air was less for horizontal. Also a small offset of 50 mm at top and bottom fan increased heat transfer by 3%.

The objective of the paper is to numerically determine cooling capacity of an ONAN power transfer radiator and to optimise it.

Nomenclature

u, v, w	Velocity components in x, y, and z directions
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
K	Thermal conductivity (W/mK)

2. Problem Description

Power transformers are equipped with detachable radiators, in order to provide the necessary cooling surface. Radiators are steel plate heat exchangers that are installed vertically next to transformers. As shown in Fig. 1, a typical radiator consists of top header pipe, bottom header pipe and sections. Two identical steel plates are pressed and welded to each other to form a radiator section. And each section consists of seven channels for oil passage. Each channel is equipped with two internal throughout wings to increase the heat transfer rate from section. At the upper and lower parts of radiator section, semi-circular channels are provided for oil flow entry and exit. Oil from transformer flows to the top header and it directs the oil to semi-circular channels. These channels direct the oil into the provided ways inside the section. Finally, oil is collected in lower semi-circular channel and flows back to the transformer. The radiator analyzed consists of 20 sections, each with a width of 520 mm and length of 1500 mm and placed at a spacing of 45 mm. In the current study, radiator is considered as a separate element with oil flow from top to bottom and outer surfaces with constant convective heat transfer coefficient. The oil flow rate is normally in the range of $1x10^{-3}$ m^3/s to $2x10^{-3}$ m^3/s. [6]

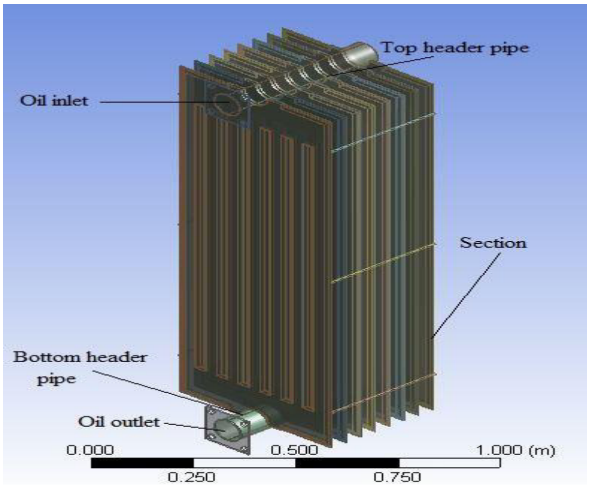

Fig. 1. A Typical ONAN radiator.

2.1 Determination of Cooling Capacity of Existing ONAN Radiator

The performance of radiator was analyzed in two stages, so as to simply the simulation. In first stage, the flow through top header pipe was simulated and the outlet velocities at the exits were determined. Fig. 2 modelled top header pipe.

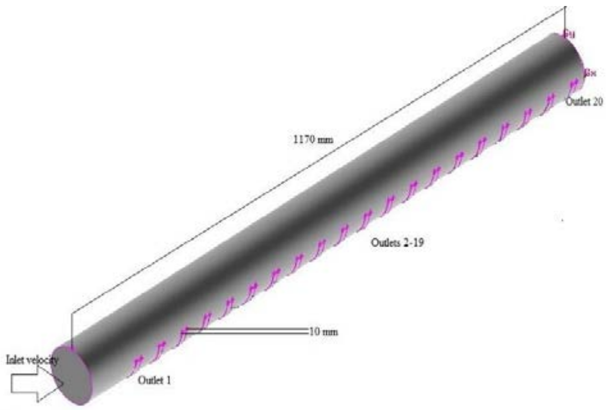

Fig. 2 Top header pipe.

In second stage, the outlet velocities obtained in first stage were used as inlet velocities to the sections and each section was simulated separately. The oil outlet temperature at all sections was determined and cooling capacity corresponding to each section was calculated. The cooling capacity of radiator is the sum of cooling capacities of all 20 sections. Fig.3 shows modelled radiator section.

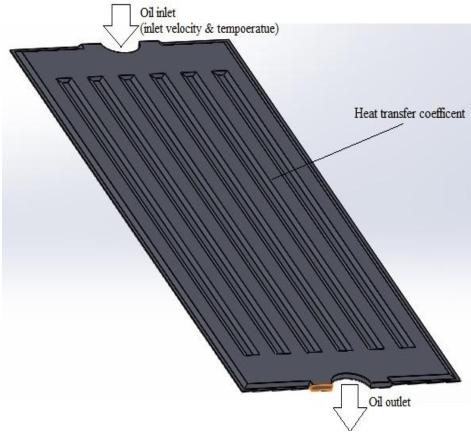

Fig. 3. Radiator section.

2.2 Determination of Optimum Spacing Between Sections

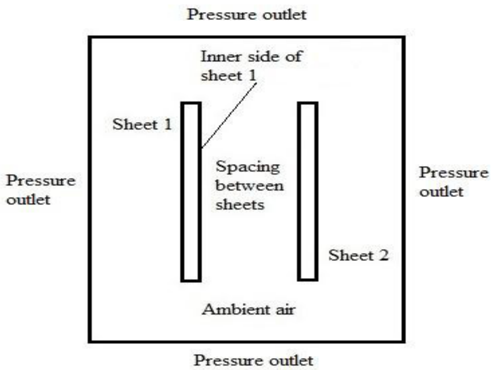

Fig. 4 2D model of two sheets.

The optimum spacing between sections of radiator was determined by simulating 2d models of two steel sheets of length 1500 mm and thickness 1.2 mm placed vertically in ambient air with constant source of energy per unit volume (equivalent to cooling capacities of two sections) subjected to each sheet for spacing of 10 mm 20 mm 30 mm 40 mm and 50 mm between them. The variation of total heat transfer coefficient taking in account of convection & radiation effect on inner side of a sheet with spacing was studied. Fig. 4, shows 2D model of two sheets with computational domain.

2.3 Determination of Optimum Length of Section

The optimum length of sections of radiator was determined by simulating a 2d model of two steel sheets of length 1500 mm and thickness 1.2 mm placed vertically and at a spacing of 25 mm between them in ambient air with constant source of energy per unit volume (equivalent to its cooling capacities two sections) subjected to each sheet. The sheets were divided into 10 equal segments, each of 150 mm. The variation of total heat transfer coefficient taking in account of convection & radiation effect on inner side of a sheet along its length was studied. Fig. 5, shows 2D model of two sheets with 10 equal segments and computational domain.

The models were developed and meshed using gambit 2.4.6. The grid independent models were simulated fluent 6.3.26.

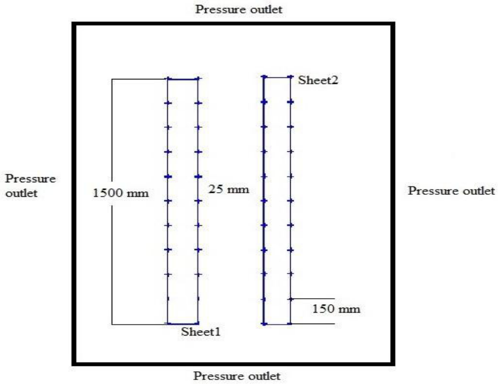

Fig. 5. 2D model of two sheets with ten equal segments on each.

2.4 Assumptions

- Steady state.
- The oil flow is 3D, incompressible.
- Wall of the top header pipe are approximated as adiabatic.
- Boussinesq approximation was used to determine optimum spacing and length.

2.5 Boundary Conditions

Boundary conditions play a crucial role in CFD simulations. In the present study oil inlet mass flow rate to the top header pipe was assumed as $1.8*10^{-3}$ m^3/s and oil inlet velocity to sections were obtained from header pipe simulation. The inlet oil temperature to sections was taken as 348 K and ambient air temperature as 300 K. The constant convective heat transfer coefficient on the walls of section is found to be 8.065 W/m^2K for existing design and 7.37 W/m^2K for proposed design.

Residuals of continuity, momentum and discrete ordinate intensity were set at 10^{-6} and that of energy was set at 10^{-12}. Iterations were carried out till solution converged. Iterations were carried out till solution converged.

2.6 Governing Equations

The governing equations can be written as

Continuity equation:

$$divV = 0 \tag{1}$$

Momentum equation

In X-direction:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -1/\rho\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

In Y-direction:

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -1/\rho\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

In Z-direction:

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -1/\rho\frac{\partial p}{\partial z} + \nu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

Energy equation

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \frac{k}{\rho\, Cp}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Se \tag{5}$$

3. Results And Discussion

Fig. 6 (a), the velocity vector in mid plane of section indicates that the oil flow through the section is not uniform. The oil velocities are maximum at middle three channels and minimum at other four channels. This means that most of oil flow through these three middle channels. As a result other four channels of the section are not effectively used in heat dissipation and this lowers their contribution. A wider oil inlet could improve the section heat dissipation capacity.

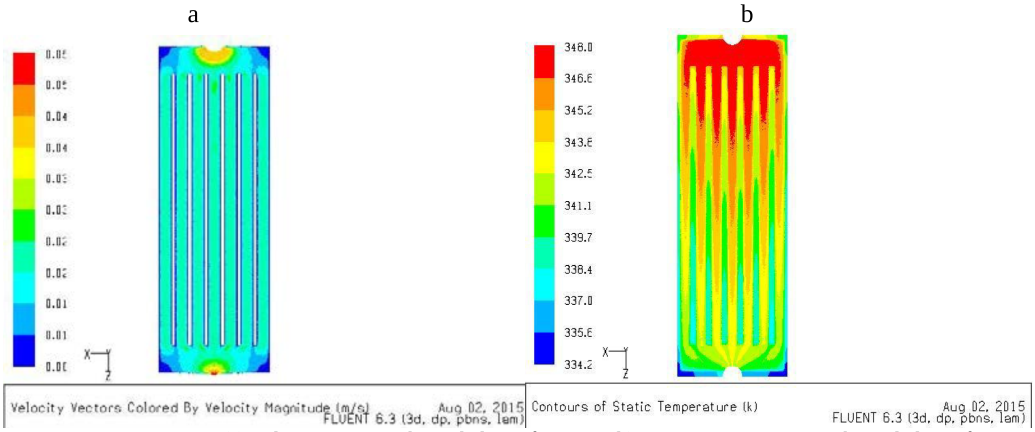

Fig. 6. (a) Velocity vector in the mid plane of section; (b) Temperature contour in the mid plane of section.

Fig. 6(b), the temperature contour in mid plane of section indicates that the warmer oil flows through three middle channels, whereas in the other four channels temperature is lower. The uneven oil temperature distribution in the section is due to non-uniform mass flow rate. The cooling capacity of section is not completely utilised as the contribution of other four channels in heat dissipation is less.

Fig.7 shows the cooling capacity of 20 sections of the existing radiator design. The inlet velocity to the 20th section is nearly 38% lower than the first section. As a result of low velocity oil gets longer residence time inside the section, which in turn leads to lower outlet temperature. This compensates the low inlet velocity to section and decrease in cooling capacity of 20th section is only by 13%. Thus the 20 numbers of sections in existing radiator design is justifiable and further increase in number of sections is also advisable.

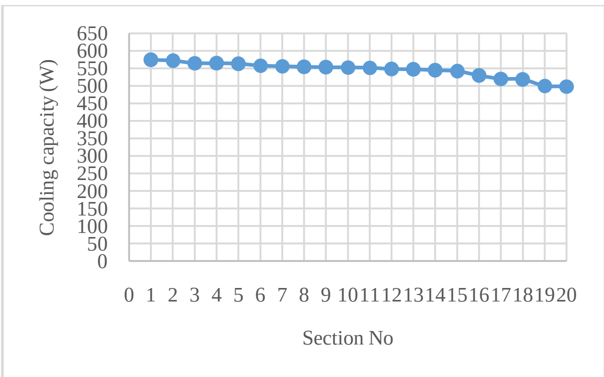

Fig. 7. Cooling capacity of various sections of existing radiator.

Fig. 8 shows the variation of total heat transfer coefficient with section spacing. The total heat transfer coefficient is found to be a maximum for section spacing of 25 mm and there after it decreases. Therefore the optimum spacing between sections of a radiator block is 25 mm.

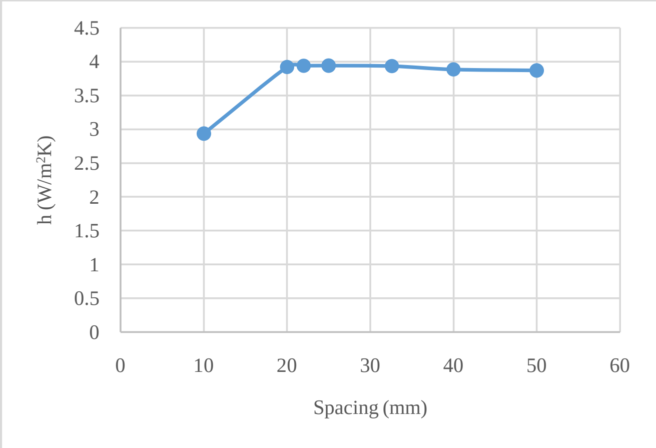

Fig. 8. Total heat transfer coefficient on the inner side of sheet1 Vs spacing

From fig.9, it's evident that cooling capacity decreases away from the leading edge of sheet. Reduction in cooling capacity till the length of 750 mm is only 7% whereas reduction in cooling capacity is 15% after length of 750 mm. Thus the first 750 mm of the sheet length contribute maximum in heat dissipation. Thus in the first 750 mm of the sheet length contribute maximum in heat dissipation.

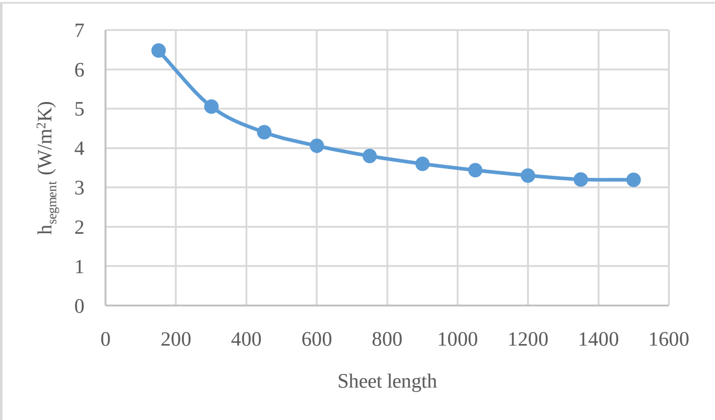

Fig. 9. Total heat transfer coefficient on the inner side of sheet1 Vs its length

A radiator design was proposed and its cooling capacity was determined. Its specifications are shown in Table I.

Table 1. Proposed Radiator Specifications

Specifications	Proposed Design
Length of section	750 mm
Width of section	520 mm
No of section	40
Thickness of sheet	1.2 mm
Spacing between sections	25 mm

Fig. 10 shows the cooling capacity of sections of proposed radiator. The cooling capacity doesn't decrease much for 40 sections as compared to first. Therefore the proposed design is also justifiable.

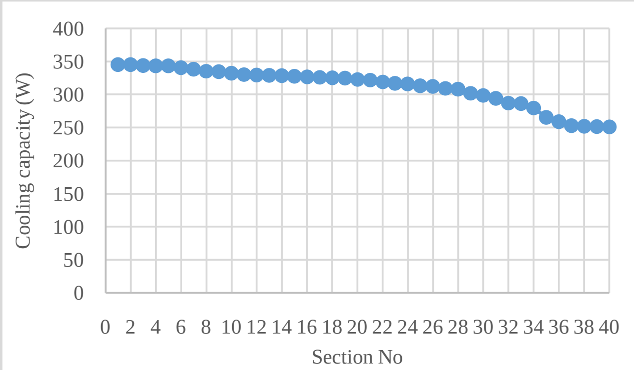

Fig. 10. Cooling capacity computed for different sections.

5. Conclusions

The cooling capacity of existing ONAN radiator is found to be 10.91 kW while that of proposed radiator is found to be 12.46 k W. The proposed design is 14% efficient than existing. The optimum spacing between sections of radiator was found to be 25 mm rather than 45 mm as in existing design. The optimum length of section was found to be 750 mm whereas the length of sections in existing design is 1500 mm.

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