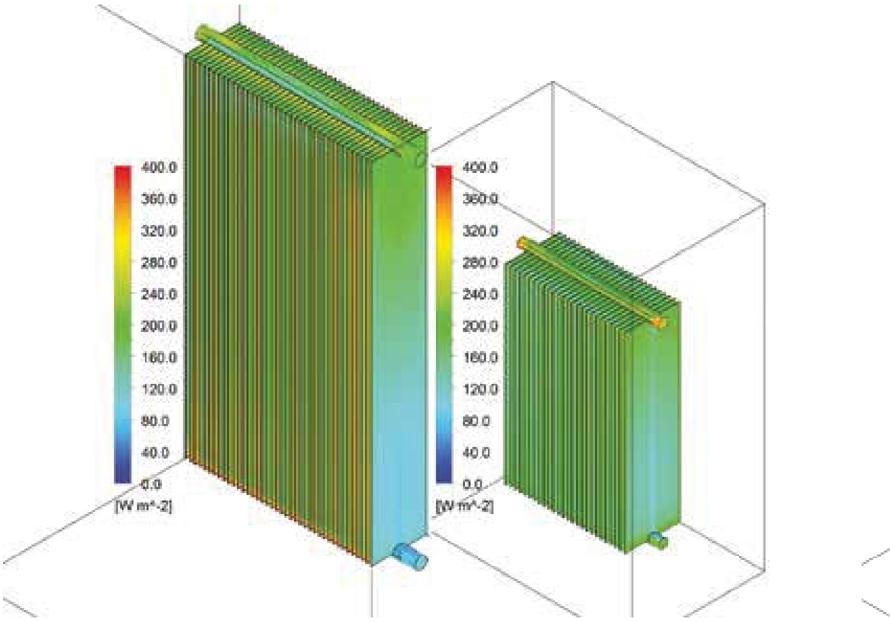
> **Radiation heat transfer is often neglected in thermal design due to its complicated nature and misperceptions about its significance**



Significance of radiation heat transfer on cooling performance of transformer radiator

Is transformer radiator a misnomer?

ABSTRACT

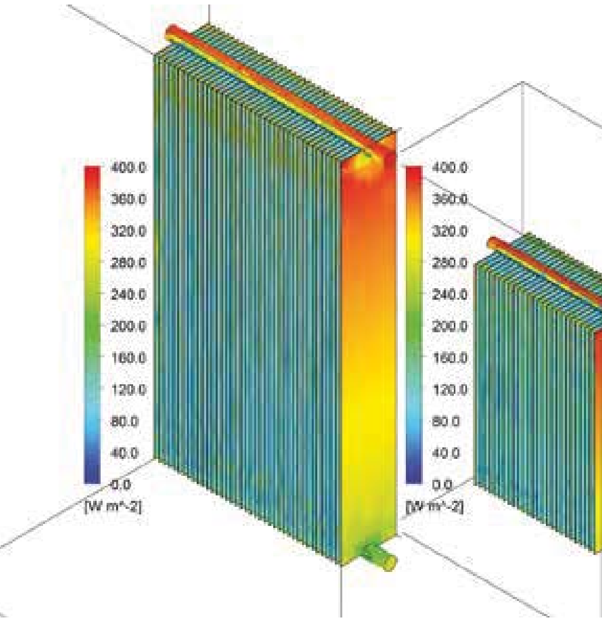
The article demonstrates significance of radiation heat transfer on cooling performance of radiators used in power transformers with air natural cooling configuration using analytical calculations and computational fluid dynamics simulations on two different case studies. Convective and radiative heat transfer mechanisms are modelled on a single radiator and a good agreement with the experimental measurement results is observed. The radiation contributes 21.3 % of total heat dissipation and thus has a significant impact on overall heat dissipation and cannot be neglected. This study will be useful – for the transformer designer – to point on the relevance of the radiative heat transfer in cooling.

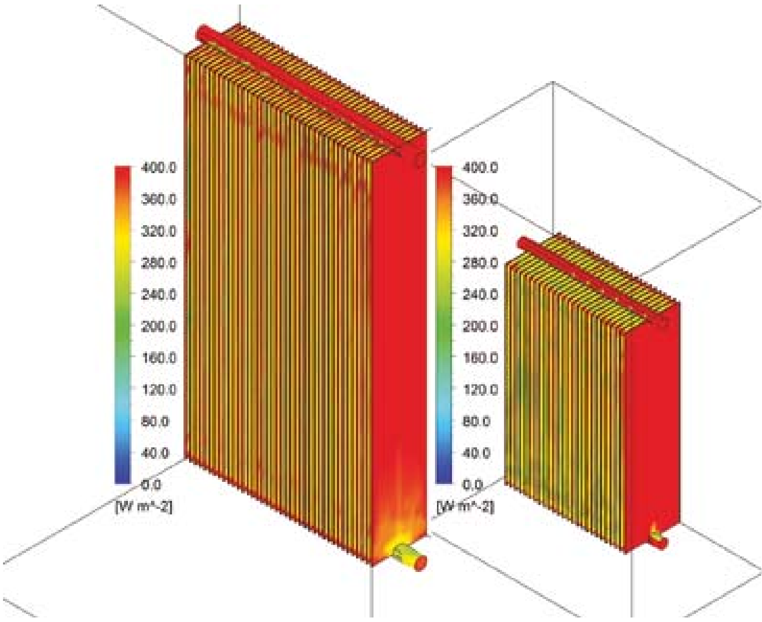
KEYWORDS

transformer, radiator, radiation, convective, heat transfer

1. Introduction

Transformers are critical components in the electrical distribution network and in order to have continual operation of the transformer, its thermal management plays an important role. The losses generated inside the transformer are dissipated to the surrounding air by heat exchangers called radiators mounted next to the transformer. The heat from winding is transferred to the dielectric medium normally used as mineral oil and then the heat from the oil is transferred to the ambient air





by convection in the oil, conduction from steel radiator fin, and, finally, convection and radiation from the fin to the air. Radiation heat transfer is often neglected in thermal design due to its complicated nature and misperceptions about its significance in cooling of transformer. In fact, radiation can be a major contributor in natural convection and low velocity applications. Thermal radiation refers to energy emitted by objects due to their temperatures. Unlike other means of heat transfer, radiation does not require a medium between cold and hot surfaces.

> **Thermal management plays an important role for continual operation of transformers**

Limited experimental and numerical work related to power transformer radiator cooling performance has been reported [1]-[6]. Cha et al. [1] described the numerical simulation for improving heat transfer in a power transformer, with the help of the thermal head (difference in elevation between the centre of the coils and the centre of the radiators). Nabati et al. [2] carried out numerical modelling of temperature distribution and flow pattern in a block radiator for ONAN (Oil Natural Air Natural) cooling without considering the effect of radiation heat transfer. They mainly focused on studying the relation between radiator block characteristics and cooling behaviour of the system. Kim et al. [3] presented numerical prediction and experimental study on the cooling performance of radiators used in oil filled power transformer applications with non-direct flow and direct-oil-forced flow. Radiator temperature distribution and cooling performance was predicted using theoretical calculations, then validated using CFD (Computational Fluid Dynamics) simulation results for convective cooling mechanism only. Chandak et al. [4] performed conjugate heat transfer simulations using CFD and the effect of radiation on oil flow distribution is studied. They observed that the end fins of radiator dissipate more heat compared to middle fins as one full face is exposed to ambient. 3-D coupled internal oil and external air flow simulations, together with a conjugate heat transfer model are used to analyse the effect of blowing direction on the thermal performance of a five radiators block by Paramane et al. [5]. Recently, semi-analytical calculations, computational fluid dynamic simulations and experimental measurements accomplished on a typical 30 MVA power transformer are reported by Rodriguez et al. [6]. From the literature survey, to the best of author's knowledge, no study is found about the effect of radiation on overall heat dissipation from the radiators of power transformer except Chandak et al. [4] and Paramane et al. [5]. However, they have not focused much on the radiation heat transfer mechanism and its overall impact on the heat dissipation of the radiator in their research. Thus, the present work is aimed at determination of radiation heat transfer analytically, as well as numerically, and on demonstration of its significance on cooling performance of the radiator of power transformer by using two case studies from the literature. The paper will focus on the significance of radiation heat transfer on overall heat dissipation from radiator and will help transformer designers to account for it during the design of cooling system.

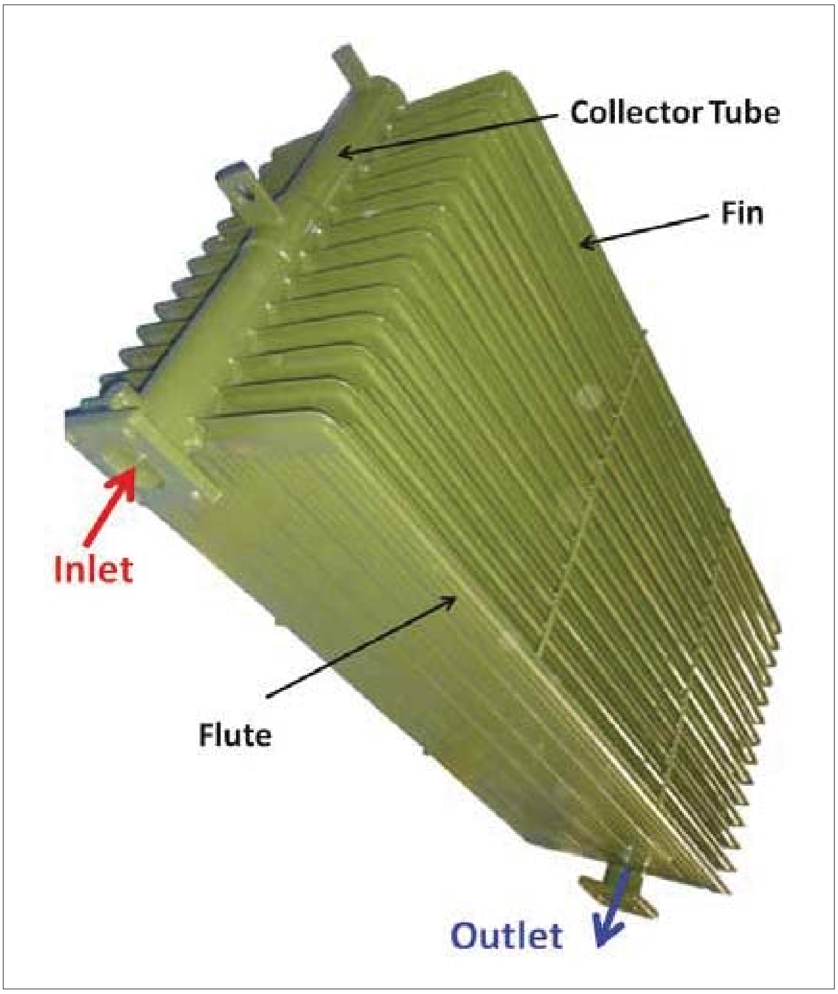


Figure 1. Radiator used in transformer

> **Radiation needs to be taken into account for ONAN cooling because it has a significant effect on the evacuated heat (up to 21.3% in this analysis)**

2. Radiator geometry

Radiators consist of a number of fins, made up of two steel plates which are pressed and welded together. A passage for oil flow is formed in the radiator by creating channels between the steel plates of the fins. Figure 1 shows an isometric view of the radiator with the horizontal flow of a hot oil inlet at the top and a cold oil at the bottom. As the oil flows through these channels vertically, heat is transferred from the oil to the steel plate and further to the air flowing between the radiator fins. Finally, the oil flowing downwards in the radiator fins exits from the outlet and enters into the bottom header pipe where it comes back to the transformer tank. The flows through the radiator can thus be described as a counter flow with oil flowing from top to bottom and air flowing from bottom to top.

3. Description of case studies

In the work presented, two case studies are evaluated for analytical and numerical simulations to determine the heat dissipation from the radiator in air natural cooling. The first case study is from [3] where they reported analytical calculations, CFD simulations and experimental measurements to determine the heat dissipation of the radiator for ONAN and ODAN (Oil Directed Air Natural) cooling configurations. Figure 2 (a) shows a radiator geometry of case study 1, consisting of 40 fins of 3.3 m height, 0.52 m width and 0.0085 m thickness; they are horizontally spaced with a gap of 45 mm. Analytical and numerical simulations are performed for inlet oil flow rates from 0.001 m^3/s to 0.004 m^3/s in the steps of 0.001 m^3/s whereas experimental measurements are carried out at 0.001 m^3/s, 0.0033 m^3/s and 0.0042 m^3/s oil flow rates. The reported deviation between analytical and CFD results is 17.8%. The major limitation of the calculations that caused this deviation is attributed to the following assumptions: that the radiator model is a vertical-flat plate, that there is a constant surface temperature and that radiation heat transfer is neglected for analytical and numerical simulations.

Figure 2(b) shows the radiator geometry of case study 2 from [6], consisting of 26 fins of 1.8 m height, 0.52 m width and 0.0085 m thickness; with a spacing of 45 mm. Authors proposed an analytical model for prediction of thermal performance of the transformer radiator and also performed CFD simulations for internal oil flow and temperature distribution of 1/4th geometry of single fin. The temperatures evaluated are used for external flow with temperature specified boundary condition only. Their simulations show that the heat dissipation determined from the CFD analysis is 35.7 % higher compared to measurement results. They also neglected radiation heat transfer in analytical and numerical calculations.

4. Numerical methodology

Commercial CFD software (Ansys CFX Version 14.5 [7]) is used in this work. The equations that govern the present problem are the steady state Navier-Stokes equations for incompressible fluid [7]. Since we are interested in a quantitative comparison between with and without radiation case scenarios, only air domain is modelled and linear temperature pro-

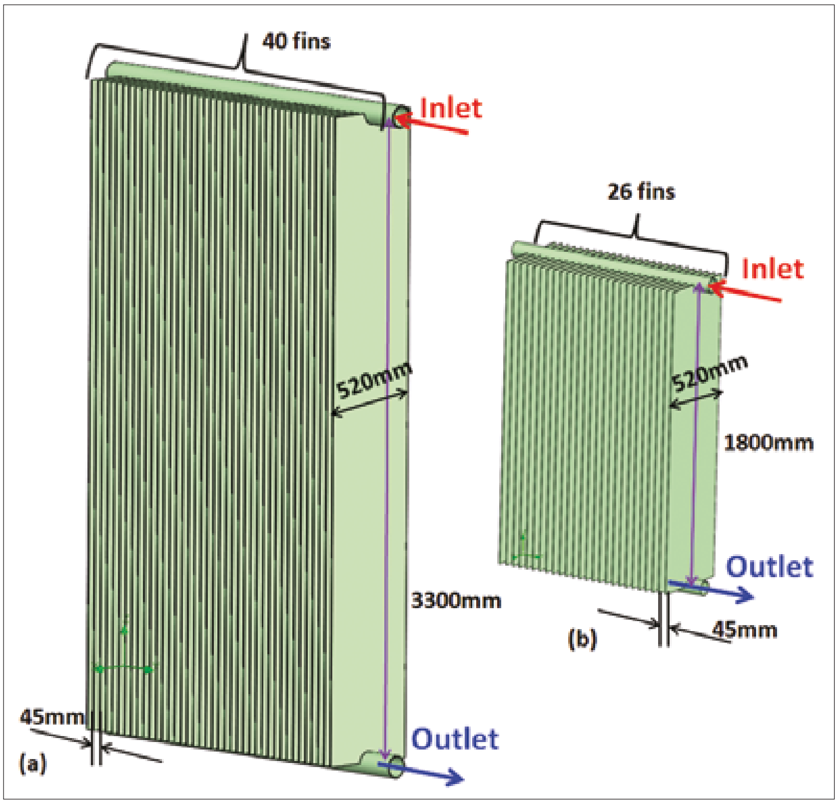


Figure 2. Geometry of radiator (a) Case 1: Radiator model from [3] and (b) Case 2: Radiator model from [6].

> **External CFD calculations can be used to study the effect of the radiation heat transfer**

file corresponding to top and bottom oil temperature is applied to the radiator surface as the thermal boundary condition. These temperature profiles are taken from the CFD analysis performed for volumetric oil flow rate of 0.001 m^3/s, 0.002 m^3/s, 0.003 m^3/s and 0.004 m^3/s for case 1 [3] and at 0.000527 m^3/s for case 2 [6]. The Discrete Transfer Model (DTM) [7] is applied to model a surface radiation heat transfer for both configurations with emissivity value of 0.95 applied on the radiator surface. The radiation is represented by particles which are tracked through the air domain using a Raytracing method [8]. After a grid independence study, a grid size of around 3.5 million and 1.2 million was found to be adequate and is used in this work. Rayleigh number calculated for air domain for the temperature corresponding to volumetric oil flow rate of 0.004 m^3/s is 1.4×10^{11} for case 1 and 0.000527 m^3/s is 1.8×10^{10} for case 2. Therefore, the flow is turbulent and Shear Stress Transport (SST) model is used here for modelling turbulence. Convergence is achieved by ensuring that root mean square (rms) residuals are below 10^{-4} and imbalance within the domain is less than 1%.

5. Results and discussion

This section presents the analytical and numerical results for convection and radiation heat transfer with air natural cooling configuration. Afterwards, these experimental and numerical results for the total heat dissipation are compared.

5.1 Analytical calculations of heat dissipation

The goal of the first part of the study is to determine the heat dissipation of the radiator with convective and radiative heat transfer using analytical calculation and evaluate the impact of the radiation on total heat dissipation from the radiator. For this purpose, analytical calculation for convective heat transfer is determined as per the method described in [4] with the ambient and average surface temperature taken from their CFD calculation for different volumetric oil flow rates. Radiative heat dissipation is determined by following equation

$$q_{rad} = \varepsilon \sigma A \left(Ts^4 - Ta^4 \right) \tag{1}$$

Where

ε is the emissivity of radiator surface, which in the present case is 0.95

σ is Stefen-Boltzmann constant, 5.67×10^{-8}, W/m^2K

A is an enveloping area (outer area) of the radiator, m^2

T_s is the average surface temperature of the radiator in K and

T_a is the ambient temperature in K

Total heat dissipation of the radiator, along with its convective and radiative heat transfer components, are plotted for various oil flow rates and shown in Figure 3.

It can be seen from the Figure 3 that for oil flow rate of 0.001 m^3/s the contribution of radiation with respect to convection is 27.7 % (5.6/20.2=27.7 %) and to total heat dissipation is 21.7 % (5.6/25.8=21.7 %). Thus, the average contribution of radiation for all flow rates is 27.6 % and 21.6 % to convection and total heat dissipation, respectively for the case 1. For the second case, radiation component calculated from analytical method is 30.7 % (2.4/7.8=30.7 %) with the respect to convection and 23.5 % (2.4/10.2=23.5 %) to total heat dissipation. Thus, both these cases show that the radiation has significant impact on the air natural cooling of the radiator and cannot be neglected. If a transformer designer designs a cooling system by neglecting radiation, he will overdesign the system thereby providing more number of radiators which will result in more weight and cost. Thus, it is necessary and worthwhile to perform more accurate numerical simulations using CFD analysis to obtain the contribution of radiation component on total heat dissipation from the radiator in air natural cooling.

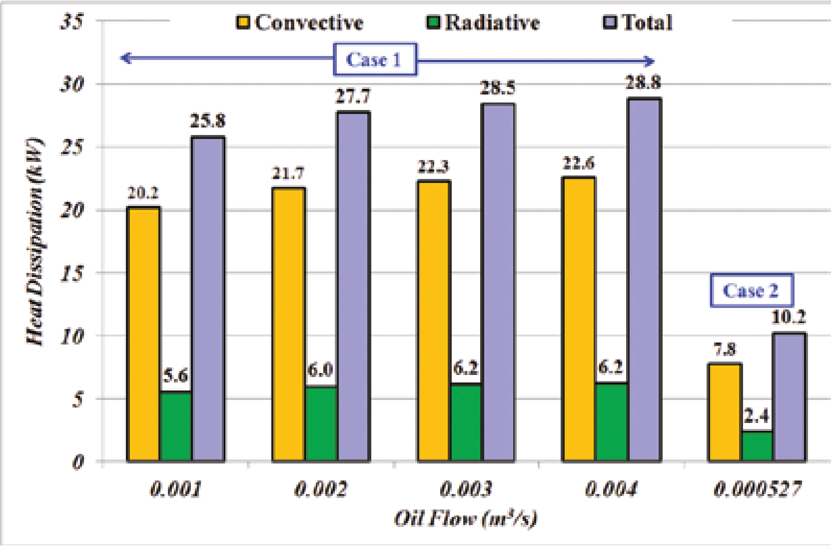


Figure 3. Analytical calculation of heat dissipation from radiator

> **If the cooling system is designed by neglecting radiation, it will be overdesigned with a greater number of radiators which will result in more weight and cost**

5.2. Numerical simulations for calculations of heat dissipation

The heat and fluid flow of a radiator configuration is a combined internal and external flow; internal oil-flow in the channels of the radiator fins and external air-flow over the configuration. In this second part, where we are interested in studying the effect of radiative heat transfer, an internal flow simulation is avoided, to reduce the computational complexity of the present problem without compromising much on the accuracy of results. This is done by approximating the linear temperature variation on the surface of the radiator corresponding to top and bottom oil.

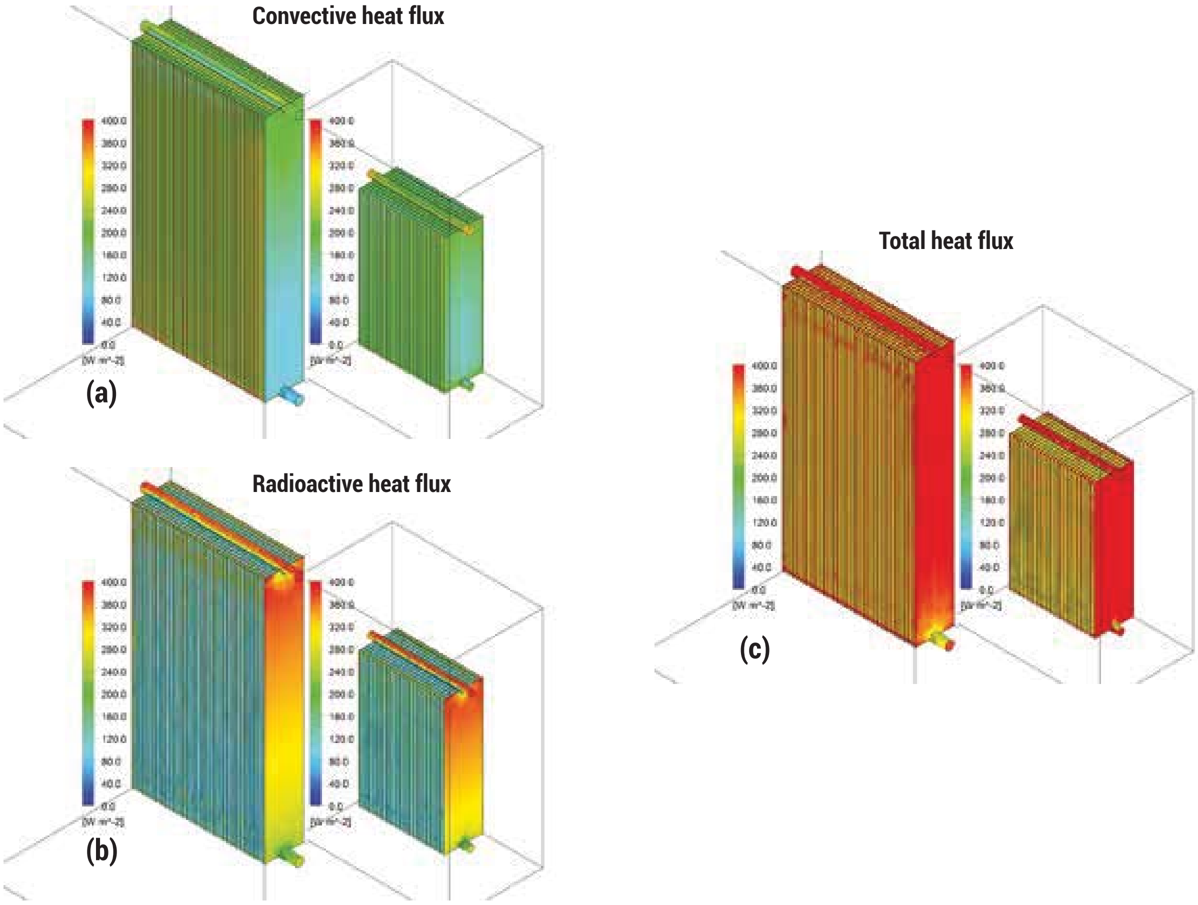


Figure 4. Heat flux distribution over the radiator surface a) Convective heat flux b) Radiative heat flux (c) Total heat flux.

> **Results of this study can be useful for designers to understand heat transfer characteristics for different transformer cooling configurations**

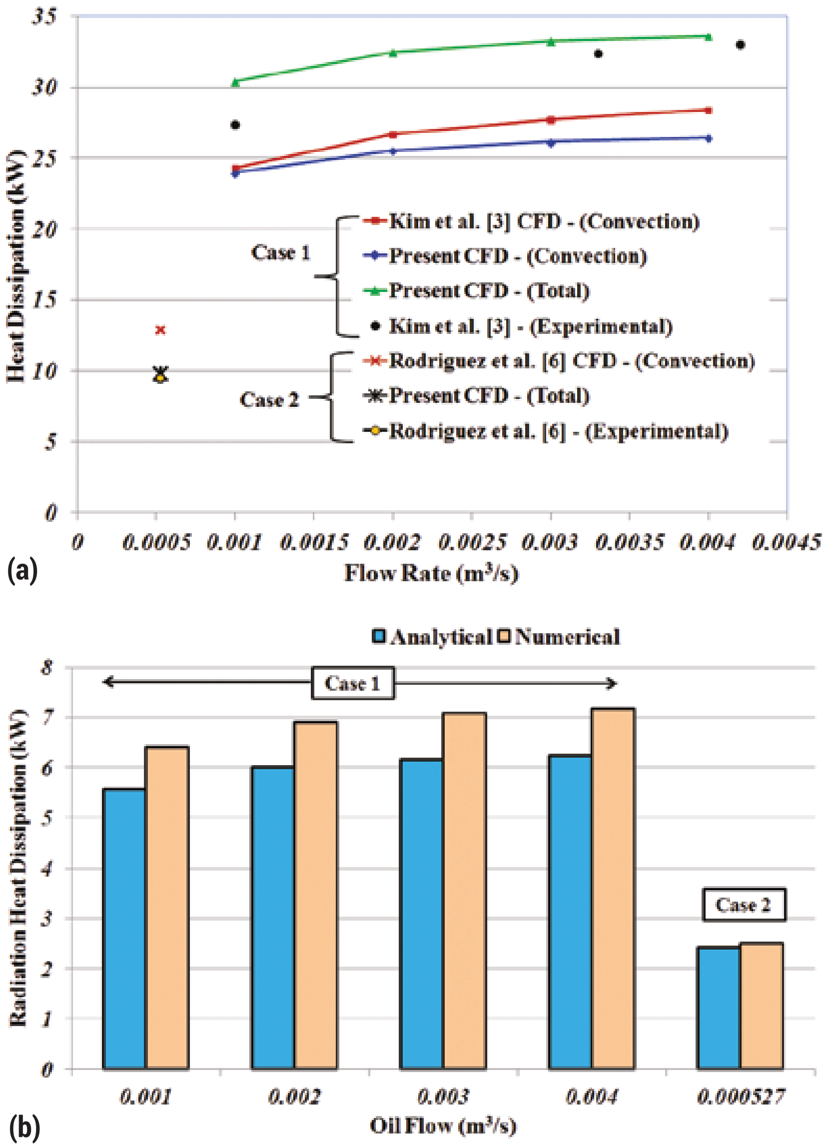


Figure 5. (a) Heat dissipation from the radiators for convective and radiative heat transfer mechanism and comparison with experimental results of [3] and [6] (b) Comparison of radiation heat dissipation using analytical and numerical results.

Figure 4(a) and (b) shows the convective and radiative heat flux distribution over the radiator, respectively for case 1 and 2.

It can be observed that convective heat flux is higher than the radiative heat flux for middle fins, but not for the end fins where the effect of radiation is pronounced. This effect is visually highlighted with red on the end fins of the radiator for radiative heat flux. This is because these fins are directly exposed to ambient air and can radiate freely to the environment (view factor = 1). Furthermore, for the end fins complete surface is available for the heat dissipation to the environment. Thus, qualitatively it shows that the radiation has an important role to play in the total heat dissipation for air natural cooling for the study carried out in the present case. Total heat flux distribution, which is addition of convective and radiative heat flux over the radiator surface, is shown for case 1 and 2 in Figure 4 (c). The red coloured region marks end fins indicating higher heat flux for these fins compared to middle fins.

5.3. Comparison of overall heat dissipation

Figure 5(a) shows the comparison of overall heat dissipation determined from numerical and experimental methods for the different cases considered. With the linear temperature profile boundary condition, Figure 5 (a) shows the convective, as well as total heat dissipation from the radiator. It shows that the present external flow simulation results with the temperature profile boundary condition matches well with internal and external flow simulation for convection heat transfer performed by [3]. Comparison of total heat dissipation in the present study with experimental results, shows that, at lower oil flow rate, heat dissipation is slightly overpredicted. However, as the flow rate increases, predicted values are in line with the experimentally measured results. Thus, there is a good agreement of the present results with convection and radiation with the experimental results of [3]. Furthermore, figure also shows the comparison for the present CFD results with the [6] for case 2. It shows a good agreement of present results with the measurement results; however, there is overprediction of the heat dissipation for CFD simulations from [6] with only convection heat transfer. Actually, CFD simulation should predict lower heat dissipation as they have neglected radiation heat transfer.

Thus, with radiation considered in the simulations, it is observed that heat dissipation increased by an average 21.3 % of total heat dissipation for all flow rates which is quite significant for air natural cooling. This finally confirms the importance of radiation component in the overall heat dissipation from the radiator.

It is to be noted that this difference is magnified due to the lesser dominant natural convection being the primary mode of heat transfer. Above mentioned methodology shows that the

The radiator is not misnomer and it actually highlights its significance on overall heat dissipation

radiation effects can be considered without modelling oil domain and thickness of the radiators, thus saving a significant amount of meshing and computational time. This will also help in designing the cooling system of transformers with reduced number of radiators and thus lowering the cost and weight of the thermal system.

Figure 5(b) shows the comparison of radiation heat dissipation calculated from analytical results in subsection 5.1 with the numerically calculated heat dissipation in subsection 5.2 for case 1 and case 2. Figure 5(b) shows that heat dissipation from numerical calculation is about 15 % higher for case 1 and 3.7 % higher for case 2, compared to analytical calculation for all flow rates. These numerically calculated values are closer to the experimental results. This confirms that the simplified CFD calculation methodology can be successfully used for the determination of radiation heat dissipation from the radiators.

Conclusion

The conclusions drawn from the present work are as follows:

- A CFD application and analytical analysis is presented to study the effect of thermal radiation on heat dissipation characteristics of the radiator of transformer by using two case studies. Detailed analysis shows that the middle fins of the radiator provide higher convective heat dissipation, while the end fins expectedly provide much higher radiation heat dissipation due to one complete surface being exposed to the ambient. This study shows that radiation needs to be included in the natural convection case (ONAN) because:
- It has a significant effect on the evacuated heat (21.7 % to 23.5 %). Thus, the radiator is not misnomer and it actually highlights its significance on overall heat dissipation.
- Internal and external calculations can be simplified to only external calculations to study the effect of the radiation heat transfer.
- Radiation must be included in the model, which can be confirmed with simple mathematical calculation and is also compared with experimental results from the literature.
- These results can be useful for designers to understand the effectiveness of radiator-fan configuration and heat transfer characteristics for different transformer cooling configurations.

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