Numerical investigation to study effect of radiation on thermal performance of radiator for onan cooling configuration of transformer

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Abstract. In the present work, flow and temperature distribution in the radiator fins of a power transformer is studied numerically with conjugate heat transfer using commercial CFD software to study the effect of radiation on heat dissipation. The approach considered here is a complete 3D geometry of the radiator fins with average height of the flute geometry of the fins for meshing and computational time reduction. Simulations are performed for ONAN (Oil Natural Air Natural) case for one radiator configuration. The simulations also study the effect of radiation and its impact on the overall heat dissipation. These results would give a holistic picture of heat transfer phenomenon to the designers.

1. Introduction

Transformers are one of the primary components for the transmission and distribution of electrical energy. They are extensively used in electric power systems to transfer power by electromagnetic induction between circuits at the same frequency, usually with changed values of voltage and current. The energy losses in the power transformers are proportional to the load. These losses are transformed into heat and consequently temperature of the cooling medium rises and must be cooled.

In most power transformers, the cooling is provided through circulation of oil between ducts in the active parts and radiators outside the transformer tank. The internal flow of oil in the radiator and the external flow of air over the radiator results in a heat transfer by natural or forced convection. Thus, the cooling modes in a transformer are ONAN (oil natural air natural), ONAF (oil natural air forced), OFAF (oil forced air forced) and ODAF (oil directed air forced). Most of the published literature is on internal cooling of the power transformer i.e. cooling of windings. Whereas, for external cooling of the transformer which corresponds to the cooling of radiators, very few work is found.

Radiators-fan constitutes a major portion of thermal system of transformer. It is necessary that this radiator-fan system should be efficient and with lesser weight. Transformer manufacturers are keen to reduce the weight of the system, without compromising on the thermal performance. Due to advanced tools like CFD, now it is possible to visualize virtually the air flow and temperature distribution over the radiators compared to expensive experiments. Furthermore, air flow distribution will give more insight for improving thermal performance of the system.

Limited experimental and simulated theoretical work related to power transformer radiator cooling performance has been reported. In some previous efforts, the focus was on thermal design and methods to predict hot-spot and top-oil temperature [1, 2]. Conventional calculations of internal transformer temperature are not only complicated and difficult, but also lead to conservative estimates obtained on the basis operating condition assumptions [3, 4]. With computational numerical techniques, it is possible to calculate transformer losses and temperature distributions in power transformers and cooling systems [5, 6]. There are still natural convection analysis problems with
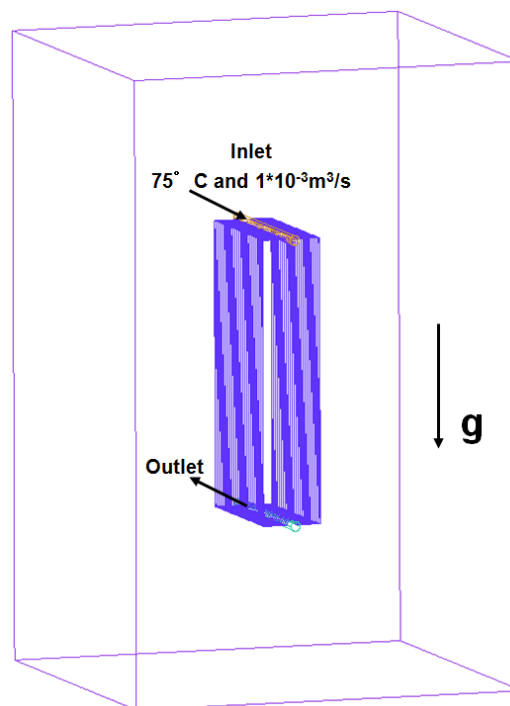
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convergence, calculation time, and even accuracy [7]. Nabati et al. [8] carried out numerical modeling of temperature distribution and flow pattern in a block radiator used in power transformer cooling system. They mainly focused on studying the relation between radiator block characteristics and cooling behavior of system. The results indicate that recirculation occurs whenever pressure increase at the end of a radiator block that consequently prevents the enough oil flow through the last radiator of block. Amoiralis et al. [9] studied optimum designs of ONAN transformer cooling system by means of advanced numerical thermal field and computational fluid dynamics techniques. Novel tank designs are examined in conjunction with other crucial parameters, as the number and location of the winding cooling ducts, so as to define the best optimum geometry that ensures maximum efficiency of the transformer cooling system performance. In recent times Kim et al. [10] presents prediction and experimental study on the cooling performance of radiators used in oil filled power transformer applications with non-direct flow (ONAN) and direct-oil-forced flow (ODAN). Radiator temperature distribution and cooling performance was predicted using theoretical calculations, then validated using CFD simulation results. To the best of the author's knowledge there has been no paper found where the effect of radiation on heat transfer from the radiator is reported.
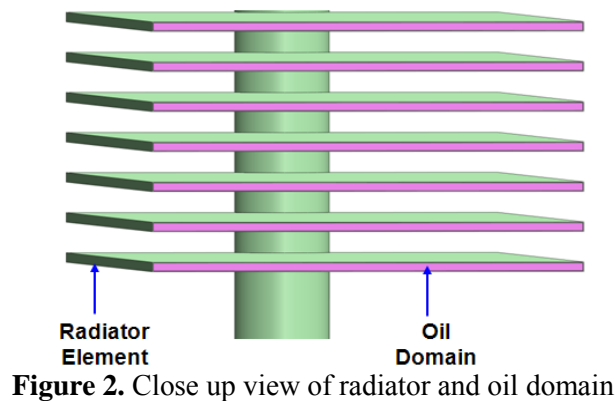
Present study focuses on determination of effect of radiation on various performance parameters of the radiator.

2. Geometry Description

The geometry is composed of one radiator of 520mm width having 2500mm height and 27 fins. The geometry considered for analysis in the present study is shown in figure 1. Oil enters at the top and leaves from the outlet at the bottom of the radiator and air domain surrounding the radiator is shown in figure 1. Close up view of radiator and oil domain is shown in figure 2.

Figure 1. Geometry of the radiator-fan configuration

Figure 2. Close up view of radiator and oil domain

3. Methodology Description

The geometry of radiator is made in Solid works modeling software from the geometrical description and imported in Ansys ICEM-CFD mesh generation software. Mesh quality is important for accuracy and stability of the numerical calculation and needs to be of high quality. The domains of the model of the radiator, the inner oil and the surrounding ambient air are discretized into a finite set of control volumes. Hexahedral mesh is used for the radiators for better convergence, accuracy and resolving detailed flow features. By using different options provided in ICEM-CFD, it is possible to have a good control over all parts of the mesh. The image of figure 3 shows a mesh that is used for the CFD analysis. Relatively coarser mesh is used for the regions which are away from the radiators and fine mesh is used near to the radiator and fan. This is because most of the action is happening near to the radiators due to higher gradients of velocity and temperature near these parts. The total size of the mesh used was 2.6 million nodes.
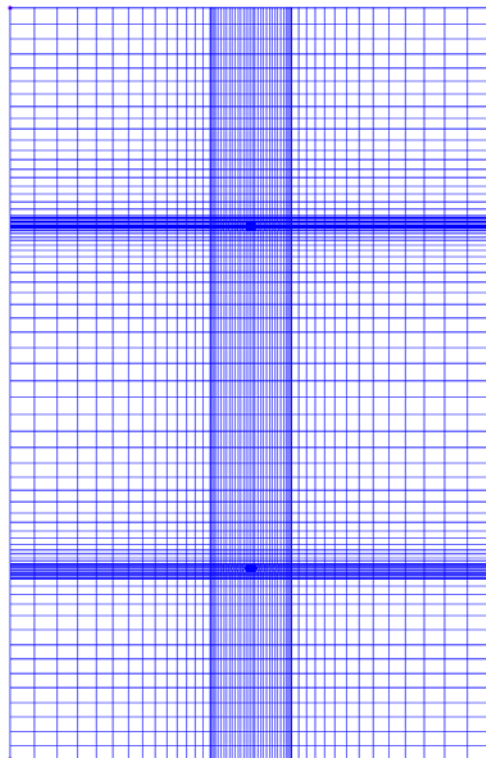

Figure 3. Hexahedral Mesh of radiator

Ansys CFX pre and solver is used for preprocessing and solving, respectively whereas post processing of the results is done in CFX post. In this case, it has been ensured that residuals for all solved quantities are below 10^{-4} and imbalance within domain is less than 1% after which it is considered that convergence is achieved.

Due to natural convection, momentum and energy equations are coupled. Temperature dependent oil properties are used for analysis. Computation time required for completing one simulation on four parallel processors is 120hrs.

4. Configurations studied
Two configurations, both in ONAN, are studied.
1. Radiation is not considered in this case. Oil mass flow rate is specified which is generally observed for heat run test of transformer in ONAN configuration.
2. Radiation is considered in this case. Oil mass flow rate is specified which is generally observed for heat run test of transformer in ONAN configuration.

5. Simulation Parameters
This section summarizes the different parameters and boundary conditions that are used for the numerical simulations

5.1. Material Properties
In the present calculations, the fluid that flows in the transformer winding is a mineral oil having the following properties with the temperature of oil, T_{oil} expressed in Kelvin.

$C_{pf} = 821.19 + 3.563 \times T_{oil}$ (J kg^{-1} K^{-1})

$k_f = 0.15217 - 0.0000716 \times T_{oil}$ (W m^{-1} K^{-1})

$\mu_f = 0.08467 - 0.0004 \times T_{oil} + 0.0000005 \times T_{oil}^2$ (Pa s)

$\rho_f = 1067.75 - 0.6376 \times T_{oil}$ (kg m^{-3})

where C_{pf} is the specific heat, k_f is the thermal conductivity, μ_f is the dynamic viscosity and ρ_f is the density. All the fluid properties, except for the dynamic viscosity, vary linearly with temperature. The material for radiators is taken as steel.
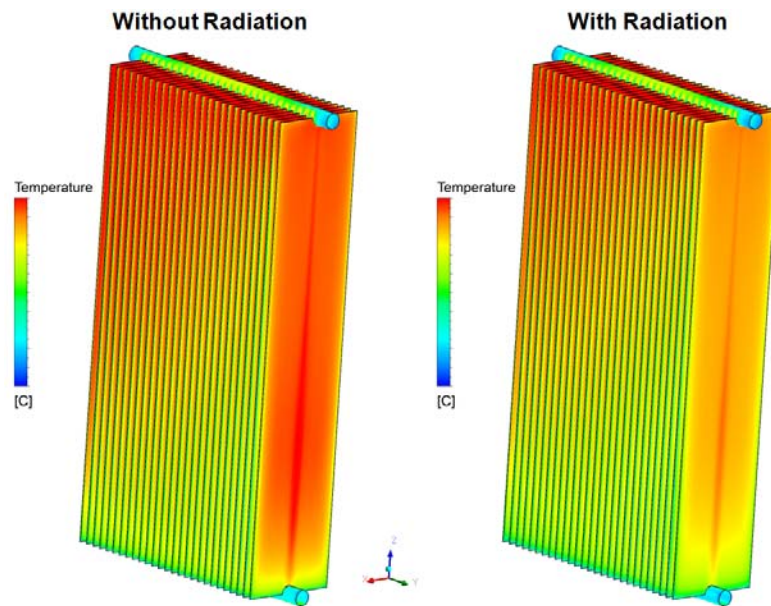
5.2. Boundary conditions
The fluid domain has an inlet boundary condition where a mass flow rate and an oil temperature are specified. At the domain exit, a pressure condition (p_{avg}= 0 Pa) is set. Mass flow rate specified at inlet is 1*10^{-3}m^3/s (0.845865kg/s) for both the cases. Flow is considered to be laminar for both cases.
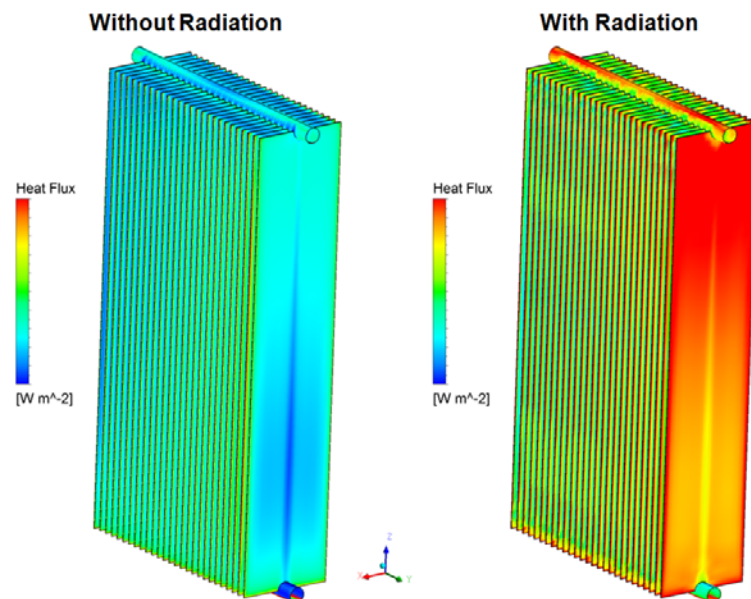
6. Results and Discussions
This section discusses the results obtained from CFD analysis for both the ONAN cases considered in the present study.

Figure 4 below shows the temperature distribution on the radiator for both the cases (without and with radiation). This clearly shows the difference in temperature distribution in the end fins for both the cases. This can be attributed to better heat transfer for the latter case (the one with radiation considered), which thereby results in better cooling leading to lesser oil temperature, hence lesser surface temperature. It was observed that the qualitative temperature plot for rest of the fins in the middle looks similar for both the cases. This is because shape factor is same for the middle fins as they are facing each other.

The better heat dissipation of end fins is further affirmed in figure 5, which compares the heat flux distribution on the radiator surface between the two cases. It is qualitatively evident that the end fins are cooled better for the case with radiation considered. Now, comparison of quantitative results will be made for the two cases along with the results from the theoretical model presented by Kim et al. [10].
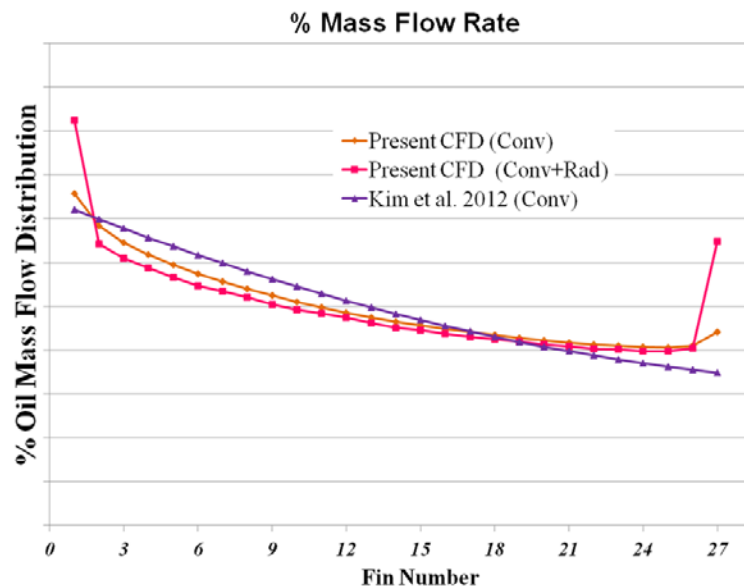
Figure 4. Comparison of Radiator Surface Temperature with and without Radiation

Figure 5. Comparison of Heat Flux Distribution on Radiator Surface with and without Radiation
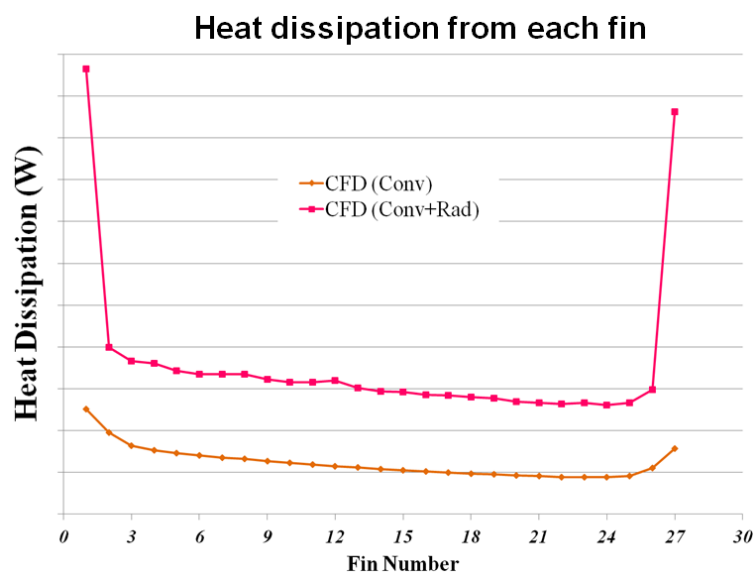
Figure 6 below shows the percentage oil mass flow distribution among the radiator fins for the two ONAN cases from CFD along with the prediction from the theoretical model. The mass flow distribution predicted from our CFD based model with only convection considered closely matches with the model of Kim et al. [10]. Thereby, the present CFD approach is validated and can be used to compare the convection model (without radiation) with the convection plus radiation model which is shown by the third curve. There is a steep hike in oil flow for the front and the back fins. This can be attributed to the additional radiation heat transfer which provides better cooling at the front and back fins exposed to air. It is to be noted that for the radiation included CFD model, the 1st fin has 29.9%

higher mass flow compared to 2nd fin. The 27th fin has 34.4% higher mass flow compared to 26th fin. The last fin (27th) has 22.6% lower mass flow compared to the 1st fin thereby highlighting the skewed mass flow distribution among the fins. This difference is found even in the other two cases which do not consider radiation.

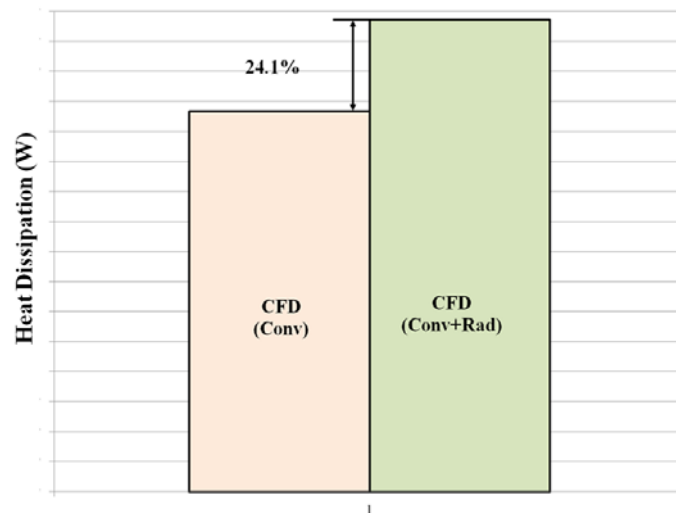**Figure 6.** Mass Flow Rate Distribution across the Radiator Fins

Figure 7 shows the distribution of heat dissipation for each fin for the two CFD cases (with, without radiation). It is observed that as compared to without radiation case, the heat dissipation in each of the middle fins with radiation case is at least 100 Watts higher. For end fins, this difference is much higher. This emphasizes the role radiation plays in not just the end fins but also the middle fins for heat dissipation. Also, with radiation case, the 1st fin dissipates 51.3% more heat as compared to the 2nd fin and the 27th fin 55.6% more than the 26th fin.

Figure 7. Fin-wise Heat Dissipation Distribution for various cases

Figure 8 shows the comparison of overall heat dissipation from the radiator for the 2 cases considered. Upon including radiation in the CFD model, it is observed that heat dissipation shoots up

by 24%. This finally affirms the importance of radiation in the overall heat dissipation from the radiator. Although, it has to be noted that this difference is magnified due to the lesser dominant natural convection being the primary mode of heat transfer. In the cases of forced convection (ONAF), the effect of radiation will not be so high.

Figure 8. Overall Heat Dissipation for various cases

7. Conclusion
CFD analysis is performed to evaluate the effect of radiation on heat dissipation of transformer radiator. Furthermore, oil flow and heat dissipation distribution among the different fins in the radiators is studied for ONAN cooling configuration without and with radiation. It highlights the significant contribution of radiation in the overall heat dissipation. Detailed analysis shows even the middle fins of the radiator providing higher heat dissipation, the end fins expectedly provide much higher dissipation due to one full face being exposed to the ambient. Thereby, it was observed that radiation needs to be included in the natural convection case (ONAN). These results can be useful for the designers to understand the effectiveness of radiator-fan configuration and heat transfer characteristics for different transformer cooling configurations.

8. Acknowledgements

9. References
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