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Research Paper

A numerical study of the effect of a hybrid cooling system on the cooling performance of a large power transformer

Young Joo Kim[a], Myunggeun Jeong[a], Yong Gap Park[b], Man Yeong Ha[a,*]

[a] School of Mechanical Engineering, Pusan National University, Jang Jeon 2-Dong, Geum Jeong Gu, Busan 609-735, Republic of Korea
[b] Rolls-Royce and Pusan National University Technology Centre in Thermal Management, Jang Jeon 2-Dong, Geum Jeong Gu, Busan 609-735, Republic of Korea

HIGHLIGHTS

- This study carried to investigate the cooling performance of radiators.
- The values of the FOM in the hybrid cooling system depended on the fan position.
- The values of the FOM in the hybrid cooling system depended on the oil flow rate.

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ABSTRACT

This study analyzed the conjugate heat transfer and fluid flow of radiators used in a power transformer to investigate the cooling performance. The flow and temperature distributions around the radiators were analyzed to investigate the fundamental mechanisms of radiator cooling in the hybrid cooling system. The oil flow rate in the radiators was varied in the range of 44.4 LPM ~ 309.6 LPM. The cooling fan location was also varied along the bottom and right surfaces of the radiators, and their effects on the cooling performance were evaluated. The computational results using the standard $k-\varepsilon$ turbulence model were compared with the measured data, showing the good agreement between them with the difference which is less than 5%. The cooling fans located at the center of the bottom surface and the bottom of the right surface resulted in the best cooling performance regardless of the insulating oil flow rate due to the positive interaction between the vertical and horizontal air flows induced by fans, giving about 22% higher cooling performance than the worst cooling performance at all flow rate.

1. Introduction

A power transformer generates heat loss during the process of electricity conversion. If the heat generated in this process is not emitted efficiently to the surroundings, the temperature in the transformer increases significantly, which can compromise the performance of the transformer's insulators, shorten its lifespan of the transformers, and cause malfunctions or explosions [1,2]. The size and weight of transformers have been significantly reduced with the recent trend towards high efficiency and miniaturization, but this has increased the rate of heat generated per unit volume of windings in the transformer. Therefore, it is essential to develop a high-performance cooling technology to maintain an allowable temperature for stable operation [3].

A power transformer is cooled down by a radiator mounted on the outside, which can also be used in diverse places besides a power transformer. Various studies have examined radiators for air-conditioners and automobiles. Kim and Cho [4] carried out a study to improve the heat exchange performance and pressure drop using different radiator fin pitches at low Reynolds number. Kim and Bullard [5] used the Colburn j-factor and Fanning friction factor to evaluate the heat exchange performance and pressure drop of various types of radiators according to the factors such as the fin pitch and louver fin angle. Bintoro et al. [6] conducted a study on a cooling method for an electronic device using an impinging jet with deionized water as the working fluid. Other research has looked at improving and optimizing the cooling performance of thermal management systems and heat exchangers [7–14].

Although much research has been done on air conditioners and automotive radiator systems, there is relatively little research on external cooling systems of power transformers. Cooling systems for the power transformer have been designed to have more radiators than required to for cooling. Therefore, there were no big problems with

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[*] Corresponding author.
E-mail address: myha@pusan.ac.kr (M.Y. Ha).

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cooling. However, in recent years, the number and size of radiators have been reduced to decrease costs due to increasing prices for raw materials. Thus, it is necessary to study radiator design, which is indispensable for the optimal cooling system of a power transformer.

Nabati et al. [15] used commercial CFD code to investigate the flow and temperature distribution of insulating oil flowing inside a radiator for cooling a transformer. As the oil flowed farther from the inlet of the radiator, there were decreases in the flow rate of the insulating oil distributed from the distribution manifold at the upper surface of the radiator to each fin. A recirculation region occurs around the radiator fins located farthest from the inlet of the radiator, which causes a sharp decrease in the flow rate of the insulating oil flowing into the radiator fins located farthest from the inlet.

Tălu and Tălu [16,17] studied the cooling performance of a 630 kV A transformer radiator using FEM. They examined different temperature conditions of the air outside the radiator. They found that the cooling performance of the radiator improves when the inclination angle between the distribution manifold of the radiator and the transformer is about 20 degrees. Seong et al. [18] carried out a numerical analysis on the fluid flow and heat transfer distribution in the radiator of a transformer using commercial CFD code. They analyzed the cooling performance of the radiator using different cooling methods. They found that increasing the length of the radiator was more effective than increasing the number of radiator fins for improving the cooling performance.

Kim et al. [19] numerically predicted the cooling performance of a radiator using commercial CFD code. The cooling performance obtained under the ONAF cooling system condition was 20.1% higher than that under the ONAN conditions. Kim et al. [20] conducted a numerical study to optimize the radiator fin shape for efficient cooling using commercial CFD code. They selected the optimal fin shape of the radiator in the oil directed–air natural (ODAN) cooling system using multiple objective functions. They also evaluated the effect of the optimal fin shape on the thermo-hydraulic design and performance of the radiator.

Fdhila et al. [21] numerically analyzed the cooling performance of radiators according to the number and size of the cooling fans using commercial CFD code. They performed a flow analysis on the air side of the radiator using a porous media model and showed that the cooling performance of the radiator improved as the size and number of cooling fans increased. Paramane et al. [22] numerically investigated the effects of the locations of cooling fans on the cooling performance of a radiator. They showed that installing cooling fans on the bottom surface of the radiator provided higher cooling efficiency than installing them on the side surface. In addition, installing the cooling fans on the radiator surface with an offset provided 3% higher cooling efficiency than installing them uniformly.

Chandak et al. [23] numerically analyzed the effects of radiation on the heat dissipation of a transformer radiator and observed that radiation needs to be included in the natural convection case. Paramane et al. [24] studied the thermal performance of a radiator in a power transformer with different fan mounting arrangements using commercial CFD code (one-sided mounted, opposite side mounted, staggered mounted, and bottom mounted). They showed that placing fans opposite to each other has a negative impact on the heat transfer dissipation and created a large counter pressure on each fan, resulting in a large leakage of air flow and vertical air flow in the middle radiators of the radiator group.

Anishek et al. [25] numerically studied the cooling performance of a power transformer with ONAN cooling. They performed an optimization analysis of the radiator, and the proposed radiator design had 14% better cooling performance than an existing design for the same material cost. Paramane et al. [26] conducted experimental and numerical studies to predict the cooling performance of a transformer radiator. They verified their numerical analysis method by comparing the results with measured data. Horizontal cooling had 6.1% better performance than vertical cooling. Van der Veken et al. [27] developed a full thermo-hydraulic radiator model to increase the efficiency of thermal calculations. They compared the results with measured data to validate the model.

For efficient cooling, a large power transformer uses different external cooling systems depending on its total heat loss. If the total heat loss is low, the cooling is performed using an ONAN cooling system, but above a certain level, ONAF or oil directed–air forced (ODAF) cooling systems are used. In an air-forced (AF) cooling method, cooling fans are generally installed on one of the side surfaces of the radiator (vertical or horizontal) for efficient manufacturing and transportation. However, effective cooling is difficult because the base capacity of the transformer increases, and as a result, over-designing with additional sets of radiators occurs because of the limited space available for fans.

Therefore, this study considers a hybrid cooling system based on the OD cooling method, in which cooling fans are installed on the radiator surface along the horizontal and vertical sides simultaneously. A three-dimensional numerical analysis was carried out to investigate the fluid flow and heat transfer phenomena inside and outside the radiator. The numerical method was validated by the results with experimental data using four sets of radiators for AN, AF-vertical, and AF-horizontal cooling systems. The cooling mechanisms of the radiator were identified by comparing and analyzing the characteristics as a function of the oil flow rate. The main factors affecting the cooling performance of the radiator were derived, and a method is proposed to install cooling fans effectively for efficient radiator cooling. In addition, the cooling performance factor of merit (FOM) was evaluated for five sets of radiators.

2. Numerical methodology

The conjugate heat transfer and fluid flow were analyzed to determine the flow and temperature fields for the insulating oil flowing inside a radiator, the cooling air flowing outside the radiator, and the temperature fields in the solid portion of the radiator. The temperature on the radiator surface is generally less than 320 K, so the effect of radiative heat transfer is much smaller than that of convective heat transfer and was not considered, similar to the study by Kim et al. [8]. The conservation equations governing the 3-dimensional, incompressible turbulent fluid flow and heat transfer are defined as follows:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_i}\left(\mu\frac{\partial u_j}{\partial x_i} - \rho\overline{u_i' u_j'}\right) + \rho g_j \beta(T - T_0) \tag{2}$$

$$\frac{\partial(\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{k_f}{C_{P,f}}\frac{\partial T}{\partial x_i} - \rho\overline{u_i' T'}\right) \tag{3}$$

$$\frac{\partial}{\partial x_i}\left(k_S\frac{\partial T}{\partial x_i}\right) = 0 \tag{4}$$

Eqs. (1)–(3) represent the conservation equations for mass, momentum, and energy of the fluid (oil or air), respectively, inside and outside the radiator. The terms $-\rho\overline{u_i' u_j'}$ and $-\rho\overline{u_i' T'}$ in (2) and (3) represent the Reynolds stress and turbulent heat flux. The term $\rho g_j \beta(T - T_0)$ in (2) represents the buoyancy term for the cooling air outside of the radiator, which is defined by the Boussinesq approximation. The subscripts i and j used in (1)–(4) represent the tensor notation. The numerical solutions for (1)–(4) were obtained using FLUENT. The second-order upwind scheme was used for the numerical integration of the convection terms. The SIMPLE algorithm was used for the velocity–pressure coupling technique, and the conductive heat transfer of the radiator fins was simulated using the shell-conduction method provided by FLUENT.

Fig. 1 shows the full model and computational domain for the