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Prediction and evaluation of the cooling performance of radiators used in oil-filled power transformer applications with non-direct and direct-oil-forced flow

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ABSTRACT

Lifetime and reliability of a power transformer are highly dependent on cooling modes as excessive heat generation is the major cause of deteriorating insulation performance. For these reasons, optimal cooling design is necessary to avoid operating faults and materials degradation due to thermal damage. This paper 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. In the experiment, cooling capacity was evaluated with the ONAN and the ODAN flow. For ODAN flow, the maximum cooling capacity was enhanced 20.1% more than ONAN flow. These results confirm that the prediction and the evaluation of radiator cooling performance can be applied to design optimization of cooling mode for oil-filled power transformer applications.

1. Introduction

A power transformer is an essential item for the conversion of electrical energy in transmission and distribution network systems for domestic and international energy transport and industry applications. In this electrical conversion, some power is lost through transformation into heat within the power transformer. Overloading to windings also increase interior power transformer temperature. Coolant, insulating oil was generally used in oil-filled power transformers, in practice heated in winding disks, then cooled through radiators. The increase in winding heat generation per unit volume is a serious problem with power transformers, with the size and weight of transformers continually being reduced in efforts towards high efficiency and miniaturization [1]. For heat dissipation within power transformers, the hot-spot temperature is the most important limiting factor in transformer loading [2,3]. The hot-spot temperature should be kept under a prescribed limit. Inadequate heat dissipation leads to excessive increases in winding hot-spot temperatures, which could cause winding insulation and insulating oil quality deteriorations, premature transformer aging, malfunction and even explosive accidents. Also, lifetime of a power transformer is highly dependent on the winding insulation condition, and insulating oil quality is expected to decline rapidly [4,5]. For these reasons, optimal oil-filled power transformer cooling design is necessary to avoid operating faults and materials degradation due to thermal damage. Moreover, thermal management for optimum power transformer utilization should be monitored continuously taking into account technical and economic considerations.

Average winding temperature is determined primarily by oil circulation. The oil circulation can be modified by appropriate choice of power transformer cooling modes [6]. Power transformer cooling systems based on non-direct oil flow (ONAN, oil natural and air natural) is commonly used in electrical power delivery networks as this technique is the most reliable. Oil circulation via ONAN flow is thermally driven as a consequence of changes in oil density [7]. Thermal driving force should be equal to the total flow resistance at a steady state along the thermosyphon loop [8]. Adequate oil temperature rise is necessary to maintain oil circulation, and at the same time, the hot-spot temperature must be under control. Oil circulation in the ONAN cooling system is naturally maintained without any mechanical apparatus such as pumps. Insulating oil, on the other hand, must be forcefully circulated through power transformers to effectively cool the transformer windings. Power transformer cooling system based on direct-oil-forced flow (ODAN, oil directed and air natural) requires a pump between the tank and the radiators to obtain a high insulating oil volume flow rate [9]. The insulating oil circulating condition and cooling capacity with ODAN flow is determined primarily by pump condition in the circulation loop [10]. Major limitations in the use of ODAN cooling include mechanical vibration, noise and even breakdowns of pumps. Thorough understanding of the total temperature distribution and cooling capacity in the outer cooing circuits is therefore crucial in making the correct determination of an appropriate cooling method for the thermal management

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whether the ON or the OD method because the cooling power is highly dependent on the oil volume flow rate.

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 [7,11]. 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 [12,13]. With computational numerical techniques, it has become possible to verify complex thermal–fluid phenomenon with commercial computational fluid dynamic (CFD) simulation tools. Using these tools, it is possible to calculate transformer losses and temperature distributions in power transformers and cooling systems [14,15]. There are still natural convection analysis problems with convergence, calculation time, and even accuracy [11,16]. According to the literature reviewed, there appear to have been relatively few investigations into ONAN and ODAN flow cooling performance on radiator focused outer cooling. Correlated research into radiator cooling performance of comprising theoretical calculations, CFD simulation and experimental results have not been reported for oil-filled power transformer applications.

This paper presents detailed calculations, CFD simulations and experimental results for radiator cooling performance in oil-filled power transformer applications using non-direct and direct-forced oil flow. The aim of this work was the experimental evaluation of the radiator cooling capacity, and made comparison with two different prediction methods through the calculations and the CFD simulations. First, the temperature distribution and cooling capacity is calculated via the energy balance equation. These calculations were verified using a CFD simulation tool, then compared with the experimental ONAN and ODAN flow results.

2. Calculation and simulation

2.1. The calculation for prediction of cooling capacity

Fig. 1a shows a schematic view of an array of 4 radiators with each radiator having 40 fins. The center to center length (L) of each fin is 3300 mm and the gap between fins (S) is 45 mm. Insulating oil heated in a power transformer tank and runs to the radiators via thermal driving force or mechanical driving force via a pump. The flow rate was normally in the 1.0×10^{-3} m^3/s to 2.0×10^{-3} m^3/s range for thermal driving force but, higher flow rate over 2.0×10^{-3} m^3/s was be achieved using a pump. Generally speaking, 80–90% of transformer losses cooled through radiators transferred to the air through convection and radiation. Although radiating loss exists with radiators, it is quite small due to the symmetrical shapes of the design. Radiating loss was thus not considered in this calculation. A radiator comprising 40 fins with 102 mm connecting headers was selected to calculate cooling capacity as shown in Fig. 1b and is addressed below in detail.

To determine temperature distribution, including radiator inlet and outlet temperature (T_{inlet} and T_{outlet}), the energy balance differential equation is adopted as (1). Temperature at the top of the radiator (T_{top}) was assumed 75 °C. Temperature at the 3300 mm position is equal to T_{outlet}. To meet the temperature rise limit standards of 55 °C, the air temperature (T_{air}), outside the radiator, was assumed to be 20 °C [3,4]. Under these conditions, the solution of (1) is expressed as (2) [8].

$$h_p O(T(x) - T_{air})dx = \rho c_p Q_{oil} dT(x) \quad (1)$$

$$T(x) = T_{air} + (T_{top} - T_{air})e^{-\left(\frac{h_p O}{\rho c_p Q_{oil}}\right)x} \quad (2)$$

where h_p is the total heat transfer coefficient of a radiator (W/m^2 K), O is the circumference of outer radiator cross-section (m), $T(x)$, T_{top} and T_{air} are the temperatures at the position x, at the top of the radiator and the air (°C), respectively. ρ is the oil density (kg/m^3), C_p is the specific heat of the oil (J/kg K), and Q_{oil} is the oil flow rate through the radiator (m^3/s).

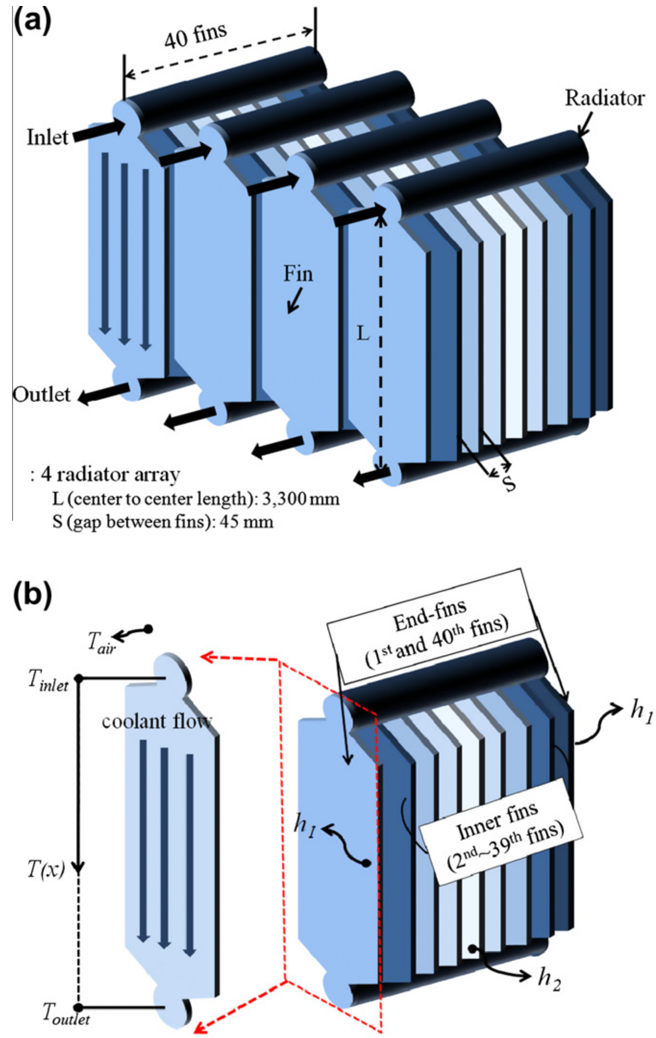

Fig. 1. Schematic views of (a) a 4 radiator arrays (1 radiator: 40 fins) and (b) radiator details for theoretical calculations.

To determine the T_{inlet} (x = 0 mm) and T_{outlet} ($x = L$ = 3300 mm) at each fin, (3) and (4) were used, respectively. The T_{inlet} at each fin is equal to T_{top}. However, the T_{outlet} is different at each fin because h_f and $Q_{oil}(N)$ are determined by the order of fins.

$$T_{inlet} = T(0) = T_{air} + (T_{top} - T_{air}) = T_{top} \quad (3)$$

$$T_{outlet} = T(L) = T_{air} + (T_{top} - T_{air})e^{-\left(\frac{h_f O}{\rho c_p Q_{oil(N)}}\right)L} \quad (4)$$

where T_{outlet} is the outlet temperatures of a fin (°C), $Q_{oil}(N)$ is the distributed oil flow rate for the order of fins (m^3/s), and h_f is the heat transfer coefficient of a fin (W/m^2 K).

The convective heat transfer of a fin (h_f) should be firstly considered to determine the T_{outlet} at each fin. The value of h_f varies with the shape of the radiator and the circumstances concerning the radiator. In the radiator surrounding the convection, the end-fins, such as the 1st and 40th fins, it can be assumed to be vertical-flat plate fins. An empirical equation that considered a vertically isolated plate was used for (5)–(7) to determine the convective heat transfer coefficient (h_1) [17]. For the inner fins from the 2nd to