Numerical study on nanofluids natural convection heat transfer inside power transformer windings

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ABSTRACT

As an innovative approach to improve the cooling efficiency of fluid, the use of nanofluids has attracted increasing attention in engineering applications. In this paper, the impact on the natural convective heat transfer in disc-type transformer windings due to transformer oil-based nanofluids is studied numerically. A low-voltage winding using nanofluid (SiC/oil) as the coolant is modelled two-dimensionally and simulated by computational fluid dynamics and the multi-phase mixture model. The numerical method is validated with the existing results of transformers using conventional oil cooling, and grid-independence study is carried out for the nanofluid flow. Compared with transformer oil cooling, the temperature of nanofluid cooled winding is significantly reduced, while the temperature trend along the flow direction remains essentially the same. Moreover, the effects of nanofluid on the mass flow rate and the coolant temperature have been taken into consideration in the heat transfer analysis.

I. INTRODUCTION

Oil-immersed power transformer is one of the most commonly used transformer types, especially for high-voltage and high-power applications. Mineral oil, which is served as the dielectric and coolant, is forced to circulate in the transformer by the thermal driving force and oil-pumps. Since natural oil cooling (ON) is simple in structure, ON transformers are widely used in industry. A relatively high temperature rise in ON transformers is required to produce enough thermal driving force for the circulation. In oil forced cooling (OF) transformers, pumps are used to increase the velocities of flow to improve the heat transfer coefficients. The faster the oil circulation, the faster is however the aging of the insulations and this could lead to severe failures.[1] Except for the ON technique and OF technique, oil directed cooling (OD) technique is adopted to force the flow through the horizontal cooling ducts in the windings. Generally, the windings are divided into several passes using oil washers. To accurately predict the temperature of windings, thermal-hydraulic networks[2] and computational fluid dynamics (CFD) method[3,4] are used to build the thermal model. Both windings and coolants are included in the thermal model, as there is a strong coupling between the heat transfer and the fluid flow, especially for ON transformers. With the ability to handle inhomogeneous flow in windings, CFD method provides detailed and accurate results. One pass of the windings is numerically studied with different modelling approximations.[3] To reflect the strong coupling between passes, the fluid domain of the whole windings is modelled and simulated.[4]

An innovative approach for enhancing the heat transfer performance of liquid coolants is to improve the inherently low thermal conductivity by dispersing nanoparticles with order-of-magnitude higher thermal conductivity into the liquids.[5] The stable suspensions are named as nanofluids. Measurement results of transformer oil-based nanofluids verify the improvement in thermal conductivity[6,7] and demonstrate the potential of applying this technique in oil-immersed transformers.[8] Moreover, the DC/AC dielectric strength of transformer oil is also enhanced after adding nanoparticles at specific concentrations.[6] Experimental and numerical investigation are carried out for nanofluids in simple containers, such as in circular tubes[9] and in microchannels.[10] Both single-phase model and multi-phase models are used and compared in the numerical analysis, and multi-phase models are found to be more precise.[9,10]

To evaluate the impact of nanofluid (SiC/oil) in transformers on their heat transfer performance, this paper develops a numerical model for the disc-type windings in natural nanofluid cooling transformers. A two-dimensional (2-D) and axisymmetric model is built for the windings with four passes, in which the conductors and the surrounding insulation papers are taken into consideration. The nanofluid flow in the wingdings is simulated using the multi-phase mixture model. The numerical method is validated using the results of conventional transformer oil cooling, which are also used as the reference for nanofluid cooling. Significant temperature reduction is observed after using nanofluid, which is reflected in the variation on heat transfer coefficient as well. Changes in mass flow rate and coolant temperature are considered in the analysis of nanofluid cooling.

II. MATHEMATICAL MODELLING

A. Geometry and boundary conditions

The low-voltage windings of an ON transformer rated at 66 MVA are divided into four passes by the oil washers.[4] Except for the first pass, which has two more discs and an additional oil washer, each pass contains 19 discs. The additional oil washer is used to direct the flow from the two inlets to the outer vertical duct, which is shown in Fig. 1. A 2-D and axisymmetric model is built for the windings using the commercial software packages for fluid analysis, ANSYS Fluent. With the second oil washer blocking the outer vertical duct, coolants in pass one flow through the horizontal ducts and into the second pass from the inner vertical duct. The other oil washers are arranged in the same way to force the flow through the horizontal ducts. As Fig. 1 shows, the insulation papers surrounding the conductors have been taken into consideration. The passes, discs and horizontal ducts are numbered from the bottom to the top.

The circulation loop outside the winding is excluded from the computational domain with the heat-run test results. The natural convection problem of an entire transformer is simplified to a forced convection problem of the windings with appropriate boundary conditions. A homogeneous flow with the velocity of 0.02695 m/s and a temperature of 319.85 K is specified on the inlets, and the outlet is set with a pressure boundary condition (0 Pa). Both transformer oil cooling and nanofluid cooling are specified with this inlet boundary condition. The reason for neglecting the influence of nanofluid on the inlet boundary conditions is to isolate the influence of nanofluid on the heat transfer performance in the winding.[11] Since the thermal conductivities of the cylinder and the oil washer are quite small, the heat fluxes over their surfaces are assumed to be zero. A convective boundary condition with the heat transfer coefficient of 100 $W\ m^{-2}\ k^{-1}$ is specified on the bottom surface of the first disc. Uniform heat generation rate (676.9$W/disc$) is assumed for the

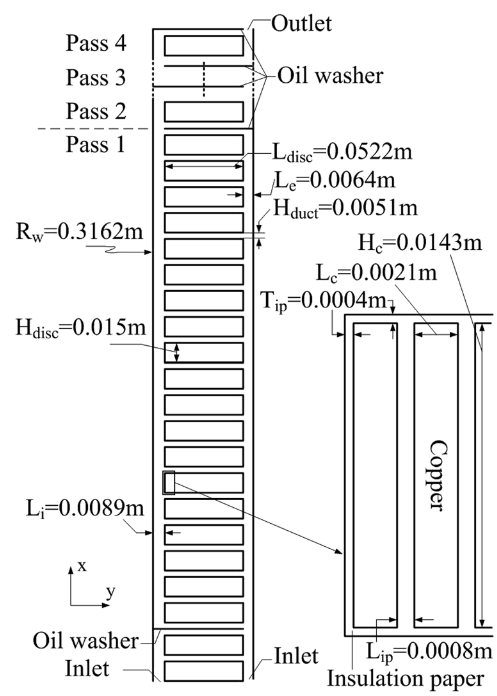

FIG. 1. The configuration of the low-voltage winding.

conductors, and the error introduced by non-uniform eddy losses is neglected.

B. Material properties

All the materials, except the transformer oil, are assumed to be temperature independent, and their properties are listed in Table I.[12] The properties of transformer oil are modified after adding the nanoparticles, and models are proposed to predict these properties for material preparation and analysis. The equivalent density and specific heat of nanofluid are formulated straightforward,

$$\rho_{nf} = (1 - \varnothing)\rho_f + \varnothing\rho_p \tag{1}$$

$$C_{nf}\rho_{nf} = (1 - \varnothing)C_f\rho_f + \varnothing C_p\rho_p \tag{2}$$

where Ø is the volume fraction of nanoparticle. It is relatively difficult to derive accurate models for the viscosity and the thermal conductivity of nanofluid. Microscopic parameters are included in the model to account for the effect of the interaction between the base fluid and the nanoparticles on the properties of the resultant oil. The viscosity model[13] based on the Einstein viscosity formula and the thermal conductivity model[14] derived by fitting measured data are used in the following analysis

$$\mu_{nf} = \mu_f\left[1 + 2.5\varnothing\left(1 + \frac{8.868}{r}\right)\right] \tag{3}$$

$$k_{nf} = k_f\left[1 + 4.4Re_p^{0.4}Pr_f^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_f}\right)^{0.03}\varnothing^{0.66}\right] \tag{4}$$

TABLE I. Material properties.

Material	Density ($kg\ m^{-3}$)	Specific heat ($W\ kg^{-1}\ K^{-1}$)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Viscosity (Pa·s)
Copper	8933	385	401	-
Insulation	930	1340	0.19	-
SiC	3160	750	490	-
Oil	$1098.72 - 0.712T$	$807.163 + 3.58T$	$0.1509 - 7.101 \times 10^{-5}T$	$0.08467 - 4.0 \times 10^{-4}T + 5.0 \times 10^{-7}T^2$

where; r is the nanoparticle radius; Pr is the Prandtl number of the base liquid; T_{fr} is the freezing point of the base liquid; the Reynolds number of nanoparticle Re_p is defined as

$$Re_p = 2\rho_f k_b T / \pi \mu_f^2 d_p \tag{5}$$

where d_p is the nanoparticle diameter (100nm). It can be seen from these formulas that the thermal conductivity, density and viscosity are increased after dispersing the nanoparticles into the base fluid. Besides, only the thermal conductivity model takes the effects of temperature into account.

C. The mixture model

To determine the pattern of fluid motion, the nanofluid flow in the winding is treated as a conventional single-phase flow. Equivalent properties of the SiC/oil nanofluid with the concentration of 1% are derived with the models introduced in the former section. The Reynolds number calculated for this problem is about 1000, which is much smaller than the critical value (2100) for laminar flow. Besides, the oil flow in this winding is reported to be laminar.[3] Hence all the flows studied in this paper are laminar and no turbulence model is required. The second order upwind scheme is used for the spatial discretization of momentum and energy, and the problem is finally solved with the pressure-based solver in a coupled manner. The convergence criterion for the residuals of governing equations is set with 1.0×10^{-6}. The temperature changes are also monitored to estimate the convergence. When the system reaches thermal equilibrium, the temperature of active parts does no rise any more, and the generated heat is totally dissipated, which can be verified after obtaining the results.

In the mixture model, the conservation equations of mass, momentum and energy are formulated for the nanofluid rather than for each phase.[9,10] Velocity differences between phases are taken into consideration in the governing equations of momentum and energy, and one more equation is formulated for the volume fraction of nanoparticle. The governing equations are given as follows:

Continuity,

$$\nabla \cdot \left(\rho_{nf} \boldsymbol{V}_m\right) = 0 \tag{6}$$

Momentum,

$$\nabla \cdot \left(\rho_{nf} \boldsymbol{V}_m \boldsymbol{V}_m\right) = -\nabla P + \nabla \cdot \tau + \rho_{nf} \boldsymbol{g} + \nabla \cdot \left(\sum_{k=1}^{2} \emptyset_k \rho_k \boldsymbol{V}_{dr,k} \boldsymbol{V}_{dr,k}\right) \tag{7}$$

Energy and,

$$\nabla \cdot \left(\sum_{k=1}^{2} \emptyset_k \boldsymbol{V}_k (\rho_k E_k + P)\right) = \nabla \cdot \left(k_{nf} \nabla T\right) + S_e \tag{8}$$

Volume fraction,

$$\nabla \cdot (\emptyset \rho_p \boldsymbol{V}_m) = -\nabla \cdot \left(\emptyset \rho_p \boldsymbol{V}_{dr,p}\right) \tag{9}$$

$\boldsymbol{V}_m$ is the mass-averaged velocity of the mixture,

$$\boldsymbol{V}_m = \frac{\sum_{k=1}^{2} \emptyset_k \rho_k \boldsymbol{V}_k}{\rho_{nf}} \tag{10}$$

τ is the stress tensor defined as

$$\tau = \mu_{nf} \nabla \boldsymbol{V}_m \tag{11}$$

The drift velocity $\boldsymbol{V}_{dr,p}$ and the relative velocity $\boldsymbol{V}_{pf}$ of the second phase are connected by the following formula:

$$\boldsymbol{V}_{dr,p} = \boldsymbol{V}_{pf} - \sum_{k=1}^{2} \frac{\emptyset_k \rho_k}{\rho_{nf}} \tag{12}$$

III. RESULTS AND DISCUSSION

Results of one single pass of the winding cooled by transformer oil are used as the reference for the numerical model and method validation.[3] The temperature contours and the mass flow rate distribution derived in this paper show good agreement with the reference. The same hot-spot location (disc 16) with the temperature of 365.04K is derived, and the error of this maximum temperature is about 3.7%. The criteria used to generate the mesh for the validation are also used in the grid-independence study for the nanofluid flow. The initial mesh with about 4.7 million cells is dominant by quadrilateral elements, and a refined mesh with 26% extra cells is generated by restraining the elements sizing globally. The maximum difference in the average temperature of discs between these two meshes is 1.1K. The results derived with the initial mesh are validated to be grid-independent.

The contours of the temperature of the winding cooled by nanofluid are shown in Fig. 2. It is found that the temperature distribution of nanofluid cooling is in good agreement with that of transformer oil cooling,[4] and the hot-spot is also located in the upper portions of the third pass (as shown in Fig. 3a). The trend of the disc temperature is related to the heat transfer coefficient of the disc and the mass flow rate through the horizontal duct, which are given in Fig. 3b and Fig. 3c, respectively. The average temperatures of the first disc in pass 2 and pass 4 are higher than the following few discs, as the inlet flows of these two passes are inhomogeneous and hot coolants are flowing through the ducts surrounding the lowest disc, which can be observed from Fig. 2. The temperature of the wingding is reduced overall after using nanofluid, which is illustrated in Fig. 3a. The change in the heat transfer coefficient relative to transformer oil cooling, as given in Fig. 3b, is another

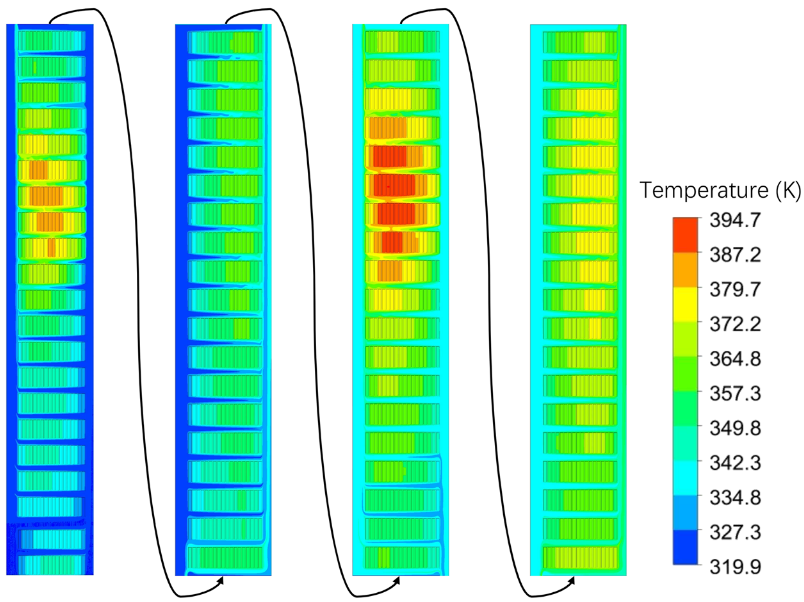

FIG. 2. The Contours of the temperature of the winding cooled by nanofluid.

reflection. The improvement on thermal conductivity is the main reason for the enhancement in cooling performance. It is indeed the effects of nanofluid on the mass flow distribution and the coolant temperature that produce the inhomogeneous temperature change as shown in Fig. 3a. However, the influence of the coolant temperature, except for the fourth pass, can be ignored.

Overall, there is no appreciable differences in the mass flow rate between transformer oil cooling and nanofluid cooling. For those

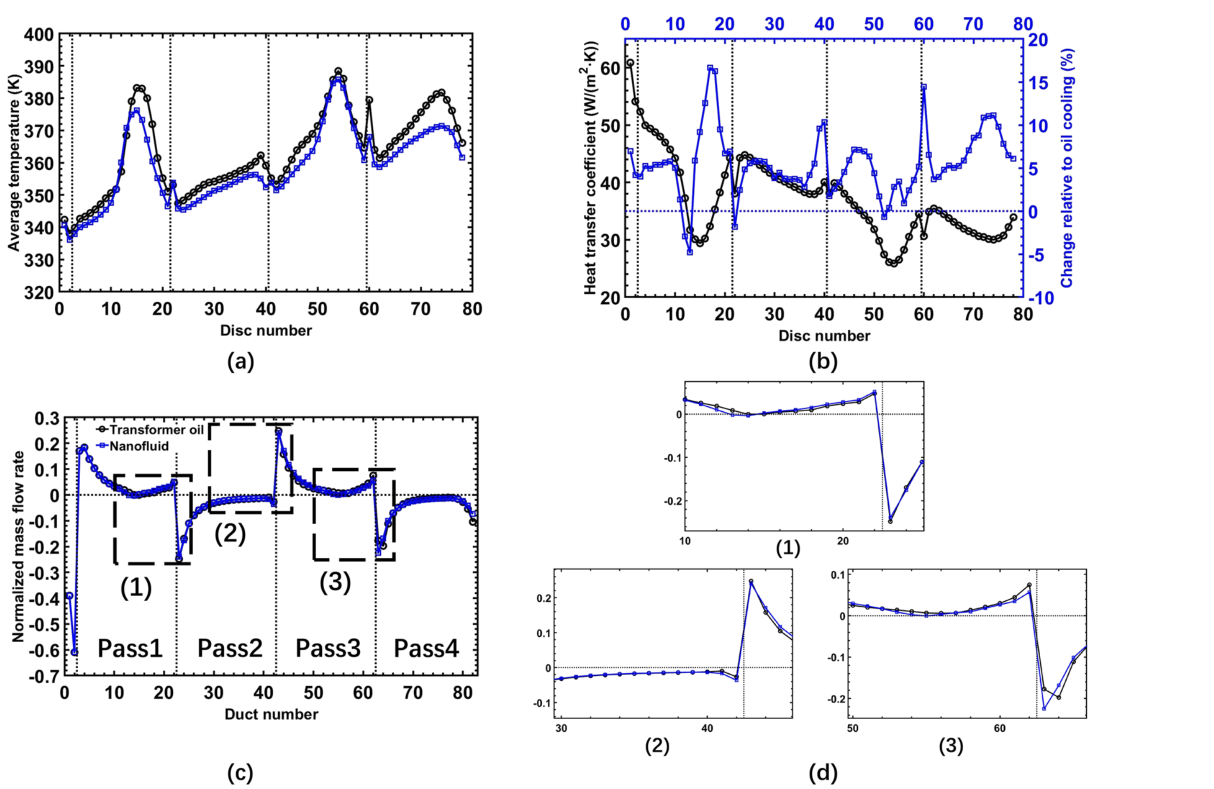

FIG. 3. (a) The average disc temperature cooled by transformer oil and nanofluid, (b) the area-weighted average heat transfer coefficient of nanofluid cooling and its change relative to oil cooling, (c) the normalized mass flow rate through the horizontal ducts, and (d) the detailed mass flow rate at the joints of passes.

ducts with low mass flow rate, the relative changes are, however, quite significant and cannot be ignored. To showcase this critical information, curves in the dashed box (1), (2) and (3) of Fig. 3c are enlarged and shown in Fig. 3d in turn. It can be observed that the mass flow rates through the middle ducts of the first pass are reduced, while the upper ducts show distinct increases in the mass flow rate. Temperatures of the corresponding discs vary in reverse, as the heat transfer coefficient is positively related to the mass flow rate. The temperature changes in the remaining passes are analyzed in the same manner. Lower coolant temperature in pass four further improves the efficiency of heat transfer, which produces the maximum reduction on the average disc temperature (see Fig. 3a). Besides, the maximum temperature rise of the winding is reduced by 3.2K.

IV. CONCLUSION

A numerical model is developed for the disc-type windings in natural nanofluid cooling transformers, with which the effect that nanofluid has on the heat transfer performance in natural cooling transformers is studied. The trend of the temperature along the flow direction is maintained after dispersing SiC nanoparticles into the transformer oil, while the average temperatures of the discs are reduced overall. The main reason for such temperature reduction is the improvement in the thermal conductivity, and the variation in mass flow rate produces a difference in the average temperature reduction in each pass. Besides, the effect of nanofluid in the fourth pass is magnified by the lower coolant temperature.

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