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Heat transfer comparison of nanofluid filled transformer and traditional oil-immersed transformer

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Dispersing nanoparticles with high thermal conductivity into transformer oil is an innovative approach to improve the thermal performance of traditional oil-immersed transformers. This mixture, also known as nanofluid, has shown the potential in practical application through experimental measurements. This paper presents the comparisons of nanofluid filled transformer and traditional oil-immersed transformer in terms of their computational fluid dynamics (CFD) solutions from the perspective of optimal design. Thermal performance of transformers with the same parameters except coolants is compared. A further comparison on heat transfer then is made after minimizing the oil volume and maximum temperature-rise of these two transformers. Adaptive multi-objective optimization method is employed to tackle this optimization problem. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5006749

I. INTRODUCTION

With the rapid modernization of cities, large capacity and miniaturization of oil-immersed transformers have attracted increasing attention. Unsatisfactory thermal performance of cooling system is the major factor that limits further development of transformers, as high temperature leads to irreversible damage to insulations and reduces the lifespan of transformers dramatically.¹⁻³ It is well recognized that the main reason of poor cooling effect is the small thermal conductivity of transformer oil. A distinct method to improve the thermal conductivity of liquid is to add solid particles of high thermal conductivity, which was initially proposed by Maxwell through a theoretical work in the year 1873.⁴ Mixture of micrometer sized particles, however, is not stable due to sedimentation. The following century witnessed this problem remaining unresolved until Eastman et al. dispersed copper nanoparticles into ethylene glycol and validated the thermal conductivity increment of nanofluid.⁵

Many literatures aimed to assess the applicability of transformer oil-based nanofluids through adding different types and/or different quantity of nanoparticles and measuring their properties related to cooling and insulation.⁶⁻⁸ To the best knowledge of the authors, no literature focuses on the application of nanofluid in transformers from the perspective of design optimization, solutions of which indicate volume or temperature reduction directly. This paper presents a comparison of the thermal performance of these two coolants based on the optimized solutions. Detailed heat transfer analysis and comparison of two transformers with identical dimensions and different coolants are also included.

II. ANALYSIS MODEL AND METHODOLOGY

A. Computation model

During transformer operation, all the power losses of windings, core and iron structures are converted into heat, resulting in temperature-rise and the heat energy is diffused into the surrounding
ambient through a complicated path. There are five stages in the heat transfer path of self-cooled transformer: 1) heat conduction in the active parts from the interior hot-spot to regions exposed to oil; 2) convective heat transfer from surfaces of the active parts to oil; 3) convective heat transfer from oil to the internal surface of the transformer tank; 4) heat conduction from the internal surface of the tank to outside surface; 5) convective heat transfer and heat radiation from the tank surface to ambient. For forced-cooled transformer, one more heat transfer path is that heat is taken away by transformer oil which is warmed up and pumped out. Temperature of transformer increases until it reaches the steady state when heat generated is totally transmitted.

In this paper a three-phase oil-immersed power transformer, rated 115-13.8kV, 60Hz and 30MVA, is studied. Fig. 1 illustrates the computational fluid dynamics (CFD) model of this transformer. As a first order of approximation, the insulation, structural parts, width of tank and heat radiation are neglected. Owing to symmetry, the model of the entire transformer is reduced to one half of its physical size. Dimensions of the active parts, including a laminated steel core of three legs and six windings, are settled. Parameters related to heat conduction of the active parts are listed in Table I. Oil is pumped into transformer from the underneath inlet at the speed of 0.03 m/s and it flows out through the outlet. Flow in the transformer is modeled by laminar flow and it is solved with finite volume method. A fixed convection coefficient of 5 W/(m² · K) is set for the tank surface with an ambient temperature of 293.15K, as the dimensional changes are relatively small.

### B. Methodology

In the studies of nanofluid, it is generally modeled as single-phase flow, as nanoparticles are so light that their fluidizations are not difficult. Speed difference between base fluid and nanoparticles, therefore, can be ignored. Another complicated manner is to model nanofluid as a two-phase flow, considering the velocity difference and interaction between base fluid and nanoparticles. Single-phase flow is employed to model nanofluid in this paper. There are four basic properties related to thermal and fluid field, namely, heat conductivity, viscosity, specific heat capacity, and density. Wasp

| Part          | Density (kg/m³) | Specific heat capacity (J/(kg · K)) | Heat density (W/m³) | Heat conductivity (W/(m · K)) |
|---------------|-----------------|-----------------------------------|---------------------|-----------------------------|
| Core          | 7850            | 480                               | 1000                | 50                          |
| Primary winding | 8900            | 390                               | 15000               | 250                         |
| Secondary winding | 8900            | 390                               | 75000               | 250                         |


TABLE II. Properties of transformer oil, nanoparticle and nanofluids of different volume fraction.

| Material                | Density (kg/m³) | Specific heat capacity (J/(kg · K)) | Viscosity (Pa · s) | Heat conductivity (W/(m · K)) |
|-------------------------|-----------------|-----------------------------------|--------------------|-------------------------------|
| Transformer oil         | 890.1           | 1630                              | 0.03388            | 0.15                          |
| SiC                     | 3160            | 750                               | -                  | 490                           |
| Nanofluid (Ø = 1%)      | 912.8           | 1621.2                            | 0.033396           | 0.15454                       |
| Nanofluid (Ø = 4%)      | 980.9           | 1594.8                            | 0.033422           | 0.16873                       |

Model[^13^] is adopted to evaluate the equivalent heat conductivity of nanofluid, given by

\[ k_{nf} = \frac{k_p + 2k_f - 2\phi (k_f - k_p)}{k_p + 2k_f + \phi (k_f - k_p)} \]  

(1)

where \( k_{nf}, k_f, k_p \) are heat conductivity of nanofluid, transformer oil and nanoparticles, respectively; \( \phi \) is the volume fraction of nanoparticles. Generally speaking, fluid viscosity will increase after dispersing nanoparticles, which is against flow advancing and heat transfer. Nguyen viscosity model[^14^] of nanofluid is employed and formulated as

\[ u_{nf} = \left(1 + 0.025\phi + 0.015\phi^2\right) u_f \]  

(2)

where \( u_{nf}, u_f \) are the viscosity of nanofluid and transformer oil, respectively. The equivalent specific heat capacity[^15^] of nanofluid is given by

\[ (C_p)_{nf} = (1 - \phi)(C_p)_f + \phi(C_p)_p \]  

(3)

where \((C_p)_{nf}, (C_p)_f, (C_p)_p\) are the specific heat capacity of nanofluid, transformer oil and nanoparticles, respectively. Based on the volume fraction of nanoparticles, a simple density model of nanofluid is formulated as

\[ \rho_{nf} = (1 - \phi) \rho_f + \phi \rho_p \]  

(4)

Equivalent properties of nanofluid of different volume fraction are derived with these models, which are listed in Table II with the transformer oil and silicon carbide (SiC) nanoparticle properties.[^12^][^16^] As these models and Table II show, the properties of nanofluid can be modulated through changing volume fraction of nanoparticles.

Based on the CFD model and property models of nanofluid, thermal performance of two transformers cooled by transformer oil and nanofluid with identical dimensions are compared. In order to carry out a more extensive and practical comparison, two transformers employing different coolants and equal active parts are optimized with the same objectives which are, namely, minimizing the volume of coolant and minimizing the highest temperature-rise. The optimization problem is formulated as follows

\[ f_1(X) = \min(V_o) \]  

(5)

\[ f_2(X) = \min(T_{max}) \]  

(6)

where \( V_o \) is the volume of oil; \( T_{max} \) is the maximum temperature-rise; \( X \) is the set of design variables, including the thickness of transformer and distance from the top, bottom, left and right surface to the core center. Adaptive multi-objective optimization method is employed to solve this problem. This method combines multi-objective genetic algorithm and Kriging response surface, which reduces the computation load of CFD and speeds up the convergence.

III. RESULTS AND DISCUSSION

To illustrate the correlation of coolants flow and active parts temperature, velocity vector and contour of temperature are shown in Fig. 2. There are no apparent differences of flow distribution in
FIG. 2. (a) Flow and temperature distribution of windings in conventional oil-immersed transformer and (b) flow and temperature distribution of windings in nanofluid filled (Ø = 1%) transformer.

these two figures and the maximum velocity difference is about 0.015%. In other words, increment on viscosity does not reduce the flow velocity significantly. It can be observed from these two figures that the flow velocity in window 1 is smaller than that in window 2 and oil flows over left and right surface at a relatively high velocity. The secondary windings of phase B, especially the top, has the highest temperature-rise, which is consistent with the loss density and flow velocity difference. Another phenomenon influenced by velocity difference is the non-horizontal isotherm on winding surface. Generally, the temperature at the top of windings is higher than that at the bottom, because oil flows from bottom to top with a continuous temperature-rise, which weakens the cooling capacity of oil. Compared with conventional oil-immersed transformer, the temperature-rise of windings of nanofluid filled transformer is reduced holistically. The maximum temperature-rise is reduced by 2.6 Kelvin. Moreover, the area of hot-spot is smaller and the reduced area is mainly located near the second window.

Two transformers using different coolants are optimized separately with five design variables, as detailed in Table III. In the whole optimization process, the parameters of active parts are settled and identical. The initial and the following population sizes of adaptive multi-objective optimization method are 100 and 50, respectively. It takes 13 iterations for conventional oil-immersed transformer to reach the convergence stability percentage of 2%, while for nanofluid-filled (Ø = 4%) transformer, the number of iterations is 10. By the optimized solutions shown in Fig. 3, compared with conventional oil-immersed transformer using the same amount of oil, the maximum temperature-rise of nanofluid-filled transformer is reduced by 8 Kelvin approximately with the usage of between

| Variable          | Range     |
|-------------------|-----------|
| Height,T/m        | [1.3, 1.5]|
| Height,B/m        | [1.3, 1.45]|
| Width,L/m         | [1.8, 1.95]|
| Width,R/m         | [1.8, 1.95]|
| Thickness/m       | [0.55, 0.7]|

^aHeight,T is the distance between top surface and core center.
^bHeight,B is the distance between bottom surface and core center.
^cWidth,L is the distance between left surface and core center.
^dWidth,R is the distance between right surface and core center.
3.3 cubic meters and 3.7 cubic meters of nanofluid. Moreover, it is observed that nanofluid ($\Phi=4\%$) saves up to 0.5 cubic meters of volume, and reduces the maximum temperature-rise by 2.6 Kelvin, simultaneously.

IV. CONCLUSION

This paper compares the thermal performance of nanofluid-filled transformer with conventional oil-immersed transformer. CFD solutions show that 1) adding few nanoparticles has a remarkable impact on the overall thermal performance of the transformer, and 2) increasing the volume fraction of nanoparticles produces more significant effects. Moreover, the reduction of oil volume and maximum temperature-rise are realized simultaneously with the application of nanofluid, which is verified by the optimized solutions.

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