# Finite Element Modeling of Heat Transfer in a Nanofluid Filled Transformer

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**Abstract—In order to investigate the heat transfer characteristics of nanoparticle containing transformer oil, a strong-coupled fluid-thermal analysis based on computational fluid dynamics is carried out in this paper. The distribution of velocity, temperature and density in a nanofluid filled transformer under natural and forced convections are achieved. The simulation results show that the efficiency of heat transfer is improved by the nanoparticle and forced convection. Whereas the distribution of nanoparticle in the oil depend on the local velocity and temperature of oil. This indicates that the local density of nanoparticle must be considered for nanofluid application in transformer because its potential influence on the properties of the oil e.g., aggregation and electrical strength, etc.**

## I. INTRODUCTION

In order to improve the heat transfer properties of transformer oil, many efforts had been done to disperse nanoparticles in transformer oil [1]. However, the heat transfer characteristics of transformer oil with nanoparticles and the influence of the nanoparticles on the electrical strength property of the nanofluid remain unclear. In this paper, to investigate the heat transfer characteristics of transformer oil with nanoparticles and the influence of oil temperature and velocity on the distribution of nanoparticles, the strong-coupled fluid-thermal analysis based on CFD (computational fluid dynamics) is carried out using finite element method. The distribution of oil temperature and velocity in a nanofluid filled transformer under natural and forced convections are simulated numerically. And the distribution of nanoparticles is calculated by applying drag law to the CFD model. The numerical simulation results show that the efficiency of heat transfer is improved by the nanoparticle. On the other hand, the distribution of nanoparticle in the oil depend on the local velocity and temperature of oil. This indicates that the local density of nanoparticle must be considered for nanofluid application in transformer because its potential influence on the properties of the oil, for example aggregation and electrical strength, etc.

## II. MATHEMATICAL MODEL FOR THE STRONG-COUPLED FLUID-THERMAL ANALYSIS

The mathematical model consisted of three governing equations expressing conservation of mass, momentum and energy can be written as below:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \qquad (1)$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla \mathbf{u}) = \nabla \cdot \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \nabla p - \frac{2\eta}{3}(\nabla \cdot \mathbf{u})^2 + \rho \mathbf{g} \qquad (2)$$

$$\rho Cp \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = -\rho Cp \mathbf{u} \cdot \nabla T + Q \qquad (3)$$

In the continuity equation (1) and momentum conservation equation (2), $\rho$ denotes the mass density (kg/m$^3$), $\mathbf{u}$ denotes the flow velocity (m/s), $p$ denotes the pressure (Pa), $\eta$ denotes the viscosity (Pa·s), and $\mathbf{g}$ denotes the gravity vector (m/s$^2$). For the energy conservation equation (3), $Cp$ denotes the heat capacity (J/kg·K), $k$ is the thermal conductivity (W/m·K), and $Q$ refers to the power density in the coil, iron core and transformer oil that serve as heat sources in the model. The fluid was assumed to have Newtonian and laminar flow characteristics. The momentum and energy equation was modified for the conjugate mass and heat transfer between solid and liquid.

## III. ANALYSIS METHOD AND CONDITIONS

The differential equations were discretized using a finite element approach. Based on an Eulerian granular multiphase model, the strong-coupled fluid-thermal analysis of the transformer oil nanoparticles is carried out to calculate the steady-state fluid-temperature distribution.

The transformer model consists iron core, primary and secondary windings. The windings of the transformer were modeled as homogeneous material for simplicity. The materials of the heat sources are shown in TABLE I and the parameters of the transformer oil are shown in TABLE II [2, 3]. The boundary temperature of the model is 293.15K.

TABLE I
THE MATERIAL AND HEAT SOURSE OF THE MODEL

| Material | Thermal conductivity (W/(m·K)) | Specific heat (J/(kg·K)) | Density (kg/$m^3$) | Heat density (W/$m^3$) |
|---|---|---|---|---|
| Primary Winding | 250 | 390 | 8900 | 15561 |
| Secondary Winding | 250 | 375 | 8745 | 74163 |
| Iron Core | 50 | 480 | 7850 | 900 |

TABLE II
THE PARAMETERS OF THE TRANSFORMER OIL

| | |
|---|---|
| Dynamic Viscosity (Pa·s) | 11.71exp(-0.02$T_{oil}$) |
| Thermal Conductivity (W/m·k) | 0.15 |
| Density (kg/$m^3$) | 1098.72-0.712$T_{oil}$ |
| Heat Capacity at Constant Pressure (J) | 1630 |

## IV. Results and Discussion

### A. *Temperature Distribution and Flow Velocity Distribution*

Figure 1 shows the steady-state temperature distribution and flow velocity distribution of the transformer oil under the condition of natural convection.

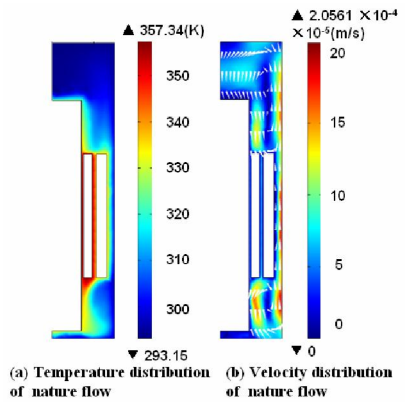


Fig. 1 The temperature distribution and velocity distribution of oil under natural convection in the transformer

Figure 2 shows the steady-state temperature distribution and flow velocity distribution of the transformer oil under forced convection, the initial flow velocity from the bottom is $2\times10^{-4}$m/s. The maximum temperature difference is 41.44K compared to that of natural convection case is 64.01K.

### B. *Density Distribution of Nanoparticles*

The density of the nanoparticle (SiC) is 3160 kg/$m^3$, the thermal conductivity is 490 W/(m K). The volume fraction of the nanofluid which contains spherical particles is 1%v/v [5]. The density distribution of nanoparticles under natural and forced convection is shown in Figure 3.

## V. Conclusion

The numerical heat transfer simulation of a nanofluid filled transformer is analyzed in this paper. The temperature distribution and flow velocity distribution of the nanofluid largely depend on the convection condition. Whereas the results illustrate that the distributions of nanoparticle in the oil depend on the local velocity and temperature of oil. Thus the local density of nanoparticles dispersed in the oil must be considered for nanofluid application in transformers due to concerns on aggregation and electrical field.

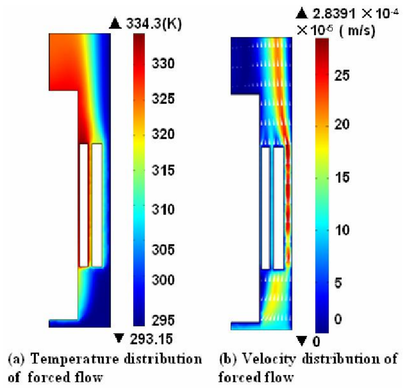


Fig.2 The temperature distribution and velocity distribution of oil under forced convection in the transformer

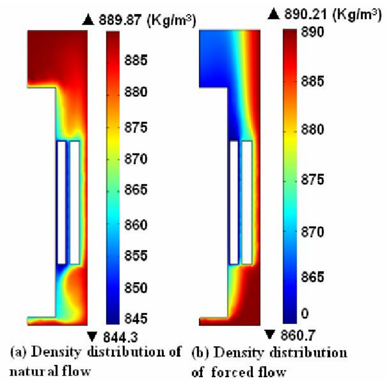


Fig.3 The density distribution of nanoparticle dispersed in the oil under natural and forced convection in the transformer

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