Cooling Performance of Vegetable Oil-Based Magnetic Nanofluid Due to Magnetoconvection Effects

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This paper reports on the cooling performance of a vegetable oil based magnetic nanofluid with different volume fractions of magnetic nanoparticles resulting from magnetoconvection effects in presence of an external magnetic field. Mineral-based oils are typically used in power transformers because of their high dielectric strength and good cooling performance under operating conditions. Owing to their environmental impact, the eco-friendly vegetable transformer oils have been lately replacing the mineral-based insulating oils. Until now, several studies reported only the dielectric breakdown characteristics of vegetable oil based magnetic nanofluids without considering any real electromagnetic system. Besides, the thermal characteristics of vegetable oil based magnetic nanofluids have not been fully discussed yet. The aim of our study, therefore, is to examine the cooling performance by adding magnetic nanoparticles to the vegetable transformer oil. To quantitatively analyze this effect, a multiphysics technique coupled with magnetic-thermal-fluidic fields was developed by using the quasi-static magnetic field approximation and conjugate heat transfer. To validate our numerical setup, some experiments were successfully conducted in a simple electromagnetic system with different insulating liquids.

***Index Terms*— Cooling, Magnetic nanoparticles, Magnetoconvection, Magnetic-Thermal-Fluidic analysis, Vegetable oils.**

I. Introduction

RECENTLY, pressing environmental issues have been raised in electric apparatus areas, and new technologies based on nanotechniques are being developed to resolve these engineering problems [1]. Until now, vegetable oils have been extensively studied as eco-friendly transformer oils [2]-[3]. Owing to the lower thermal conductivity and higher viscosity than conventional transformer oils, however, the temperature under operating conditions generally reaches a higher value than that of a conventional transformer oil. Here, to overcome this unwanted problem, we tested the use of magnetic nanoparticles (MNPs) in vegetable transformer oils.

The tunable thermal conductivity was reported in a previous research article at different magnetic fields for magnetic nanofluids [4]. Following this work, in the present study, the magnetoconvection effect will be significantly increased by adding MNPs to the vegetable transformer oil; besides, the convection effect of the vegetable transformer oil will be also enhanced, resulting in a decrease of the temperature rise. To validate this proposed performance, we showed some experimental results with a simple solenoid immersed in a vegetable oil with different volume fractions of MNPs. Additionally, to quantitatively analyze the magnetoconvection effect, we implemented a multiphysics technique employing the magnetic-thermal-fluidic analysis.

II. Magnetic-Thermal-Fluidic Analysis Using Buoyant and Magnetic Body Force Densities

The mathematical model consisted of four governing equations comprising the magnetoquasistatic (MQS) equation, the energy balance equation for temperature field, and Navier-Stoke's equation for fluidic fields as follows:

$$\nabla \times (\frac{1}{\mu_0}\mathbf{B} - \mathbf{M}) - \sigma \mathbf{v} \times \mathbf{B} = \mathbf{J} \quad (1)$$

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T = \frac{1}{\rho c_v}[\nabla \cdot (k_T \nabla T)] + \phi_d \quad (2)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (3)$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla)\mathbf{v} = \nabla \cdot [\eta(\nabla \mathbf{v} + (\nabla \mathbf{v})^T)] - \nabla p + \mathbf{F} \quad (4)$$

where μ_0 is the magnetic permeability in air, $\mathbf{B}$ is the magnetic flux density, $\mathbf{M}$ is the magnetization, σ is the electrical conductivity, $\mathbf{v}$ is the fluidic velocity, $\mathbf{J}$ is the current density, T is the temperature, ρ and c_v are the mass density and specific heat capacity, respectively. k_T is the thermal conductivity, ϕ_d reflects the electrical power dissipation term in the medium, η is the dynamic viscosity, p is the pressure, and $\mathbf{F}$ is the body force density.

To examine the magnetic convection effects, the body force density should be calculated by using the Kelvin force density. The temperature-dependent Boussinesq buoyant force was also included as follows [5]:

$$\mathbf{F} = \mu_0(\mathbf{M} \cdot \nabla)\mathbf{H} + \rho\beta(T - T_{ref})\mathbf{g} \quad (5)$$

where β is the thermal expansion coefficient, T_{ref} is the buoyant reference temperature, and $\mathbf{g}$ is the acceleration due to gravity. The Kelvin force density as a function of temperature, volume fraction, and nanoparticle size was used as the driving source for the magnetoconvection phenomena in the magnetic nanofluids.

III. EXPERIMENTAL AND NUMERICAL RESULTS FOR TEMPERATURE RISE WITH A SOLENOID COIL SYSTEM

To measure the temperature rise for the solenoid system with different media, an experimental setup was constructed; the setup was controlled by a LabVIEW program and equipped with a K-type thermocouple, as shown in Fig. 1.

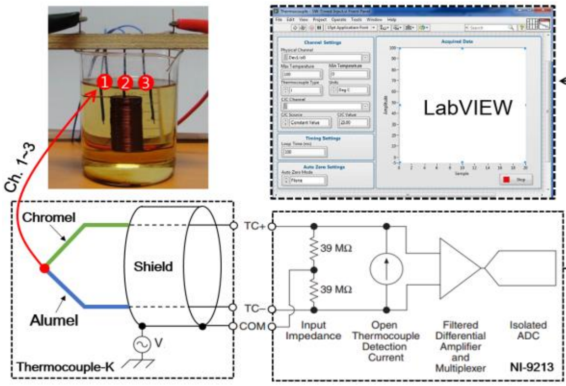


Fig. 1. Schematic diagram of a simple solenoid system with data acquisition setup for the temperature measurement.

To predict the cooling performance of the solenoid coil immersed in the vegetable oil based magnetic nanofluid, a coupled magnetic-thermal-fluidic analysis was developed to estimate the temperature rise. As shown in Table I, the material properties were obtained from [4]-[6]. Fig. 2 shows the numerical analysis model and boundary conditions for the solenoid operating at DC 6 A. Fig. 3 shows the distributions of the temperature field with the conventional vegetable oil; the hot-spot point was point (2) with a temperature of 313.5 K. Hence, the vegetable oil with a MNP volume fraction of 7% exhibited almost the same temperature distribution, but the hot spot was at 308 K. Fig. 4 shows that the experimental results obtained for the temperature rise agreed well with the simulation results. This cooling effect can be explained by the magnetoconvection phenomena resulting from the presence of MNPs.

TABLE I
MATERIAL PROPERTIES OF EACH DIFFERENT DIELECTRIC LIQUIDS

Name	Vegetable Oil	Vegetable Oil with MNP (7%)
Density [kg/m^3]	935.93-0.6376T	1221-0.63T
Thermal Conductivity [W/(m·K)]	0.165+0.00009T	0.154
Heat Capacity [J/(kg·K)]	1715+6.75T	1840+8.01T
Flow Viscosity [Pa·s]	0.134·e$^{-0.03T}$	0.00727

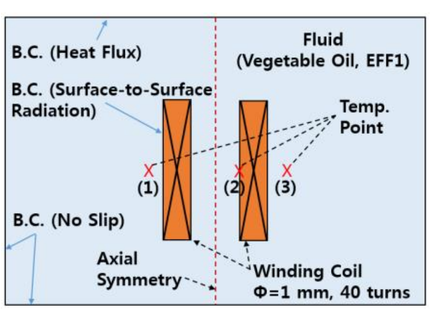
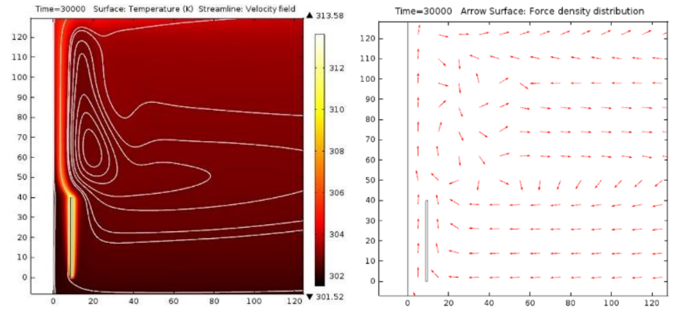


Fig. 2. Two-dimensional axial geometry and boundary setup for numerical analysis.



(a) Distribution of temperature and flow streamline
(b) Total force distribution by magnetoconvection effect

Fig. 3. Steady-state temperature and flow velocity distribution of conventional vegetable oil by forced magnetoconvection effect. The total force is given by the summation of the buoyant and Kelvin forces.

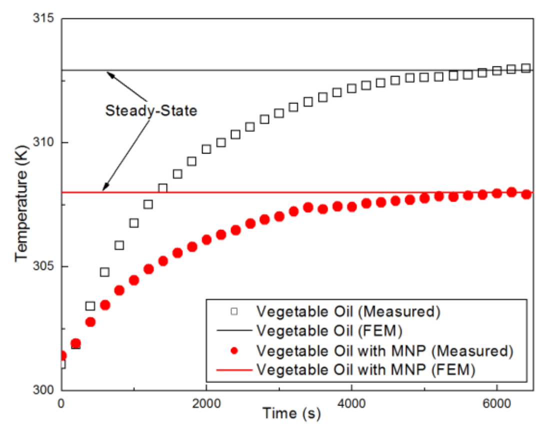


Fig. 4. Determined temperature rise at conductors with different media, i.e., conventional vegetable oil and vegetable oil with a 7% volume fraction of magnetic nanoparticles.

IV. CONCLUSION

The aim of this study was to examine the cooling performance of a conventional vegetable oil containing MNPs with respect to the temperature rise. Additionally, we also built a coupled magnetic-thermal-fluidic analysis technique for predicting the temperature rise with the vegetable oil based magnetic nanofluid. The results indicate that the cooling performance in a simple solenoid system is suitable to verify the numerical setup. In a future extended paper, we will investigate quantitatively this phenomenon in detail.

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