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BOUYANCY-INDUCED CONVECTIVE HEAT TRANSFER IN CYLINDRICAL TRANSFORMERS FILLED WITH MINERAL OIL WITH NANO-SUSPENSIONS

D.G. Walker*
Department of Mechanical Engineering
Vanderbilt University
Nashville, TN 37235-1592
email: greg.walker@vanderbilt.edu

J.L. Davidson, P.G. Taylor and K.L. Soh
Department of Electrical Engineering
Vanderbilt University
Nashville, TN 37235

Bruce Rogers
Tennessee Valley Authority
Chattanooga, TN 37415

ABSTRACT

The heat transfer characteristics of a transformer using both standard mineral oil and nanodiamond oil was investigated numerically and compared to experimental measurements. The results of the model agree well with the standard oil measurements and with theoretical convective flows from the literature. However, the simulations could not predict the magnitude of the temperature variation in the nanodiamond oil, although the appropriate trend was observed. Because properties of the nanodiamond transformer oil are not well known, good agreement is not expected. Nevertheless, nanodiamond in transformer oil shows enhanced heat transfer performance over standard transformer oil.

NOMENCLATURE

A cross-sectional area (m^2)
Bi Biot number
c_p constant pressure specific heat ($J/kg\,K$)
g gravitational acceleration ($9.8\,m/s^2$)
h heat transfer coefficient ($W/m^2\,K$)
k thermal conductivity ($W/m\,K$)
L characteristic length (m)
Nu Nusselt number
P heat generation (W)
Pr Prandtl number
q'' heat flux (W/m^2)
Q heat transfer (W)
Ra Rayleigh number
t time (s)
T temperature (K)
V velocity (m/s)
α thermal diffusivity (m^2/s)
β coefficient of thermal expansion ($1/K$)
η transformer efficiency
Γ aspect ratio
ν kinematic viscosity (m^2/s)
ρ density
θ temperature difference (K)

INTRODUCTION

Modern power distribution relies on a tremendous number of oil-immersed transformers for stepping voltages between transmission and utility modes. For example, the Electric Power Research Institute (EPRI) estimates approximately 3.5 billion gallons of mineral oil are in use as an electrical dielectric [1]. The oil provides convective cooling as well as electrical discharge protection. Maintaining low core temperatures of transformers is crucial for efficiency and longevity of service. In fact, a one degree (Celsius) temperature reduction in the core can result in a 10% increase in the life of a typical transformer [2]. Although existing mineral oil solutions have provided adequate thermal protection for decades of reliable service, all oils are terrible heat transfer fluids. The advent of nanofluids could provide significant enhancement in bulk heat transfer properties, which would

*Address all correspondence to this author.

ultimately extend the service life of oil-immersed equipment.

Nanofluids are colloidal suspensions with dispersed nanoparticles, which are known to enhance the thermal conductivity of a base fluid [3]. Intuition suggests that a higher thermal conductivity would decrease the winding temperature for a given load. On the other hand, the load of a particular piece of equipment retrofit with a nanofluid could conceivably be increased without exceeding the nameplate specifications. Either way, the nanofluid would result in a tremendous cost recover by reducing the maintenance and replacement costs of aging equipment. However, because the nature and behavior of nanofluids is generally not well understood [4], the side effects of adding nano-particulate to transformer oil must be examined carefully.

Upon adding nano-particulate to transformer oil, transformer performance may be governed by a variety of effects other than enhanced thermal conductivity. Furthermore, these effects can be critical to the safe, efficient and reliable operation of the equipment. In general the issues associated with nanofluids and oil-immersed transformer performance can be categorized into electrical, mechanical, chemical and thermal. Electrical effects include dielectric strength, discharge susceptibility and magnetic interference, for example. Chemical effects include stability, suspension, clustering and reaction with immersed components (including insulative paper). Mechanical effects include settling, viscosity, infiltration, lubrication and clogging. The present work, however, is primarily concerned with thermal performance, which is determined by not only the thermal conductivity but also the viscosity, specific heat and thermal expansion of the nanofluid.

For the present investigation, mineral oil with added nanodiamond is considered (ndxo). Nanodiamond was chosen because of its unique combination of properties. As a wide band gap semiconductor, diamond has few free electrons and therefore exhibits a low electrical conductivity, which makes it an excellent dielectric. Normally, materials with small electrical conductivity also have small thermal conductivity (Wiedeman-Franz law). However, because of diamond's strong atomic bonds, thermal energy is transferred efficiently by lattice vibrations as opposed to electrons, and it's thermal conductivity is particularly large even compared to most metals. This combination of large thermal conductivity and small electrical conductivity make it a candidate for thermal enhancement of a dielectric fluid.

The present work considers the convective heat transfer in a pole-mounted transformer due to adding nanodiamond to mineral oil. Dimensional analysis suggests that the ratio of temperature rises can be expressed in terms of Nusselt numbers and thermal conductivity. Using typical correlations (1/3 power law) to obtain a functional relationship for material properties and assuming the change in specific heat is negligible, then

$$\frac{\Delta T_{\mathrm{xo}}}{\Delta T_{\mathrm{ndxo}}} = \frac{\mathrm{Nu}_{\mathrm{ndxo}} k_{\mathrm{ndxo}}}{\mathrm{Nu}_{\mathrm{xo}} k_{\mathrm{xo}}} = \left(\frac{k_{\mathrm{ndxo}}}{k_{\mathrm{xo}}}\right)^{2/3} \left(\frac{\nu_{\mathrm{xo}}}{\nu_{\mathrm{ndxo}}}\right)^{1/3} . \qquad (1)$$

If the ratio is greater than one, then the ndxo provides enhanced cooling. From this analysis, the viscosity would have to increase by 2.25 times to overcome a thermal conductivity enhancement of 1.5. This suggests that the nanodiamond will enhance the overall cooling performance of the transformer system.

First the expected material property changes between straight mineral oil and the nanofluid composed of mineral oil and nanodiamond will be discussed along with some preliminary findings. Secondly, natural convection in the transformer canister resulting from a change in material properties will be estimated to determine the thermal efficacy of using nanodiamond in transformer oil. Because of the approximations in the simulation and assumed conditions of the tests, direct numerical comparisons can not be made. However, trends, scaling and order of magnitude estimates can be made using lumped models to learn something about the performance characteristics of the nanofluid in a transformer.

DIAMOND NANOFLUID

Nanofluids have long been known to increase the effective thermal conductivity of a fluid [5] as described by the classical model [6] for statistically homogeneous, isotropic composite materials with randomly dispersed spherical particles of uniform size [3]. However, this macroscopic theory does not incorporate nanoscale effects, which can produce increases in effective thermal conductivity that are orders of magnitude greater. For example, experimental evidence comes from Eastman et al. [7], who added $< 10\,\mathrm{nm}$ copper particles to ethylene glycol and measured the thermal properties as a function of volume fraction. They found that the thermal conductivity increased linearly with volume fraction and could be enhanced 1.14 times for a volume fraction of 0.5%. This value is for bare copper only; certain treatments can dramatically increase the enhancement factor as described later. Interestingly, this combination of materials is similar in some respects to the mineral oil/nanodiamond combination of interest. That is, the viscosity of mineral oil and ethylene glycol is similar and the thermal conductivity of copper and bulk diamond is also similar. However, the precise mechanisms responsible for the increase of thermal conductivity are still not well understood [4]. In addition, there are significant differences in the materials of the two nanofluid systems. For example, thermal energy in copper is transported via electrons, whereas in diamond it is via phonons. Therefore, drawing conclusions about the oil/diamond nanofluid based on this single data point of ethylene glycol/copper nanofluid would not be prudent.

Clearly factors other than the bulk thermal conductivity of the constituent materials are important. For example, when similar iron particles (instead of copper) are placed in ethylene glycol the enhancement factor is 1.18 (instead of 1.14) [8]. Yet, iron has a much lower bulk thermal conductivity than copper, so the improved enhancement is somewhat counterintuitive. While effects such as liquid-solid interface conductance, particle size, surface coating and agglomeration of particles can affect the thermal conductivity of a nanofluid, Eastman et al. [9] suggest that "the ability of the particles or the liquid to move must play a significant role in thermal transport." While this statement does not necessarily limit the number of mechanisms for enhanced thermal conductivity of nanofluids, it *does* suggest that the role of bulk thermal conductivity of the constituents is not necessarily of prime importance.

In the present study, nanodiamond particles of 10 nm are used and are dispersed using sonication and a surfactant. Evidence shows that surface treatment may have as much to do with the effective thermal conductivity as the bulk material properties. In fact, Masuda et al. [10][1] reported an effective thermal conductivity of oxide nanoparticles to be an order of magnitude larger than that of Lee et al. [11] for the same materials. The two tests differed in particle size and the fact that Masuda et al. [10] used a surfactant. Similar results were obtained for metallic particles (copper in ethylene glycol) when an acid was added to assist in dispersion [7], but opposite effects were observed in some tests with metallic particles [12]. Despite the lack of direct quantification of the mechanism or magnitude of enhancement, the evidence points to an increase in thermal conductivity for diamond in mineral oil.

Based on available tests of other nanofluids and prevailing hypotheses of transport mechanisms, it seems reasonable to assume that mineral oil/nanodiamond system would exhibit a large increase in thermal conductivity. For purposes of later simulations we will assume an enhancement of 1.5, which is representative of a vast majority of the data and commensurate with one example of SiC nanoparticles [13].

Thermal transport is not governed by thermal conductivity alone. For natural convection, the density, viscosity and specific heat are also important. Heat capacity (density times specific heat, ρc_p) and density can be calculated as average heat capacity and density of the constituent materials scaled by the volume fraction. For small volume fractions, then, these quantities do not change significantly from the fluid properties. Although the Einstein model for viscosity suggests that nanofluids will have a higher viscosity than their pure fluid counterparts, the prediction is strictly valid for small volume fractions only (< 0.05). Viscosity measurements, however, are perhaps even less understood [9]. In fact some studies show an increase [14] and others show a decrease [3] with the addition of nanoparticulate. Furthermore, the change in viscosity is strongly dependent on the type and amount dispersion agent. Our *preliminary* tests have indicated that the effect of nanodiamond in mineral is to increase the viscosity slightly. So as a first approximation for simulation sake, we will assume that the viscosity is not affected by low volume fraction of nanoparticulate. Ongoing tests are being performed to verify this assumption and to quantify the change in several important properties including viscosity, dielectric strength and thermal conductivity.

[1] The text could not be located, so this claim is based purely on the report by Eastman et al. [9].

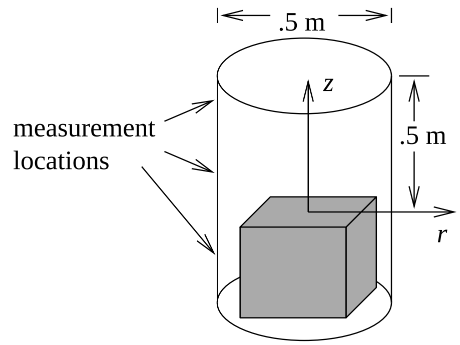


Figure 1. SCHEMATIC AND DIMENSIONS OF THE "POLE PIG" TRANSFORMER CANISTER AND DIMENSIONS FOR THE COMPUTATIONAL DOMAIN.

CONVECTION MODEL

Convection occurs within the transformer canister, which will be modeled as a cylinder whose diameter and height are $D = 50\,\text{cm}$ and $L = 50\,\text{cm}$ respectively, so the aspect ratio is $\Gamma = D/L = 1$ as shown in Figure 1. The overall heat transfer can be described by the Nusselt number

$$\text{Nu} = \frac{q''L}{k\Delta T}, \tag{2}$$

where q'' is the heat flux and k is the thermal conductivity of the fluid. The ΔT in this expression is normally calculated between the top and bottom surface. In the present case, we will assume the temperature difference to be between the maximum core temperature (located near the origin of the coordinate axis) and an estimate of the average oil temperature along the inside wall, which should be the coolest temperature in the system. The buoyancy is described using the Boussinesq approximation. Experimental and theoretical correlations from the literature usually express the non-dimensional heat transfer as a function of the Rayleigh and Prandtl number, i.e., $\text{Nu} = \text{Nu}(\text{Ra}, \text{Pr})$.

In the simulation, the bottom of the cylinder coincides with the top of the transformer. Therefore, we are considering the natural convection above the transformer and the transformer generates the heat that is imposed on the bottom surface of our computational domain. Consequently, the thermal boundary condition at the bottom of the domain is uniformly heated. The top is a free surface and the heat transfer is assumed negligible. Heat is lost, then, out the sides due to external convection in air, assuming the sidewall resistance of the thin aluminum casing is negligible. The external heat transfer coefficient is derived from the correlation for natural convection on a vertical plate (found in any undergraduate heat transfer text)

$$\overline{\mathrm{Nu}_L} = 0.68 + \frac{0.67\mathrm{Ra}_L^{1/4}}{\left[1+\left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{4/9}}, \tag{3}$$

where $\mathrm{Ra}_L = g\beta\Delta T L^3/\nu\alpha$. L is the height of the cylinder, g is acceleration due to gravity, and $\Delta T = 40\,\mathrm{K}$ is assumed. For air, $\beta = 0.0033\,\mathrm{K}^{-1}$ is the thermal expansion coefficient, $\nu = 15.89 \times 10^{-6}\,\mathrm{m}^2/\mathrm{s}$ is the kinematic viscosity, $\alpha = 22.56 \times 10^{-6}\,\mathrm{m}^2/\mathrm{s}$ is the thermal diffusivity and $\mathrm{Pr} = 0.7$ is the Prandtl number. If the thermal conductivity of air is $k_a = 26.3 \times 10^{-3}\,\mathrm{W/mK}$, then the external heat transfer coefficient is found from the average Nusselt number as

$$\overline{h_e} = \frac{\overline{\mathrm{Nu}_L}\, k_a}{L} \approx 4\,\mathrm{W/m^2K}, \tag{4}$$

and the energy is convected to ambient air $T_\infty = 300\,\mathrm{K}$ The hydrodynamic boundaries are no slip on the bottom and sides with a zero shear on the top surface.

Initial tests of the 25kVA-rated transformer were performed at $P = 5\,\mathrm{kW}$. Therefore, if the transformer is $\eta = 90\%$ efficient,[2] the heating on the bottom surface is $q'' = P(1-\eta)/A_{\mathrm{bottom}} \approx 2500\,\mathrm{W/m^2}$. Nominal temperature independent material properties were considered for mineral oil ($\rho = 980\,\mathrm{kg/m^3}$, $\mu = 0.03\,\mathrm{kg/m\,s}$ or $30\,\mathrm{cP}$, $k = 0.1\,\mathrm{W/mK}$, $c_p = 1966\,\mathrm{J/kgK}$, $\beta = 0.001\,\mathrm{K}^{-1}$).[3] All subsequent results are based on these approximate values.

The three dimensional computational grid contains 50 nodes in the vertical direction with automatic refinement at the top and bottom where we expect large gradients. The circumference is divided into 100 segments. The radial ends are discretized using an unstructured quadrilateral mesh that yields approximately 50 discretizations across the diameter. Again refinement was used at the edges. The volume was meshed using unstructured quadrilateral elements.

[2]This value is recommended by the manufacturer(GE).

[3]These properties are based on values available online (www.radcoind.com). However, because they are temperature independent, they does not precisely model an actual oil.

Table 1. NON-DIMENSIONAL PARAMETERS USED TO COMPARE NANODIAMOND TRANSFORMER OIL WITH PLAIN TRANSFORMER OIL. THESE VALUES CONTAIN A 1.5 INCREASE IN THERMAL CONDUCTIVITY, NO CHANGE IN THE VELOCITY AND THE SAME ΔT.

	Ra	Pr
xo	1.5×10^{10}	590
ndxo	1.0×10^{10}	393

EXPERIMENTAL DESCRIPTION

The experimental setup is described elsewhere [15], but consists of 2 identical transformers connected in parallel so that each experiences an identical load. The only difference between the two test rigs is the nanodiamond additive in one of the containers. Temperature readings from calibrated thermocouples were collected on the outside of the canister as shown in Figure 1. In addition, internal probes measured oil temperatures about 2 cm inside the canister wall at the same vertical locations as the external sensors. It should be noted that the actual size of the canister is slightly smaller than our simulation (for a variety of reasons). Temperatures at all locations (including ambient) were collected each second for five days, starting with the entire setup at ambient temperature (no load).

The suspending agent used to make the mineral oil/nanodiamond suspension is CAB-O-SIL®treated fumed silica.

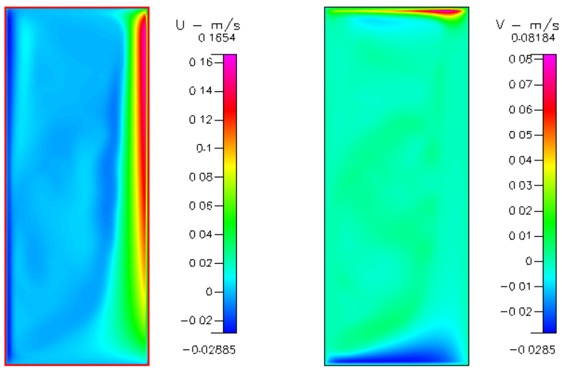
RESULTS

Ultimately we want to see whether the nanodiamond in transformer oil (ndxo) can reduce the maximum fluid temperature compared to pure transformer oil (xo). Dimensional analysis of the heat transfer suggests that by increasing the thermal conductivity by 1.5 and keeping the viscosity the same, the maximum temperature rise for a given load will decrease by 30% (see equation 1). Actually, this estimate could be considered conservative. According to Grossman et al. [16] and material properties listed in Table 1, the flow is in a regime where the bulk motion governs the Reynolds number, but the heat transfer is largely governed by the boundary layer and not the bulk flow. An appropriate correlation for this regime is [16]

$$\mathrm{Nu} = 0.33\mathrm{Ra}^{1/4}\mathrm{Pr}^{-1/12}. \tag{5}$$

Now the ratio of temperature rises scales as the conductivity enhancement to the 5/6 power (instead of 2/3), yielding a more significant cooling effect.

Unfortunately, the reality of natural convection is not that simple and simulations should be performed to estimate the heat



(a) (b)

Figure 2. VELOCITY MAGNITUDE FOR TWO-DIMENSIONAL SIMULATION. (A) AXIAL VELOCITY, (B) RADIAL VELOCITY. (RIGHT SIDE IS ALONG CENTERLINE.)

transfer. Furthermore, realize that the present case can not be compared directly to traditional Rayleigh-Bénard convection because the side walls interact with the flow hydrodynamically and cooling occurs on the side walls, not the top surface [17]. The good news is that the exponent in the power law for the Nusselt number of *any* flow regime is always less than unity [16] (and greater than zero). Therefore, as long as the thermal conductivity is the only influence on the flow, we can expect enhanced cooling.

Comparison to theory

In steady-state, we would expect the fluid to rise in the center of the cylinder and fall along the outside because the cooling takes place on the side walls. And in fact this is precisely what we find from two-dimensional simulations as shown in Figure 2. However, the simulations had trouble converging and solutions were only obtained for certain combinations of “lucky” parameters. Therefore, the results are subject to further analysis. Nevertheless, the simulated flow patterns and temperature distributions match our intuition in that plumes appear from the bottom and slowly vanish as the heat diffuses. These features in the flow suggest that the flow is probably unstable, and a steady-state solution can not generally be obtained. This behavior is typical of many natural convection flows such as Rayleigh-Bénard convection for particular values of Prandtl and Rayleigh numbers. Based on $\mathrm{Pr} \approx 590$ and $\mathrm{Ra}_L = 1.5 \times 10^{10}$, the convection regime is on the threshold of *time-dependent* convection and *turbulent* convection according to Busse et al. [18]. Either way, this means that a steady-state solution may not exist.

Due to the inherent instabilities in the flow that break the symmetry [19], two-dimensional simulations do not make much sense [20]. Therefore, full three-dimensional transient simulations were performed. Figure 3 shows a vertical cut-plane through the centerline of the canister illustrating the lack of symmetry about the axis in a full three-dimensional simulation. Results shown are at $t = 2\,\mathrm{hr}$ unless otherwise indicated.

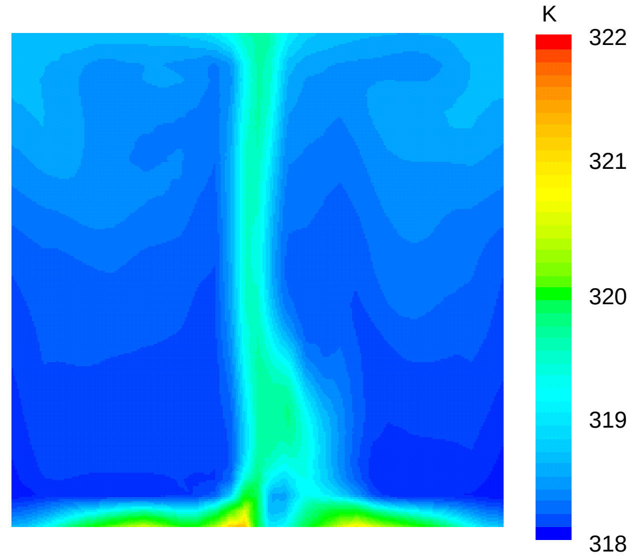


Figure 3. TEMPERATURE IN A VERTICAL CUT-PLANE THROUGH THE CENTERLINE SHOWING THE LACK OF SYMMETRY IN A THREE-DIMENSIONAL SIMULATION.

The three-dimensional simulations show that the flow is characterized by plumes emanating from the bottom surface and that the temperature everywhere in the canister is approximately constant except on the sidewalls and bottom surface. Along these surfaces, a thermal boundary layer develops that is very much thinner than the dimensions of the container. These large gradient regions govern the heat transfer so conduction is the dominant mechanism, which can be confirmed by analysis from Gelfgat et al. [19]. This feature suggests that a higher conductivity fluid such as ndxo would indeed improve the cooling of the transformer, possibly above that predicted from the dimensional analysis.

To further validate the simulations, we compared the speed of the rising plumes to analysis from Kaminski et al. [21] who reported findings on laminar plumes in high-Prandtl number fluids. They suggest that for $\mathrm{Pr} = 590$, the plume velocity can be given as

$$V_p = f(\mathrm{Pr})\sqrt{\frac{g\beta Q}{\rho \nu c_p}}, \tag{6}$$

where f is an empirically determined function of Pr. In the present case, $f(\mathrm{Pr}) \approx 1.0$. The foregoing expression depends on the plume cross sectional area ($Q = q''A$), which is unknown

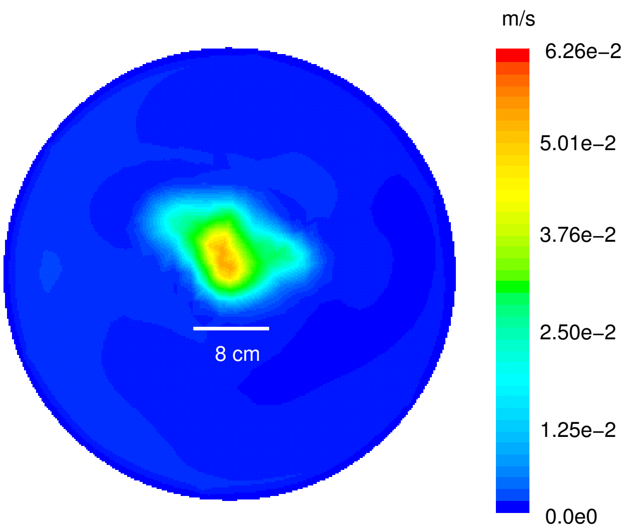


Figure 4. AXIAL VELOCITY (OUT OF THE PAGE) IN A HORIZONTAL CUT-PLANE THAT IS 20 CM ABOVE THE BOTTOM. THE HIGH-VELOCITY REGION IS A PLUME WHOSE VELOCITY AND AREA MATCH THOSE PREDICTED BY GELFGAT ET AL. [19].

but can be approximated from the simulations. For a simulated plume velocity of $V_p \approx 0.04\,\mathrm{m/s}$, the plume radius would have to be $r \approx 4\,\mathrm{cm}$. Figure 4 shows the velocity in a horizontal plane 20 cm above the bottom. The high-velocity region represents a plume whose area is commensurate with that predicted from the approximate solution.

During the transient simulation, the temperature difference between the hottest and coldest point in the container remains approximately 5 K, despite the fact that the average temperature rises nearly 100 K. In other words, this system appears to behave as a lumped system where the average temperature compared to ambient is

$$\theta = \frac{Q}{hA}\left[1 - \exp\left(-\frac{hA}{\rho V c_p}t\right)\right], \tag{7}$$

where Q is the total heat transfer from the transformer. To check the validity of this approximate analysis, we calculate a Biot number defined as the ratio of temperature rise in the transformer oil to the average temperature of the oil compared to ambient.

$$\mathrm{Bi} = \frac{T_{\text{oil, hot}} - T_{\text{oil, cold}}}{T_{\text{oil, avg}} - T_{\infty}} \approx 0.06 \tag{8}$$

A calculated value of $\mathrm{Bi} < 0.1$ is usually regarded as small enough to proceed with a lumped analysis. From this analysis we can predict the maximum temperature rise to be $\theta_{max}(t \rightarrow \infty) = Q/hA = 67.2\,\mathrm{K}$ and the rate of temperature rise to be $\theta'(t=0) = Q/\rho V c_p = 0.00264\,\mathrm{K/s}$. This initial rate of temperature rise ($0.00297\,\mathrm{K/s}$) agrees well with the lumped model. However, notice the startup behavior (1 hour) in Figure 5, which shows the temperature of the bottom center of the oil container. This location is presumably the hottest point in the simulation. We notice that the temperature rises very rapidly when conduction dominates until convection is established. Then the temperature rises much more slowly, more like our lumped model.

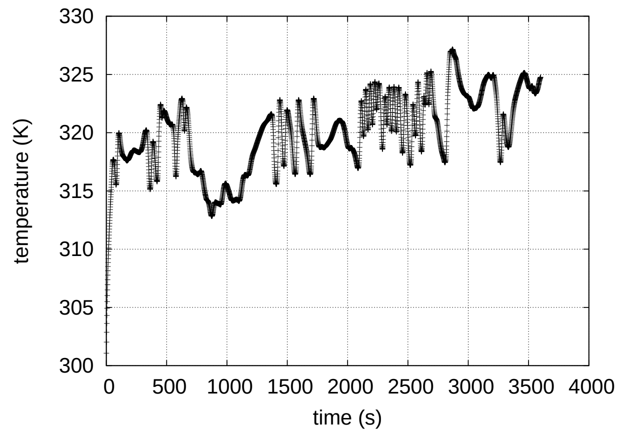


Figure 5. TEMPERATURE OF THE BOTTOM CENTER POINT IN THE CYLINDER AS A FUNCTION OF TIME IN THE STARTUP PERIOD.

Comparison to measurements

In the simulation, the standard oil required approximately 20.5 hours to reach a steady operating condition. Tests on a 25kVA transformer loaded at 5kW and instrumented with external thermocouples took approximately 10 hours to reach a steady operating state. However, realize that the simulation has a volume that is twice that of the actual test. Therefore, we would expect the simulation to require twice the time for a given load.

Also, a total 50 K temperature rise was seen in the measurements for all sensors, which is smaller than what we expect to observe in the simulation. From the temperature measurements, each sensor recorded approximately the same rate of temperature increase ($\sim 0.00278\,\mathrm{K/s}$), which matches the simulations very well. Notice that we also saw a very small difference between all the sensors (internal and external) indicating that the system does not maintain large gradients as was also found in the simulation.

The test involving the nanodiamond fluid, however, demonstrated a significantly different temperature signature that is not immediately apparent in the simulations. In essence, the temperature difference across the sensors was nearly an order of magnitude larger than the measurements obtained from the transformer without nanodiamond. In this case, the lumped model can not be used to estimate the transient behavior of the system. From the measurements, we are unsure whether the average temperature is higher or lower because we only have three interior probes. From the simulation that incorporates the lower Rayleigh number and Prandtl number (ndxo), we observe higher temperatures near the top of the canister and lower temperatures near the bottom as in Figure 3, which corresponds to the measurements, but the magnitude of the difference was not as large as the measurements.

CONCLUSIONS

Based on preliminary experimental evidence and comparison to other similar nanofluids, the application of nanodiamond to mineral oil should increase the effective thermal conductivity of transformer oil by a factor significantly greater than one. This change in thermal conductivity is accompanied by a change in viscosity due primarily to the surfactants used to maintain a suspension.

The heat transfer in the transformer canister was modeled using a finite element naturally convected flow solver. The predictions agree with flow regimes and flow structures found in the literature, a simple lumped model and measurements made on a transformer with standard transformer oil. Simulated temperatures, when compared to measurements of nanodiamond in transformer oil, are in agreement only in the trend. The magnitude of the measurements was not captured well. This deviation is likely the result of several approximations in the simulation. For example, we do not know the properties of the nanodiamond suspension. Until we can obtain reliable material properties for the nanodiamond, we can not expect accurate simulations. In addition, we have not incorporated temperature dependent properties. The viscosity of oils is know to have a strong dependence on temperature even for modest temperature ranges considered in the present context. Furthermore, we know even less about how nanodiamond might change the viscosity at different temperatures. Therefore, the lack of agreement is not surprising.

Nevertheless, the change in flow properties results in a decrease in the maximum fluid temperature for a given transformer dissipation rate. However, further simulations with adequate material properties are required to verify that the nanodiamond fluid performs as expected. Based on out preliminary analysis, we believe nanodiamond should be considered for a transformer oil additive to increase the service life of oil-immersed equipment. Additional tests such as discharge, settlement and reactivity must be performed before the material can be placed into service.

ACKNOWLEDGEMENTS

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