Investigation on heat transfer characteristics of nano titania added transformer oil with hotspot temperature

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Abstract
The heat transfer characteristics of nanofluid produced by mixing nano titania with transformer oil, facilitated by addition of surfactants are analyzed. A 2D model is used to analyze the heat transfer and fluid flow characteristics of nano fluid for understanding the formation of hot spots in the chamber filled with nanofluid. Governing equations for conservation of mass, momentum and energy for capturing the above characteristics are described. The temperature along the vertical mid line from the hot spot are measured experimentally and compared with simulation results. Temperature distribution obtained for nanofluid and transformer oil under both steady and transient state has revealed high rate of heat dissipation in nanofluid. Streamlines have shown the presence of press board affects flow in the bulk of the cavity. Nusselt number estimated across the edges of the hot spot has shown higher convective heat transfer in nanofluid.

1. Introduction
The transformer is the most crucial and expensive component in the power system network. With the increasing level of power transmission, the power rating of the transformer is getting enhanced and thermal load limit is one of the major concerns to all the transformer manufacturers. Transformer oil is conventionally used as a coolant as well as an insulant. Mineral oil is conventionally used as a coolant as well as an insulant in transformers, which takes away the heat by conduction and convection process [1].

Hotspot in transformers is one of the major concern and the temperature can rise up to 200 °C [2] In addition, it affects the loading capacity of transformers [3]. In order to reduce the size, weight and meet the growing population demand, there is a need for the development of a class of insulation system which can provide enhanced dielectric and heat transfer properties. Maxwell [4] had predicted that thermal conductivity of base fluid can be enhanced by mixing micron-sized solid particles of higher thermal conductivity.

Researchers worldwide have studied dielectric properties of transformer oil based nanofluid using insulating, conductive and semi-conductive nanoparticles and have demonstrated its improved dielectric strength and increased heat transfer capability of the liquid [5–9]. Du et al [10] studied both thermal and dielectric properties of transformer oil based nanofluid using boron nitride (BN) and Fe₃O₄ nanoparticles. They observed an increase in thermal diffusivity, thermal conductivity and breakdown strength.

TiO₂ nanoparticle have high dielectric constant with electron affinity and high thermal conductivity [11]. In addition, proper dispersion of nano fillers in transformer oil, it enhances the dielectric strength of the nano fluid [12]. Emara et al have indicated that titania nano filler can reduce the impact of thermal ageing of transformer oil [13]. Olmo et al have used titania nano filler in ester fluid and have observed increased breakdown strength but a marginal reduction in thermal conductivity is observed compared to base fluid [14]. Having known all these factors, it has become essential to understand the heat transfer and fluid flow characteristics of the nano fluid formed by mixing the optimised quantity of titania and surfactant in transformer oil.
Fontes et al. [15] performed the numerical study of natural convection of transformer oil based nano fluid with multi-walled carbon nanotubes and observed an increment in the Nusselt number and convection characteristics as compared to base transformer oil.

Having known all this, in the present study, we have made an attempt to understand the following important aspect: a model analyzed through Ansys-Fluent software, simulating hotspot in the chamber filled with prepared nano fluid to understand its heat transfer, fluid flow characteristics and experimental verification of the simulation data.

2. Experimental setup

2.1. Sample preparation

The nano fluid is prepared using titania nanoparticles (<15 nm, anatase) with Cetyl Trimethyl Ammonium Bromide (CTAB) as a surfactant. The base fluid used is transformer oil. Swati et al have concluded that by adding 1 weight % of surfactant in 0.0061 weight % of titania in transformer oil have shown uniform particle distribution with high stability [16]. In addition, the nano fluid exhibit low interfacial tension and low turbidity with high flash point [17]. The same nano fluid composition and procedure is utilized in order to ensure stability of the nano fluid investigated in the present work. At first, 1 wt% of surfactant is added to transformer oil and mixed using magnetic stirrer, to that 0.006 wt% of dried titania nanoparticles are added and the entire mixture is mixed using magnetic stirrer for 30 min followed by ultra-sonication for 3 h (Sonics Vibra-cell sonicator 500 W, 20 kHz at 40 °C). The schematic diagram of the preparation process is shown in figure 1.

2.2. Experimental setup for measurement of temperature

Figure 2 shows the experimental setup for the measurement of the temperature of oil along the vertical midline in the presence of a heating element. The fluid is kept in a 0.15 m x 0.15 m x 0.15 m cubical tank made up of mild steel. The hotspot of 433 K is created using a micro-ceramic heater (15 V, 15 W, 1.75 mm, and Tmax—873 K) with watt density of the heater element 60 W cm\(^{-2}\) (Model No. MS-M5, Sakaguchi E.H. Voc Corp, Japan). The constant temperature of the heating element is maintained using a thermostat and temperature controlled relay arrangement. The input voltage of 15 V is given to the heating element using a variable auto-transformer (Max load- 15 A, Max kVA- 4.05, 50/60 Hz). The temperature along the vertical midline is measured using a digital thermometer by varying its position along the vertical midline.
3. Mathematical modelling

Two-dimensional numerical simulations in a square cavity have been carried out using finite volume based commercial software Ansys Fluent 18.2. The transformer tank with insulant is modelled as a square cavity of dimension 2 m × 2 m. The walls of the square cavity are modelled as the isothermal surfaces of 303 K temperature, with the hotspot of dimension 0.01 m × 0.005 m and pressboard of thickness 0.001 m located at different positions. Table 1 summarizes the analysis carried out with different arrangements of hotspot and pressboard position in the modelling studies. The gap between the hotspot and pressboard is taken as 0.02 m and hotspot temperature is taken as 433 K. The initial temperature of the oil is taken as 333 K.

Figure 3 shows the computational domain with boundary conditions of square cavity in presence of hotspot for cases 1, 2, 3 and 4 with horizontal/vertical hotspot at 0.1 m, 1 m from bottom. Figure 4 shows the schematic diagram for cases 5, 6, and 7 where hotspot is present along with pressboard material. It represents the computational domain with boundary conditions of square cavity in presence of hotspot and pressboard (a) horizontal hotspot with pressboard on two sides (b) horizontal hotspot with pressboard on four sides and (c) horizontal hotspot enclosed in pressboard from all sides.

### Table 1. Various cases study with different position of hotspot and pressboard arrangement.

| Case | Description |
|------|-------------|
| 1    | Horizontal hotspot placed at 0.1 m from the bottom |
| 2    | Horizontal hotspot placed at 1 m from the bottom |
| 3    | Vertical hotspot placed at 0.1 m from the bottom |
| 4    | Vertical hotspot placed at 1 m from the bottom |
| 5    | Horizontal hotspot placed at 1 m from the bottom with pressboard on two sides |
| 6    | Horizontal hotspot placed at 1 m from the bottom with pressboard on four sides |
| 7    | Horizontal hotspot placed at 1 m from the bottom enclosed within pressboard |

3.1. Governing equation

Computations are performed for two dimensional, unsteady flow of fluid undergoing natural convection in a square cavity [18]. The governing equations for conservation of mass, momentum and energy are as follows [19].

- **Continuity equation**

  \[
  \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \tag{1}
  \]

  Where \( \rho \) is the density of the fluid in \( \frac{\text{kg}}{\text{m}^3} \) and \( \vec{V} \) is the velocity vector.
Momentum equation
\[
\frac{\partial \rho}{\partial t} \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla P + \nabla \cdot (\nabla \mathbf{V} - \rho \mathbf{g})
\]  
(2)
Where \( P \) is the static pressure, \( \rho \mathbf{g} \) is the gravitational body force and \( \nabla \mathbf{V} \) is the stress tensor which is calculated as follows
\[
\nabla \mathbf{V} = \mu \left[ (\nabla \mathbf{V} + \nabla \mathbf{V}^T) - \frac{2}{3} \nabla \mathbf{V} I \right]
\]  
(3)
Where \( \mu \) is viscosity.

Energy equation
\[
\frac{\partial (\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p \mathbf{V} \mathbf{T}) = \nabla \cdot (K \nabla T)
\]  
(4)
Where \( c_p \) is the specific heat capacity, \( K \) is the thermal conductivity and \( T \) is the temperature.

3.2. Boundary conditions
The wall of the transformer is assumed to be at isothermal condition and atmospheric temperature of 303 K is imposed on the entire wall. The hotspot which is taken as a rectangle surface which is assumed to be at 443 K. Transformer oil and nanofluid prepared with titania nanoparticles are used as the coolant for the hotspot, the properties of which are described in Table 2. The thermal conductivity and specific heat of the nanofluid samples are measured using Hot disk Transient Plane Source 500 thermal constant analyzer. Dynamic viscosity of nanofluid is measured by stress-controlled rotational rheometer MCR 301 (Anton Paar) using cone - plate.
(CP25-1) geometry with a shear rate of 100 per second. The density of the nanofluid is measured using Density and Sound velocity meter (DSA 5000 M, Anton Paar) which works on the principle of oscillating u-tube, can measure the density precisely in the 0–3000 kg m\(^{-3}\) range.

4. Results and discussions

4.1. Experimental verification

In the present study, to compare the experimental results with simulation results, only the 2D model is carried out with insulant modeled as a square cavity of dimension 0.15 m \(\times\) 0.15 m. Essentially the model is considered to know the vertical variation in temperature due to hotspot formation. The walls of the square cavity are modeled as the isothermal surfaces of 303 K temperature, with the hotspot temperature at 433 K. The experimental studies are carried out for six times, to measure the local temperature at vertical distances from the hot spot by using digital thermometer. Every location, the temperature is measured by holding at the specific location for one minute. Also the rate of rise of temperature is not high. The measured temperature showed variation of less than 3% and hence the deviation in measured temperature is not shown and the average value is indicated in figure 5. In simulation studies, the temperature along the center plane is computed which is compared to the temperature measured experimentally, essentially the present model also showed similar trend.

4.2. Heat transfer characteristics of nanofluid

From the simulation data, temperature along the vertical midline is extracted. The temperature variation along the vertical midline in transformer oil and nanofluid for horizontal hotspot (figure 6(a)) and vertical hotspot (figure 6(b)) at 0.1 m and 1 m from the bottom wall at steady state have been shown in figure 6. It is observed that the effect of hotspot on the walls of transformer is more when the hotspot is present near to the bottom wall, whereas heat dissipates uniformly in all directions when the hotspot is present at the middle of the transformer model. The temperature decay characteristics display almost the same variation with horizontal or vertical position hotspot. Based on the above results we can conclude that the presence of hotspot is more detrimental when it is present near the bottom or top wall as compared to the presence of hotspot in the middle of transformer model. It is observed that the temperature decay characteristics is almost the same for transformer oil and nanofluid at steady state.
Pressboard is kept on the sides of the hotspot to understand its impact on the hotspot effect. Figure 7 shows the temperature variation along the vertical midline in transformer oil and nanofluid without pressboard and with pressboard placed on two sides, four sides and when the hotspot is completely enclosed inside the pressboard. If we compare the no pressboard case (configuration 2) and the case with pressboard on two sides (configuration 5), a large difference in temperature of oil along vertical midline is observed in the region outside the pressboard section in the latter case. It is noted that a further marginal reduction in temperature with distance is observed when the pressboards are present on four sides of the hotspot (configuration 6). In the case when the hotspot is enclosed completely within the pressboard (configuration 7), it is observed that temperature of the oil outside the pressboard is lower, but the temperature of the oil enclosed inside the pressboard section is higher than without pressboard (configuration 5). This is because the oil inside the pressboard section is prevented from mixing with the bulk of the fluid which results in the accumulation of the heat in the small region enclosed by the pressboard. Based on the above results it can be said that the presence of pressboard helps in preventing the effect of the hotspot to affect the bulk of insulating material. The temperature dissipation characteristic is nearly the same in transformer oil and nanofluid at steady state as shown in figures 6(a) and (b) and 7.

Figure 8 shows the Nusselt number distribution calculated along the edges of the horizontal hotspot when the horizontal hotspot is present at 0.1 m (configuration 1), 1 m (configuration 2) and when the pressboard is present on two sides (configuration 5) and four sides of the hotspot (configuration 6) and when the hotspot is completely enclosed within the pressboard (configuration 7) at steady state. On comparison of configuration 1 and 2, it is observed that the Nusselt number is higher for configuration 1. This means that the convective heat transfer is more when the hotspot is present at 0.1 m as compared to 1 m. On comparison of the configurations 2, 5, 6 and 7, it is observed that the presence of pressboard above and below the hotspot leads to a decrement in the Nusselt number implying a reduction in convective heat transfer. A further marginal reduction in Nusselt
number is observed with the presence of pressboard on four sides of the hotspot. Nusselt number is observed to be least for the case when the hotspot is completely enclosed within the pressboard. The convective heat transfer is least for this case as the oil enclosed within the pressboard section is prevented from mixing the bulk of the oil which results in lesser temperature difference and hence lower Nusselt number.

Figure 9 shows the streamlines in nanofluid with a horizontal hotspot at centre without any pressboard (configuration 2). Many recirculating regions in the flow are formed which can be clearly seen in the streamline plot.

Figure 10(a) shows the streamlines for the case when pressboard is present above and below the hotspot (configuration 5). The magnified view near the hotspot for this case is shown in figure 10(b). The magnified view of streamlines near the hotspot clearly shows the formation of four recirculating regions of oil flow, near the hotspot. Hence it can be said that the pressboard is altering the flow in the bulk of the cavity when the hotspot is enclosed by two pressboards at top and bottom. Figure 10(c) shows the streamlines for the case when the hotspot is completely enclosed by the pressboard (configuration 7). For this case, magnified view near the hotspot in the section completely enclosed inside the pressboard is shown in figure 10(d). In the outside region, two major recirculating regions of fluid can be observed as shown in figure 10(c) and again two small secondary recirculating regions can be observed in the section completely enclosed within the pressboard as shown in figure 10(d).

The heat flow inside the cavity is driven by natural convection due to the temperature gradient between the hotspot and the walls. Natural convection is the driving force for the oil flow inside the cavity. Initially, the temperature of nanofluid inside the cavity is uniform throughout the cavity. As time progresses, due to the presence of hotspot, the temperature of cooling oil near to it gradually increases. To account for this, transient
simulations are carried out and the initial state of the cavity where the oil temperature is uniform is set as 0 s and flow times refer to the time incremented after the initial condition. Figure 11 shows a typical temperature variation along the midline in the transient state at different flow times. It is observed that temperature is first concentrated at the hotspot and then dissipates slowly due to natural convection and finally reaches a stable value at steady state.

Figure 12 shows the temperature variation along the vertical midline in transformer oil and nano-fluid for configurations 2, 4 and 7 at a flow time of 50 s. It is observed that for all the configurations, the temperature at any point along the Y-axis is lower in nano-fluid as compared to transformer oil. If we compare figures 12(a) and (c), the temperature profile is the same as the effect of pressboard is not felt at a flow time of 50 s. At higher flow time, the presence of pressboard will lead to a further decrement in temperature. As the hotspot temperature is same in both transformer oil and nano-fluid and temperature at any point at any fixed flow time is lower for nano-fluid, it can be stated that the process of heat dissipation is faster in nano-fluid as compared to transformer oil.

Berber et al. [20] studied the thermal conductivity of carbon nanotubes and suggested that the large phonon mean free path could be the reason for the observance of unusual high thermal conductivity. Eapen et al. [21] also suggested that the percolating amorphous like interface can provide a path for heat conduction in a nano-fluid. Zhu et al. [22] studied thermal conductivity of Fe₃O₄ nano-fluid and stated that the formation of clusters and alignment gives a long path for heat transfer which leads to the high thermal conductivity of the nano-fluid. Brownian motion of nanoparticles in nano-fluid and the convection caused by it could also lead to enhancement in thermal conductivity [23].

Figure 13 shows the Nusselt number distribution calculated over the edges of the hotspot at a flow time of 50 s for transformer oil and nano-fluid for all studied configurations. Higher Nusselt number values for
nanofluid signifies that convective heat transfer is higher in nanofluid as compared to transformer oil for all the studied configurations.

5. Conclusions

Based on the above studies, major conclusions are as follows:

- The hotspot near the bottom of the transformer tank is more detrimental to the insulation as compared to the presence of hotspot in the middle of the transformer. The temperature dissipates more uniformly when the hotspot is present in the middle of the transformer as compared to any other position at steady state.

- The presence of pressboard prevents the effect of the hotspot to affect the nearby insulating materials. The temperature of the oil along the vertical midline due to the hotspot is low when the pressboard is present as compared to the no pressboard case at steady state.

- The streamlines in nanofluid with a hotspot at the centre shows that many recirculating regions in the flow are formed. With the presence of pressboard above and below the hotspot, the formation of four recirculating regions of oil flow near the hotspot is observed. For the case when the hotspot is completely enclosed within the pressboard, two regions are formed. In the outside region, two major recirculating regions of fluid can be observed and again two small secondary recirculating regions can be observed in the section completely enclosed within the pressboard. Hence it can be said that the pressboard alters the flow in the bulk of the cavity.

- Transient study results show that temperature along the vertical midline at any particular flow time is lower in nanofluid as compared to transformer oil which show that heat dissipation is faster in nanofluid as compared to transformer oil.

- Nusselt number calculated along the edges of the hotspot indicates that convective heat transfer is more in nanofluid as compared to transformer oil for all the studied configurations.

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