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# Heat Transfer Characteristic of $Al_2O_3$ Nanofluid with Naphthenic Transformers Oil as Base Fluid

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**ABSTRACT**

Power transformers are static electrical devices with the highest costs compared to other components in the power grid system. Damage to these transformers can lead to significant financial losses, emphasizing the need for high efficiency. One method to enhance transformer oil quality is by adding nanoparticles. $Al_2O_3$ is commonly used in transformer oil research due to its ability to increase thermal conductivity and breakdown voltage. In this study, $Al_2O_3$ is incorporated at a concentration of 0.01 wt% and testing equipment is designed to replicate power transformer conditions using an ONAN cooling system. The experimental setup in this study comprised a reservoir made of SUS 304 material, with a thickness of 2 mm and internal dimensions of 300 x 200 x 150 mm. In the center of the reservoir, there is a 650-watt cylindrical heater that simulates a transformer winding. Type K thermocouples monitored temperature changes recorded every 2 seconds over 3 hours. The research results indicate that the most significant temperature increase occurred during the first phase for all samples, with the highest rate recorded at 2.75 °C per minute for a 200-watt input power. Heat transfer coefficient increases with the increasing power in both uninhibited naphthenic mineral oil and nano insulating liquid $Al_2O_3$ 0.01 wt%. The heat transfer coefficient of the nano insulating liquid $Al_2O_3$ 0.01 wt% tends to be greater than that of the base fluid, and the same trend is observed in the Nusselt number. What differs is that the value of Ra decreases with the addition of $Al_2O_3$. The decrease in Ra is an indication that conduction becomes more dominant than convection. Therefore, the use of a small concentration of $Al_2O_3$ is recommended to minimize the impact of the decrease in Ra. Overall, $Al_2O_3$ has great potential for use as a cooling oil in power transformers at low concentrations, but further research is needed on other factors to ensure its suitability for industrial applications.

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## 1. Introduction

Power transformers are static electrical devices with the highest costs compared to other components in the power grid system [1,2]. Damage to these transformers can result in substantial financial losses, highlighting the importance of maintaining high efficiency [3]. One way to improve transformer efficiency is by minimizing energy losses, with a key strategy being the enhancement of the transformer's cooling system. The most cost-effective cooling method is the oil natural air natural (ONAN) system, which operates without the need for additional equipment, such as pumps or fans. This system relies solely on natural oil convection [4,5]. To further increase cooling capacity, radiators are added to the transformer tank. Although additional radiators enhance cooling performance, they also raise costs. Therefore, the quality of transformer oil (TO) is crucial for both cooling efficiency and overall operational performance, emphasizing the need for efforts to improve oil quality.

One method to enhance the quality of TO is by adding nanoparticles (NPs) [6]. Incorporating NPs can improve both the thermal and electrical properties of the oil. $Al_2O_3$ is commonly used in TO research due to its ability to increase thermal conductivity, raise breakdown voltage (BDV), and reduce oil viscosity [7-10]. Nanofluids (NFs) offer better heat transfer than base fluids due to their higher thermal conductivity [11-15]. However, the effectiveness of $Al_2O_3$ depends on its concentration. Excessive amounts may degrade the TO's quality, with optimal performance typically achieved at low concentrations. Beyond a certain threshold, increasing NP concentration leads to a decline in BDV [16].

Improving the thermal and electrical properties of TO alone is insufficient to demonstrate an enhancement of a transformer's cooling system. TO with added NPs must undergo experimental testing under conditions that simulate real transformer operations. These tests are designed to assess the heat transfer characteristics of NFs. Various studies have explored different test setups and NP types. In 2014, Beheshti *et al.,* [17] used a reservoir measuring 203 x 100 x 221 mm and multi-walled carbon nanotubes (MWCNT), showing improvements in both natural and forced convection heat transfer. In 2015, Amiri *et al.,* [18] replicated the study using the same dimensions and NPs, but with different thermocouple placements, reporting a significant increase in the heat transfer coefficient for both convection modes at very low NP concentrations. In 2017, Amiri *et al.,* [19] used amine-treated graphene quantum dots (AGQD), demonstrating a notably higher heat transfer coefficient in forced convection than pure TO. More recently, in 2023, Pourpasha *et al.,* [20] conducted a similar study with a reservoir measuring 0.22 x 0.1 x 0.2 m, using $TiO_2$-doped MWCNTs. Their results showed a 16.54% increase in the heat transfer coefficient for natural convection.

The above-mentioned previous studies indicate that adding NPs significantly enhances the cooling performance of TO under both natural and forced convection conditions. Several references confirm that NPs improve the thermal and electrical properties of TO, as well as its heat transfer coefficient. Unlike previous studies, this research uses uninhibited naphthenic mineral oil (UNMO) as the base fluid, chosen for its wide availability and low cost. UNMO has been widely used in the power transformer industry since 1982. In this study, $Al_2O_3$ is utilized at a concentration of 0.01 wt%, and testing equipment is designed to simulate power transformer conditions using the ONAN cooling system. This research aims to evaluate nano insulating liquid (NIL) with UNMO as the base fluid under conditions closely replicating actual transformer operations, providing a more practical approach for real applications. By addressing these proposed aspects, the present research work on $Al_2O_3$ nanofluids with UNMO as the base fluid contributes to developing more efficient and reliable cooling solutions for power transformers and potentially other industrial applications.

## 2. Methodology

### *2.1 Materials*

The base fluid used in this study is UNMO from Nynas Nitro Libra, which complies with standard specifications for new oil, as detailed in Table 1. UNMO was selected due to its wide availability and relatively low cost. It has been extensively used as an insulating and cooling oil in power transformers, with most large power transformers worldwide utilizing mineral oil (MO) [21,22]. Additionally, UNMO is favored in approximately half of large power transformers globally due to its superior resistance to oxidation compared to inhibited MO.

**Table 1**
Specification of Nynas Nitro Libra [23]

| Property | Unit | Test method | Specification limits | | Typical data |
|---|---|---|---|---|---|
| | | | Min. | Max. | |
| Viscosity at 40 ℃ | $mm^2/s$ | ISO 3104 [24] | n/a | 12.0 | 9.6 |
| Viscosity at -30 ℃ | $mm^2/s$ | ISO 3104 [24] | n/a | 1800 | 1100 |
| Pour point | ℃ | ISO 3016 [25] | n/a | -40 | -51 |
| Water content | mg/kg | IEC 60814 [26] | n/a | 30 | <20 |
| BDV before treatment | kV | IEC 60156 [27] | 30 | n/a | 40-60 |
| BDV after treatment | kV | IEC 60156 [27] | 70 | n/a | >70 |
| Density at 20 ℃ | $kg/dm^3$ | ISO 3675 [28] | n/a | 0.895 | 0.875 |
| DDF at 90 ℃ | - | IEC 60247 [29] | n/a | 0.005 | <0.001 |

The NPs used in this study are $Al_2O_3$ in the form of a white powder, with a particle size of approximately 50 nm, a pH value ranging from 6 to 8, and a purity level exceeding 99%. $Al_2O_3$ was selected for its relatively high thermal conductivity compared to other NPs, making it more effective in enhancing the heat transfer capabilities of TO and improving the cooling system's efficiency [30].

### *2.2 Preparation $Al_2O_3$ NIL*

The UNMO was measured using a measuring glass, and *Oleic Acid* (OA) surfactant was added at a concentration of 1 vol%. The mixture was stirred using a Thermo Scientific Cimarec hot plate magnetic stirrer at 1500 rpm at room temperature for approximately 10 minutes. The $Al_2O_3$ were weighed using a Sonic Electronic Balance to achieve the desired concentration of 0.01 wt%. The $Al_2O_3$ was then added to the UNMO-OA mixture, stirring for 120 minutes. Following this, the entire mixture was processed in a high-frequency ultrasonic shaker (Daihan Scientific) at room temperature for 60 minutes. As a result, well-dispersed NIL was successfully obtained, as shown in Figure 1.


**Fig. 1.** Preparation of nano insulating liquid

### *2.3 Experimental Set-up*

The experimental setup in this study comprised a reservoir made of SUS 304 material, with a thickness of 2 mm and internal dimensions of 300 x 200 x 150 mm. A heater with a maximum capacity of 650 watts was installed vertically at the center of the reservoir, featuring a cylindrical sheath with an outer diameter of 38 mm and a length of 195 mm. This cylindrical heater simulates the windings that generate heat energy in an actual power transformer. Type K thermocouples were mounted on the heater jacket and within the fluid to accurately monitor temperature variations. The distance between thermocouples on the heater wall ($Tw_1$-$Tw_2$-$Tw_3$) and in the fluid ($Tb_1$-$Tb_2$-$Tb_3$) is 65 mm, respectively. Similarly, the distance between the thermocouples on the heater wall (*Tw*) and in the fluid (*Tb*) is also 65 mm. Temperature data were continuously recorded for 3 hours using a data logger, automatically capturing measurements every 2 seconds. This systematic approach allowed for detailed tracking of temperature fluctuations and enabled a comprehensive analysis of the thermal performance of the NFs over time. The configuration of the reservoir and its components is illustrated in Figure 2, while the actual configuration is presented in Figure 3.

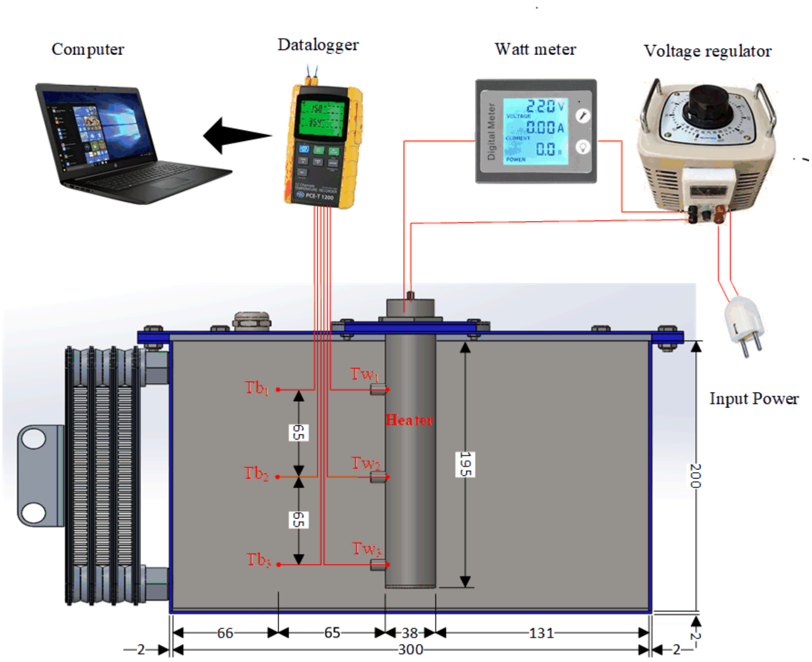



**Fig. 2.** Research scheme

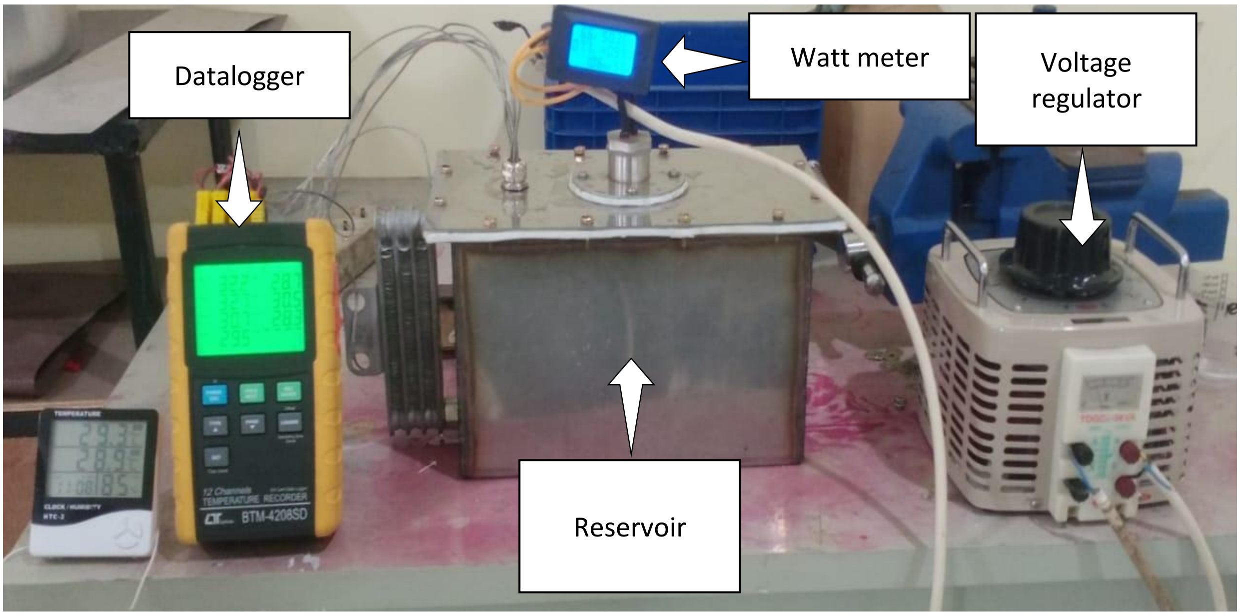



**Fig. 3.** Actual configuration of reservoir

### *2.4 Heat Transfer Calculations*

The research began with temperature data collection using six type K thermocouples, with three placed vertically along the heater jacket wall and three installed on the reservoir wall immersed in the fluid. The primary source of heat energy was generated by converting electrical energy into heat through the heater. The amount of electrical energy consumed was calculated using Eq. (1) [17-20].

$$P = V \cdot I \tag{1}$$

In Eq. (1), $P$ represents the input power of the heater in watts, $V$ is the electrical voltage (volts), and $I$ is the electrical current (amperes). Since the heater operates for 3 hours, the energy supplied by the heater, denoted as $Q_{in}$ in joules, can be calculated by multiplying the input power by the time, $t$ (seconds). Therefore, it can be determined using Eq. (2).

$$Q_{in} = P \cdot t \tag{2}$$

Thus, the energy stored in the fluid can be determined using Eq. (3).

$$Q_{fluid} = m \cdot cp \cdot \Delta T_{fluid} \tag{3}$$

where $Q_{fluid}$ represents the energy stored in the fluid (joules), $m$ is the mass of the fluid (kg), and $c_{\mathrm{p}}$ is the specific heat capacity of the fluid (J/kg°C). Not all the energy generated by the heater is converted into heat; some energy is lost due to conduction to the materials or convection to the environment. While the losses from conduction, convection, and radiation are not calculated in detail, they are estimated overall using Eq. (4).

$$Q_{loss} = Q_{in} - Q_{fluid} \tag{4}$$

Thus, the total energy transferred to the fluid, expressed in watts, can be calculated using Eq. (5).

$$q_{fluid} = \frac{Q_{fluid}}{t} \tag{5}$$

By knowing the total energy transferred to the fluid, the convective heat transfer coefficient (*h*) from the heater jacket wall to the fluid can be determined using Eq. (6).

$$h = \frac{q_{fluid}}{A(Th_{ave} - Tb_{ave})} \tag{6}$$

Where $A$ represents the area of the heater jacket in contact with the fluid, and $Tw_{ave}$ and $Tb_{ave}$ represent the average temperatures of the heater and the fluid, respectively. To analyze the natural convection heat transfer characteristics of a vertical cylinder, several dimensionless numbers are required, including the Nusselt number (*Nu*), Prandtl number (*Pr*), Grashof number (*Gr*), and Rayleigh number (*Ra*), each defined by Eq. (7) to Eq. (10).

$$Nu = \left( \frac{0.68 + (0.67 Ra^{\frac{1}{4}})}{\left[ 1 + \left( \frac{0.492}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{4}{9}}} \right) \tag{7}$$

$$Pr = \frac{Cp \cdot \mu}{k} \tag{8}$$

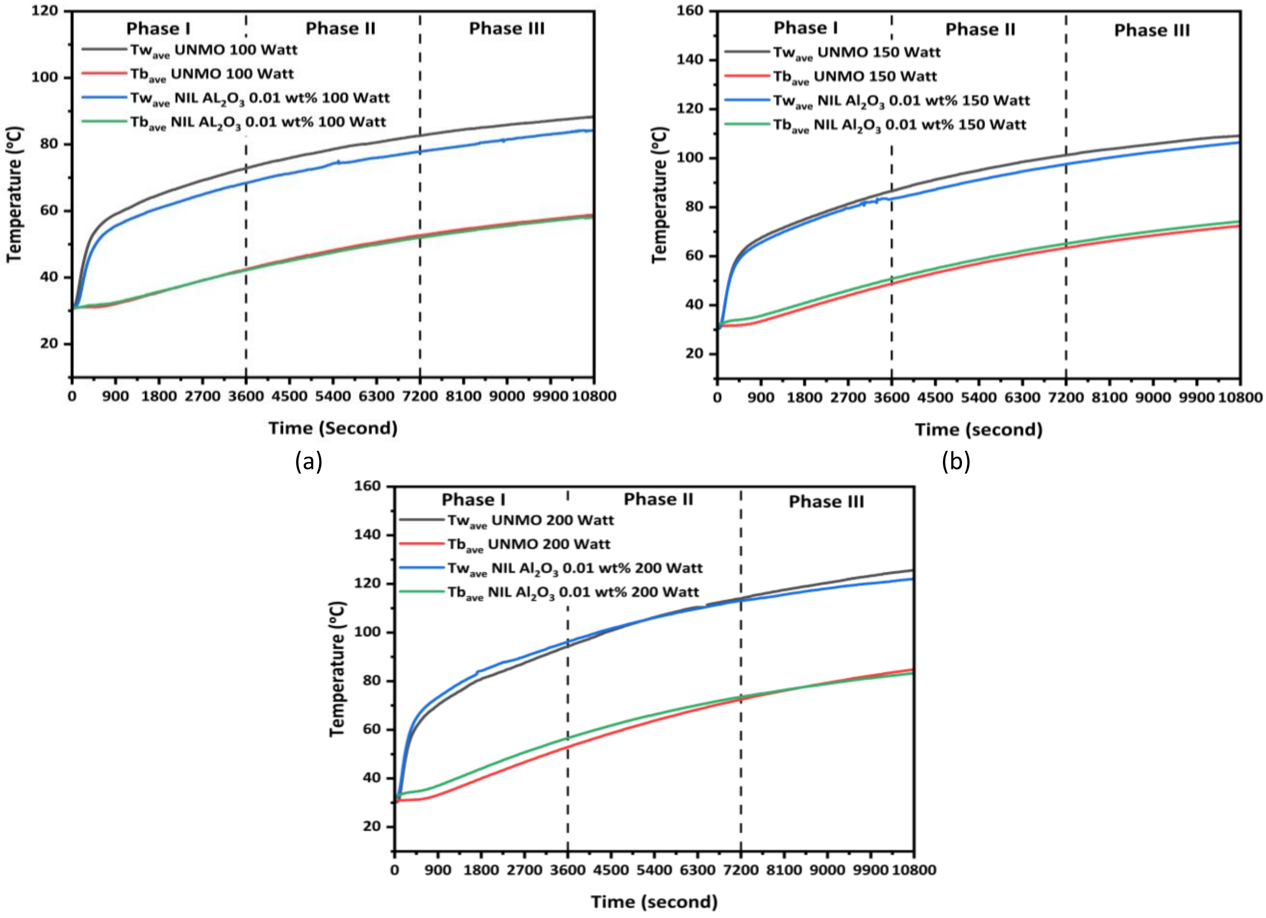
$$Gr = \frac{g\beta(T_w - T_b)L^3}{v^2} \tag{9}$$

$$Ra = Pr \cdot Gr \tag{10}$$

## 3. Result and Discussion

### *3.1 Temperature Profile*

Temperature measurements were taken at various input power levels over a period of 3 hours and recorded every 2 seconds using a data logger. The 3-hours period was divided into three phases: first, second, and third, each lasting one hour. As seen in Figure 4, the most significant temperature increase occurred during the first phase for all samples and input power levels. In the first 15 minutes, the highest temperature rise was observed in the NIL wall temperature with a 200-watt input power, with a rate of increase up to 2.75 °C per minute. The lowest rate was recorded in the NIL with a 100-watt input power at 1.6 °C per minute.




(a) (b) (c)

**Fig. 4.** Temperature profiles at various input powers: (a) 100 watts, (b) 150 watts, (c) 200 watts

At input powers of 100 and 150 watts, $Tw_{ave}$ in UNMO was higher than that in the NIL. Conversely, at an input power of 200 watts, the $Tw_{ave}$ in the NIL was higher than in the UNMO. However, this only occurred until the middle of the second phase, and by the end of the third phase, the $Tw_{ave}$ in UNMO was again higher than in the NIL. This was due to a significant temperature difference between the upper and lower parts of the $Tb_{ave}$. At the start of heating, the $Tb_{ave}$ in UNMO was lower than in the NIL across all input powers. At 100 watts input power, an intersection occurred at the end of the first phase, resulting in the $Tb_{ave}$ in UNMO being higher than in the NIL. At 150 watts input power, the gap remained consistent from the beginning to the end of heating, with the $Tb_{ave}$ in UNMO being lower than that in the NIL. At 200 watts input power, another intersection occurred at the start of the third phase, with the $Tb_{ave}$ in UNMO continuing to increase until the end.

Temperature difference (*ΔT*) between $Tb_{ave}$ and $Tw_{ave}$ follows a similar pattern, with a significant increase during the first 900 seconds, followed by a gradual decrease until the end of the phase. As seen in Figure 5, the highest temperature difference was observed in UNMO at an input power of 200 watts, while the lowest was in the NIL at 100 watts. This trend remained consistent across all input powers, with the temperature difference in UNMO being greater than in NIL. At the initial stage, the temperature difference was below 0 °C. This occurred because, before the heater was turned on, the temperature of the heater jacket was lower than the fluid temperature. A few seconds after the heater was turned on, the temperature of the heater jacket increased more rapidly, causing the temperature difference to rise above 0 °C.

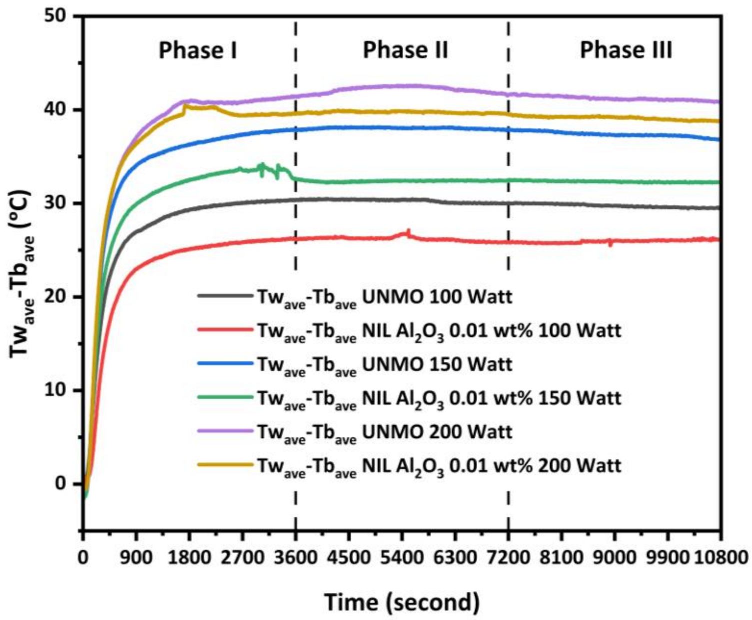
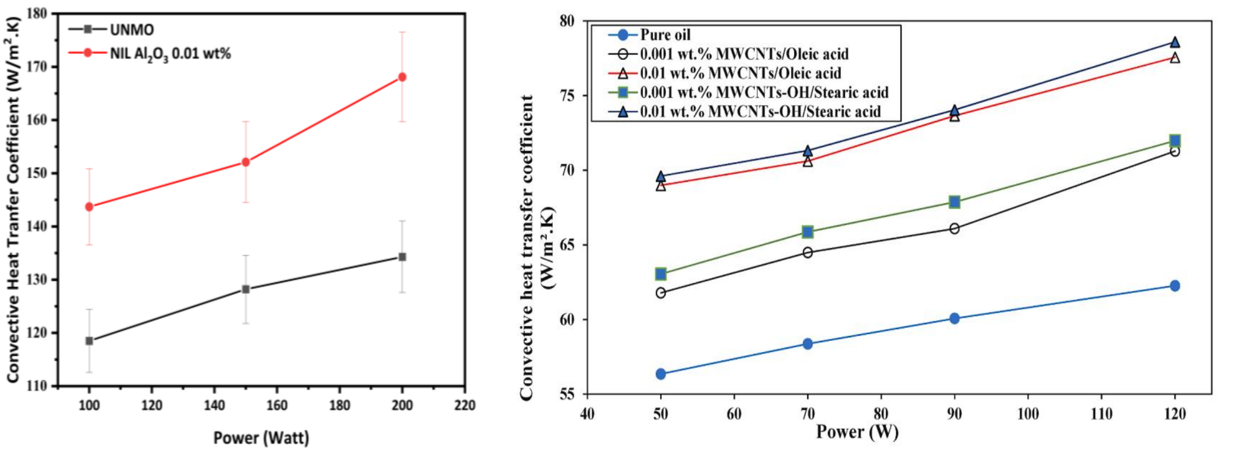



**Fig. 5.** *ΔT* profiles at various input powers

### *3.2 Heat Transfer Characteristic*

The calculation of heat transfer rates is conducted after the heating process reaches 3 hours. During the heating period, not all the energy supplied by the heater is entirely converted into heat energy within the fluid. This is due to energy losses through conduction on the walls, radiation, and convection from the walls and radiator to the surroundings. Using Eq. (1) to Eq. (5), the total value of the natural convection heat transfer coefficient with a 5% error bar is presented in Figure 6(a). Figure 6(b) shows the results of the study by Alizadeh *et al.,* [31], which used different NPs, namely MWCNTs, with the same concentration as the current study (0.01 wt%). The results indicate a similar trend, where the value of *h* increases with increasing input power.

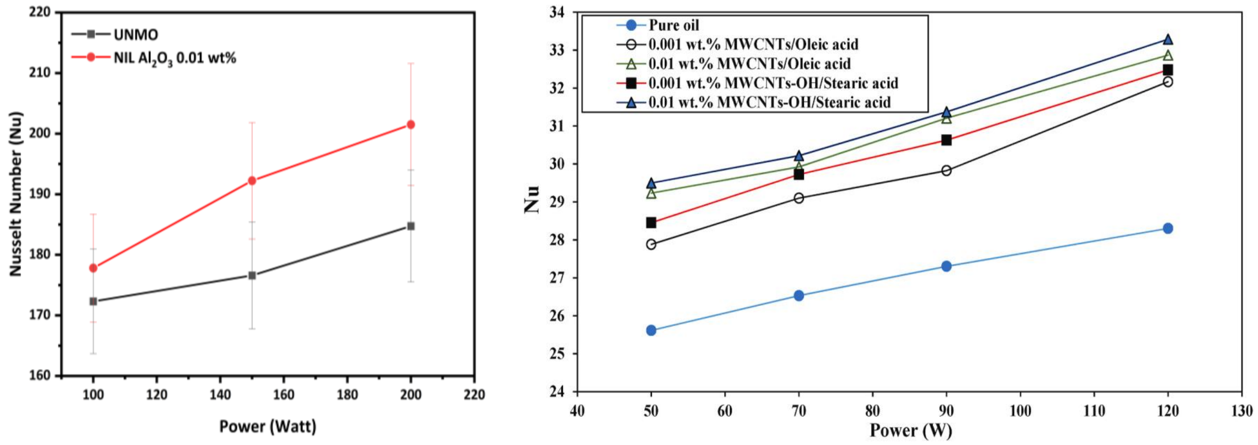



(a) (b)

**Fig. 6.** Convective heat transfer coefficient profiles at various input powers: (a) current study, (b) Alizadeh *et al.,* [31]

Heat convection is a crucial heat transfer phenomenon within fluid flow. One parameter used to measure heat convection is the *Nu*, which represents the ratio between heat convection and heat conduction along the surface in contact with the fluid. As shown in Figure 7(a), the *Nu* increases with rising input power for both UNMO and NIL $Al_2O_3$ 0.01 wt%. The increase in input power directly influences heat convection within the fluid flow.

With a 5% error bar, the endpoints of the bars for UNMO and NIL still overlap. This indicates that the increase in *Nu* is not particularly significant, as the 5% margin still suggests overlapping values between UNMO and NIL. Figure 7(b) presents the results of the study by Alizadeh *et al.*, [31], which examined various concentrations and surfactants. The observation focuses on the same parameter as the current study, specifically at a concentration of 0.01 wt% with *Oleic Acid* as the surfactant, showing a similar trend where the value of *Nu* increases with higher input power.

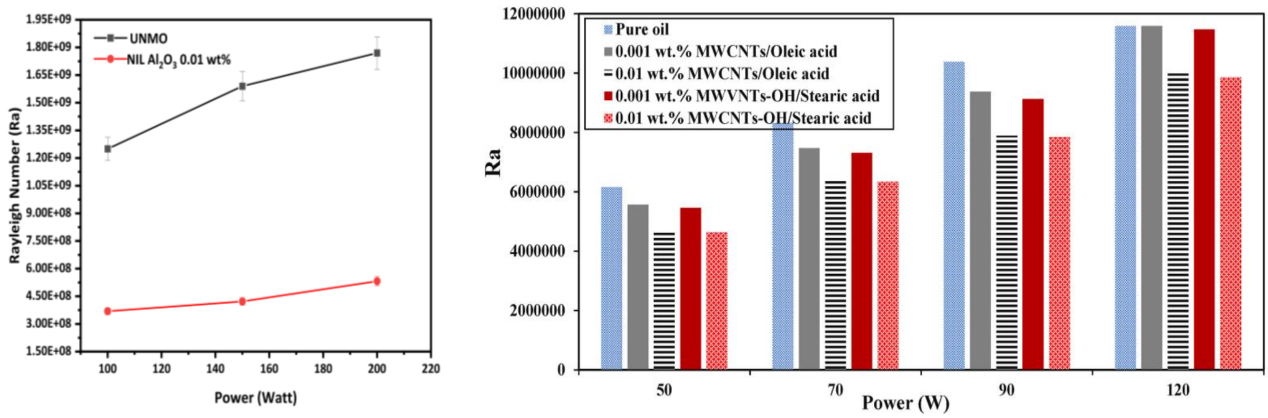



(a) (b)

**Fig. 7.** Nusselt number profiles at various input powers: (a) current study, (b) Alizadeh *et al.,* [31]

The *Ra* is a key parameter in natural convection, representing the ratio between gravitational forces and viscous forces in fluid flow due to temperature differences. The data indicates that increasing input power or temperature differences in both UNMO and NIL $Al_2O_3$ 0.01 wt% directly impacts the *Ra*, suggesting that the greater the temperature difference between mediums, the stronger the natural convection. As shown in Figure 8(a), the impact of increasing input power on natural convection in both UNMO and NIL $Al_2O_3$ 0.01 wt% is highlighted, focusing on changes in the

*Ra*. These findings demonstrate that greater temperature differences between mediums lead to stronger natural convection, providing valuable insights into the heat transfer mechanisms in different types of fluids. The addition of NPs also leads to a decrease in *Ra*, both in the current study and in previous study by Alizadeh *et al.,* [31] presented in Figure 8(b). This is due to changes in thermal conductivity and viscosity caused by the addition of NPs. This phenomenon results in conduction heat transfer becoming more dominant than convection.




(a) (b)

**Fig. 8.** Rayleigh number profiles at various input powers: (a) current study, (b) Alizadeh *et al.,* [31]

$Al_2O_3$ is a promising NPs for enhancing the performance of transformer oil, particularly UNMO. As shown in Table 2, the addition of $Al_2O_3$ increases *h* and *Nu* but decreases *Ra*. The decrease in *Ra* is an indication that conduction becomes more dominant than convection. This phenomenon is not exclusive to $Al_2O_3$ but also observed with other NPs, such as MWCNT, as studied by Alizadeh *et al.,* [31]. With increasing input power, the enhancement in *Nu* becomes more pronounced, indicating that the addition of $Al_2O_3$ has good performance at high temperatures, even reaching nearly 120 °C at an input power of 200 watts. Such high temperatures are already considered emergency conditions in the actual operation of transformers.

**Table 2**
Increase and decrease trends in *h*, *Nu*, *Ra* as a function of input power in NIL

| Input power (Watt) | Increase/decrease (%) | | | | | |
|---|---|---|---|---|---|---|
| | Current study: $Al_2O_3$ 0.01wt% | | | Alizadeh *et al.,* [31]: MWCNT 0.01 wt% | | |
| | *h* | *Nu* | *Ra* | *h* | *Nu* | *Ra* |
| 50 | - | - | - | 21.43 | 12.79 | -31.15 |
| 70 | - | - | - | 22.41 | 12.83 | -24.69 |
| 90 | - | - | - | 23.33 | 14.34 | -28.18 |
| 100 | 21.27 | 3.20 | -70.48 | - | - | - |
| 120 | - | - | - | 24.19 | 16.67 | -15.97 |
| 150 | 18.64 | 8.86 | -73.46 | - | - | - |
| 200 | 25.17 | 9.07 | -69.94 | - | - | - |

## 4. Conclusions

The experimental setup in this study comprised a reservoir made of SUS 304 material, with a thickness of 2 mm and internal dimensions of 300 x 200 x 150 mm. In the center of the reservoir, there is a 650-watt cylindrical heater that simulates a transformer winding. Type K thermocouples monitored temperature changes recorded every 2 seconds over 3 hours. The research results indicate that the most significant temperature increase occurred during the first phase for all samples, with the highest rate recorded at 2.75 °C per minute for a 200-watt input power. Heat transfer coefficient increases with the increasing power in both UNMO and NIL $Al_2O_3$ 0.01 wt%. The heat transfer coefficient of the NIL $Al_2O_3$ 0.01 wt% tends to be greater than that of the base fluid, and the same trend is observed in the *Nu*. What differs is that the value of *Ra* decreases with the addition of $Al_2O_3$. The decrease in *Ra* is an indication that conduction becomes more dominant than convection. Therefore, the use of a low concentration of $Al_2O_3$ is recommended to minimize the impact of the decrease in *Ra*. Overall, $Al_2O_3$ has great potential for use as a cooling oil in power transformers at low concentrations, but further research is needed on other factors to ensure its suitability for industrial applications.

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