Experimental investigation on thermal conductivity and viscosity of purified aged transformer oil based SiO$_2$, Al$_2$O$_3$ and TiO$_2$ nanofluid for Electric Multiple Unit Train

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Abstract. High voltage traction transformer of electric train demands reliable transformer oil with good heat transfer properties. Anyhow thermal stress due to high temperature initiates premature thermal ageing that deteriorates the properties of transformer oil even after multiple purification process. Influence of silicon dioxide (SiO$_2$), aluminium oxide (Al$_2$O$_3$) and titanium oxide (TiO$_2$) nanoparticles on treating purified aged transformer oil (PATO) has been addressed in this study. Oil samples were collected after validation process using colour condition standards. Each nanoparticle was suspended in the aged oil using magnetic stirrer and ultrasonic bath at 0.1% volume concentration. Stability analysis was conducted using photo capturing and zeta potential analyser method. Thermal conductivity and viscosity were investigated from temperature range of 30$^\circ$C to 70$^\circ$C. Based on the experimental results, PATO-based SiO$_2$ nanofluid was chosen as no sedimentation detected even after 144 hours with zeta potential value of 71.83mV. Thermal conductivity of PATO was enhanced up to 20.83%. Besides that, the suggested nanofluid obeys Newtonian fluid law with the viscosity enhancement up to 6.7%. On the other hand, it was found that the properties of PATO were improved with the suspension of SiO$_2$ nanoparticles, thus helps railway industry to optimize the life span of transformer oil.

Keywords: transformer oil-based nanofluid; thermal conductivity; traction transformer; viscosity; zeta potential analysis
1. Introduction

Traction transformer in the electric train is also called as the onboard power electronic traction transformer (PETT) [1]. Traction transformer plays the main role as the power collector from the overhead contact system of the electrification system which then distributes the desired power to the corresponding components in an electric train [2]. The high voltage from the substation will be converted and transferred according to the needs of each electrical parts via the windings in the traction transformer [3]. Insulating fluid or transformer oil acts as a coolant and insulating fluid in the oil-immersed traction transformer system.

Thermal aging was reported to be the prominent contributor for aging process of oil-paper insulation in any oil-immersed traction transformer [4]. Due to its high load and frequent ridership, transformer oil faces faster thermal ageing due to temperature differences, the existence of moisture, impurities, oxidation, thermal stress and presence of dissolved gas which led to numerous studies on alternative insulating fluids [5] [6]–[8]. Temperature is the direct factor that influence the thermal aging status of oil-paper insulation. It has been reported that the lifespan of transformer may reduce up to 17.8 years compared to real expected lifespan of 35 to 40 years due to insulating fluid issues [9]. The rail industry could not afford to withstand the major tragedy caused by any failure of the transformer as it involves higher budget for either maintenance or replacement. The current practice in the rail industry is to treat aged transformer oil using oil purification machine with membrane separator which involves heating, filtration, vacuum and regeneration processes [10]. The purification process is expected to eliminate dirt contamination, moisture, trapped gas content, removes the polarity materials, deep oxides and improves the colour condition of aged oil [11]. Although this process treats aged oil, it was found that over a period of time, the treated aged oil still losses its thermal properties faster than expected in comparison with new oil [12] which might give negative impacts to the rail operation and safety of passengers. Nevertheless, improving the heat transfer and life span of aged transformer oil with acceptable values of viscosity is still one of the significances in railway engineering. Moreover, it is highly required to look for potential approach to improve the insulating, thermal and heat transfer qualities of aged, insulation liquid of transformers.

An encouraging study revealed that the properties of transformer oil can be modified using nanofluid colloidal [13] which is later named as insulating nanofluid or transformer oil-based nanofluid. Intensive investigations in engineering field such as in heat exchanger, cooling system, lubrication, solar panel and semiconductor indicate that nanofluids can influence the heat transfer capabilities for both equipment and the operating fluid [14]. Choi [15] was referred as one of the pioneers who investigated the thermal conductivity of fluids with the addition of nanoparticles. Since then, numerous investigations were done towards the thermophysical properties of transformer oil-based nanofluid. Among the thermophysical properties, thermal conductivity and viscosity are considered as the most important parameters for any fluid to determine the efficiency of thermal system [16]. Rafiq et al. [17] demonstrated a scientometric review featuring literature survey from 2004 until 2019 which shows the

### Nomenclature

| Symbol | Description |
|--------|-------------|
| SiO₂   | Silicon dioxide/Silica |
| TiO₂   | Titanium oxide |
| Al₂O₃  | Aluminium oxide/Alumina |
| Fe₃O₄  | Iron (III) oxide |
| CuO    | Copper oxide |
| ZnO    | Zinc oxide |
| NTO    | New Transformer Oil |
| PATO   | Purified Aged Transformer Oil |
| UPATO  | Unpurified Aged Transformer Oil |

### Greek symbols

- \( \rho \) Density (kg/m³)
- \( \mu \) Dynamic viscosity (Pa.s)
- \( \phi \) Volume concentration (%vol conc)
intensity of integration research between nanotechnology and transformer oil, mostly showing positive enhancement in the insulation properties compared to conventional transformer oils.

In addition, the researchers also covered about myriad factors that influence the thermophysical features such as the stability of nanofluids, various base fluids, formulation techniques, type, size, shape, surface modification and volume fraction of nanoparticles of nanoparticles. Due to aging issue, the physicochemical properties of oil-paper insulated transformer does deteriorate gradually and affect the electrical properties of the transformer oil as well. According to that, any modification of the transformer oil should consider the impact towards the insulating characteristic as well and the impact of pre- and post-modification were well described by Wang et al. [18]. Besides that, various attempts were done in order to incorporate nanofluid in high voltage transformer for the benefit of improving the deteriorating characteristics of either new or aged oil [19]–[22]. These literature reviews strongly suggest that transformer oil – based nanofluid are very advantageous and need to be given more importance by researchers and industries.

There are many factors that influence the enhancement of thermal conductivity of nanofluid such as stability, volume concentration, and type of particles. Wang et al. [23] investigated the impact of TiO$_2$ nanoparticles on the breakdown performance of mineral oil with the aid of a surfactant. Similarly, a few researchers have also studied the effects of TiO$_2$ nanoparticles on aged mineral oil [24]–[26]. TiO$_2$ nanoparticles are commonly used due to its good thermal conductivity, high dielectric constant and low electrical conductivity. It is important to note that maintaining the lowest value of electrical conductivity for transformer oil avoids voltage arcing. In addition, significant enhancement of heat transfer properties was also observed in transformer oil based Al$_2$O$_3$ nanofluid corresponding to the increase of volume concentration from 0.1g/L to 0.5g/L [27]. A group of researchers conducted a comparative study on the insulating properties of transformer oil-based nanofluid using Fe$_3$O$_4$, Al$_2$O$_3$ and TiO$_2$ nanoparticles [28]. They suggested that insulative and semi-conductive nanoparticles can exhibit good improvement to the base fluid. Besides that, the optimum concentration is needed as higher volume concentration leads to agglomeration and inaccurate viscosity measurement. The researchers also added that other factors such as temperature and shape of nanoparticle play a major role as corresponding functions to thermal conductivity [28][29]. The use of SiO$_2$ nanoparticles was investigated by Rajda and Patel [30] for virgin and aged transformer oil. They revealed that insulative nanoparticles can trap electron, thus, refining the dielectric properties of aged oil which did not significantly affect the viscosity at 0.01% mass fraction. Taro et al. [31] conducted an investigation by dispersing SiO$_2$, TiO$_2$, CuO and ZnO into mineral oil and also a synthetic ester called MIDEL 7131. The considered volume fractions were 0.1%, 0.3%, 0.5%, 0.7% and 1% for 50mL of base fluid. Based on their observation, SiO$_2$ nanofluid was chosen as no sedimentation were observed. They also concluded that the viscosity of mineral oil increases constantly unlike MIDEL 7131.

Viscosity is the flow resistance of a fluid towards shear or external force that influences the heat removal rate via conduction cooling. Larger viscosity describes higher resistance to the fluid flow in any thermal system and vice versa for lower viscosity. Like thermal conductivity, W.H. Azmi et al. [32] also stated in their studies that viscosity is strongly influenced by concentration of nanoparticles besides temperature, shear rate, shape and size of nanoparticles [33] [34]. They also reported that viscosity has inverse relationship with temperature unlike thermal conductivity. A comprehensive study was conducted by Esfahani et al. [35] on the experimental outcome of viscosity and thermal conductivity in transformer oil without the use of surfactant. They built a model to predict the viscosity and thermal conductivity and treated volume concentration as an input factor. They added that the viscosity of copper was higher compared to Ag and TiO$_2$ nanofluid under the same 0.05% volume concentration at 20°C. Furthermore, they also revealed that although the higher concentration of nanoparticle might yield higher thermal conductivity and heat transfer rate, this increment will also lead to higher viscosity that might result in pressure drop and blockage in the transformer oil cooling system. These findings prove that viscosity must be highly considered during the attempt of treating the thermal conductivity for any nanofluid as higher viscosity will disrupt the heat exchanger system and increase pump power.
To date, no investigation has been reported involving qualitative analysis (colour conditioning and stability analysis using photo capturing) and quantitative analysis (zeta potential stability test, thermal conductivity and viscosity) for aged traction transformer oil-based nanofluids. Furthermore, there are very few studies done on the aged transformer oil collected from any electric train. Hence, in this study, the effects of spherical shaped – insulative/semi conductive nanoparticles without the addition of surfactant on thermal conductivity and viscosity were investigated.

Formulation of transformer oil colloidal suspensions
Three different transformer oil samples were collected from the train and oil purification machines namely New Transformer Oil (NTO), Unpurified Aged Transformer Oil (UPATO) and Purified Aged Transformer Oil (PATO). The properties of the inhibited transformer oil are as shown in Table 1. NTO was purchased from Shell Lubricant oil supplier. UPATO was collected from an electric train which was later purified through the oil purification machine for almost 4 to 5 hours to produce PATO. UPATO was in service for more than 8 years. The insulative nanoparticles (SiO$_2$, Al$_2$O$_3$) and semiconductive nanoparticles (TiO$_2$) were procured from Beijing K Nanotechnology Co. Ltd. Figure 1 shows the image from Field Emission Scanning Electron Microscope (JEOL JSM 7600F - FESEM) for SiO$_2$, Al$_2$O$_3$ and TiO$_2$ nanoparticles. The details obtained from the figures confirm that the average size of the nanoparticles is in the range of 20 to 30 nm and the shape is spherical. Nanofluid can be prepared either using one-step or two-step. One-step method involves simultaneous making and uniformly dispersing nanoparticles in the base fluid using physical or chemical approach yet generally, this method could not be used to formulate nanofluid in larger scale and operation cost is high too. In two-step method, nanoparticles will be produced as dry powder first before dispersing into fluid according to desired concentration via homogenising, magnetic stirring, ball milling and high-shear mixing and sonic agitation process [19]. In this study, a two-step preparation method was employed to prepare PATO based nanofluid with 0.1% volume concentration. Table 2 indicates the properties of the selected nanoparticles. The mass of required nanoparticles was calculated using Equation (1).

$$\phi = \left[ \frac{(m_p/\rho_p)}{(m_p/\rho_p + m_l/\rho_l)} \right] \times 100$$  \hspace{1cm} (1)

where $\phi$ is the volume concentration (% vol conc.), $m_p$ is the mass of nanoparticles (grams), $\rho_p$ is the density of nanoparticles (kg/m$^3$), $m_l$ is the mass of the base fluid (gram) and $\rho_l$ is the density of the base fluid (kg/m$^3$). The weight of nanoparticles was measured using a precision balance with an accuracy of 0.0001 g. In preparing 200 ml of 0.1 vol% SiO$_2$ nanofluids, about 0.444 g of SiO$_2$ nanoparticles were added. Nanoparticles were dispersed in measured PATO using a magnetic stirrer for 30 minutes. The fluid was then homogenised using ultrasonic bath vibrator (Fisherbrand FB15051, 320 Watts, and 50 kHz) for 2 hours to breakdown the agglomeration between the nanoparticles. These steps were repeated for TiO$_2$ and Al$_2$O$_3$ nanofluid as well. Microbubbles might be formed throughout the stirring and sonication process; therefore, the samples were let to rest before further analysis.

**Table 1.** Properties of Shell Diala S4 ZX-1 transformer oil.

| Density (kg/m$^3$) at 20°C (ISO 3675) | Kinematic Viscosity (mm$^2$/s) at 40°C (ISO 3104) | Standard Breakdown voltage (kV) (IEC60156) | Corrosive Sulphur (DIN51353) |
|--------------------------------------|-----------------------------------------------|----------------------------------------|--------------------------|
| 895                                  | 12                                            | Min 30                                 | Not corrosive            |

No surfactant was used in this preparation as the performance of surfactants was reported to raise big concern at higher temperature. Surfactant might contaminate the heat transfer media and increase the possibilities of producing foams during continuous heating and cooling process by the heat exchanger systems. Furthermore surfactant limits the enhancement of the effective thermal conductivity by enlarging the thermal resistance between nanoparticles and molecules of base fluid [19], [36].
Table 2. Properties of semi conductive and insulative nanoparticles.

| Properties               | SiO$_2$ | Al$_2$O$_3$ | TiO$_2$ |
|--------------------------|---------|-------------|---------|
| Particle diameter, nm    | 30      | 20          | 30      |
| Density kg/m$^3$         | 2220    | 4000        | 4230    |
| Thermal conductivity, W/mK| 1.4     | 36          | 8.4     |

(a) SiO$_2$ nanoparticles (X100000)  
(b) Al$_2$O$_3$ nanoparticles (X100000)  
(c) TiO$_2$ nanoparticles (X100000)

Figure 1. FESEM images for SiO$_2$, Al$_2$O$_3$ and TiO$_2$ nanoparticles (X100000).

2. Nanofluid stability

2.1 Colour conditioning and stability analysis using photo capturing

Aged transformer oil is subjected to colour changes due to contamination, oxidation, deterioration and suspension of light-absorbing groups [37]. ASTM D1500 and ASTM D1524 standards will be used as an initial guideline to grade the oil in service samples before dispersing nanoparticles. ASTM D1500 is the standard test method (colour scale) used for petroleum products while ASTM D1524 is the standard test method for visual examination of used electrical insulating oils of petroleum origin in the field. Figure 2 summarises the colour coding used to assess the condition of transformer oil based on ASTM D1500 colour scale standard where the values towards further right indicates bad oil.
Agglomerated nanoparticles will result in the settlement/sedimentation and clogging of pumping system in the heat exchanger system thus, decreases the thermal conductivity of nanofluids as well. To conduct visual sedimentation analysis, photo capturing method was selected as the qualitative investigation tools prior employing any quantitative approach. The nanofluid samples were placed in glass test tubes upon preparation, where the occurrence of any sedimentation was recorded and photographed at intervals. Nanofluid samples were not disturbed or shaken throughout the observation period. Only samples with less/no visual sedimentation were selected for the next stage which stability evaluation using zeta potential analyser.

2.2 Stability investigation using zeta potential analyser

To verify the observation method, quantitative analysis was performed on the selected insulating nanofluid samples using zeta potential analyser (Anton Paar Lifesizer). Zeta potential assesses stability prediction by evaluating the electrostatic interactions in colloidal dispersion and dependency on the electrochemical equilibrium of nanoparticle – liquid interface [39]. Stability is referred to as the resistance of the colloidal mixture towards the changes of dispersion with time [40]. Zeta potential is measured at the slipping plane of the Electrical Double Layer (EDL) as shown in Figure 3. The stern layer consists of oppositely charged molecules compared to the particle surface. Meanwhile, beyond the stern layer, the surface charge on the nanoparticle will decrease based on the distance [25].

**Figure 2.** ASTM D1500 colour scale [38].

**Figure 3.** Electrophoresis Zeta Potential Analysis.
3. Thermal conductivity and viscosity measurement

Thermal conductivity refers to the ability of a material to conduct heat. In this study, thermal conductivity was measured from 30°C to 70°C with intervals of 10°C using a single needle thermal property analyser (KD2 Pro, Decagon Devices Inc) as shown in Figure 4. Its function was based on the transient hot-wire method where the needle will be dipped into the sample. Measurement was taken in accordance with ASTM D5334 and IEEE 442-1981 standards. A water bath was used to maintain a constant sample temperature during measurement process. The KD2 Pro thermal conductivity sensor was calibrated using standard verification liquid glycerine. The value measured was 0.284 W/m K with accuracy of ±0.35%. Measurements were repeated several times and the average value from five sets of readings was considered for each temperature. Thermal conductivity was expected to be dependent upon temperature as the Brownian motion of insulating nanofluid is also temperature-dependent.

Dynamic viscosity is measured using a rotational rheometer (Anton Paar, Rheolab QC) equipped with a Peltier temperature device as shown in Figure 5. The system is equipped with a digital encoder and servo motor. Double gap cylinder measuring system was used during the measurement of transformer oil with low viscosity. Base fluids and nanofluids with different concentration were loaded by turn into the filling cup. The measurements were taken from 30°C to 70°C, resembling the approximate ambient temperature and maximum operating temperature of the traction transformer. Measurements were recorded once the system reaches steady state or constant temperature. The measurements were repeated 5 times for each volume concentration and temperature. Later the average from each reading was taken.

4. Results and discussion

4.1 Colour conditioning and stability analysis using photo capturing method

Based on ASTM D1500 and ASTM D1524, PATO falls under colour coding 1.0 (refer Figure 2) which indicates that the oil sample is still in good condition. As PATO was purified and filtered, oil sample was free from any contaminants, moisture and reduces oxidation effects. As stated by Hadjadj et al. [37], oxidation is the main cause for oil darkening to occur. These findings indicate that the oil is qualified for nanoparticle dispersion.

Figure 6(a) – 6(d) shows the sedimentation photographs at various time intervals. Unlikely, PATO-based Al₂O₃ nanofluid indicated significant initial separation within 9 hours of preparation as shown in Figure 6(b) and achieved complete separation after 24 hours as shown in Figure 6(c). This shows that Al₂O₃ is not compatible with the selected base fluid which leads to poor stability and low thermophysical
properties, PATO-based TiO$_2$ nanofluid was inclined to sedimentation after 30 hours of preparation. At higher concentration, the possibilities of TiO$_2$ nanoparticles to agglomerate is high, hence reduces the charges trapping capacity and decreases the interface with oil molecules and nanoparticles as shown in Figure 6(c). Based on the visual observations, PATO-based SiO$_2$ nanofluid yielded no visual sedimentation even after 144 hours as shown in Figure 6(d). These findings suggested that further investigation should be employed on PATO-based SiO$_2$ nanofluid.

4.2 Stability using zeta potential Analyser

Nanofluids with higher zeta potential value are deduced to be good electrically stabilised, whereas coagulation and sedimentation are common happenings for solution with low zeta potential value. Mostly, zeta potential value of 25 mV will be considered as the imaginary value that differs low-charged surfaces from highly charged surfaces. The insulating nanofluids within the zeta potential range of 40mV to 60mV are considered to be stable, while values more than 60mV are considered to have excellent stability [41][19]. After measurement, it was found that the mean zeta potential value of SiO$_2$ insulating nanofluid was 71.83mV, indicating excellent stability and validated the result from photo capturing method (visual sedimentation analysis).

![Figure 6](image)

**Figure 6.** Sedimentation photographs of nanofluids at 0.1% volume concentration (Nanofluids: Sample 1- Al$_2$O$_3$, Sample 2 - TiO$_2$, Sample 3 - SiO$_2$ and pure PATO: Sample 4)

4.3 Thermal conductivity of insulating nanofluid

Thermal conductivity values of PATO-based SiO2 nanofluid in comparison with other oil samples are illustrated in Figure 7. The experimental data obtained are in good agreement with the theory and data presented in the literature [42] where the temperature increment resulted in enhancement of thermal conductivity. There are a few novel findings discovered throughout this study.

Thermal conductivity of UPATO was identified to be higher or almost like PATO and NTO from 30°C to 60°C. So, the presence of water content in UPATO is able to increase the thermal conductivity of transformer oil as suggested by researchers [43]. Even though this analysis exhibited promising contribution to thermal conductivity, the presence of moisture caused by insulation ageing and cellulose paper degrading will negatively impact the dielectric properties of oil and accelerate cellulose paper depolymerization in traction transformer. PATO is the product of oil purification process and is expected to be reused in the traction transformer system. Anyhow, based on Figure 7, the thermal conductivity of PATO was not like NTO which might have been caused by the loss of physical or chemical properties of PATO over the time in service. If PATO is continuously used, it will reach to a stage where it could not be treated anymore and should be disposed. Discarding PATO could impose environmental and
economic impacts as it involves huge volumes and the maximum lifespan of the transformer oil could not be utilised, respectively. Moreover, the findings also suggest that the purification process has successfully reduced dissolved water/moisture content by comparing the thermal conductivity value of pure UPATO and pure PATO.

PATO-based SiO$_2$ nanofluid demonstrated a good agreement to the theory that suitable nanoparticles can improve the thermophysical properties of aged transformer oil. Based on Figure 7 (a), the increased thermal conductivity of insulating nanofluids is due to the increment of temperature that directly affects the Brownian motion of SiO$_2$ nanoparticles. Besides that, it can be observed that thermal conductivity of UPATO, PATO and NTO has inverse relationship with temperature which was caused by the long molecular chain of transformer oil and decrease in density [44]. Moreover, PATO establishes lower thermal conductivity compared to NTO, proving that PATO losing its thermal properties over time. As compared to NTO and PATO, UPATO has higher thermal conductivity due to presence of water content prior filtration process. Figure 7(b) summarises a significant enhancement comparison of PATO-based SiO$_2$ nanofluid where it possesses higher advantages compared to pure oil samples especially at high temperature. The extreme improvement that can be achieved is up to 20.83% and the lowermost is 2.29% in comparison with pure PATO. The promising enhancements as described strongly suggest that the purification process with the addition of SiO$_2$ nanoparticle suspension can be practised to treat aged transformer oil. In addition, the selection of SiO$_2$ nanofluid was predicted in previous study as SiO$_2$ nanoparticle could reduce the diffusion volume for low moisture concentration by restricting the free movement of water in the oil [45]. This property also implied that the hydrophilic behaviour of SiO$_2$ nanoparticle will continually trap any free water content in the transformer oil even after the purification process or during train operation which can be very beneficial for dielectric properties.

4.4 The viscosity of insulating nanofluid

Figure 8(a) presents the dynamic viscosity of PATO-based SiO$_2$ nanofluid against shear rate in temperature range of 30°C to 70°C. Results demonstrates that dynamic viscosity remains constant with the increase of shear rate at every temperature. This indicates that the suggested nanofluid behaved as Newtonian fluid where it is independent to shear rate and pressure. In addition, the value of viscosity
also decrease as temperature increases as higher temperature causes higher thermal energy which forces the oil molecules to move freely, thus reducing the bonding between the molecules.

These findings in Figure 8(b) are in good agreement with the standards [46] where viscosity of insulating oils perform inversely with temperature rise. Subsequently, nanoparticles could also affect the viscosity of any base depending to the type and concentration. Table 3 summarizes the enhancement comparison between nanofluid and oil samples. The addition of 0.1% volume concentration of SiO₂ nanoparticles into PATO enhances the viscosity in the range of 1.9% to 4.4% and 3.1% to 6.7% in comparison with NTO and PATO, respectively. Higher viscosity should be avoided as gel-like suspensions might occur, thus influences the pressure loss and will eventually increase the pumping power load in the cooling system [47]. Treating aged oil using nanoparticles is a distinguished approach in terms of viscosity enhancement as viscosity of pure PATO is lower than NTO. Furthermore, PATO begins to crack thermally to smaller molecules as the oil operates at extreme high temperatures due to high voltage, which causes decrease in viscosity over the time. It was discovered that the viscosity of SiO₂ nanofluid is slightly higher than pure NTO, UPATO and PATO, showing that nanoparticles can improve the viscosity of aged insulating oil. Presence of impurities such as metal particles or dust might increase the viscosity, hence, SiO₂ nanoparticles are suggested to be suspended into PATO instead in UPATO to avoid any misleading confusion during the measurement of physical, thermal, and dielectric properties.

### Table 3. Enhancement percentage of nanofluid against oil samples.

|                | Enhancement percentage (%) |
|----------------|-----------------------------|
|                | 30°C | 40°C | 50°C | 60°C | 70°C |
| PATO           | +3.1%| +4.2%| +4.9%| +5.7%| +6.7%|
| UPATO          | +4.6%| +5.2%| +5.7%| +5.7%| +6.6%|
| NTO            | +2.0%| +3.2%| +2.7%| +1.9%| +4.4%|

### 5. Conclusion

In the present study, an investigation of a novel method on treating PATO used in an electric train is conducted. The main objective is to improve the thermal conductivity of oil using spherical shaped – insulative/semi conductive nanoparticles without the addition of surfactant is demonstrated. In addition,
stability and rheological properties of PATO-based mono nanofluid are investigated from temperature range of 30°C to 70°C. In conclusion, the findings of the investigation can be generalised as following:

- The experiment revealed that PATO-based SiO$_2$ nanofluid is more stable without sedimentation even after 144 hours as compared to TiO$_2$ and Al$_2$O$_3$ nanofluid via visual sedimentation and zeta potential analyser. Hence, SiO$_2$ nanofluid is selected for further investigation which is thermal conductivity and rheological properties analysis.
- The maximum thermal conductivity improvement that can be achieved is up to 20.83% in comparison with PATO, UPATO and NTO due to Brownian motion. In addition, thermal conductivity of nanofluid demonstrates linear relationship with temperature.
- The properties of viscosity prove that the nanofluid obeys Newtonian fluid law against the increase of shear rate besides having inverse association with temperature.
- The addition of SiO$_2$ nanoparticles into PATO enhances the viscosity in the range of 1.9% to 6.7%.
- The configuration and important properties such as formulation and stability are the most important parameter to determine the thermal and rheological properties of nanofluid.
- Future studies on using lower concentrated SiO$_2$ nanoparticles should be initiated to seek the impact towards viscosity and thermal properties.
- Hence, this approach will help the railway industry to treat aged oil while optimising the life span. It also opens a potential opportunity to reuse aged oil in the traction transformer system and reduce the impact on the environment.
- Nevertheless, the impact of Al$_2$O$_3$ and TiO$_2$ nanoparticles should not be completely discarded. Further investigation on the stability and sedimentation of Al$_2$O$_3$ and TiO$_2$ nanoparticles in the Shell Diala S4 type transformer oil should be given priority as well.

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**Compliance with Ethical Standards**

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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