electronics

Article

Assessment of Thermophysical Performance of Ester-Based Nanofluids for Enhanced Insulation Cooling in Transformers

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Abstract: Nanotechnology provides an effective way to upgrade the thermophysical characteristics of dielectric oils and creates optimal transformer design. The properties of insulation materials have a significant effect on the optimal transformer design. Ester-based nanofluids (NF) are introduced as an energy-efficient alternative to conventional mineral oils, prepared by dispersing nanoparticles in the base oil. This study presents the effect of nanoparticles on the thermophysical properties of pure natural ester (NE) and synthetic ester (SE) oils with temperature varied from ambient temperature up to 80 °C. A range of concentrations of graphene oxide (GO) and TiO_2 nanoparticles were used in the study to upgrade the thermophysical properties of ester-based oils. The experiments for thermal conductivity and viscosity were performed using a TC-4 apparatus that follows Debby's concept and a redwood viscometer apparatus that follows the ASTM-D445 experimental standard, respectively. The experimental results show that nanoparticles have a positive effect on the thermal conductivity and viscosity of oils which reduces with an increase in temperature.

Keywords: upgraded insulant; ester oil-based nano fluids; thermal conductivity; relative viscosity; nanoparticles effect; alternative fluid; temperature change

Citation: Khan, S.A.; Tariq, M.; Khan, A.A.; Alamri, B.; Mihet-Popa, L. Assessment of Thermophysical Performance of Ester-Based Nanofluids for Enhanced Insulation Cooling in Transformers. *Electronics* **2022**, *11*, 376. https://doi.org/10.3390/electronics11030376

Academic Editors: Tamás Orosz, David Pánek, Anton Rassõlkin and Miklos Kuczmann

Received: 4 December 2021
Accepted: 21 January 2022
Published: 26 January 2022

1. Introduction

Mineral oil is traditionally used in transformers as an insulating liquid due to its excellent dielectric and heat transfer capabilities, but its operation under excessive surrounding temperatures may lead to fire explosions which are hazardous to the environment [1]. The efficient and proper working of transformers depends upon the dielectric strength and cooling functionalities of the insulating oil used [2]. Therefore, it is important to investigate the thermal and physical properties of insulating oils used in transformers and find ways to improve them or look for a better alternative.

The dielectric mineral oil plays the dual role of insulation as well as heat dissipation in power transformers that are operated at high voltages [3]. Proper functioning of transformers at high loads generally requires continuous monitoring and maintenance of the insulating oil used in transformers. It is important to analyze the properties of the insulating material to determine its useful life, which is directly related to the lifetime and optimal design of transformers [4,5]. Therefore, to analyze and improve the thermal performance of transformers, thermophysical properties such as thermal conductivity and viscosity are important to study the heat transfer characteristics and cooling functionalities of insulating oils used in transformers. The main source of heat generation in oil-immersed transformers is the loss occurring in the core and the windings. These losses are transformed into heat, which results in the dissipation of heat in the transformer tank and eventually in the increase of the temperature of insulating oil [6,7]. It is desirable to have better heat dissipation power of the insulating liquids used in transformers in order to achieve improved efficiency and better heat transfer performance. The application of nanofluids to improve transformers' cooling systems is under investigation to create optimal transformer design by improving the cooling capacity of conventional oils [8].

In the last decade considerable effort has been put into preparing nanofluids by dispersing nanoparticles into oil to determine dielectric and electrical properties [3,9]. However, researchers now are mainly concerned with measuring the thermal and physical characteristics of oils. It is reported in the literature that nanoparticle addition would greatly improve the thermal conductivity of mineral oils [10,11]. Many investigations have been performed to determine the effect of various types of nanoparticles and temperature on the thermal conductivity and viscosity of mineral oil [12], but the effect on ester-based oils still needs to be investigated. It has been reported by Zhang et al. that the addition of TiO_2 and Al_2O_3 nanoparticles would improve thermal conductivity with an increase in their concentrations [13]. However, most of the studies on the dielectric and thermal properties are related to the mineral oil-based nanofluids and limit themselves only to these properties or those of mineral oils [14,15]. Recently, considerable research has been performed to determine the effect of temperature and nanoparticle concentration on the thermophysical properties of mineral, synthetic ester and natural ester oils [16–18], but there is a need to investigate these parameters for natural and synthetic ester oils simultaneously and to compare these parameters based on the nanoparticles' effect and temperature in order to present an environment friendly alternative to mineral oil with enhanced performance [19,20].

In the present study, novel Graphene oxide and TiO_2 nanoparticles are included in the natural ester (NE) and synthetic ester (SE) oils with the aim to enhance their thermophysical properties. In addition, apart from analyzing the effect of nanoparticles on the thermophysical properties of insulating liquids, the effect of temperature has also been examined by plotting the variation of thermal conductivity and viscosity of pure ester oils as well as nanofluids against temperature. Natural ester oil is basically a vegetable oil produced from rapeseed, and synthetic ester is obtained by the treatment of alcohol with carboxylic acids to give a robust fluid [21]. The most commonly used method—called the two-step method—used to prepare nanofluid is a widely recognized method due to its low cost and better compatibility with oils [22]. Oleic acid is added as a surfactant to the the base oil to improve the long-term stability of the nanofluids that are discussed in the paper.

The main contribution of this paper is to enhance the thermophysical characteristics of ester-based nano-oils using novel graphene oxide nanoparticles that provide better cooling functionality and a longer life than the conventional insulating oils used in transformers. The purpose of developing nano-oil is to decrease power waste by improve cooling capability during transformer operation. The correlation between thermal conductivity and viscosity of natural and synthetic ester oils for a particular concentration and temperature is carried out for their better industrial application. The remaining sections are organized as follows: Section 2 discusses the nanofluid preparation, experimental technique and heat transfer performance of nanofluids. The results are presented in Section 3. Section 4 of the paper presents the conclusion.

2. Experimental Technique, Nanofluid Preparation and Heat Transfer Performance

The flow chart describing the steps involved in this section is shown in Figure 1. The transmission electron microscopy image (TEM) of TiO_2, and the scanning electron microscopy image (SEM) of Graphene oxide (GO) nanoparticles are shown in Figure 2. The experiment to determine thermal conductivity is carried out on a thermal conductivity apparatus (TC-4 model) with a temperature control unit and a nanofluid cell, and the viscosity of oils is performed on a redwood viscometer as shown in Figure 3a,b respectively.

The experimental standard used to determine viscosity of oils is ASTM-D445. All the experimental testing is performed at a 230 V, 50 Hz AC supply. In the experiment, six individual samples of nano-oil are prepared by incorporating three different concentrations, i.e., 0.01, 0.03 and 0.05 wt% of each type of nanoparticles, namely TiO_2 and Graphene oxide (GO) in the pure ester-based oils. Then, these samples are tested to determine the thermal conductivity and viscosity for fresh as well as for nano- oil, for different temperatures starting from room temperature up to 80 °C at intervals of 20 °C. The thermal conductivity apparatus consists of the electronic unit, a nanofluid cell of 7 MHz frequency, and the temperature control unit, which uses the novel ultrasonic approach to test the liquids for thermal conductivity [23]. In addition, the relative viscosity is determined using a redwood viscometer apparatus that is used to test the physical parameters of pure oils and nanofluids. The temperature controller unit is used to maintain the desired temperature up to 90 °C. The properties of nanoparticles used in the study are shown in Table 1. The insulating oils used in the experiment are commercially obtained, and its properties are shown in Table 2.

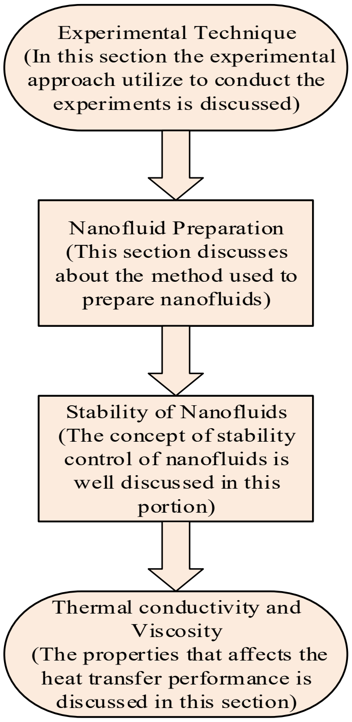


Figure 1. Flow-chart showing the steps involved in Section 2.

Table 1. Specifications of Nanoparticles.

Parameters	TiO_2	Graphene Oxide
Particle size	80–110 nm (TEM)	100–120 nm (SEM)
Density (gm/cc)	3.8	2.7
Melting point (°C)	1800	3652
Thermal conductivity (W/m.K)	8.5	18.0

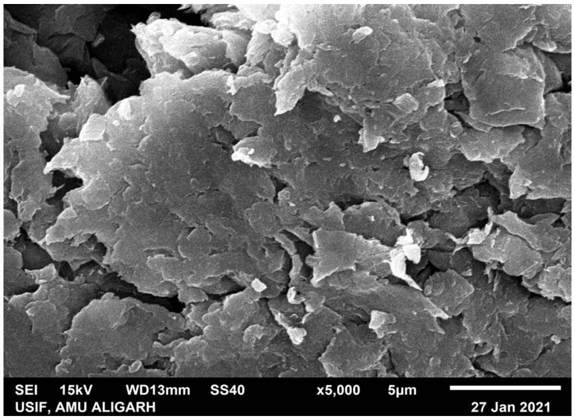
Table 2. Properties of Ester-based Oils**.**

Parameters	Natural Ester	Synthetic Ester
Viscosity (Cst) at 40 °C	38	29
Density (gm/cm^3)	0.92	0.97
Water content (ppm)	<50 mg/kg	<50 mg/kg
Pour point (°C)	−31	−56

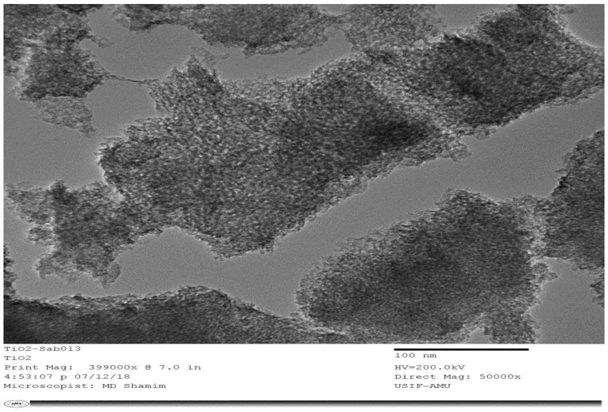
Breakdown Voltage (kV)	>75	>75
Thermal Conductivity (W/m.K) at 24 °C	0.16–0.17	0.14–0.15

2.1. Nanofluid Preparation

The widely recognized two-step method is used to prepare the nanofluid samples as shown in Figure 4 [22,24]. The ester oils were initially filtered, and the nanoparticles were synthesized using the top-down nano-technique [25]. Oleic acid is added as a surfactant in the pure oil to improve the long term stability and dispersion stability of the prepared nano-oil samples. Magnetic stirring of the oil sample is performed for about 20–25 min to ensure removal of excess moisture and unwanted contaminants from the oils. The next step is adding nanoparticles in the base oil. Finally, the ultra-sonication process follows, which involves generation of high frequency (40 kHz) waves that disperse the nanoparticles uniformly into the base oil. In this way, the sample of nanofluids is ready for testing. The power rating of sonicator is 360 W (230 V AC, 50 Hz).



(**a**) Graphene oxide (GO)



(**b**) TiO_2

Figure 2. TEM and SEM images of nanoparticles: (**a**) GO and (**b**) TiO_2.

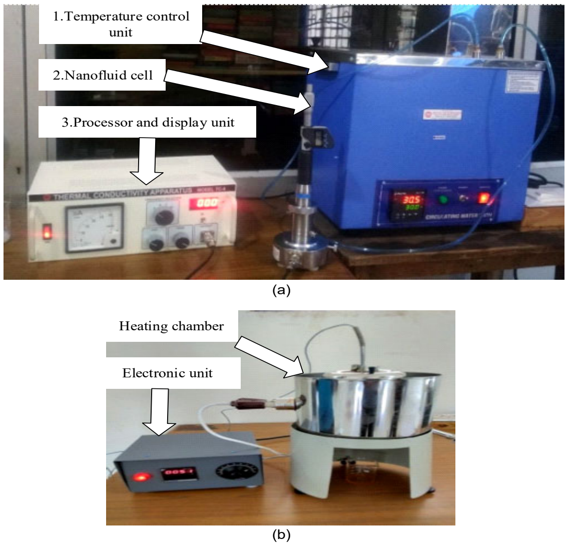


Figure 3. Experimental set-up to measure: (**a**) thermal conductivity and (**b**) viscosity of ester oils and nanofluids.

2.2. Stability of Nanofluids

The main problem encountered in the preparation and application of nanofluids is its stability. How to improve the long term stability of nanofluid dispersions is an important concern for researchers because after the addition of nanoparticles in the base oil they may agglomerate and become an aggregate-like matter. These nanoparticles lose their size properties and, thus, limit their ability to improve the thermophysical properties of the insulating oils. In order to resolve this problem and to improve the long-term stability of the prepared nanofluid samples, surfactant is added in the form of oleic acid. The surfactant addition would introduce a repulsive force that will overcome the Van der Waals attractive force acting between the nanoparticle surfaces based on DVLO theory [26]. In this way, the nanoparticles do not agglomerate and they give stable nano-oil dispersions for longer a period of time. This concept of steric stabilization is explained by DVLO theory. Among all the prepared samples of nanofluids, the samples with 0.03 wt% concentration give stable dispersions for the nanoparticles based on the simple bottle test performed on them, which show no sedimentation even after 72 h of their preparation.

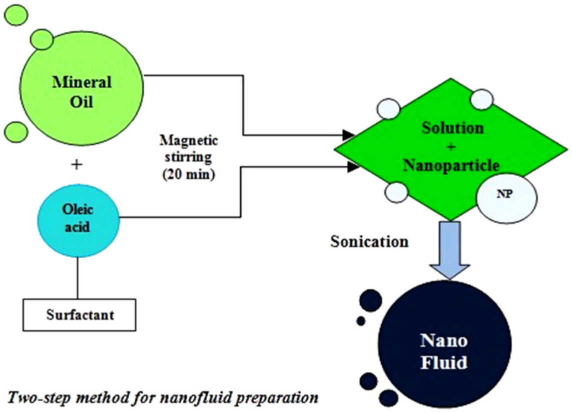


Figure 4. Two-step method for the nanofluid preparation of insulating oils.

2.3. Thermal Conductivity

This is the key parameter to examine the heat transfer performance of the insulating oil. It is desirable that the oils should have a high value of thermal conductivity because liquids with high thermal conductivity absorb more heat [27]. This reduces losses and eventually improves efficiency of the power system. Thermal conductivity is determined using the TC-4 apparatus, and the measurement is conducted for the temperature range of room temperature to 80 °C. The thermal conductivity apparatus [23] follows the theory of heat conduction in liquids based on Debye's concept. In this process of measurement hydro acoustic waves are generated in the oils, and these waves are responsible for heat transfer in oils. On the basis of above heat transfer mechanism, Bridgman obtained a relation between thermal conductivity and sound velocity as given below.

$$k = 3.0\left(\frac{N}{V}\right)^{\left(\frac{2}{3}\right)} K.v_s \tag{1}$$

where k is the thermal conductivity, v_s is the ultrasound velocity, N is Avogadro's number, V is the molar volume and K is the Boltzmann constant.

The thermal conductivity apparatus consists of three parts, namely, an electronic unit with a display to indicate the measured micrometer reading, a nanofluid cell of frequency 7 MHz and the temperature control unit to set the desired temperature. A volume of 100 mL of oil is poured into the nanofluid cell, and, then, ultrasonic waves of known frequency (7 MHz) are produced; their wavelength is measured as indicated by the micrometer display. Seven to eight iterations at each temperature are recorded and the mean value is reported. Finally, the sound velocity is measured using the relation given below,

$$v_s = \lambda.f \tag{2}$$

where v_s is the sound velocity, λ is the wavelength and f is the frequency of ultrasound waves.

After calculating the velocity of sound in nanofluids, the value of thermal conductivity for oils and nanofluids is finally determined.

2.4. Viscosity

Viscosity of insulating oil is also one of the vital parameters to understand its heat transfer characteristics. The high value of viscosity of oils will reduce its flow in the transformer and ultimately affect the heat transfer capability of oils [27]. Hence, viscosity affects the cooling functionality of insulating oils. The redwood viscometer apparatus is used for the measurement of viscosity of the pure ester-based oil and corresponding nanofluids for the temperature range of room temperature to 80 °C at intervals of 20 °C. The apparatus follows the ASTM D445 experimental standard [28], which allows the volume of liquid (50 mL) to flow through a capillary and the time to collect 50 cc of oil is recorded to determine the viscosity of the oils. The process is repeated three times to calculate the mean value. The electronic display unit is utilized to determine the viscosity of the oils.

3. Experimental Procedure and Analysis Results

The thermal conductivity is determined after calculating the velocity of sound waves as obtained from equation (2) and substituting the calculated value in equation (1). The test is performed on a 230 V, 50 Hz (AC) supply for the complete set of experiments. The value of Boltzmann's constant (K), i.e., 1.3807×10^{-23} and Avogadro's number (N), i.e., 6.023×10^{23} are used in equation (1) to determine thermal conductivity of oils. In addition, the viscosity is measured using the density of oils and the mean time to flow. Correspondingly, the graphs are plotted for thermal conductivity and viscosity of pure and nano- oils with nanoparticle concentration and temperature. The flow-chart showing the steps followed in Section 3 is shown in Figure 5.

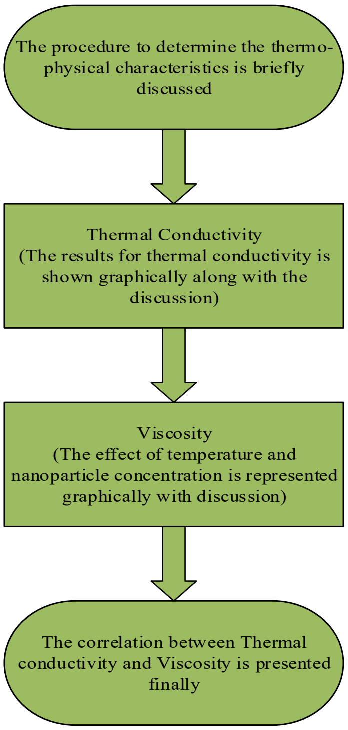


Figure 5. Flow-chart describing the procedure performed in Section 3.

3.1. Thermal Conductivity

The results for the thermal conductivity of pure ester oils and equivalent nanofluids (i.e., TiO_2 and GO nanofluids) with temperature and concentration variation is graphically presented as shown in Figures 6–9. The graphs clearly show that the addition of both the nanoparticles improves the thermal conductivity of ester-based oils almost for the complete temperature range, reducing with the temperature increase. As can be seen, the natural ester-based GO nanofluid shows more enhancement for thermal conductivity compared to natural esters modified by TiO_2 nanoparticles under the same nanoparticle concentration and temperature. However, synthetic ester oil has an almost similar enhancement for both GO and TiO_2 nanoparticles. At a 60 °C temperature, the thermal conductivity of GO modified NE oil reaches a value of 0.0164 W/m-K at a concentration of 0.01 wt%, which is even higher than TiO_2 modified NE oil at a concentration of 0.05 wt% as shown in Figures 6 and 7. At a concentration of 0.05 wt%, the thermal conductivity of GO modified NE oil at 80 °C is equal to TiO_2 modified NE oil at a temperature of 40 °C as shown in Figures 8 and 9. In general, the linear declining variation is shown by ester-based oils for thermal conductivity with temperature, except for TiO_2 modified NE oil at higher temperatures. Similarly, the thermal conductivity of oils show enhancement with an increase in nanoparticle concentration except for NE at 0.05 wt% concentration and at a particular temperature.

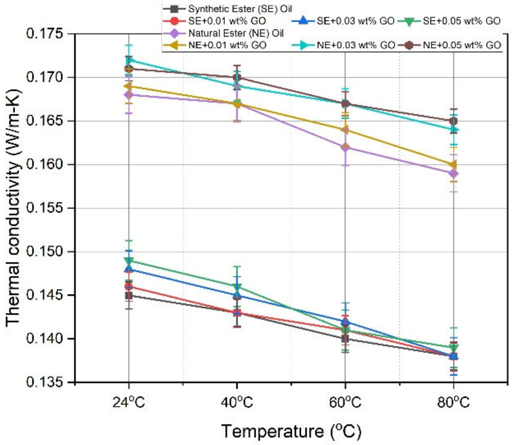


Figure 6. Thermal conductivity variation of ester oils with temperature.

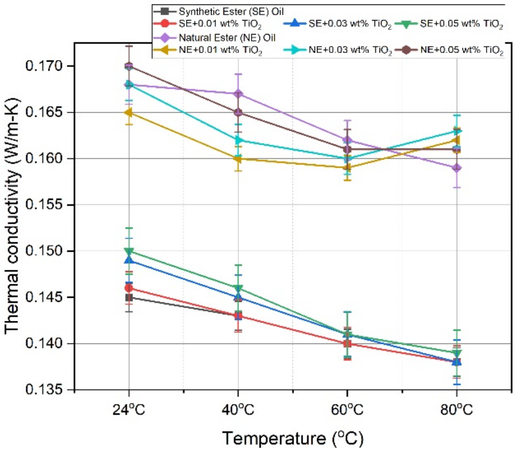


Figure 7. Thermal conductivity variation of ester oils with temperature.

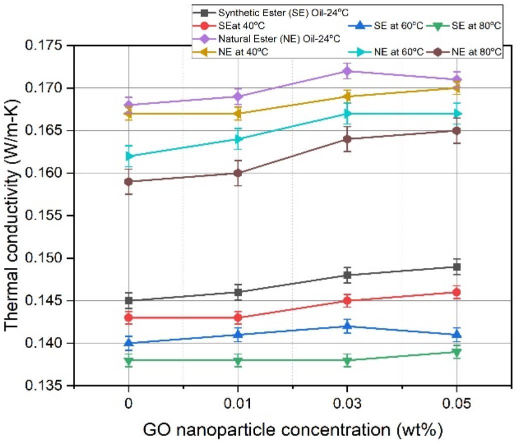


Figure 8. Thermal conductivity of ester oils versus nanoparticle concentration.

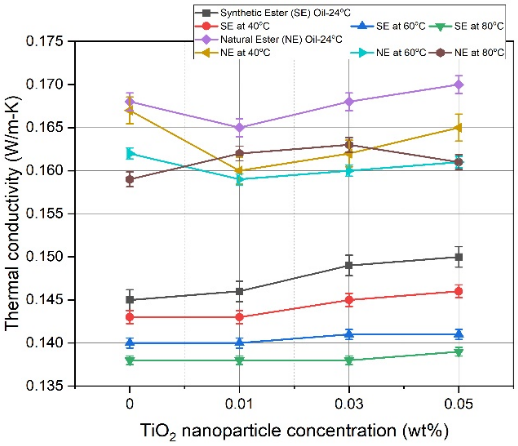


Figure 9. Thermal conductivity of ester oils versus nanoparticle concentration.

The interfacial region formed due to the addition of nanoparticles in the oils acts as the main reason for the significant improvement in thermal conductivity. The nanoparticle links with the oil molecule and further forms a bridge by linking with other nanoparticle/oil layers that will result in significant improvement [29]. Furthermore, the theory suggested by Keblinski, according to which a phonon generated in one particle will extend to surrounding particles, leads to considerable improvement at lower concentrations [30]. The high thermal conductivity of GO-based nanofluids vs. TiO$_2$ modified esters can be attributed to the high thermal conductivity of GO nanoparticles. The thermal conductivity of nano liquids increases as the concentration of nanoparticles increases due to the increase of Brownian motion as the collision of more particles will occur at higher concentration. Moreover, the improvement could be attributed to the interfacial region due to nanoparticle addition and ballistic phonon transport between nanoparticles. The thermal enhancement phenomena are explained based on the theories of Brownian motion of the nanoparticles in oil, conductive cover and bridges due to particle agglomeration and ballistic phonon transport [19], as shown in Figure 10.

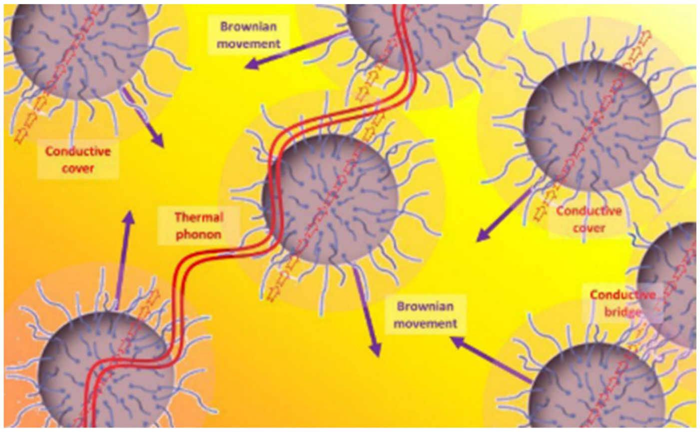


Figure 10. Thermal enhancement phenomena in nanofluids.

3.2. Viscosity

Viscosity is an important parameter to analyze the condition of insulating oils used in distribution/power transformers as it is related to the cooling functionality of oils [31]. Mineral oil should have a low viscosity value so that it can flow easily inside transformer. The measured value of viscosity of ester oils tested is presented as shown in Figures 11–

14. For the graph plotted for viscosity, it is observed that, initially, at room temperature pure oils possess lower viscosity than GO and TiO_2 nanofluids, which further reduces correspondingly with temperature increase, with the exception of TiO_2 nanofluids at higher temperatures as seen in Figures 11 and 12. At 40 °C, the viscosity of NE-based GO nanofluid (NF) is lower than pure NE for higher concentration range (i.e., 0.03 and 0.05 wt%) as shown in Figure 13. Similarly, NE-based TiO_2 nanofluids (NF) show lower viscosity than pure oil even at elevated temperatures as shown in Figure 14.

In general, the viscosity of synthetic esters and their nanofluids is lower than the natural esters and their corresponding nanofluids for the entire temperature and concentration range as can be seen from Figures 11–14, which might be due to the low pour point and better oxidation stability of synthetic esters. The low viscosity of GO-based NF is due to low contamination of ester oils at high temperatures by GO nanoparticles as they have high density and form stable dispersions. A high value of viscosity is observed for the TiO_2 nanofluid due to oxidation of the TiO_2 nanoparticles at high temperature. The viscosity may rise due to presence of contaminants or due to nanoparticle aggregation with the rise in temperature [19]. In general, viscosity of nanofluids increases with nanoparticle concentration, which might be due to formation of clusters that are bonded together due to their forces, resulting in higher resistance to the flowability of nanofluids. It is observed that viscosity decreases with further addition of nanoparticles due to the self-lubricating property of these materials [32]. This effect is generally observed in graphene nanomaterials due to its very strong graphene layers. This effect develops a layer that provides lubrication and reduces friction over the surface. Moreover, this trend of lower viscosity at higher nanoparticle loading is also seen in TiO_2 nanofluids, which may be due to the lower oxidation stability of TiO_2 nanoparticles, particularly at higher temperature, which results in a loss of bonding force and decreases the resistance of nanofluids. This, hence, results in lower viscosity of the nanofluids.

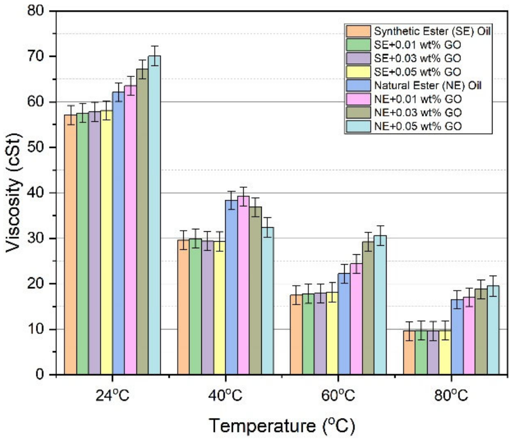


Figure 11. Viscosity variation of ester oils with temperature.

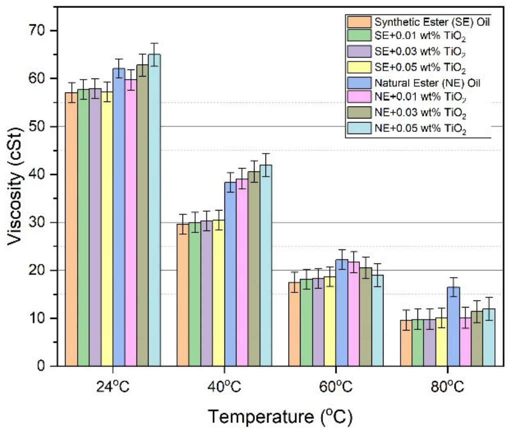


Figure 12. Viscosity variation of ester oils with temperature.

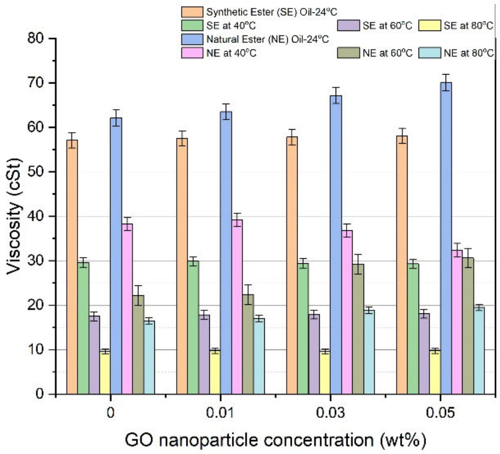


Figure 13. Viscosity of ester oils versus nanoparticle concentration.

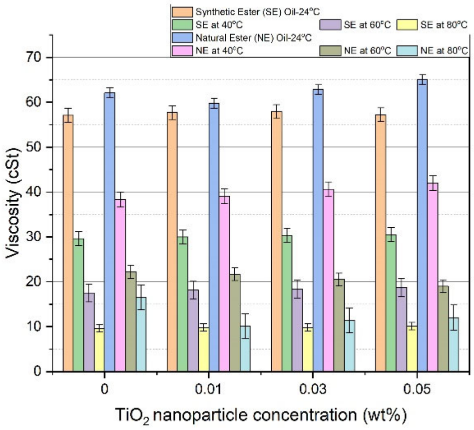


Figure 14. Viscosity of ester oils versus nanoparticle concentration.

3.3. Relation between the two Parameters

The comparison between thermal conductivity and viscosity of ester-based oils for GO nanoparticles with temperature is performed to understand the relationship between them in affecting the cooling capability of insulating oils as shown in Figures 15 and 16. The relation shows a positive correlation as both the parameters decline linearly with temperature. However, it is important to optimize these parameters for better performance. For example, at 40 °C both the parameters give the desired results, but natural esters produce a better combination of results than synthetic esters for GO nanoparticle at 0.03 wt% concentration.

The key motivation of transformer oils in improving the cooling functionality of insulation is enhancing the thermal conductivity. Therefore, to obtain better cooling conditions the thermal conductivity of any desired fluid should be significantly improved, which can be achieved by the addition of nanoparticles in the base oil. However, nanoparticle loading may deteriorate the viscosity of oils, which affects the heat transport in fluids. As such, despite of the deterioration of the viscosity, efficient heat transport can be achieved with natural ester-based nanofluids due to their high thermal conductivity.

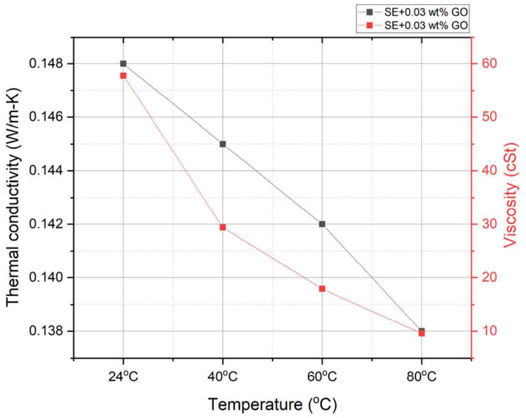


Figure 15. Correlation between thermal conductivity and viscosity for GO-based synthetic ester (SE) oil.

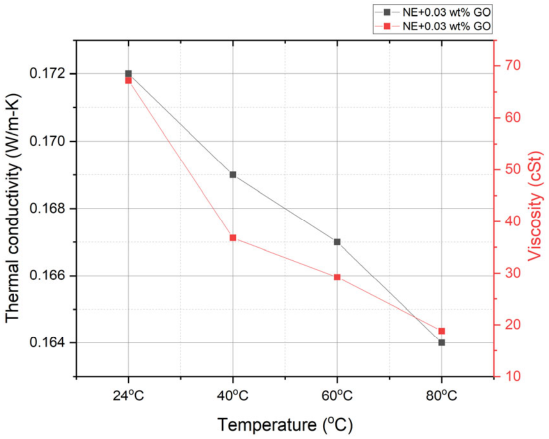


Figure 16. Correlation between thermal conductivity and viscosity for GO-based natural (NE) oil.

4. Conclusions

The effects of temperature and nanoparticles on the thermophysical properties of natural and synthetic ester oil and its nanofluids is experimentally observed and presented in this paper. The aim of this study is to improve the thermophysical properties of insulating liquids tested. Among the insulating oils tested, GO-based nanofluids exhibit superior thermal and physical characteristics; TiO_2 nanoparticle may get oxidized easily at high temperatures, which results in the deterioration of the TiO_2 nanofluid thermophysical characteristics. The GO nanoparticle is chemically inert, forms stable dispersions and has a lesser affinity towards oxidation at elevated temperatures. Therefore, there will be less contamination in the oil, which results in lower viscosity of the nanofluids. In addition, the GO nanoparticle has a higher surface-to-volume ratio than TiO_2 nanoparticle; as a result GO-based nanofluids exhibit higher thermal conductivity than pure ester oils and TiO_2 nanofluids.

GO nanoparticles show a maximum thermal conductivity enhancement of 3.77% for pure natural ester oil at 0.05 wt% concentration and 80 °C. Similarly, TiO_2 nanoparticle gives a maximum enhancement of 3.44% for synthetic ester oil at 0.05 wt% concentration and 24 °C. The high thermal conductivity of natural esters can be attributed to their lower oxidation rate at high temperatures than synthetic esters. However, the superior value of thermal conductivity and optimal viscosity of the GO nanofluid under high temperatures concludes that the GO-nanofluid can be a better alternative to conventional mineral oil for cooling functionality in transformers. However, nano-oil is a new area that needs to be researched more. Therefore, there are some challenges that need to be explored, which are also briefly highlighted in Table 3.

Table 3. Limitations and future work of Ester-based nanofluids.

Limitations	Future Work
Stability of Nanofluids	Stability for longer durations of time still need to be investigated.
Selection of nanoparticle type	Selection of nanoparticles that enhance thermal conductivity of ester-fluids.
Preparation of low-cost nanoparticles	Improve the preparation process with low cost.

- Stability of prepared nanofluids are investigated in the present study but stability for longer durations with respect to temperature is still need to be investigated.
- The present research shows the effect of different nanoparticles on the thermal conductivity and viscosity of ester oils. Therefore, a selection of nanoparticles with enhanced thermal conductivity should possess optimum viscosity for excellent thermophysical performance of nanofluids. Hence, the choice of nanoparticle needs to be researched.
- Most of the research used the two-step method to prepare nanofluids, which requires a high production cost. The question of how to improve the nanofluid preparation process with a reduce cost will be important research in the future.

Nano-oil and nano-oil paper insulation systems are a new area of research and, therefore, need to be investigated more either in terms of their thermal performance or insulation capabilities. Many problems related to the long-term stability of nanofluids still need to be explored as it is a challenge for their industrial application. In the future, nanofluid dispersions need to be tested more for thermal characteristics to find an even better alternative in the form of a nano-oil that can replace mineral oil for transformers.

Author Contributions: Conceptualization, S.A.K., M.T. and A.A.K.; Formal analysis, S.A.K., M.T., A.A.K., B.A. and L.M.-P.; Funding acquisition, M.T. and B.A.; Investigation, S.A.K., M.T. and A.A.K.; Methodology, S.A.K., M.T. and A.A.K.; Supervision, M.T. and A.A.K.; Validation, S.A.K. and M.T.; Writing—original draft, S.A.K. and M.T.; Writing—review & editing, A.A.K., B.A. and L.M.-P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by Taif University Researchers Supporting Project Number (TURSP-2022/278), Taif University, Taif, Saudi Arabia, in part by the Smart City Development Consultancy Project and Collaborative Research Grant Scheme [CRGS/MOHD TARIQ/01 and CRGS/MOHD TARIQ/02] projects, Department of Electrical Engineering, Aligarh Muslim University, India.

Acknowledgments: The authors also acknowledge the technical support provided by the Hardware-In-the-Loop (HIL) Lab and Dielectrics and Insulation Lab, Department of Electrical Engineering, Aligarh Muslim University, India.

Conflicts of Interest: The authors declare no conflict of interest.

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