



# Deep Understanding of the Mechanism and Thermophysical Properties of Prepared Nanofluids Lube Oil Stock-60 with Al<sub>2</sub>O<sub>3</sub> NPs

<sup>1</sup>Alyaa M. Awad, <sup>1</sup>Khalid A. Sukkar\*, <sup>2</sup>Dalia M. Jaed

<sup>1</sup>Department of Chemical Engineering/University of Technology – Iraq

<sup>2</sup>Petroleum Research and Development Centre/ Ministry of Oil – Iraq

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### \*Corresponding Author:

Khalid A. Sukkar

[khalid.a.sukkar@uotechnology.edu.iq](mailto:khalid.a.sukkar@uotechnology.edu.iq)

## Abstract

Iraqi petroleum refineries produce large quantities of base lubricating oils (lube oils). Managing the influence of nano-additives on the lube oil nanofluids is required deep understanding to explain the resulting new specifications of produced nano-lubricants. The present study investigated the effect of Al<sub>2</sub>O<sub>3</sub> NPs addition on the thermal properties of lube oil stock-60. Different mass additions of 0.25, 0.65, 1.05, 1.45, and 1.85 wt.% of Al<sub>2</sub>O<sub>3</sub> NPs at operating temperatures of 20-50°C were evaluated. Also, the thermal conductivity coefficient of the prepared nanofluid was studied at the full range of the experimental temperatures (20-50°C). It was noted that the addition of Al<sub>2</sub>O<sub>3</sub> NPs improved the thermal properties of the prepared nano-lubricant due to the high thermal conductivity of the added Al<sub>2</sub>O<sub>3</sub> NPs. Moreover, the greatest improvement in the thermal conductivity of modified nano-lubricating oil was 13.02% at added Al<sub>2</sub>O<sub>3</sub> mass fraction of 1.85%. The results indicated that the viscosity index of the prepared nano-lubricant was improved dramatically with Al<sub>2</sub>O<sub>3</sub> NPs addition increase at measured standard temperatures of 40 and 100°C. The viscosity index of lubricant nanofluid is increased up to 2.46% at a weight fraction of 1.85%. The flashpoint increased by 1.33, 3.54, 5.75, 7.52, and 9.73% for mass fraction of 0.25, 0.65, 1.05, 1.45, and 1.85 wt.%, respectively. Furthermore, the highest flashpoint value was 248°C of prepared nanofluid lube oil with 1.85 wt.% of Al<sub>2</sub>O<sub>3</sub> NPs. Finally, the produced nano-lubricating oil has high operating quality with economic feasibility. Furthermore, an accurate correlation for predicting the viscosity of both types of nano-lubricants was provided.

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## 1. Introduction

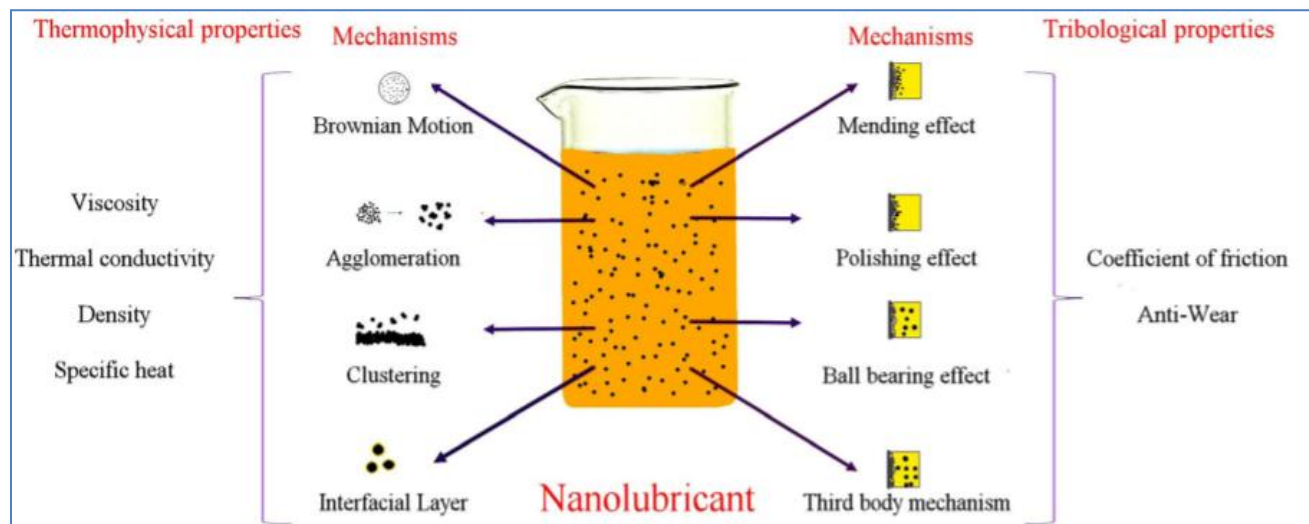
Base lube oils are the main constituent of lubricating oil which comprise more than 90% of the lubricating oil composition. Anti-corrosion and anti-wear materials, for example, are commonly added to lubricating oils to

enhance their characteristics [1-3]. All of these additions are the result of increased operational costs. Moreover, enhancing energy conservation in the internal combustion engines required a high-quality lubricity system for engine moving parts [2,4]. All internal combustion engines used lubricating oil to prevent friction, corrosion, and overheating of moving parts and reduce their abrasion caused by continuous contact [5-8]. Accordingly, from a technical point of view, enhancing lube oil quality with nano-additives will reduce the manufacturing costs of lubricating oil and provide high lubricity performance [9-14]. The addition of nanomaterials into lubricating oil improves their specifications due to the unique properties of these materials and their specific shape and size [14,20]. Then, the produced nano-lubricants will have enhanced viscosity, rheological properties, and thermal conductivity [21-23]. Rajkumar et al. [24], Dalkılıç et al. [25], and Choi et al. [26] observed that the nano-lubricating oil has a high ability to form an oil thin film. This film will adhere to the moving parts for a longer time and provide superior protection against wear and friction problems. Many authors studied the influence of nanomaterial additions on the rheological properties of lubricating oil. Vakili-Nezhaad [27] studied the effect of multi-walled carbon nanotubes on the viscosity index of the lubricating oil different nano-additions from 0.01 to 0.2 wt.%. They observed that the viscosity index of the nano-lubricant increased by 14.6% at 0.2 wt.%. Sepyani et al. [28] observed that adding ZnO NPs into engine oil (SAE 50) increases the viscosity of nano-lubricating oil by 12% at a volume fraction of 1.5 wt.%. Rashed [29] tested the tribological behaviour of the lubricating oils type 20W-50 and 15W-50 by adding SiO<sub>2</sub> NPs and TiO<sub>2</sub> NPs at different temperatures of 40, 80, and 100°C. The authors showed that the lubricant oils' friction coefficient and wear rate were reduced for TiO<sub>2</sub> NPs addition of 1.0% wt., while nano-lubricating oil with SiO<sub>2</sub> NPs does not significantly improve the tribological behavior. Wu et al. [30] investigated the antiwear ability of diesel engine lubricating oil by adding a nano-lanthanum hydroxide/ graphene oxide mixture. They observed that the nano-addition combination enhanced the efficiency of the nano-lubricant significantly. Rashed [31] improved the tribological properties of Al<sub>2</sub>O<sub>3</sub> NPs/20W-50 lubricating oil. The authors indicated that the lowest coefficient of friction was obtained at nano-addition of 0.4 wt.% and operating temperature of 50 °C. Furthermore, the thermal conductivity and surface properties of nano-lubricants improved dramatically in these types of nanofluids. Then, the engine efficiency will have increased due to low consumed energy and long operating lifetime [32-34]. Also, nano-lubricants reduced the amounts of consumed fuel in automobiles due to the efficient heat transfer process and good lubricity of moving parts [4,8,13]. Furthermore, the preparation of nanofluid from the addition of suspension nanomaterials into the base fluid leads to an apparent enhancement in the thermal performance of these fluids [5,35]. This enhancement is attributed to the Brownian motion of nanoparticles in the base fluid, which improves the heat transfer mechanism. Saedinia et al. [36] studied the thermal conductivity of nanofluid type CuO NPs/oil at laminar flow conditions. The volume fraction of nano-addition was in the range of 0.2-2%, and the operating temperature was in the range of 24-70°C. The authors observed that the most significant enhancement in thermal conductive was 18% at 2% of nano-addition at 70°C. Ahmadi et al. [37] investigated the addition of MWCNTs into (20W50) lubricating oil at volume fractions of 0.1, 0.2, and 0.5% and temperature of 20°C. The results revealed that the most significant improvement in thermal conductivity was 22.7% at the volume fraction of 0.5%. Agarwal et al. [38] prepared different nanofluids by mixing CuO NPs with engine lubricating oil in varying volume fractions of 0.25–2% at different operating temperatures (10–70°C). The authors observed that the thermal conductivity of nano-lubricating oil improved by 19%. Also, Sukkar et al. [39] measured the flashpoint of the CuO NPs and TiO<sub>2</sub> NPs nano-lubricating. The authors noted that the flashpoint increased by 12.62% and 9.3% for nano-lubricating oil of CuO NPs and TiO<sub>2</sub> NPs, respectively. Accordingly, nanomaterials into lubricating oil produced nanofluids with high thermal conductivity, high tribological performance, and stable lubricity. Evaluating the rheological behavior of nano-lubricating oil required more understanding to explain the mechanism of variation of viscosity, thermal conductivity, flashpoint, and pour point [40-42]. Additionally, no previous work deals with enhancing specifications of base lube oil with nano-additives. Therefore, this research aims to develop a comprehensive mechanistic understanding of the effects of Al<sub>2</sub>O<sub>3</sub> NPs concentration on the thermophysical properties of base lube oils (stock 60).

## 2. Mechanism of Prepared Nano-lube Oil Operations

The behaviour of nano-lubricants depends upon their thermophysical properties. Usually, the thermophysical properties of the nano-lubricant are directly affected by the physical and chemical structures of the nano-lubricant, which themselves are affected by various parameters such as operating temperature, the volume fraction of NPs, particles size, surface area, atomic and chemical structure. Also, in many cases, the preparation method of nano-lubricant plays a significant role in the final specifications of the product [5,17,40]. The

numerous techniques involved in improving the thermophysical and tribological characteristics of nano-lubricants are depicted in Figure 1. Brownian motion [43], particle agglomeration [44], clustering [45],



interfacial layer [46], and other factors impact the thermophysical characteristics of nano-lubricants. In addition, dispersed nanoparticles have a role in tribological quality enhancement through mending, polishing, ball bearing, and third body mechanisms [46-50].

**Figure 1:** Graphical performance of various mechanisms involved with nano-lubricant [47].

### 3. Experimental Procedure

#### 3.1. Materials

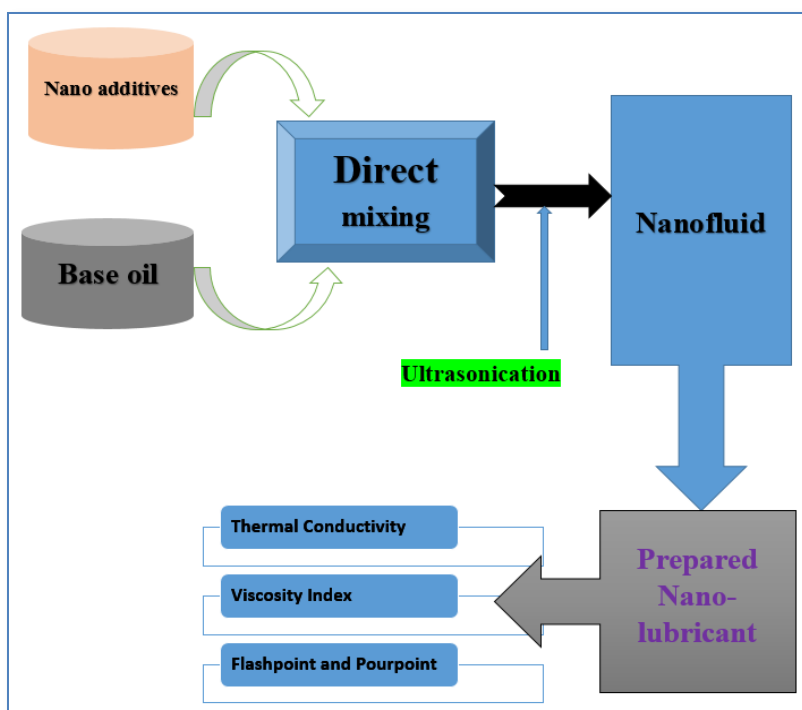
The lube oil base stock-60 was used as the base fluid in the present investigation and obtained from the vacuum distillation unit, Al-Daura Refinery, Baghdad, Iraq. Table 1 summarizes the general specifications of the stock-60 lubricating oil. Also,  $\text{Al}_2\text{O}_3$  NPs (with a purity of 99.6 %, density of  $2.33 \text{ g/cm}^3$ , a particle diameter of 28 nm, and surface area of  $144 \text{ m}^2/\text{g}$ ) were imported from C.S.M. Tech. Company.

**Table 1:** The general specification of the base lube oil (stock 60).

Property	Value
Kinetic viscosity (cSt) at $100^\circ\text{C}$	8.45
Kinetic viscosity (cSt) at $40^\circ\text{C}$	64.89
API gravity	28.9
Density at $15^\circ\text{C}$ ( $\text{g/cm}^3$ )	0.893
Flash point ( $^\circ\text{C}$ )	228
Color (ASTM)	3.5
Pour point ( $^\circ\text{C}$ )	-3.2
Viscosity index	102

#### 3.2. Synthesis of nano-lube oil

The  $\text{Al}_2\text{O}_3$  NPs were dispersed in the base lubricating oil (stock-60) to obtain high desperation nano-lubricants. Accordingly,  $\text{Al}_2\text{O}_3$  NPs at different nano-additions of 0.25, 0.65, 1.05, 1.45, and 1.85 wt.% were mixed with the base lubricating oil. Then, the required amount of the  $\text{Al}_2\text{O}_3$  NPs was carefully weighed using an accurate electronic digital balance and then mixed with the base lubricating oil in two steps. The first one is achieved by combining the produced nanofluid with a mechanical mixer for 30 minutes. In the second step, the nanofluid is exposed to an ultrasonic bath (P120-Elmasonic) for 1 hr. The sonication method was achieved at  $40^\circ\text{C}$  and 20 kHz [16,18,22,31]. Figure 2 summarizes the schematic diagram of the nanofluid (nano-lubricating oil) preparation stages.



**Figure 2:** Schematic diagram of preparation stages of the nano- lubricating oil.

### 3.3. Measuring of Viscosity and Viscosity Index

The viscosity index of parent oil and nano-lubricants at different concentrations of NPs was measured using Stabinger viscometer (SVM 3000). First, the kinematic viscosity ( $k$ ) of parent and nano-lubricants were measured to varying concentrations of added  $\text{Al}_2\text{O}_3$  NPs (0.25, 0.65, 1.05, 1.45, and 1.85 wt.%) at standard operating temperatures of 40 and 100°C. For reliability, and error reduction, each test is repeated three times, and the mean value is considered. Then, the kinematic viscosity was measured at standard characteristics temperatures of 40°C and 100°C. Accordingly, the base oil and nano lubricants viscosity index was calculated using the following equation, based on standard ASTM D-7042 [10,22] and ASTM D-2270 [6,15,24].

$$VI = \left[ \frac{L-U}{L-H} \right] \times 100 \quad (1)$$

Where U, L, and H are the oil's kinematic viscosity at 40 °C, the values of kinematic viscosity at 40 °C for oils of viscosity index 0, and 100, respectively, which have the same kinematic viscosity at 100 °C. Furthermore, when the kinematic viscosity at 100 °C is in the range of 2–70 cSt, then the values of L and H are taken from ASTM D-2270 tables. On the other hand, when the kinematic viscosity > 70 cSt, the values of L and H are estimated from the following correlations:

$$L = 0.8353 k^2 + 14.67 k - 216 \quad (2)$$

$$H = 0.1684 k^2 + 11.85 k - 97 \quad (3)$$

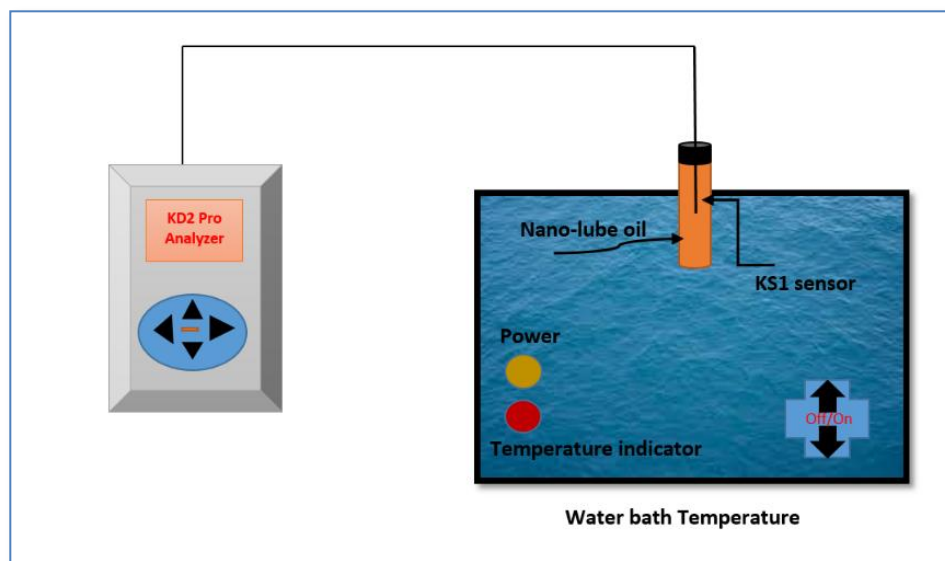
where,  $k$  is the kinematic viscosity at 100°C of the engine lubricating oil whose viscosity index is to be evaluated.

### 3.4. Thermal Conductivity of Prepared Nano-lube Oil

In the present experimental part, the thermal conductivity of nano-lubricating oils was measured to study their capability to deliver heat transfer. The KD2 Pro, a portable device, was used to characterize thermal properties based on the hot wire technology. This device was located at the Polymer Engineering Department, University of Babylon. This instrument has a probe of 1.3 mm diameter, cable length 50 cm, and 60 mm long. A high accuracy water bath was used for temperature control during each measurement. Table 2 illustrates the main specifications of the KD2 Pro analyzer, and Figure 3 shows the schematic representation of the thermal conductivity measuring system. The thermal conductivity was tested at different concentrations of  $\text{Al}_2\text{O}_3$  NPs (0.25, 0.65, 1.05, 1.45, and 1.85 wt.%) and various operating temperatures of (20, 30, 40, and 50°C).

**Table 2:** Specifications of thermal conductivity measuring system.

Property	Value
Power (Volt)	3
Measurement Range ( $\text{W/m}^\circ\text{C}$ )	0.1-2
Accuracy (%)	3
Speed of Measurement (min)	2
Operating Temperature ( $^\circ\text{C}$ )	5-50



**Figure 3:** Schematic representation of the thermal conductivity measuring system.

### 3.5. Measuring of Flashpoint and Pour Point

The lube oil and nano-lube oil flashpoints were measured using the standard test method of Cleveland open cup for flash and fire points (model: FP92 5G2, USA) according to ASTM D-92 with a maximum error of  $\pm 2\%$ . On the other hand, the pour point of nano-lubricating oils was tested using an automatic cloud and pour point device (CPP 5GS, USA) depending on ASTM D-97. Also, the XRD apparatus (Shimadzu 6000) and FE-SEM (JEOL-7610F) are used to identify the structural and morphological specifications of  $\text{Al}_2\text{O}_3$  NPs.

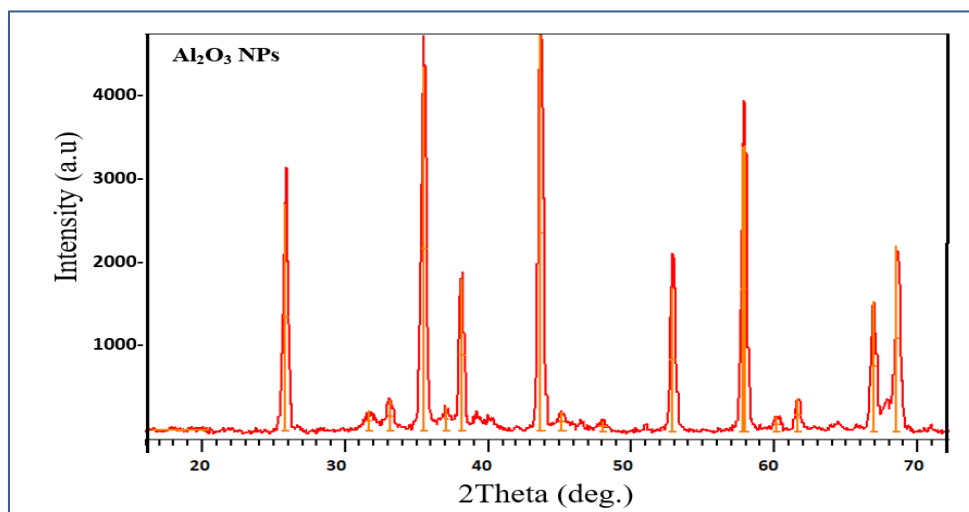
## 4. Results and Discussion

### 4.1. Identification of $\text{Al}_2\text{O}_3$ NPs

Figure 4 shows the XRD measurements of the crystalline structures of the  $\text{Al}_2\text{O}_3$  NPs. Then, from this figure, it can be noted that the  $\text{Al}_2\text{O}_3$  NPs have a high crystalline structure with high purity due to present the general standard peaks in the structure. For example, the constant standard characteristics peaks of  $\text{Al}_2\text{O}_3$  NPs at  $2\theta^\circ$  were 36.5, 39.12, 42.8, 45.1, 53.4, 57.8, 64.4, 68.6, 74, and 77.29°. Also, from the results of the XRD pattern,

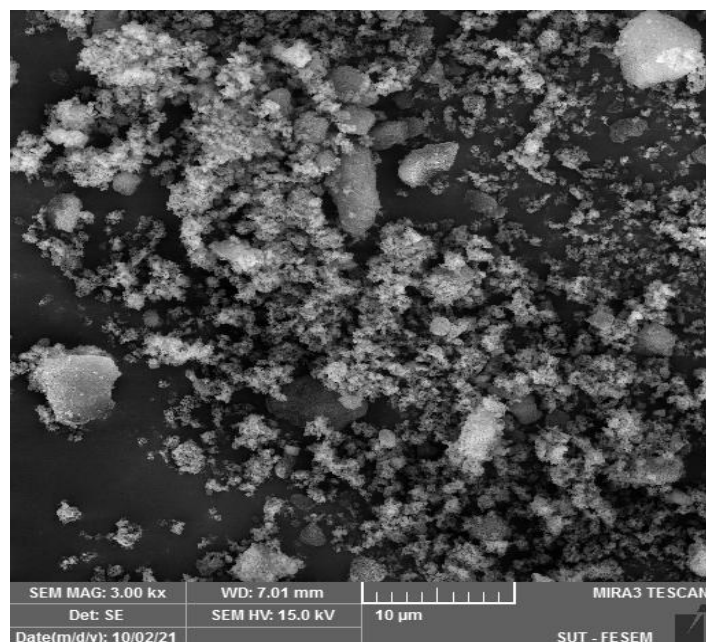


the  $\text{Al}_2\text{O}_3$  NPs in the current study have the same key characteristics peaks of standard  $\text{Al}_2\text{O}_3$  NPs of PDF-Card-00-048-1548.



**Figure 4:** The XRD results of the crystalline structure of  $\text{Al}_2\text{O}_3$  NPs.

Also, the morphological properties specifications of the  $\text{Al}_2\text{O}_3$  NPs were analyzed using FE-SEM images. Figure 5 reveals the morphological feature of the  $\text{Al}_2\text{O}_3$  NPs. The results indicated that the nanoparticles are spherical. This shape provided excellent rolling specifications for the lubricity of moving parts required for internal combustion engines. Furthermore, the morphological results pointed to that the primary average particles size of  $\text{Al}_2\text{O}_3$  NPs was 28 nm. Additionally, it can be observed that most  $\text{Al}_2\text{O}_3$  NPs are agglomerated before disperse in the base stock lubricating oil [10,14,27].



**Figure 5:** The morphological surface topography of  $\text{Al}_2\text{O}_3$  NPs by FE-SEM.

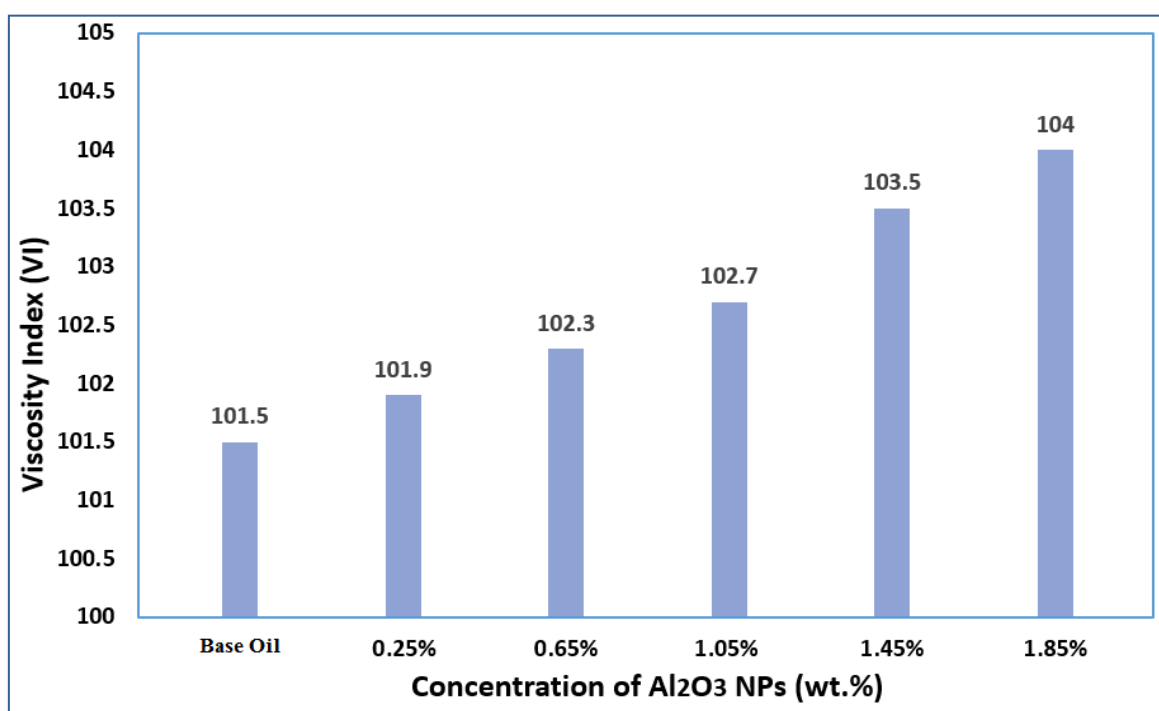
#### 4.2. Viscosity-Index of Nano-lube Oil

Evaluating the viscosity index (VI) is an essential step to understanding the influence of nanomaterial addition on the rheological behaviour of lubricating oil. This index can be obtained from the results of kinematic viscosity at standard operating temperatures of 40 °C and 100 °C according to equation (1). Table 3 illustrates the changes

in the viscosity index with the concentration of added  $\text{Al}_2\text{O}_3$  NPs. Then, the results in this table indicated that the viscosity index increased with nano-additions. Accordingly, for both standard temperatures of 40 and 100 °C, it was noted that as the kinematic viscosity of the prepared nano-lubricant increased, the viscosity index of these lubricants was undergone an apparent increase. The maximum viscosity index was at 2.46% at nano-addition of  $\text{Al}_2\text{O}_3$  NPs of 1.85 wt.%. Additionally, Figure 6 illustrates the changes in the viscosity index with a concentration of added  $\text{Al}_2\text{O}_3$  NPs. The results show that the viscosity of nano-lubricating oil increases with increasing the concentration of added  $\text{Al}_2\text{O}_3$  NPs. This behaviour can be attributed to the Brownian motion of nanoparticles that allows collision of nanoparticles and then make the particles narrow to each other. Accordingly, in this case, the system tends to form clusters of  $\text{Al}_2\text{O}_3$  NPs attracted to each other due to strong van der Waals forces between them. Then, as the concentrations of nanoparticles recorded higher numbers, more collisions between nanoparticles are produced, and big clusters are formed. Furthermore, an increase of the cluster size leads to a clear increase in the shear stress of the nanofluid and then increases the viscosity of lubricating oil previous investigations by researchers Dalkılıç et al. [25] and Sepyani et al. [28] have validated these findings.

**Table 3:** The measured VI values of nano-lubricating oil at various additions of  $\text{Al}_2\text{O}_3$  NPs.

$\text{Al}_2\text{O}_3$ NPs (wt.%)	0	0.25	0.65	1.05	1.45	1.85
Viscosity Index (VI)	101.5	101.9	102.3	102.7	103.5	104
Enhancement (%)	-	0.39	0.79	1.18	1.97	2.46

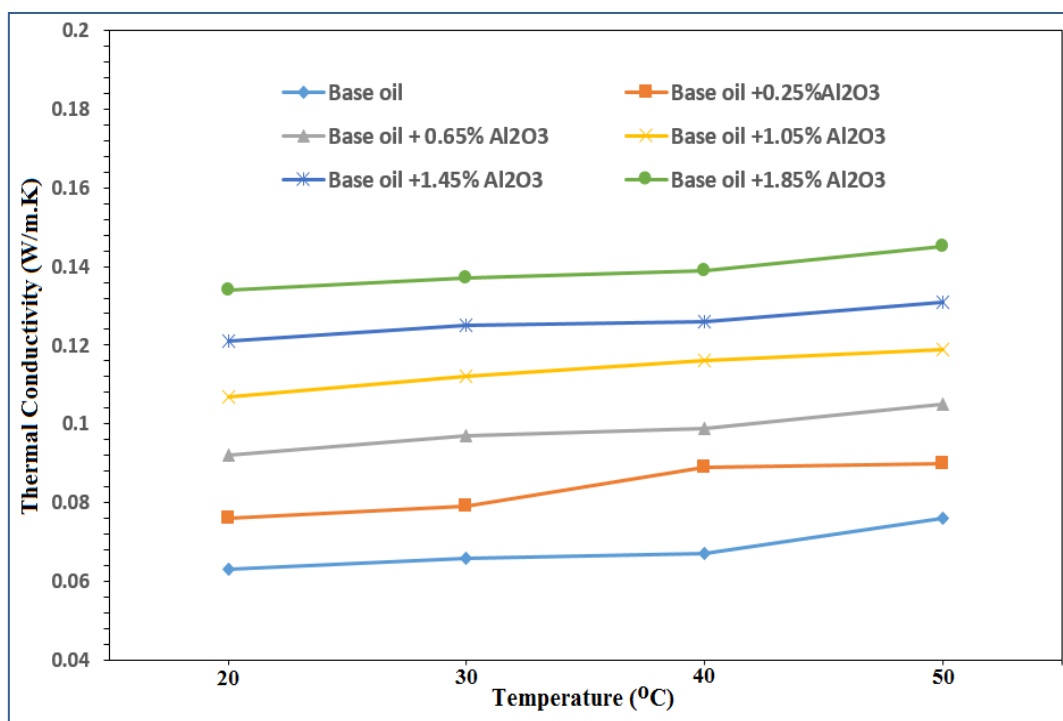


**Figure 6:** Influence of  $\text{Al}_2\text{O}_3$  NPs additions on the viscosity index.

#### 4.3. Thermal Conductivity of Nano-lube Oil

The thermal conductivity measurements were achieved to evaluate the ability of  $\text{Al}_2\text{O}_3$  NPs to improve the thermal specification of base stock lubricating oil. The results of the measured thermal conductivity of base lubricant and nano-lubricants are shown in Figure 7. The results indicated that the nano-lubricants have higher thermal conductivity values than the base stocks lubricating oil. Then, it can be seen that, with increased  $\text{Al}_2\text{O}_3$  NPs additions, the thermal conductivity of the prepared nano-lubricants increased. These results are related to the high thermal conductivity of the  $\text{Al}_2\text{O}_3$  NPs compared to that of the parent engine lubricating oil. According

to the results of many authors, the properties of the base fluid and the added nanoparticles are the two key factors in determining the final specifications of nano-lubricant [16,22,29]. Also, the results in Figure 7 indicated that the values of thermal conductivity increase with operating temperature increase. For example, the highest thermal conductivity value was recorded at a temperature of 50°C and nano-addition of 1.85% of  $\text{Al}_2\text{O}_3$  NPs. It is essential to mention here that one duty of engine oil is to cool the engine down, and then it is suggested that the nano-lubricants with 0.25 wt.% concentration of  $\text{Al}_2\text{O}_3$  NPs a suitable for engine lubricity due to enhanced heat transfer properties and thermal conductivity. Dey et al. [14], Ali et al. [17], and Dambatta et al. [20] indicated that the thermal conductivity of a nanofluid is a key factor that determines the lubricity performance of engine lubricating oil. Higher thermal conductivity of a lubricant means the heat transfer process occurs at a greater rate, and better cooling is achieved. The performance of nano-lubricant is related to the concentration, size, shape, and thermophysical properties of added nanomaterials [3,8,30]. The mechanisms of the effect of thermal conductivity on the thermal specification of nanofluids can be related to the Brownian motion of nanoparticles in the system [33-37]. Moreover, according to the collision of theory, the Brownian motion usually improves with thermal conductivity, and a solid-solid conduction heat transfer can be achieved. Also, as the thermal conductivity of nano-lubricants increases with motion, the convective heat transfer mechanism will be highly effective [11,20,22]. Finally, the stability of the prepared nano-lubricating oils (nanofluids) was evaluated for 60 days.

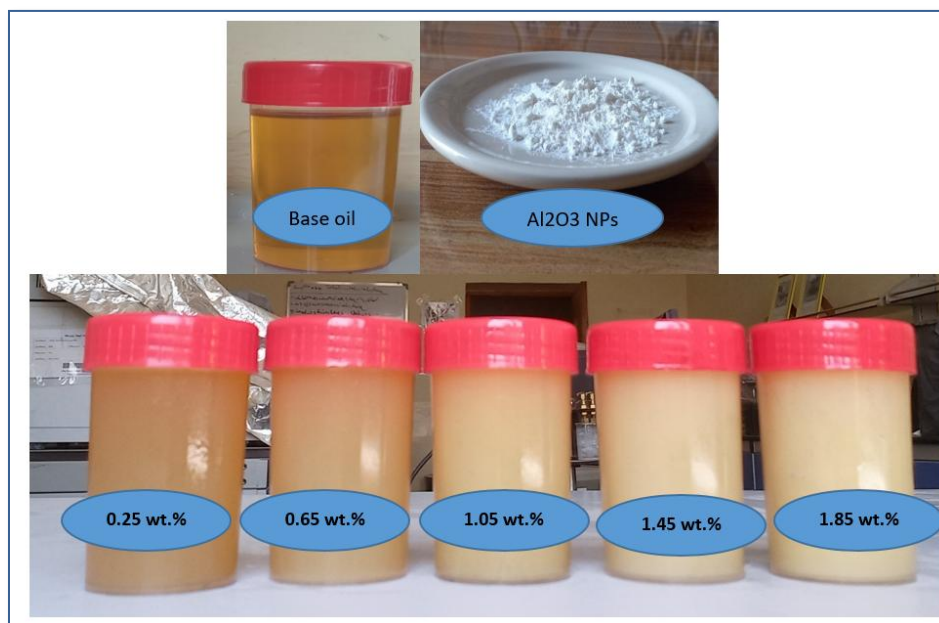


**Figure 7:** The influence of operating temperature and  $\text{Al}_2\text{O}_3$  NPs additions on the thermal conductivity value of nano-lube oils.

Figure 8 shows a photograph of the parent and nano-lubricating oils at different additions of  $\text{Al}_2\text{O}_3$  NPs. It was observed a high stable and high dispersion of  $\text{Al}_2\text{O}_3$  NPs in the base stock lubricating with testing time. In other words, the high stability of nanomaterials within the bulk lubricants is attributed to the high dispersion provided by the ultrasonic mixing step. Accordingly, utilizing the ultrasonic dispersion technique enhanced  $\text{Al}_2\text{O}_3$  NPs in the base stock lubricating oil with a more uniform distribution with time. Many publications pointed to the high influence of the sonication method on nanofluid stability [5,8,12,25-27]. Finally, it is essential to mention here that the thermal conductivity of lubricants plays a dominating role in determining their heat transfer and cooling behaviour. However, the low thermal conductivity of conventional base lubricant oils limits their performance.



Recent researches show the application of nanoparticles as thermal conductivity improvers. Thus, nanoparticles have played an important role in improving the efficiency of internal combustion engines, reducing maintenance requirements and more extended service periods for lubricants, and improving fuel economy in automotive [21,30,42].



**Figure 8:** Testing nano-lubricants stability for 60 days at different  $\text{Al}_2\text{O}_3$  NPs additions.

#### 4.4. Evaluation of Flashpoint and Pour Point

Flashpoint and pour point determine the high and low-temperature abilities of lubricants. Flashpoint is the temperature at which lubricant vapour starts burning and then gets extinguished, thus limiting its high-temperature abilities [1-6]. From an operating point of view, the flashpoint is a major property for lubricating oil inside the internal combustion engine due to its direct interaction with operating and environmental temperatures. Table 4 exhibits the values of flashpoints at five various mass fractions. This table shows that the flashpoints of nano-lubricants were enhanced dramatically with the  $\text{Al}_2\text{O}_3$  NPs additions. Then, the flashpoint increased by 1.33, 3.54, 5.75, 7.52, and 9.73% for nano-additions of 0.25, 0.65, 1.05, 1.45, and 1.85 wt.%, respectively. Also, it was seen that the highest flashpoint value was  $248^\circ\text{C}$  at  $\text{Al}_2\text{O}_3$  NPs addition of 1.85 wt.%. Accordingly, in this case, the ability of lube oil toward ignition increased due to increasing thermal conductivity with a concentration of nano-additions. Consequently, the improved flashpoint can be considered an advantage in improving the lubricity of base lube oil. This is in good agreement with previous research [7,8,18,33-38].

**Table 4:** Variation of flash point at various  $\text{Al}_2\text{O}_3$  NPs concentrations.

No.	$\text{Al}_2\text{O}_3$ NPs (wt.%)	Flash Point ( $^\circ\text{C}$ )	Increment (%)
1	0	228	-----
2	0.25	229	1.33
3	0.65	234	3.54
4	1.05	239	5.75
5	1.45	243	7.52
6	1.85	248	9.73

Additionally, the pour point refers to the lowest temperature at which oil stops flowing and thus becomes important for low-temperature surroundings. Table 5 shows the impact of the  $\text{Al}_2\text{O}_3$  NPs additions on the pour point temperature of the lube oil. The result indicated that the pour point values of nano-lube oils decreased with

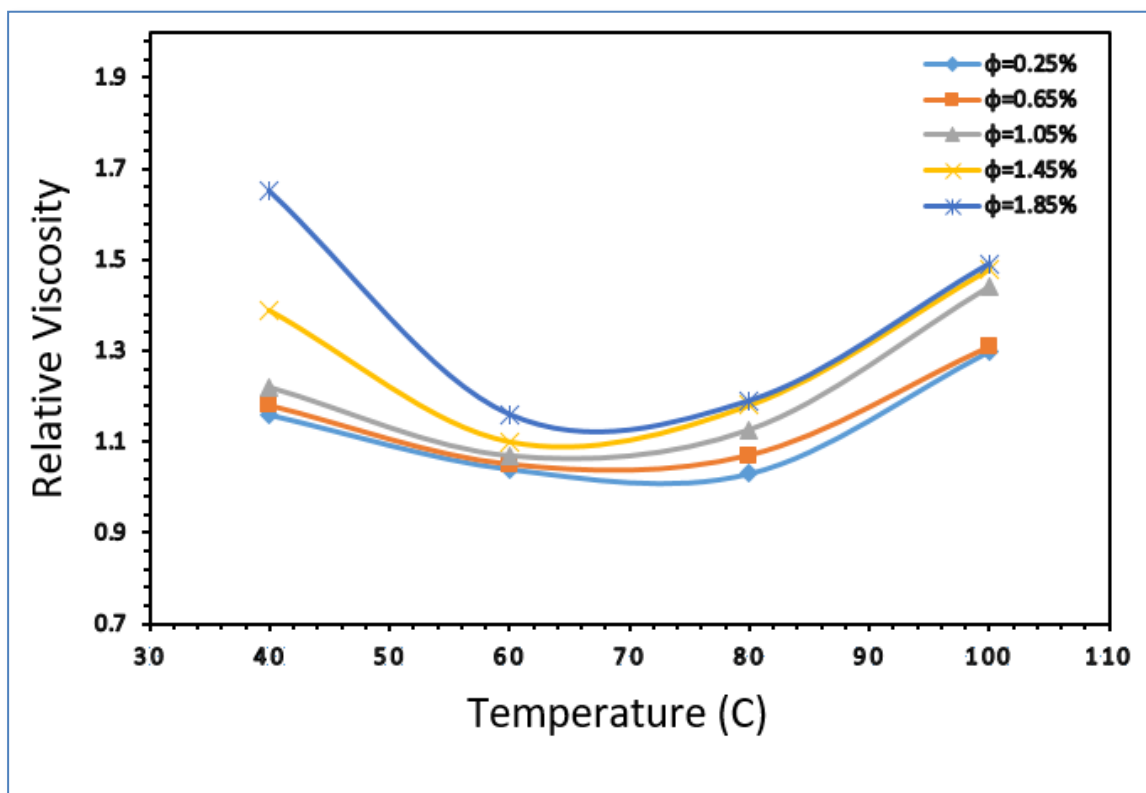
increasing of  $\text{Al}_2\text{O}_3$  NPs additions in comparison with the base lube oil. The reduction in the values of the pour point of nano-lube oil is related to the significant thermophysical properties of  $\text{Al}_2\text{O}_3$  NPs. This table noted that the best concentration of  $\text{Al}_2\text{O}_3$  NPs addition was 1.45 wt.%, which provides an acceptable pour point of  $-5.7^\circ\text{C}$  with the enhancement of 90%. This concentration represents the perfect nano-addition with no agglomeration of  $\text{Al}_2\text{O}_3$  NPs inside the engine. Therefore, temperature reduction decreases the convenient movement of nanoparticles; furthermore, the effectiveness of the nanoparticles decreases due to the agglomeration of the nanoparticles at higher concentrations. Moreover, nano-addition of more than 1.05 wt.% of  $\text{Al}_2\text{O}_3$  NPs is not favourable due to no higher change in the pour point value have been observed. It is essential to mention that as the operating temperature was reduced, the lubricating oil motion will be restricted with the increasing nano-addition due to agglomerated NPs.

**Table 5:** Variation of pour point at diverse concentrations of the  $\text{Al}_2\text{O}_3$  nano-lubricants.

No.	$\text{Al}_2\text{O}_3$ NPs (wt.%)	Pour Point ( $^\circ\text{C}$ )	Reduction (%)
1	0	-3.2	-----
2	0.25	-4.1	36.67
3	0.65	-4.3	43.33
4	1.05	-5.4	80
5	1.45	-5.7	90
6	1.85	-5.9	96.7

#### 4.5. Effect of Temperature and Volume Concentration on Relative Viscosity of Nano-lubricant

The relative viscosity ( $\frac{\mu_{nf}}{\mu_{bf}}$ ) of nanofluids may be used to indicate the fluctuation of dynamic viscosity of nano-lubricants at different temperatures for both nano-additives. For example, Figure 9 shows the relative viscosity of  $\text{Al}_2\text{O}_3$  nano-lubricants at different temperatures ( $40^\circ\text{C}$ ,  $60^\circ\text{C}$ ,  $80^\circ\text{C}$ , and  $100^\circ\text{C}$ ), as well as different  $\text{Al}_2\text{O}_3$  solid fractions. As seen in Figure 9, the relative viscosities vary significantly as temperature changes.

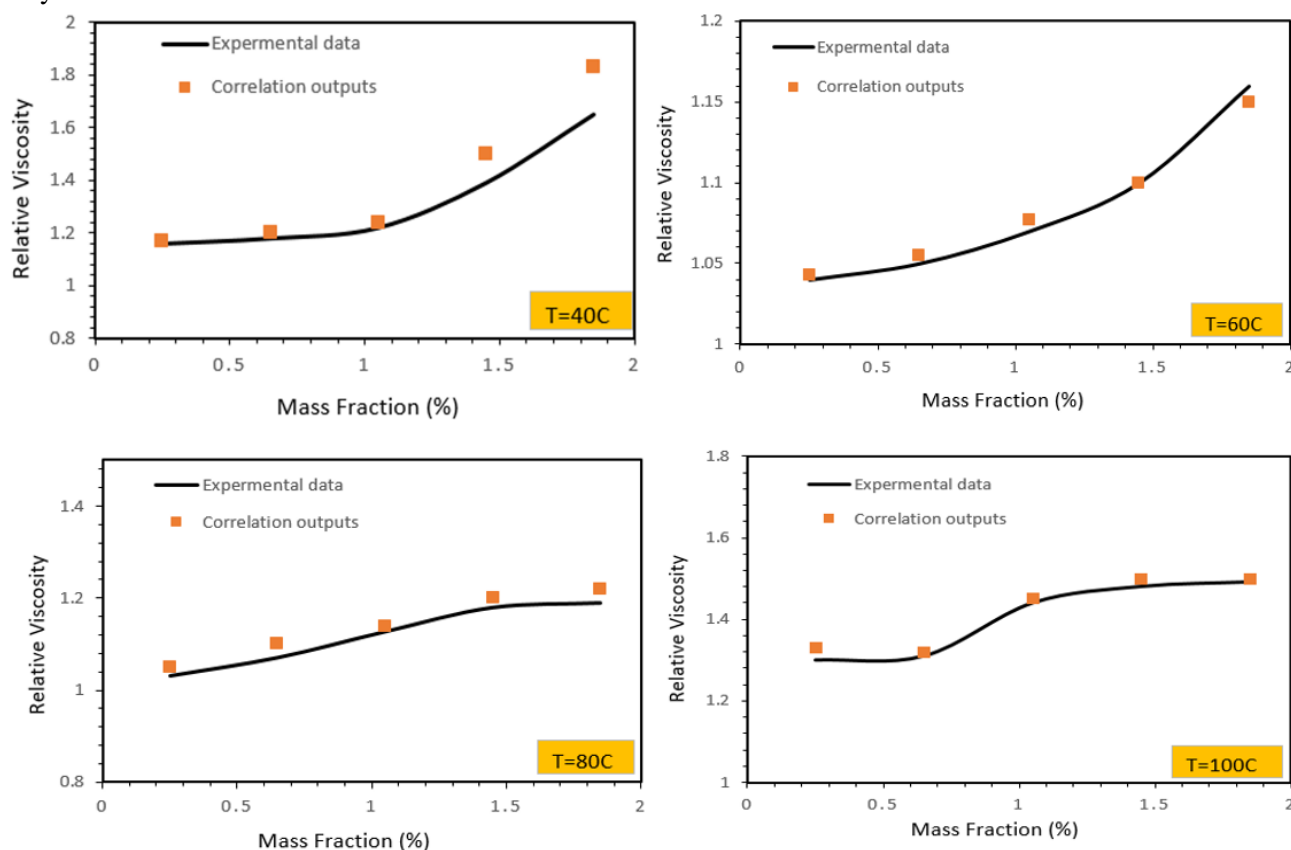


**Figure 9:** Relative viscosity of Al<sub>2</sub>O<sub>3</sub> nano-lubricant versus temperature in various mass fractions.

Also, Figure 9 demonstrates that when the temperature rises from 40°C to 60°C, the relative viscosity of Al<sub>2</sub>O<sub>3</sub> nano-lubricant with various five mass fractions decreases significantly, but relative viscosity values soon begin to fall increase as the temperature rises to 80°C and 100°C. When the temperature rises above 80°C, the agglomeration of spherical nanoparticles of alumina oxide, which are perpendicular to the direction of the fluid flow during the viscosity measurement process and thus work to increase the relative viscosity compared to the base fluid, rather than decrease, where the nanospheres work on sliding the fluid layers over each other, causes the relative viscosity to increase. The aggregation disintegrates due to weak intermolecular adhesion forces [48-50]. Furthermore, Minitab optimization and statistical program version 19 was used to fit the curves of nano-lubricant experimental data. Then, the following predicted mathematical correlation equations (number 4) were achieved to represent the present experimental results. This equation is dependent on the temperature and volume fraction, and the viscosity of the Al<sub>2</sub>O<sub>3</sub> nano-lubricant.

$$\mu_r = 13.321 - 10.11 T^{0.042} + 0.251 \phi^{1.47} \quad (4)$$

Where  $\mu_r$ ,  $\phi$ , and  $T$  are the relative viscosity of Al<sub>2</sub>O<sub>3</sub> nano-lubricant, mass concentration, and temperature, respectively. These correlations may be used at temperatures ranging from 40 to 100 °C, with mass fractions ranging from 0.25 to 1.85 %. To test the correctness of the correlation above, Figure 10 compares experimental data with data obtained by the proposed correlation at various temperatures. The absence of variation between these two data groups implies that the recommended correlation for predicting these nano-viscosity lubricants is pretty accurate.

**Figure 10:** Comparison between Experimental data and correlation outputs with various mass fractions at T=40°C, T=60°C, T=80°C, and T=100°C.

## 5. Conclusions

The rheological and thermal characteristics of base stock-60 lubricating were improved successfully by adding  $\text{Al}_2\text{O}_3$  NPs. The kinematic viscosity of nano-lubricating oil showed an apparent increase with increasing mass fraction of  $\text{Al}_2\text{O}_3$  NPs additions. Also, the viscosity index rises dramatically with the rise in the concentration of  $\text{Al}_2\text{O}_3$  NPs as measured at standard temperatures of 40 and 100 °C. The highest value of viscosity index was 2.46% at  $\text{Al}_2\text{O}_3$  NPs addition of 1.85wt.%. Moreover, the experimental results indicated that the thermal conductivity of nano-lubricating oil increased as the operating temperature increased with nano-addition. Furthermore, it is suggested that the nano-lubricants with nano-addition of 0.25 wt.% are more suitable for engine lubricity due to enhanced heat transfer properties and thermal conductivity. The flashpoint indicates the quality and operating of the lubricant oil in hot seasons and especially at the highest temperatures. By adding nanoparticles, the flashpoint increment from 228 °C to 248 °C. This advantage enhances the nano-lubricant oil performance at high temperatures. The results of the pour point show that the lube oil performance has improved in lower temperatures. The best mass fraction of nano additives was 1.05 wt.%, giving a pour point of -5.4 °C with an enhancement of 80%. This fraction represents a good nano-addition with no agglomeration of alumina oxide inside the engine. Under these conditions, this nano-lubricant can be used in state base oil at lower temperatures. The experimental data were then fitted using the curve fitting approach. To forecast the relative viscosity of nano-lubricant, new correlations were developed. Relationship of  $\mu_{nf}$  in the other direction with temperature. A novel experimental correlation for estimating the relative viscosities of nano-lubricants of each kind of nanomaterial was presented. With acceptable accuracy, the suggested correlation could anticipate nano-lubricant dynamic viscosity. The correctness of the recommended models was determined by comparing the data to the correlation outputs.

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## Conflict of Interest

The authors declare that they have no conflict of interest.

## References

- [1] M.K. Ali and H. Xianjun, "Exploring the lubrication mechanism of  $\text{CeO}_2$  nanoparticles dispersed in engine oil by bis (2-ethylhexyl) phosphate as a novel antiwear additive", *Tribology International*. vol. 22, p.107321, 2021.
- [2] M. Akbari, M. Afrand, A. Arshi, et al. "An experimental study on rheological behavior of ethylene glycol based nanofluid: proposing a new correlation as a function of silica concentration and temperature", *J. Mol. Liq.*, vol. 233, p.352–357, 2017.
- [3] K. Trivedi, "Analyzing lubrication properties of magnetic lubricant synthesized in two lubricating oils", *Wear*. vol. 20, p. 203861, 2021.
- [4] T. Mohsen, and K. Arash, "Improve the thermal conductivity of 10w40-engine oil at various temperature by addition of  $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$  nanoparticles", *J. Mol. Liq.*, vol. 283, p.660–666, 2019.
- [5] H. Khodadadi, D. Toghraie, A. Karimipour, "Effects of nanoparticles to present a statistical model for the viscosity of  $\text{MgO}$ -water nanofluid", *Powder Technol.* vol. 342, p. 166–180, 2019.
- [6] A. Shahsavari, S. Khanmohammadi, A. Karimipour, et al. "A novel comprehensive experimental study concerned synthesizes and prepare liquid paraffin- $\text{Fe}_3\text{O}_4$  mixture to develop models for both thermal conductivity & viscosity: a new approach of GMDH type of neural network", *Int. J. Heat Mass Transf.* vol. 131, p. 432–441, 2019.
- [7] M.K. Ahmed Ali, H. Xianjun, R.F. Turkson, et al. "Enhancing the thermophysical properties and tribological behavior of engine oils using nano-lubricant additives", *RSC Adv.* vol. 6, p.77913–24, 2016.
- [8] R. Ranjbarzadeh and R. Chaabane, "Experimental study of thermal properties and dynamic viscosity of graphene oxide/oil nano-lubricant". *Energies*, vol.14, p. 2886, 2021.

- [9] K., M.H. Esfe, M.R. Safaei, et al. "Mixed convection of copper–water nanofluid in a shallow inclined lid driven cavity using the lattice Boltzmann method", *Physica A: Statistical Mechanics and its Applications* vol.402, p. 150–168, 2014.
- [10] K., A.H. Nezhad, A. D'Orazio, et al. "Simulation of copper–water nanofluid in a microchannel in slip flow regime using the lattice Boltzmann method", *European Journal of Mechanics-B/Fluids* vol.49, p. 89–99, 2015.
- [11] S. ShashaVali, and A. Patil, "Experimental investigation of tribological properties of TiO<sub>2</sub> nanoparticles in engine oil", *Materials Today: Proceedings*, vo. 46, p. 883-889, 2021.
- [12] P.M. Nafchi, A. Karimipour, M. Afrand, "The evaluation on a new non-Newtonian hybrid mixture composed of TiO<sub>2</sub>/ZnO/EG to present a statistical approach of power law for its rheological and thermal properties", *Physica A: Statistical Mechanics and its Applications*, vol.516, p. 1–18, 2019.
- [13] A.A. Alrashed, A. Karimipour, S.A. Bagherzadeh, et al. "Electro-and thermophysical properties of water-based nanofluids containing copper ferrite nanoparticles coated with silica: experimental data, modeling through enhanced ANN and curve fitting", *Int. J. Heat Mass Transf.* vol. 127, p.925–935. 2018.
- [14] K. Dey, S. Paul, P. Ghosh. "Multifunctional additive properties of acrylate based ZnO Nano composite for lubricating oil", *Asian Journal of Nanosciences and Materials*. vol. 4, p.159-70, 2021.
- [15] K. S. Borkakoti, P. Deval, S.K. Ghosh, "Review of inter Facial layer's effect on thermal conductivity in nanofluid", *Heat Mass Transf.* vol.53, p.1–11, 2017.
- [16] S.A. Ahmed, M. Ozkaymak, A. Sözen, et al. "Improving car radiator performance by using TiO<sub>2</sub>-water nanofluid", *Eng. Sci. Technol. Int. J.* vol.21, p.996–1005. 2018.
- [17] M.K.A. Ali, H. Xianjun, L. Mai, et al., "Improving the tribological characteristics of piston ring assembly in automotive engines using Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> nanomaterials as nano-lubricant additives", *Tribol. Int.* vol.103, p. 540–554, 2016.
- [18] B.K. Bharath, and V.A.M. Selvan, "An experimental investigation on rheological and heat transfer performance of hybrid nanolubricant and its effect on the vibration and noise characteristics of an automotive spark-ignition engine" *International Journal of Thermophysics*, vol. 42, No.3, p.1-30, 2021.
- [19] K. A. Sukkar, H. Y. Mahmood, W. K. Mikhelf, "Heat transfer performance improving for brass tubes heat exchanger coated by nanoparticles," *International Review of Mechanical Engineering* vol. 13, No. 10, p.597-607, 2019.
- [20] Y.S. Dambatta, M. Sayuti, A.A. Sarhan, et al. "Tribological performance of SiO<sub>2</sub>-based nanofluids in minimum quantity lubrication grinding of Si<sub>3</sub>N<sub>4</sub> ceramic", *Journal of Manufacturing Processes*, vol. 41, p.135-147, 2019.
- [21] K. and S.K. Ghosh, "Experimental analysis for rheological properties of aluminium oxide (Al<sub>2</sub>O<sub>3</sub>)/ gear oil (SAE EP-90) nanolubricant used in HEMM", *Industrial Lubrication and Tribology*, vol. 67, No. 6, p. 600-605, 2015.
- [22] G. Huminic, A. Huminic, C. Fleaca, et al. "Thermo-physical properties of water based SiC nanofluids for heat transfer applications", *Int. Commun. Heat Mass Transfer*, vol. 84, p. 94–101. 2017.
- [23] A.A. Mohammed, K.A. Sukkar, Z.Y. Shnain, "Effect of graphene and multiwalled carbon nanotube additives on the properties of nano-reinforced rubber", *Chemical Papers*, vol. 75, No.7, p.3265-3272, 2021.
- [24] R.M. Rajkumar, K. Kiruthiga, S. Induja, et al. "Studies on tribological behaviour of ZnO nanorods suspended in SAE 20w 40 engine oil " *Solid State Communications*, vol. 328, p.114235. 2021.
- [25] A.S. Dalkılıç, G. Yalçın, B.O. Küçükyıldırım, et al. "Experimental study on the thermal conductivity of water-based CNT-SiO<sub>2</sub> hybrid nanofluids", *Int. Commun. Heat Mass Transfer*. vol. 99, p.18–25, 2018.
- [26] C. Choi, M. Jung, Y. Choi, et al. "Tribological properties of lubricating oil-based nanofluids with metal/carbon nanoparticles", *Journal of nanoscience and nanotechnology*, vol.11, p. 368-371, 2011.
- [27] G. Vakili-Nezhaad and A. Dorany, "Investigation of the effect of multiwalled carbon nanotubes on the viscosity index of lube oil cuts", *Chem. Eng. Commun.* vol. 196, p. 997–1007, 2009.



- [28] K. Sepyani, M. Afrand, M.H. Esfe, "An experimental evaluation of the effect of ZnO nanoparticles on the rheological behavior of engine oil", *J Mol Liq.* vol. 236, p.198–204, 2017.
- [29] R. and A. Nabhan "Effects of TiO<sub>2</sub> and SiO<sub>2</sub> Nano Additive to Engine Lubricant Oils on Tribological Properties at Different Temperatures" 20th International Conference on Aerospace, Mechanical, Automotive and Materials Engineering, Rome-Italy, vol.20, No.10, p. 2463-2472, 2018.
- [30] S. Yousif, J. Ali, K. Sukkar, May Ali Alsaffar, and Mohammad F. Abid. "A Computational Fluid Dynamics Study of Liquid–Solid Nano-fluid Flow in Horizontal Pipe." *Arabian Journal for Science and Engineering*, p. 1-9, 2021.
- [31] W. B., Song H., Chuan L., et al. "Enhanced tribological properties of diesel engine oil with Nano-Lanthanum hydroxide/reduced graphene oxide composites", *Tribology International*, vol.141, p.105951, 2020.
- [32] R. A. and Nabhan A. "Friction and vibration analysis of sliding surfaces lubricated by engine oils dispersed by aluminum oxide nanoparticles" 20th International Conference on Aerospace, Mechanical, *Journal of the Egyptian Society of Tribology*, vol. 17, p.14 - 26, 2020.
- [33] Z. Khedaer, D. Ahmed, and S. Al-Jawad, "Investigation of morphological, optical, and antibacterial properties of hybrid ZnO-MWCNT prepared by sol-gel" *Journal of Applied Sciences and Nanotechnology*, vol. 1, p. 66-77, 2021.
- [34] M.H. Esfe, S. Esfandeh, M.K. Amiri, et al. "A novel applicable experimental study on the thermal behavior of SWCNTs (60%)-MgO (40%)/EG hybrid nanofluid by focusing on the thermal conductivity", *Powder Technology*, vol. 342, p. 998-1007, 2019.
- [35] S. Navdeep, U. Irfan, R. Ankush, et al. "Synthesis and tribological investigation of Al-SiC based nano hybrid composite", *Alexandria Eng. J.* vol. 57, p.1323 – 1330, 2018.
- [36] S. Ketan, Y. Singh, A. Rajendra Surana, et al. "Experimental evaluation of the friction and wear of jojoba oil with aluminium oxide (Al<sub>2</sub>O<sub>3</sub>) nanoparticles as an additive." *Materials Today: Proceedings* vol.25, p. 699-703, 2020.
- [37] A. Mohammed, K. Sukkar, and Z. Shnain. "Effect of graphene and multiwall carbon nanotube additives on the properties of nano-reinforced rubber." *Chemical Papers*, vol. 75, no. 7, p. 3265-3272, 2021.
- [38] M. Saeedinia, M. Akhavan-Behabadi, P. Razi, "Thermal and rheological characteristics of CuO–base oil nanofluid flow inside a circular tube", *Int. Commun. Heat Mass Transf.* vol. 39 p. 152–159, 2012.
- [39] H. Ahmadi, A. Rashidi, A. Nouralishahi, et al. "Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant", *Int. Commun. Heat Mass Transf.* vol. 46, p.142–147, 2013.
- [40] R. Agarwal, K. Verma, N.K. Agrawal et al. "Synthesis, characterization, thermal conductivity and sensitivity of CuO nanofluids". *Appl Therm Eng.* vol. 102, p.1024– 1036, 2016.
- [41] K.A. Sukkar, A.A. Karamalluh, and T.N. Jaber, "Rheological and thermal properties of lubricating oil enhanced by the effect of CuO and TiO<sub>2</sub> nano-additives", *Al-Khwarizmi Engineering Journal*, vol. 15, p.24-33, 2019.
- [42] J. Anwar, Q. Thewaini, and S. Al-Musawi. "Cytotoxicity Effect and Antibacterial Activity of Al<sub>2</sub>O<sub>3</sub> Nanoparticles Activity against Streptococcus Pyogenes and Proteus Vulgaris." *Journal of Applied Sciences and Nanotechnology*, vol.1, no. 3, 2021.
- [43] S. Aberoumand, and A. Jafarimoghaddam, "Experimental study on synthesis, stability, thermal conductivity and viscosity of Cu–engine oil nanofluid", *J. Taiwan Inst. Chem. Eng.* vol. 71, p.315–322, 2017.
- [44] N. Nikkam and M.S. Toprak, "Fabrication and thermo-physical characterization of silver nanofluids: An experimental investigation on the effect of base liquid", *Int. Commun. Heat Mass Transfer*, vol. 91 p.196–200, 2018.

- [45] A. Barra, A. Sukkar Khalid, and A. Jenan Al-Najar. "Characterization and Aerodynamics of Synthesized Polymeric Nanofibers via Electrospinning Process to Capture PM10 and PM2. 5 from Air." *Journal of Applied Sciences and Nanotechnology*, vol.1, no. 4, p. 91-104, 2021.
- [46] J. Seok Pil, and Stephen US Choi. "Role of Brownian motion in the enhanced thermal conductivity of nanofluids." *Applied physics letters*, vol. 84, no. 21, p. 4316-4318, 2004.
- [47] K. Madhusree, and T. K. Dey. "Effect of aggregation on the viscosity of copper oxide–gear oil nanofluids." *International Journal of Thermal Sciences*, vol. 50, no. 9, p. 1741-1747, 2011.
- [48] K. Madhusree, and T. K. Dey. "Role of interfacial layer and clustering on the effective thermal conductivity of CuO–gear oil nanofluids." *Experimental thermal and fluid science*, vol. 35, no. 7, p. 1490-1495, 2011.
- [49] K. Ankit, Sheeba Borkakoti, Piyush Deval, and Subrata Kumar Ghosh. "Review of interfacial layer's effect on thermal conductivity in nanofluid." *Heat and Mass Transfer*, vol. 53, no. 6, p. 2199-2209, 2017.
- [50] S. Hassan, Z. Rasheed, and J. Oleiwi. "Synthesis and Physical Characterization of PMMA/PP and PMMA/PAN Composites for Denture Applications." *Journal of Applied Sciences and Nanotechnology*, vol.1, no. 3, p. 13-23, 2021.