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The Effecting of Various Parameters on the Thermophysical and Rheological Properties of SiO_2 Nano-lubricating Oil in Petroleum Refineries

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Abstract

The improvement of the performance of automotive engines necessitated the use of effective lubricating oil. Experimentally explored are the thermophysical characteristics and rheological behavior of Nano-lubricating oil made by mixing SiO_2 nanoparticles with stock-60. Nano-lubricant has been prepared with a two-step method using a magnetic stirrer as a first step mixing and an ultrasonic homogenizer. The rheological properties were investigated at various shear rates, temperature, and solid volume percent. This research was carried out on concentrations ranging from 0.1 % to 1.0 %. The results showed elevation in temperature, the dynamic viscosity dropped in all shear rates due to lower SiO_2 NP concentrations and that all samples exhibited Newtonian behavior at all temperatures fixed. The thermal conductivity of nano-lubricating oil was tested at various temperatures ranging from 20°C to 50°C. The different solid volume percent of SiO_2 NPs were in the range of 0 to 1% maximum enhancement value was achieved at higher temperature with increased volume percent of SiO_2 NPs. Other important thermophysical properties of lube oil including flashpoint and pour point were also measured. The results revealed that adding SiO_2 NPs to stock-60 at a solid volume percent of 1% will result in a maximum improvement of 12 % in flashpoint over the base oil, while the improvement of pour point was achieved at nano-addition of 0.75% and 1% compared with the base oil was increased from -3°C to -6°C.

Keywords: Base (stock-60) oil; Thermal conductivity; Flashpoint; Pour point, Dynamic viscosity.

Open Access
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1. Introduction

Nanofluids are currently being employed in engine lubrication, rolling processes, ball bearings in engines, and also gearbox lubrication. Nano-lubricants have an influence not only on engine performance and thermal efficiency but also on the engine part's durability and wear. As a result, research into nanofluids utilized as lubricants and coolants under a variety of engine loads and speeds is crucial for enhancing engine performance [1-4]. Nano-lubricants are used in internal combustion engines. Baskar et al. [5] found that enough nano-lubricating oil reduced journal bearing system friction and wear. According to their ideal results, the coefficient of friction (COF) and specific wear rate was reduced utilizing a load of 100 N, a sliding speed of 2 m/s, and bronze bearing material/SN500 base oil with 0.5wt. % CuO NPs. Aberoumand and Jafarimoghaddam [6] discovered that adding 1wt. % of Cu NPs to motor oil increased thermal conductivity and viscosity by 49% and 37%, respectively.

Understanding the impact of nano-lubricants on shear rate and shear stress has been aided by the rheological behavior of nano-lubricating oil [7]. Moreover, the viscosity of nano-lubricating oil is important for understanding their tribological characteristics. The addition of nanoparticles to engine oil has been shown to minimize friction and wear of the engine parts that come into contact during movement. At temperatures ranging from 20 ^{o}C to 60 ^{o}C, Aghahadi et al. [8] investigated the rheological behavior of WO_3-MWCNTs/engine oil Newtonian fluid with varied volume fractions ranging from 0 % to 0.6 %. they noted that the base fluid and nano-lubricating oil are both Newtonian fluids, according to the authors. In addition, when the temperature rises, the viscosity of nano-lubricant reduces, whereas the viscosity rises as the volume fraction of nano-additions rises. Various factors affecting the rheological behavior of nanofluids were examined by Nadooshan et al. [9]. They discovered that size of nanoparticles, volume percent, and shear rate all influence rheological properties. Kharabati et al. [10] studied the impacts of adding SiO2 NPs on the rheological and thermal characteristics of lubricant at various temperatures in a low range of gasoline and diesel engines with solid fractions varying between 0.05 % and 1%. They found that the viscosity drops in all shear rates when the temperature increases. At 30°C and 1% volume percent, the greatest thermal conductivity value recorded was 0.169 (W/m. K). At various temperatures and solid percentages, Kashefi et al. [11] investigated the rheological behavior and tribological characteristics of a nano-lubricant comprising SiO_2 NPs in engine oil. The authors

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demonstrated that nano-lubricating oil had a non-Newtonian performance. Additional key variables such as pour point and flash point were also measured, revealing that adding SiO_2 NPs to the lubricating oils at a volume percent of 0.1 % improves the flashpoint by 3.8 % when compared to the initial oil. According to Mousavi et al. [12], adding MoS_2 NPs to diesel oil boosts nano-lubricant viscosity index and viscosity, with the maximum viscosity index and viscosity obtained at a mass fraction of 0.7 weight percent of NPs The results revealed that the additives had no appreciable anti-friction and anti-wear capabilities when compared to the basic oil at various fractions. In addition, as compared to base oil, the MoS_2 NPs in base oil did not affect the friction factor readings. Shafi and Charoo [13] investigated the rheological properties of oil combined with various fractions of ZrO_2 nano-additives and the influence of shear rate, solid portions, and temperatures on oil rheological behavior. The tests are carried out at different temperatures and with different shear rates. At a temperature of 40 °C, the authors reported that a rise in the viscosity of produced nano-lubricating oil with maximal improvement at mass fraction1.5 weight fractions is equivalent to 5.8%. The pure oil and nano-lubricant are representations of Newtonian behavior as measured by the power law.

Hu et al. [14] investigated graphite/engine oil viscosity, solid fractions, and shear rates at various temperatures. The findings demonstrated that adding graphite NPS does not influence the viscosity of base oil, indicating that graphite is a suitable NPs addition. When the temperature was decreased, the viscosity increased by 593%. Nano-lubricant behaved as Newtonian fluids in the lower shear rate limit, but as non-Newtonian fluids in the higher shear rate range. The findings showed that solid fraction and temperature have no influence on the power-law index, but that increasing the temperature resulted in a clear decrease in the consistency index. Based on temperature, the volume percentage of NPs, and shear rate, Esfe et al. [15] investigated the viscosity of SAE40 engine oil using MWCNTs and SiO_2 NPs. The nano-lubricant flow regime was discovered to be a non-Newtonian fluid, according to the authors. The nano-lubricant developed the largest increase of 42.53 % at a volume percentage of 1%, a temperature of 45 °C, and a shear rate of 6665/s. The temperature has a greater impact on nano-lubricant viscosity than other parameters. It was also discovered that the viscosity-temperature, solid-fraction-temperature relationships are direct, inverse, and direct, respectively. Del et al. [16] used two separate pristine graphene nano-platelets to study the tribological characteristics of nano-lubricating oil. The lateral diameters of these GNPs are 7

Open Access
No. 37, December 2022, pp. 68-91

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and 40 µm, and the thickness is 3 and 10 nm. Various amounts of nano-additives were utilized. The visual control and the refractive index evolution over time were used to study the stability of nano-lubricants, demonstrating slightly superior stability for nano-lubricants formed with the biggest lateral size graphene nanoplatelets (GNP40). At a temperature range of 0–60°C, Heris et al. [17] evaluated the rheological characteristics of nano-lubricating oil with a dispersion of zinc oxide NPs with varied mass fractions ranging from 0.1 % to 4 %. They demonstrated that nano-lubricating oil and base oil act similarly to Bingham fluid. The influence of particle concentration on the viscosity of nano-lubricants. Rheological tests demonstrated that nanoparticles agglomerate in the lubricating oils in this way. Furthermore, the influence of temperature on the synthesized nano-lubricating oil's viscosity and yield stress. Esfe et al. [18] investigated the viscosity of an alumina oxide nano-lubricating oil using different solid percentages and temperatures. The nano-lubricants were made in various solid percent at varied working temperatures, and novel correlations for estimating the viscosity of aluminum oxide/ engine oil were provided. They demonstrated that all nano-lubricant samples behave in the same way as a Newtonian fluid. The results indicated that when the solid percentage grows, the viscosity of the nano-lubricant increases. Furthermore, it was discovered that the viscosity of nano-lubricants reduces with rising temperature, and it was more noticeable at lower temperatures. The greatest viscosity improvement of nano-lubricating oil was 132% when compared to base oil, according to the findings. The purpose of this study is to explore the impacts of SiO_2 NPs additions on the rheological behavior, thermal conductivity, flash point, and pour point of base stock-60 oil in an experimental setting.

2. Experimental Work

2.1 Materials

In this study, the base stock-60 lube oil was received as products for the vacuum distillation unit from Iraqi refineries (Middle Oil Refining Company, Baghdad, Iraq). It is employed in the experiments as a base fluid. The impacts of SiO_2 nano-additives were compared to the effects of pure stock-60) oil to study the SiO_2 NPs as lubricant additives. The parameters of the employed Iraqi base stock, as well as the test method, were listed in Table (1). In addition, Changsha Santech Material Tech Co., Ltd. supplied SiO_2 (purity: 95%; diameter: 20–30 nm; specific surface area 362 m^2/g). The parameters and specifications of the SiO_2 NPs utilized are

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
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shown in Table (2). X-ray (XRD) diffractometer (Schimadzu 7000, Japan) was used to determine the crystalline structure of the samples, scanning electron microscopy was used to examine the morphology (SEM, Quanta FEG 250, FEI, Republic of Czech) and Fourier transform infrared spectroscopy (FTIR) spectroscopic study of the sample was performed by (Tensor 27, Bruker, Germany), using KBr as a reference. The following equation was used to calculate the amounts of SiO_2 NPs required for specific solid volume fractions:

$$\varrho=\left[\frac{\left(\frac{w}{\rho}\right)_{NPs}}{\left(\frac{w}{\rho}\right)_{bf}+\left(\frac{w}{\rho}\right)_{NPs}}\right] \quad (1)$$

The terms (ρ), (ϱ), and (w) density of the nano-lubricant, the particle volume percent of the SiO_2 NPs, and needed mass for the target particle volume percent, respectively, are used in the above equation.

Table (1) Stock-60 oil characteristics.

Specifications	Unit	Stock (60)	Standard Test Method
Viscosity index	-----	102	ASTM D-7042
Kinetic viscosity at 100 ^oC	cSt	8.4567	ASTM D-7042
Kinetic viscosity at 40 ^oC	cSt	64.898	ASTM D-7042
Density at 15 ^oC	g/cm^3	0.8937	ASTM D-7042
Thermal Conductivity	$W/m.^oC$	0.0745	ASTM D2717-95
Flashpoint	^oC	228	ASTM D-92
Pour point	^oC	-4	ASTM D-97

Table (2) SiO_2 NPs characteristics.

Specifications	Unit	SiO_2 NPs
Structure	-----	spherical
Purity	%	95
Density	g/cm^3	4.2
Surface area	m^2/g	362
Color	-----	White
Average particle size	nm	20-30

Open Access
No. 37, December 2022, pp. 68-91

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2.2 Preparation of nano-lubricant

As illustrated in Figure (1), a two-step approach was employed to manufacture nano-lubricating oils, with no dispersion agent or surfactant used in the process [4-10,13,14,17]. Volume percent of SiO_2 NPs were dispersed in 300 ml of base oil (φ= 0.1%, 0.25%, 0.5%, 0.75%, and 1%). To reduce the early aggregation of the nano-additions in the base oil, each sample was agitated for 2 hours at room temperature with a continuous stirring at 1600 rpm to guarantee adequate dispersion of the nanoparticles in the base oil. After that, all samples were subjected to 3 hours of temperate sonication [ultrasonic bath, oscillating frequency 20 kHz, power 100 W]. This technique was utilized to break down agglomeration between the particles, resulting in a stable suspension and uniform dispersion.

The samples were placed in closed vials and placed in a 45°C water bath. During the sonication process, there was no substantial change in the temperature of the samples. Following that, all suspensions were kept in hermetic containers at room temperature. There was no discernible phase separation before and after the rheological measurements. The creation of suspensions with a solid Before and after the rheological tests, there was no obvious phase separation. In all of the conditions tested, creating suspensions with a solid volume percentage of 2% resulted in samples that were no longer liquid but rather pasty and behaved like gels (no flow under the effect of gravity, by turning the vial upside down). As a result, present work is restricted to a solid concentration of less than 1.5 weight percent. Figure (2) shows a picture of SiO_2 NPs, as well as base (stock-60) oil and nano-lubricant samples.

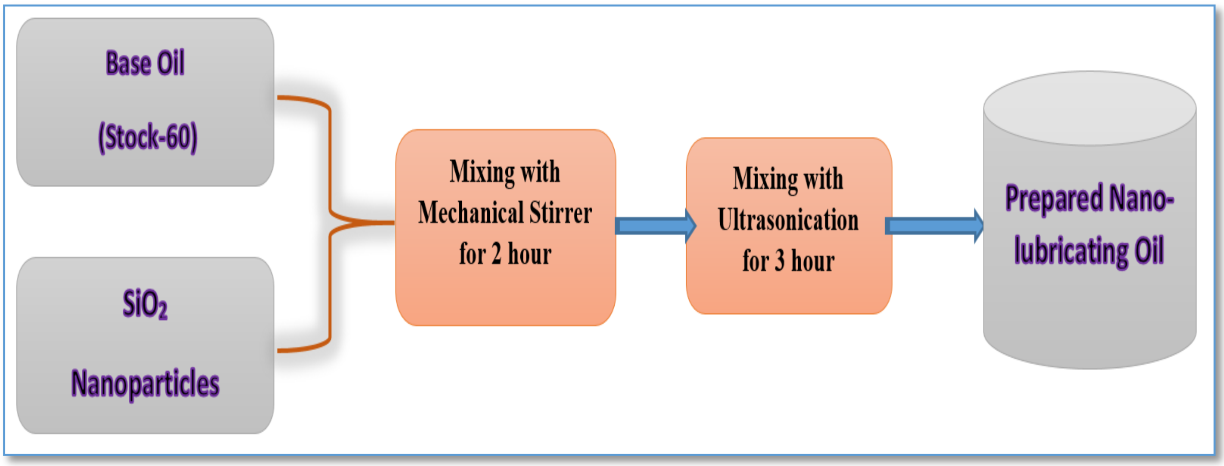

Fig. (1): Two-step method for preparing nano-lubricating oil samples.

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

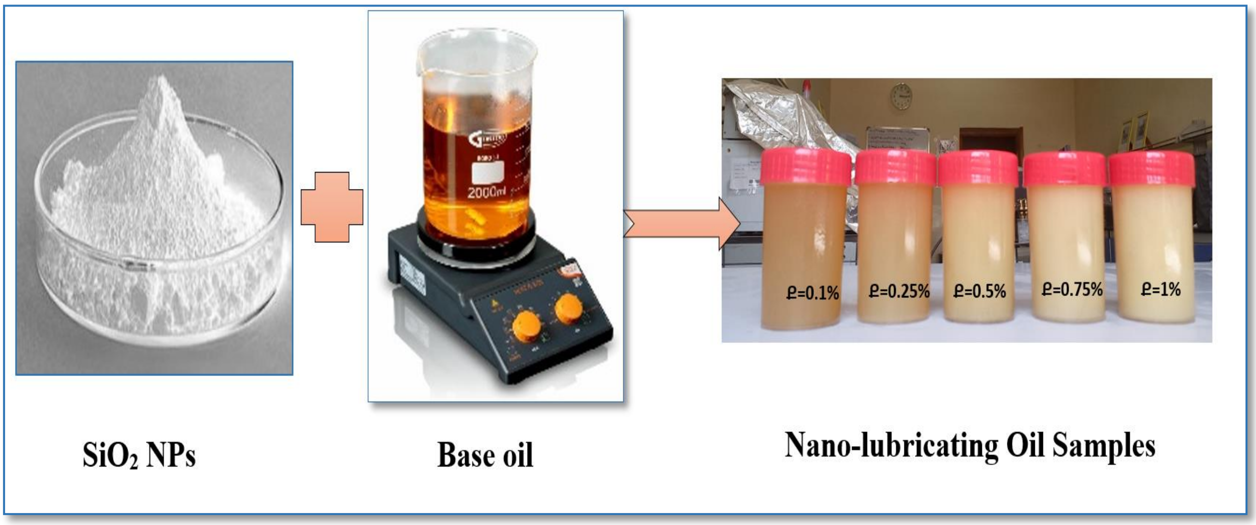

Fig. (2): Photographic showed the prepared nano-lubricant samples, base oil, and silica oxide nanoparticles.

2.3 Rheological measurement

The viscosity and shear stress of prepared nano-lubricating oil with nanoparticles concentration ranging from 0 vol.% to 1 vol.% were evaluated using a [Brookfield Viscometer DV3TLV, USA] analysis software device at four temperature range: 40°C, 60°C, 80°C, and 100°C, with shear rates ranging from 6.115/s to 12.236/s. The adaptor for the ULA-49EAY water jacket, a cylindrical experiment container, and the ULA spindle will be utilized as a part of the setup. The test sample container has a capacity of 16 ml, and the spindle is put within the sample and rotated swiftly to calculate the torque while maintaining a consistent temperature throughout the sample. A temperature sensor will be immersed into the sample to measure the temperature. The Viscometer system has a precision of 1% and repeatability of 0.2%. Because temperature has a direct influence on fluid viscosity, a circulating temperature control system with a 0.1^{o}C precision was utilized to maintain the temperature of the samples throughout the experiment. For this part, the temperature bath model LAUDA Alpha RA 8 was used. Table (3) lists some of the data collected.

Open Access
No. 37, December 2022, pp. 68-91

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Table (3) Some of the information gathered from nano-lubricant viscosity measurements.

Solid Fraction (%)	Temperature (^oC)	Shear Rate (1/s)	μ_{nf} (cp) of Prepared Nano-lubricant
Ք = 0.25 %	60	6.115	34
	80	9.784	17.25
	100	12.236	14.89
Ք = 0.5 %	60	6.115	45
	80	9.784	20
	100	12.236	21.88
Ք = 1 %	60	6.115	68
	80	9.784	42.22
	100	12.236	34.88

2.4 Thermal conductivity coefficient of SiO_2 nano-lubricant

In the present experimental part, the thermal conductivity of nano-lubricating oils was measured to study their capability to deliver heat transfer. Thermal characteristics based on hotwire technology were characterized using the KD2 Pro, a transportable instrument. 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. Figure (3) shows the photographic of the thermal conductivity measuring system. The thermal conductivity was tested at different volume percent of SiO_2 NPs (0.1, 0.25, 0.5, 0.75, and 1%) and various operating temperatures of (20, 30, 40, and 50°C).

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

KD2-PRO Instrument (measuring conductivity of nano-lubricant oil at room temperature)

KD2-PRO measuring the thermal conductivity of the nano-lubricant samples inside bath water

Fig. (3): Thermal conductivity measurement system (KD2-Pro)

2.5 Measuring of flashpoint and pour point

The Iraqi Ministry of Oil's Oil Research and Development Center (Baghdad/Iraq) has a flash point apparatus (model FP92 5G2, ASTM D-92, standard test technique for flash and fire points using Cleveland open cup, France) with a maximum error of ±2%, that may be used to investigate the flashpoint of nano-lubricant.

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 SiO_2 NPs.

3. <u>Results and Discussion</u>

3.1. Characterization of SiO_2 nanoparticles

FE-SEM analysis was used to examine the morphological properties of SiO_2 nanoparticles, such as particle diameter and morphological parameters. Figure (4) depicted the morphological characteristics of SiO_2 NPs, respectively. The morphology of the SiO_2 NPs shows that is virtually spherical in the form to a degree, providing a perfect winding interface in the bulk of the lubricating oil. The particles are in the shape of agglomerates, as can be observed. To make a

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

stable suspension, these agglomerates must be broken down during the nano-lubricant preparation process. Magnetic and ultrasonic agitation can be used to achieve this. The average particle volume diameter of the SiO_2 NPs was 20-30 nm, according to the morphological examination.

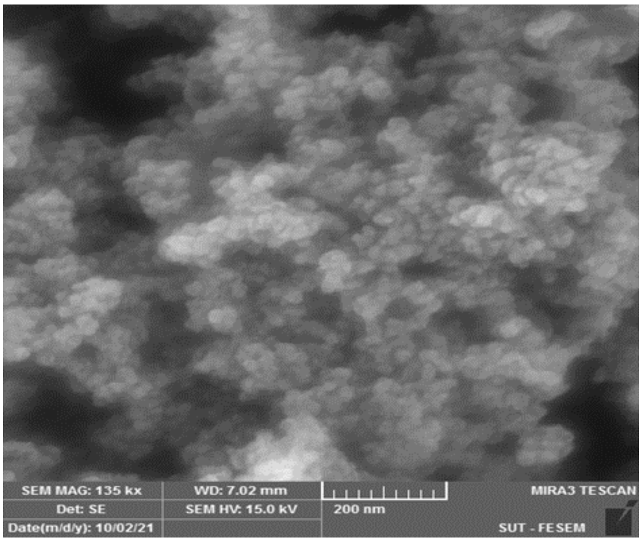

Fig. (4): SEM morphological images of SiO_2 NPs

EDX testing is used to determine the elemental composition of SiO_2 NPs, as illustrated in Figure 5. The needed composition of Si and oxygen for SiO_2 NPs was accomplished without the appearance of any contaminant, and the atomic percentage of Si and O_2 was SiO_2, as shown in Figure 5. The NPs are composed of Si and O elements. Little amounts of other elements were present in the SiO_2 nanoparticles.

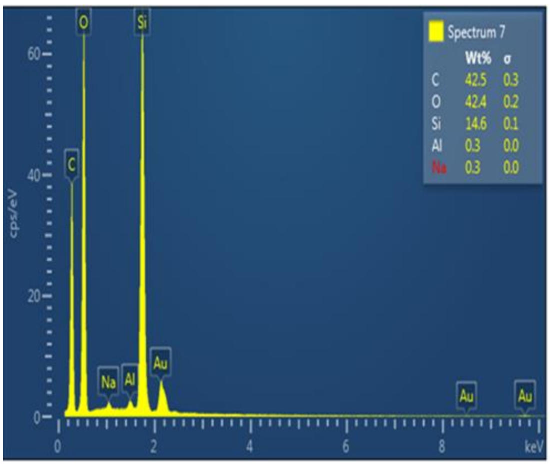

Fig. (5): Energy dispersive X-ray analysis(EDX) pattern of SiO_2 NPs

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

Figure (6) shows FTIR spectra of the silica oxide nanoparticles. The band in the vicinity ~ 797.92/cm is equivalent to Si-O [19] in the Si-O-Si plane, bending oscillation occurs when oxygen travels at a right angle to the Si-Si lines [20, 21].

The Si-OH bending oscillation is shown by the absorption at ~ 968/cm. The band about 1088 /cm corresponds to an asymmetric stretching vibration of the Si-O-Si band, in which the bridging oxygen atom travels in the reverse direction of its Si neighbors, parallel to the Si-Si lines. The silica particles are particularly hygroscopic, according to FTIR measurements.

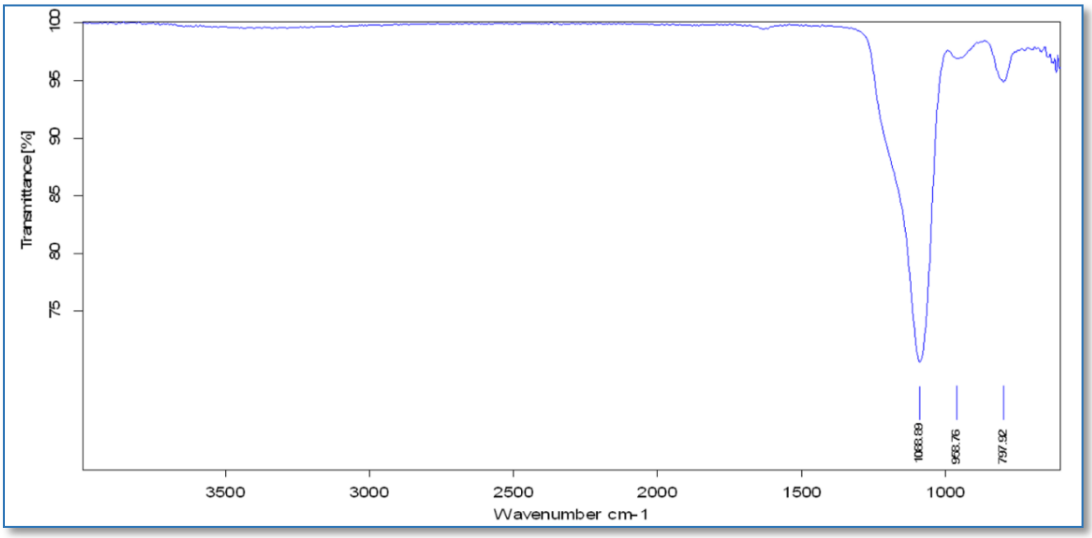

Fig. (6): FTIR of SiO_2 NPs.

3.2 Rheological Behavior of Base Oil and Nano-lubricating Oil

The viscosity of base oil (stock-60) and SiO_2/stock-60 nano-lubricant at five NPs volume percent (0.1 vol.%, 0.25 vol.%, 0.5 vol.%, 0.75 vol.%, and 1 vol.%), shear rate (6.115/s up to 12.236/s), and temperatures (40^{o}C, 60^{o}C, 80°C, and 100°C) were measured to assess the rheological properties.

Figure (7) shows the viscosity and shear stress vs shear rate at various temperatures to analyze the rheological characteristic of lube oil (stock-60). The dynamic viscosity of lube oil is usually constant with a rising shear rate, except for 60 ^{o}C, when it visibly decreases with a rising shear rate. Such variation might be due to the heat created by the viscometers' high rotational speed. As a result, at different working temperatures, base oil (stock-60) behaves Newtonian. Rather, the temperatures of 40°C and 100°C may be used to test the rheological

Open Access
No. 37, December 2022, pp. 68-91

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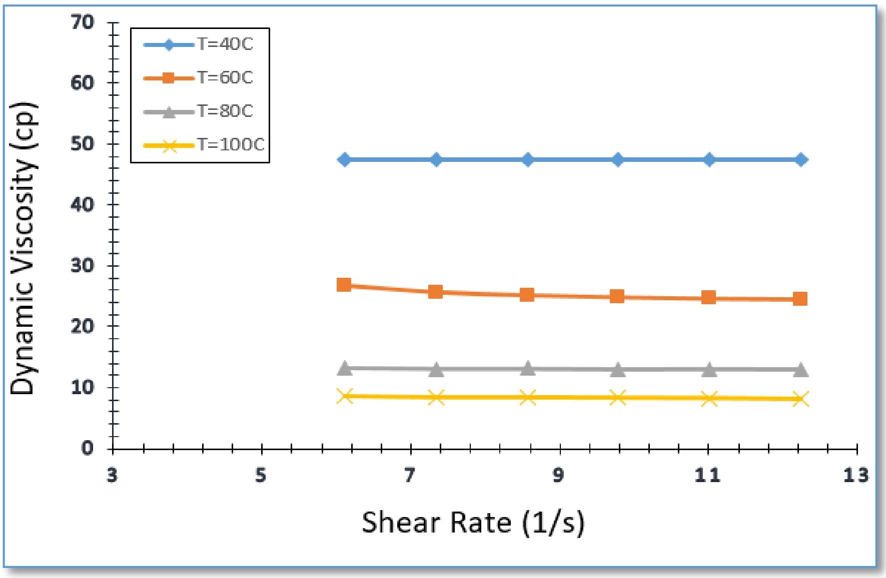
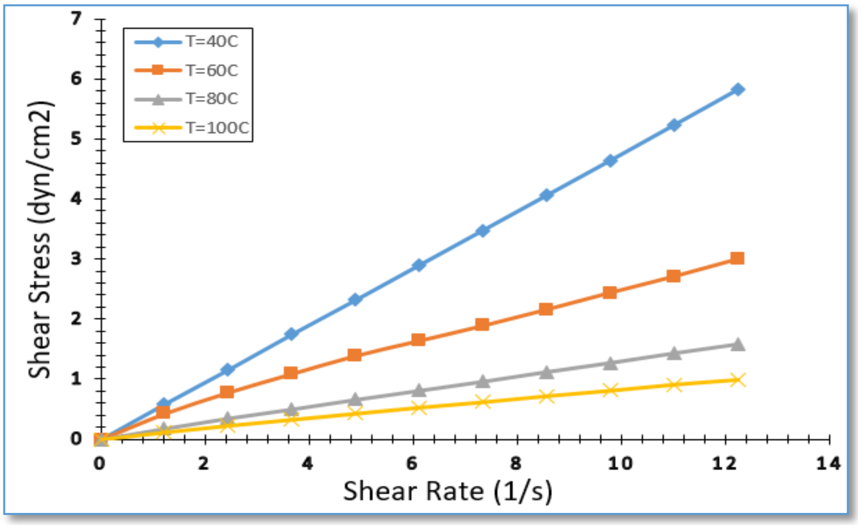
and thermal physical characteristics of lubricating oils since they are standard temperatures. With rising shear rate and lower operating temperature, the shear tension of base stock-60 increases.



(A)



(B)

Fig. (7): Rheological behavior of base oil (stock-60) (A) Dynamic viscosity vs shear rate, (B) Shear stress vs shear rate at different temperatures.

The time has come to investigate the rheological behavior of base lube oil and nano-lubricating oil, as well as the relationship between viscosity and shear rate at various temperatures. For Newtonian

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

fluids, the connection between shear stress and shear rate is linear; this result of shear stress was displayed in Figure (8) to analyze the rheological behavior under different solid fractions. At most temperatures, the action of SiO_2 nano-lubricant is Newtonian, and different SiO_2 NPs quantities, this result agrees with much previous work [7, 12, 13, 17], and that it is similar to the base oil, which is consistent with the results of Ranjbarzadeh [22], except for the behavior of nano-lubricant at two concentrations of 0.75% and 1% at temperature 40^{o}C, which showed non-Newtonian fluid of the Pseudo-plastic fluids. The dynamic viscosity of these fluids will decrease as the shear rate increases.

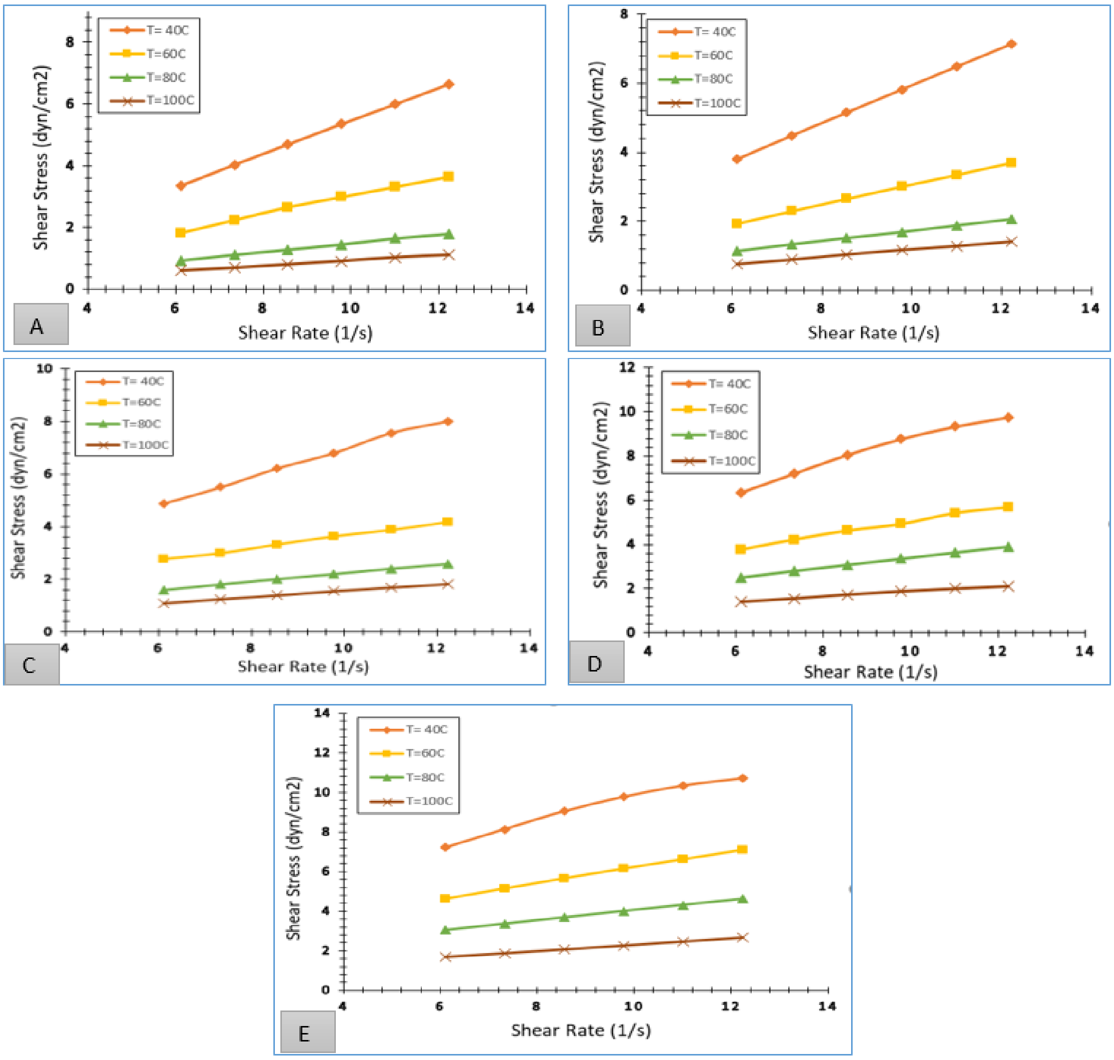


Fig. (8): Variation of shear stress of SiO_2 nano-lubricating oil for different shear rates at four operating temperatures at NPs concentration (A) ₽=0.1%, (B) ₽=0.25%, (C)₽=0.5%, (D)₽=0.75%, and (E)₽=1%

Open Access
No. 37, December 2022, pp. 68-91

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Figure (9) depicts viscosity variations as a function of shear rate in various solid volume fractions. The slope of the lines in solid concentrations is near to zero in all temperatures, as seen in these figures (0.1%, 0.25%, and 0.5%). By increasing the solid volume percentage by 0.75 % and 1 %, the deviation from zero slopes of lines is enhanced.

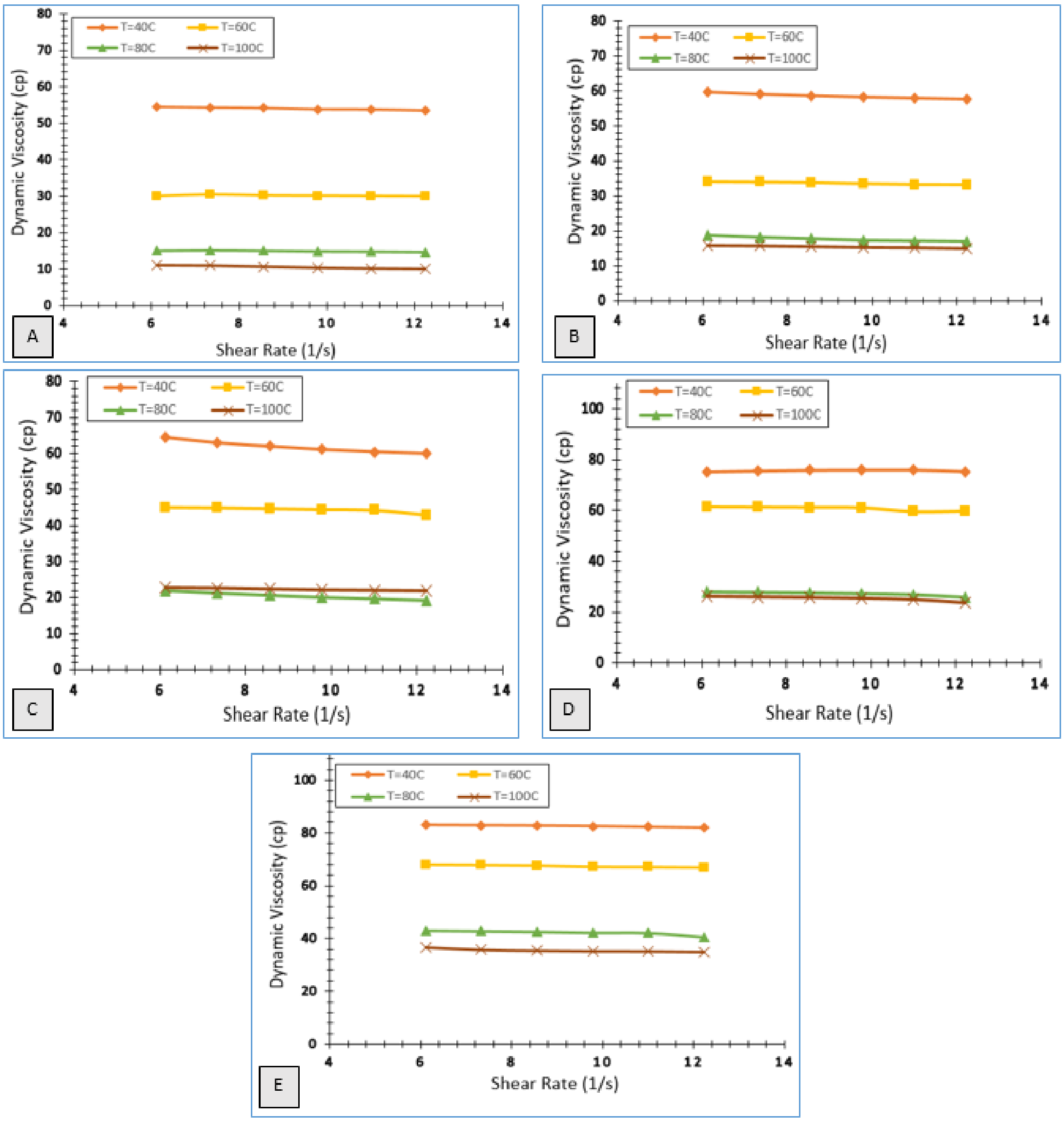

Fig. (9): Variation of viscosity of SiO_2 nano-lubricating oil for different shear rates at four operating temperatures at NPs concentration (A) Ꝑ=0.1%, (B) Ꝑ=0.25%, (C)Ꝑ=0.5%, (D)Ꝑ=0.75%, and (E)Ꝑ=1%

The non-Newtonian (shear-thinning) behavior may be seen since viscosity decreases as the shear rate increases. Because stress rates impact viscosity, the connection will be non-linear, as

Open Access
No. 37, December 2022, pp. 68-91

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seen by power-law index values less than 1 for these nano-lubricant samples. Shear tension will arise in these liquids if they are sheared at low speeds. Shear stress causes the molecules to rearrange to lower overall stress, which is consistent with Kashefi's findings [23].

The results in Figure (10) demonstrate that when the temperature rises, the viscosity decreases dramatically. The distance between the molecules of the nanoparticles and the base fluid will increase as the temperature rises, reducing the resistance of the flow layers and the viscosity of the nano lubricant. At low temperatures of 40°C and high solid concentrations of 1% SiO_2 NPs, high viscosity can be seen. The flow resistance increases as the solid proportion of SiO_2 in the base oil increases, implying that the nanoparticles clash more while traveling randomly. The presence of Van der Waals's force raises the viscosity by increasing the number of nanomaterials in a fixed amount of base oil. Because the nanoparticle's physical structure prevents the layers from sliding on top of each other, the viscosity rises. Earlier studies have shown that the form, size, and weight percentage of nanomaterials have a direct impact on dynamic viscosity [24-25].

Rising temperature aids particles in overcoming Van der Waals attraction contacts, which may dissolve clusters of nanoparticles floating in the base fluid, reducing viscosity by reducing intermolecular connections between molecules [23-26]. The Brownian motion will grow as the temperature increases, generating chaos and lowering the viscosity of the nano-lubricating oil [23, 25].

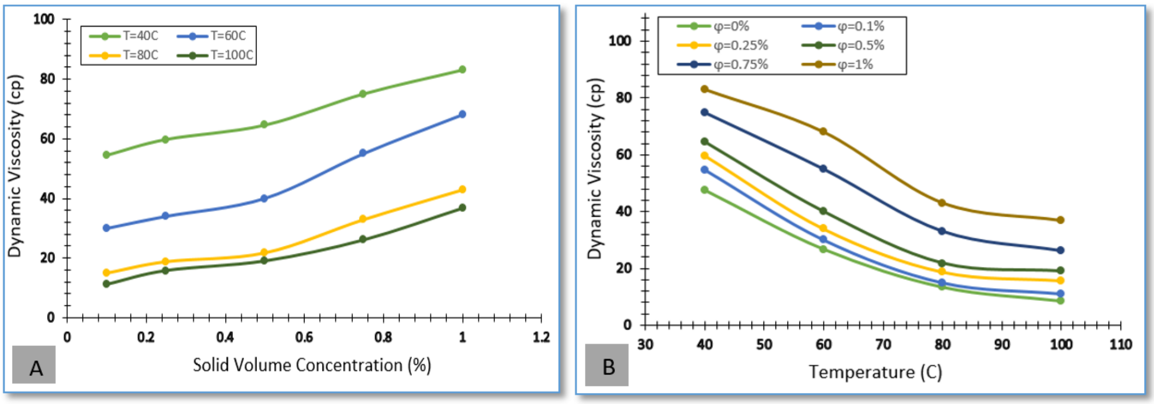

Fig. (10): Viscosity of the SiO_2 nano-lubricants samples concerning (A) Solid concentration in different temperatures, and (B) Temperature in different solid concentration

3.3 Thermal conductivity coefficient of SiO_2 nano-lubricant

The measurements of thermal conductivity were achieved to evaluate the ability of SiO_2 NPs to improve the thermal specification of base stock lubricating oil. The results of the measured

Open Access
No. 37, December 2022, pp. 68-91

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thermal conductivity of base lubricant and nano-lubricants are shown in Figure (11). The results indicated that the nano-lubricants have values of thermal conductivity greater than that of the base stocks lubricating oil. Then, it can be seen that, with increased SiO_2 NPs additions, the thermal conductivity of the prepared nano-lubricants increased. These results are related to the high thermal conductivity of the SiO_2 NPs in comparison with 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 [24-27]. Also, the results in Figure (11) indicated that the values of thermal conductivity increase with operating temperature increase. The highest value of thermal conductivity was recorded at a temperature of 50^{o}C and nano-addition of 1% of SiO_2 NPs. It is important 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 a 0.5% concentration of SiO_2 NPs a suitable for engine lubricity due to enhanced heat transfer properties and thermal conductivity**.**

One of the variables determining enhanced service life is lubricant oil's heat transferability. The thermal conductivity of the lube oil is critical for sustaining the lube oil's characteristics and service life [24]. Temperature and thermal conductivity are found to be strongly connected in many studies, with most liquids seeing a drop in thermal conductivity as temperatures rise [25, 28, 29]. The thermal conductivity of nanofluids increases as the temperature rises, according to previous research [24, 30-33].

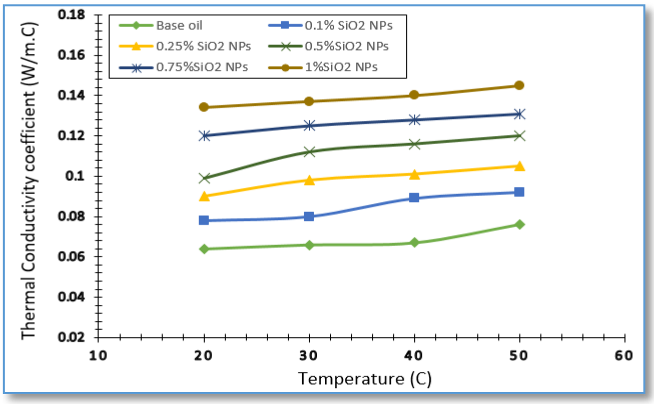

Fig. (11): Thermal conductivity of SiO_2 nano-lubricant with various volume percent at different temperatures.

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

3.4 Flash Point and Pour Point of SiO_2 Nano-lubricant

The major distinctive identification for this oil functioning in internal combustion engines under various operating situations is its lubricating oil parameters. When an ignition fire is conducted over this sample, the flashpoint as property usually denotes the minimal temperature at which the vapor above the lubricating oil will quickly ignite [2, 3, 7].

The connection between the flashpoint of lubricating oil and the concentration of SiO_2 nano-additions is noted in Figure (12). The mixing of NPs with lube stock-60 oil has resulted in a change in the flashpoint, which causes it to rise until it reaches a substantial level [29, 31, 33]. With a nano-additive increase, the flashpoint was raised [4, 11, 12]. In contrast to base stock lubricating oil, the flashpoint increased by 5.042 %, 6.612 %, 8.502 %, and 10.67 % for SiO_2 NPs concentrations of 0.25 %, 0.5%, 0.75%, and 1%. These findings are in line with those of several other researchers [22, 23, 33-36].

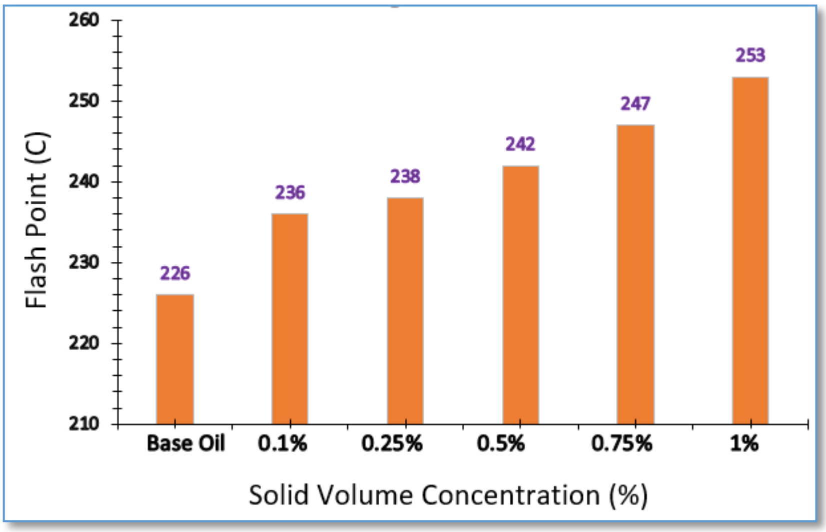

Fig. (12): Flashpoint of SiO_2 nano-lubricant oil with various solid fractions.

In general, managing the quality of nano-lubricating oil is a critical component of improving lubricant specifications for increased energy conservation in the mechanical system inside the engine [3, 4, 22, 23]. After then, the addition of NPs to the base lubricating oil will focus on high-performance operation for a long-lasting engine [4]. The peculiar features of SiO_2 NPs additions are to blame for this. Then, with the addition of SiO_2 NPs nanoparticles, the flashpoint improves, indicating that high-performance operation is possible [4, 12, 22, 28].

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

The pour point in lubricating oil systems is defined as the temperature limit beyond which liquid cannot travel [22, 23]. The largest value of wear on the engine occurs when the internal combustion engine first starts up. When lubricating oil is pumped, it does not reach all areas of the engine quickly, and to avoid and prevent this problem, the lubricating oil must be sufficiently viscous stirred to flow smoothly and rapidly to all sections of the engine [19, 22, 24, 28]. The pour point of lubricating lubricants was next investigated using nano-additions of SiO_2 NPs at various mass fractions, see Figure (13).

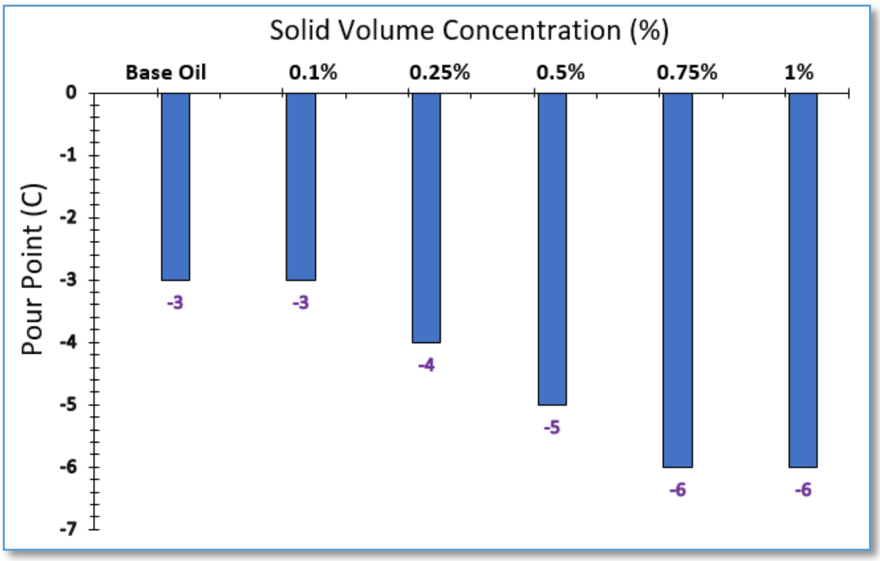

Fig. (13): Pour point of SiO_2 nano-lubricant oil with various solid fraction

Furthermore, the pour point of lubricating oil specifies the temperature at which the lubricant is still in a fluid state and flows under the working circumstances, according to several authors' interpretations [22-24, 28]. The pour point values of lubricants are typically in the range of (-2 to -30)°C. The temperature range is determined by the kind of lubricating oil used and the additives used. As a result, when the lubricating oils pour point is reached, the paraffin's compounds solidify at the freezing point, forming a cross-link between them. The lubricating oil seems to be milky in color and cloudy in this situation [25, 31-33].

The lubricating oil's viscosity rises until it becomes a semi-solid substance. As a result, when nano-additions of SiO_2 NPs were added to the base stock-60 lubricating oil, the pour point parameters were improved in the current study [4, 13, 17, 22, 31].

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

4. Conclusions

The additions of SiO_2 NPs to base stock-60 lubricating oil enhanced the rheological behavior and thermophysical properties. The experimental results indicated that the stock-60 lube oil and all nano-lubricating oil samples are to be Newtonian fluids. Also, it was noted that the viscosity was unaffected by the shear rate or the type of nano-lubricant utilized. Moreover, the NPs concentration at a fixed temperature rising the viscosity, and rising the temperature in a fixed NPs volume percent reduces the viscosity of the oil. It's also noted that increasing the solid volume percent of nanoparticles is achievable as long as the nanoparticles don't agglomerate and silt. With a solid percentage of 1%, the critical temperature for maximal viscosity improvement is 40°C. At a temperature of 100 °C and a solid concentration of 0.1 %, the examined nano-dynamic lubricant's viscosity increased by 28 %, while at a temperature of 40°C and a solid volume percent of 1 %, it increased by 75%. Furthermore, the flashpoint was boosted by a nano-additive increase. For SiO_2 NPs volume percent of 0.25 %, 0.5 %, 0.75 %, and 1 %, the flashpoint rose by 5.042 %, 6.612 %, 8.502 %, and 10.67 %, respectively, compared to base stock lubricating oil. While the pour point of nano-lubricant decreased with increased SiO_2 NPs percentage from -3^{o}C to -6^{o}C maximum enhancement was achieved at solid fraction 0.75% and 1%.

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

References

1. Hatami, Mohammad, Maryam Hasanpour, and Dengwei Jing, "Recent developments of nanoparticles additives to the consumables liquids in internal combustion engines: Part II: Nano-lubricants.", Journal of Molecular Liquids, 114156, 2020.
2. Khalid A. Sukkar, Abullhassan A. Karamalluh, and Thulfiqar N. Jaber, "Rheological and thermal properties of lubricating oil enhanced by the effect of CuO and TiO_2 nano-additives.", Al-Khwarizmi Engineering Journal, 15, no. 2, pp. 24-33, 2019.
3. Akhavan-Behabadi, M. A., F. Hekmatipour, S. M. Mirhabibi, and B. Sajadi, "Experimental investigation of thermal–rheological properties and heat transfer behavior of the heat transfer oil–copper oxide (HTO–CuO) nanofluid in smooth tubes.", Experimental Thermal and Fluid Science 68, pp. 681-688, 2015.
4. Jaber, Thulfiqar N., Khalid A. Sukkar, and Abullhassan A. Karamalluh. "Specifications of Heavy Diesel Lubricating Oil Improved by MWCNTs and CuO as Nano-additives." In IOP Conference Series: Materials Science and Engineering, vol. 579, no. 1, p. 012014. IOP Publishing, 2019.
5. Baskar, S., G. Prabaharan, S. Arumugam, and N. Nagabhooshanam, "Modeling and Analysis of the Tribological Evaluation of Bearing Materials under the Influence of Nano Based Marine Lubricant Using D-optimal Design", Materials Today: Proceedings vol. 5, no. 5, pp. 11548-11555, 2018.
6. Sadegh Aberoumand, Amin Jafarimoghaddam, "Experimental study on synthesis, stability, thermal conductivity and viscosity of Cu–engine oil nanofluid", Journal of the Taiwan Institute of Chemical Engineers, Vol. 71, pp. 315-322, 2017.
7. Mohamed Alaa, Mohamed Hamdy, Mohamed Bayoumi, and Tarek Osman, "Experimental investigations of Rheological behavior and thermal conductivity of nano grease", Industrial Lubrication and Tribology, 2017.
8. Aghahadi, Mohammad Hasan, Mohammadreza Niknejadi, and Davood Toghraie, "An experimental study on the rheological behavior of hybrid Tungsten oxide (WO3)-MWCNTs/engine oil Newtonian nanofluids", Journal of Molecular Structure, vol. 1197, pp. 497-507, 2019.

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

9. Nadooshan, Afshin Ahmadi, Hamed Eshgarf, and Masoud Afrand, "Evaluating the effects of different parameters on the rheological behavior of nanofluids: a comprehensive review", Powder Technology, vol. 338, pp.342-353, 2018.
10. Kharabati, Sajjad, Seyfolah Saedodin, and Seyed Hadi Rostamian, "Experimental investigation of thermal and rheological behavior of silica/soybean oil nano lubricant in low-temperature performance of internal combustion engine", Energy Sources, Part A: Recovery, Utilization, and Environmental Effects pp. 1-15, 2021.
11. Kashefi, Mohammad Hossein, Seyfolah Saedodin, and Seyed Hadi Rostamian, "Effect of silica nano-additive on flash point, pour point, rheological and tribological properties of lubricating engine oil: an experimental study", Journal of Thermal Analysis and Calorimetry vol. 147, pp. 4073–4086, 2022. https://doi.org/10.1007/s10973-021-10812-4
12. Mousavi, Seyed Borhan, Saeed Zeinali Heris, and Mir Ghasem Hosseini, "Experimental investigation of MoS2/diesel oil nanofluid thermophysical and rheological properties." International Communications in Heat and Mass Transfer, vol. 108, 104298, November 2019. https://doi.org/10.1016/j.icheatmasstransfer.2019.104298
13. Shafi, Wani Khalid, and M. S. Charoo, "Rheological properties of hazelnut oil mixed with zirconium-dioxide nanoparticles", Materials Today: Proceedings, vol. 26, pp. 745-749, 2020. DOI:10.1016/j.matpr.2020.01.019
14. Hu, Xichen, Deshun Yin, Jingpeng Xie, Xuan Chen, and Chunyu Bai, "Experimental study of viscosity characteristics of graphite/engine oil (5 W-40) nanofluids", Applied Nanoscience, vol. 10(21–22), pp. 1-14, 2020. http://dx.doi.org/10.1007/s13204-019-01240-w
15. Esfe, Mohammad Hemmat, Seyfolah Saedodin, and Davood Toghraie, "Experimental study and modeling the SiO2-MWCNT (30: 70)/SAE40 hybrid nano-lubricant flow based on the response surface method to identify the optimal lubrication conditions", International Communications in Heat and Mass Transfer, vol. 130, 105771, 2022. https://doi.org/10.1016/j.icheatmasstransfer.2021.105771
16. del Río, José M. Liñeira, María JG Guimarey, Jose I. Prado, Luis Lugo, Enriqueta R. López, and María JP Comuñas, "Improving the tribological performance of a biodegradable lubricant adding graphene nanoplatelets as additives", Journal of Molecular Liquids, vol. 345, 117797, 2022. https://doi.org/10.1016/j.molliq.2021.117797

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

17. Zeinali Heris, Saeed, Mohammad Amin Razbani, P. Estellé, and O. Mahian, "Rheological behavior of zinc-oxide nano-lubricants", Journal of Dispersion Science and Technology, vol. 36, no. 8, pp. 1073-1079, 2015. https://doi.org/10.1080/01932691.2014.945595
18. Esfe, Mohammad Hemmat, Masoud Afrand, Samira Gharehkhani, Hadi Rostamian, Davood Toghraie, and Mahidzal Dahari, "An experimental study on the viscosity of alumina-engine oil: effects of temperature and nanoparticles concentration", International Communications in Heat and Mass Transfer, vol. 76, pp. 202-208, 2016.
19. Hernandez, C., and A. C. Pierre, "Influence of the sol-gel acidic synthesis conditions on the porous texture and acidity of SiO2− Al2O3 catalysts with a low Al proportion", Langmuir vol. 16, no. 2, pp. 530-536, 2000.
20. Moncada, Edwin, R. Quijada, and Jaime Retuert, "Nanoparticles prepared by the sol-gel method and their use in the formation of nanocomposites with polypropylene", Nanotechnology, vol. 18, no. 33, 335606, 2007.
21. El Rassy, H., and A. C. Pierre, "NMR and IR spectroscopy of silica aerogels with different hydrophobic characteristics", Journal of Non-Crystalline Solids vol. 351, no. 19-20, pp. 1603-1610, 2005.
22. Ranjbarzadeh, Ramin, and Raoudha Chaabane, "Experimental Study of Thermal Properties and Dynamic Viscosity of Graphene Oxide/Oil Nano-Lubricant", Energies, vol. 14, no. 10, 2886, 2021.
23. Kashefi, M.H., Saedodin, S. & Rostamian, S.H. Effect of silica nano-additive on flash point, pour point, rheological and tribological properties of lubricating engine oil: an experimental study. J Therm Anal Calorim 147, 4073–4086 (2022). https://doi.org/10.1007/s10973-021-10812-4
24. Seyed Borhan Mousavi, Saeed Zeinali Heris, Mir Ghasem Hosseini, “Experimental investigation of MoS2/diesel oil nanofluid thermophysical and rheological properties”, International Communications in Heat and Mass Transfer, Volume 108, 2019, 104298, https://doi.org/10.1016/j.icheatmasstransfer.2019.104298.
25. Motahari, Kazem, Mohammad Abdollahi Moghaddam, and Mojtaba Moradian, "Experimental investigation and development of new correlation for influences of temperature and concentration on dynamic viscosity of MWCNT-SiO_2 (20-80)/20W50 hybrid nano-lubricant", Chinese Journal of Chemical Engineering, vol. 26, no. 1, pp. 152-158, 2018.

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

26. Mohamed Kamal Ahmed Ali, Hou Xianjun, "Improving the heat transfer capability and thermal stability of vehicle engine oils using Al_2O_3/TiO_2 nanomaterials", Powder Technology, vol. 363, pp. 48-58, March 2020.
https://doi.org/10.1016/j.powtec.2019.12.051

27. Farid Soltani, Davood Toghraie, and Arash Karimipour, "Experimental measurements of thermal conductivity of engine oil-based hybrid and mono nanofluids with tungsten oxide (WO_3) and MWCNTs inclusions", Powder Technology, vol. 371, pp. 37-44, 2020. https://doi.org/10.1016/j.powtec.2020.05.059

28. Mohamed Kamal Ahmed Ali, Hou Xianjun, Richard Fiifi Turkson, Zhan Peng and Xiandong Chen,"Enhancing the thermophysical properties and tribological behavior of engine oils using nano-lubricant additives", RSC advances, vol. 6, no. 81, pp. 77913-77924, 2016.

29. Mukherjee, Sayantan, Smita Rani Panda, Purna Chandra Mishra, and Paritosh Chaudhuri, "Enhancing Thermophysical Characteristics and Heat Transfer Potential of TiO_2/Water Nanofluid", International Journal of Thermophysics 41, no. 12, pp. 1-33, 2020. https://doi.org/10.1007/s10765-020-02745-1

30. Das, Pritam Kumar, "A review based on the effect and mechanism of thermal conductivity of normal nanofluids and hybrid nanofluids", Journal of Molecular Liquids, vol. 240, pp. 420-446, 2017. https://doi.org/10.1016/j.molliq.2017.05.071

31. Tian, Xiao-Xiao, Rasool Kalbasi, Cong Qi, Arash Karimipour, and Hong-Li Huang, "Efficacy of hybrid nano-powder presence on the thermal conductivity of the engine oil: an experimental study", Powder Technology, vol. 369, pp. 261-269, 2020. https://doi.org/10.1016/j.powtec.2020.05.004

32. Tonk, Ravinder. "The science and technology of using nano-materials in engine oil as lubricant additives." Materials Today: Proceedings, Volume 37, Part 2, pp. 3475-3479, 2021. https://doi.org/10.1016/j.matpr.2020.09.384

33. Tianyi Sui, Mei Ding, Chunhui Ji, Shuai Yan, Jinhua Wei, Anying Wang, Feifei Zhao and Jixiong Fei, "Dispersibility and rheological behavior of functionalized silica nanoparticles as lubricant additives", Ceramics International, vol. 44, no. 15, pp. 18438-18443, 2018. https://doi.org/10.1016/j.ceramint.2018.07.061

34. Bahaa M. Kamel, Emad El-Kashif, W. Hoziefa, Mohamed S. Shiba & Abou Bakr Elshalakany, "The effect of MWCNTs/GNs hybrid addition on the tribological and rheological properties of

Open Access
No. 37, December 2022, pp. 68-91

P- ISSN: 2220-5381
E- ISSN: 2710-1096

lubricating engine oil", Journal of Dispersion Science and Technology, Volume 42, Issue 12, pp. 1811-1819, 2021.
https://doi.org/10.1080/01932691.2020.1789470

35. Kotia, Ankit, and Subrata Kumar Ghosh, "Experimental analysis for rheological properties of aluminum oxide (Al_2O_3)/gear oil (SAE EP-90) nano lubricant used in HEMM", Industrial Lubrication and Tribology, vol. 67, no. 6, pp. 600-605, 2015. https://doi.org/10.1108/ILT-03-2015-0029

36. J. Patel and A. Kiani, "Tribological Capabilities of Graphene and Titanium Dioxide Nano Additives in Solid and Liquid Base Lubricants," Applied Sciences, vol. 9, no. 8, p. 1629, Apr. 2019, http://dx.doi.org/10.3390/app9081629