



# Effect of silica nano-additive on flash point, pour point, rheological and tribological properties of lubricating engine oil: an experimental study

Mohammad Hossein Kashefi<sup>1</sup> · Seyfolah Saedodin<sup>1</sup> · Seyed Hadi Rostamian<sup>2</sup>

Received: 21 November 2020 / Accepted: 29 March 2021 / Published online: 26 April 2021  
© Akadémiai Kiadó, Budapest, Hungary 2021

## Abstract

In this study, the rheological behavior and tribological properties of a nano-lubricant containing SiO<sub>2</sub> nanoparticles in SAE40 engine oil are experimentally investigated. Nano-lubricant has been prepared with two-step method using an ultrasonic homogenizer. The rheological behavior of nano-lubricant checked out in all studied temperatures (ranging from 15°C to 65°C) and different solid volume fractions (ranging from 0 to 1%) and it shows non-Newtonian behavior (pseudoplastic). Also, an accurate correlation is presented for the prediction of nano-lubricant's viscosity based on experimental data. A pin-on-disk tribometer was performed to investigate the tribological behavior of nano-lubricant. Results revealed that in  $\varphi = 0.1\%$ , the wear rate and friction coefficient have been decreased by 50% and 18.46%, respectively, compared with the base oil. In addition, the nano-lubricant with optimum concentration and base oil was tested in the operational condition of diesel engines at the same condition and the abrasive elements of these engine oils were analyzed. Other important factors including pour point and flash point were also determined which showed that the addition of SiO<sub>2</sub> nanoparticles to the base oil in  $\varphi = 0.1\%$  will cause a 3.8% improvement in flash point compared with the base oil.

**Keywords** Nano-lubricant · SiO<sub>2</sub> nanoparticles · Rheological behavior · Tribological properties · Engine oil

## List of symbols

R	Regression coefficient
W <sub>r</sub>	Wear rate (mm <sup>3</sup> N <sup>-1</sup> m <sup>-3</sup> )
Δm	Mass reduction
L	Distance (m)
F	Exerted load (N)

## Greek symbols

$\varphi$	Solid volume fraction
$\tau$	Shear stress (Pa)
$\dot{\gamma}$	Shear rate (s <sup>-1</sup> )
$\rho$	Density (g mm <sup>-3</sup> )

## Abbreviations

ANOVA	Analysis of variance
SAE	Society of automotive engineers
SEM	Scanning electron microscopy
XRD	X-ray diffraction

## Introduction

Improving lubrication properties is an essential economic parameter in overall energy consumption of mechanical systems. Nowadays, all of the lubricants with mineral or synthetic base need additives to gain intended properties. Nano-lubricants are a new level of lubricants that are prepared by dispersion of particles of nano-sized in the base oil. Using chemical additives with unique properties causes an improvement in physical, chemical, and mechanical properties of the base oils [1–3]. As an example, the addition of nanoparticles to base oil improves its thermal characteristics. Enhancement of heat transfer is affected by Brownian motions and inter-particle forces [4–6]. Viscosity changes need to be considered along with the enhancement of heat transfer in nanofluid compared to the base fluid, since it is

✉ Seyfolah Saedodin  
s\_sadodin@semnan.ac.ir

✉ Seyed Hadi Rostamian  
H.rostamian@du.ac.ir

<sup>1</sup> Faculty of Mechanical Engineering, Semnan University,  
35131-19111 Semnan, Iran

<sup>2</sup> School of Engineering, Damghan University,  
36716-41167 Damghan, Iran

an important parameter in the evaluation of needed power for pumping in thermal systems. Addition of nanoparticles causes a change in the rheological behavior of the base oil. Researchers have lots of studies on rheological properties of nanofluids [7–18]. For example, Krishnakumar et al. [19] have studied rheological properties of  $\text{Al}_2\text{O}_3$ -ethylene glycol nanofluid and showed that despite the behavior of the base fluid, nanofluid shows shear-thinning behavior in low temperatures and shear rates. Hemmat and Abbasian Arani [20] have shown that carbon nanotubes considerably affect the non-Newtonian behavior of nano-oil containing MWCNT- $\text{TiO}_2$ . Also, they showed that by increasing the concentration, the shear-thinning behavior of nano-oil will be intensified. Sepiani et al. [21] have investigated ZnO/SAE50 nano-oil viscosity in  $\phi = 0$ –1% in different temperatures and shear rates. They proved that the viscosity of this nano-oil increases by 12% with increasing the amount of ZnO nanoparticles. In another research, Nadoushan et al. [22] have predicted the rheological behavior of  $\text{SiO}_2$ -MWCNT/10W40 hybrid nano-lubricant using an artificial neural network. Soltani and Akbari [23] have investigated the effects of temperature and solid volume fraction on the viscosity of MgO-MWCNT/EG hybrid nanofluid. In this research that was done in  $\phi = 0$ –1% and  $T = 30$ –60 °C, the maximum viscosity enhancement was 168% in  $\phi = 1\%$ . Hemmat esfe et al. [24] have shown that maximum viscosity enhancement in alumina-engine oil nano-lubricant was 132% compared to the base oil. Table 1 gives a brief summary of researches accomplished on nano-lubricants viscosity.

Furthermore, applications of nano-lubricants are very wide due to their abilities for improving surface properties and engine efficiency and decreasing maintenance and costs of systems. Researchers have synthesized different nanomaterials from metallic, organics, and minerals for application in nano-lubricant production with improved tribological properties [34–43]. Using nanoparticles causes a reduction of wear and friction coefficient in oil. There are some mechanisms for this favor behavior of nanoparticles in oil. These mechanisms are as follows:

- Rolling effect of nanoparticles improves relative motion of contacted surfaces [44–46]
- These nanoparticles have repairing effect on surfaces in a way that it fills surface perforations and results in an improvement in roughness of the surface [47–49].
- These nanoparticles create a strong protective film between the surfaces to ease their lubrication [50, 51].

Lee et al. [52] have investigated lubrication properties of nano-oil with dispersed fullerene nanoparticles with disk on disk tribometer. Results of this experiment, which was carried out in different exerted forces and solid volume fractions, have shown that the presence of these nanoparticles decreases friction and wear. Nasiri Khozani et al. [53] stated that using nanoparticles in tractors engine decreases wear in cylinder, shaft, and bearings by 68%. Table 2 gives a brief summary of researches on tribological properties of nano-lubricants.

Some of the researchers have studied other important factors of engine oil including flash point and pour point. Ahmadi et al. [59] measured flash point and pour point of nano-oils containing MWCNT nanoparticles with three different concentrations. They observed that the flash point and pour point increase by 13% and 3.3%, respectively, with a mass percentage of 0.2%. Moreover, these properties decrease with further increase in concentration. In another research, Ahmadi et al. [60] dispersed CuO nanoparticles in engine oil. They noticed that flash point has enhanced by 7.9% in a concentration of 0.1% compared with the base oil.

Most researchers have discussed the rheological and tribological properties of nano-lubricants with different nanoparticles and base oils. In this paper, for the first time, despite the fact that the effects of  $\text{SiO}_2$  nanoparticles on different properties of SAE40 engine oil (pour point, flash point, rheological, and tribological properties) have been investigated experimentally, the anti-wear characteristic of this nano-lubricant has been evaluated by using it into diesel engines in real condition, and the abrasive analysis has been performed. The purpose of using  $\text{SiO}_2$  nanoparticles

**Table 1** A brief summary of studies accomplished on nano-lubricants viscosity in different temperatures and concentrations

References	Nano-additives	Base fluid	Concentrations/Vol %	Temperature
Vakili-Nezhaad and Dorany [25]	MWCNTs	SAE40	0–2%	25–50 °C
Afrand et al. [26]	$\text{SiO}_2$ -MWCNTs	SAE40	0–1%	25–60 °C
Chen et al. [27]	MWCNTs	Silicone oil	0.2–1%	10–60 °C
Hemmat Esfe et al. [28]	ZnO-MWCNTs	SAE40	0–1%	25–60 °C
Shababi et al. [29]	$\text{TiO}_2$ - MWCNTs	SAE50	0–1%	25–50 °C
Asadi et al. [30]	MWCNTs-MgO	SAE50	0–2%	25–50 °C
Asadi and Asadi [31]	ZnO-MWCNTs	10W40	0–1%	5–50 °C
Hemmat Esfe et al. [32]	MgO	5 W-50	0–2%	5–65 °C
Dardan et al. [33]	$\text{Al}_2\text{O}_3$ -MWCNTs-	SAE40	0–1%	25–50 °C

**Table 2** A brief summary of studies accomplished on tribological properties of nano-lubricants

References	Lubricant	Nano-additives	Conc./mass%	Optimum conc
Jatti and Singh [54]	Mineral-based multi-grade engine oil	CuO	0.5, 1, 1.5	1.5
Chen and Liu [55]	Liquid paraffin	PbS	0.05–0.2	0.2
Jiao et al. [56]	–	Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>	0.05, 0.1 0.5,1	0.5
Viesca et al. [44]	PAO6	Cu	0.5,2	0.5
Koshy et al. [57]	Mineral oil	MoS <sub>2</sub>	0.25, 0.5, 0.75, 1	0.58%
Ran et al. [58]	60SN base oil	ZnO	0.5	0.5

**Table 3** Properties of SAE40 engine oil

Parameter	Value	Units
Kinematic viscosity at 100 °C	15.5	cSt
Viscosity index	85	–
Density at 15 °C	0.893	g cm <sup>-3</sup>
Flash point	234	°C
Pour point	–12	°C

is easy-suspending of these nanoparticles as they are oil-friendly. Moreover, the spherical shape of SiO<sub>2</sub> nanoparticles is crucial matter in order to improve the tribological properties of engine oil. Hence, these factors are critical ones to choose suitable nanoparticles in engine oils.

## Preparation of nanofluid

The samples used in this study vary from 0% to 1%, and the concentrations have been chosen to have meaningful changes.

## Materials

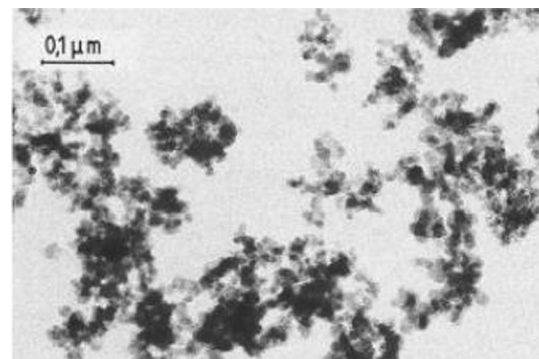
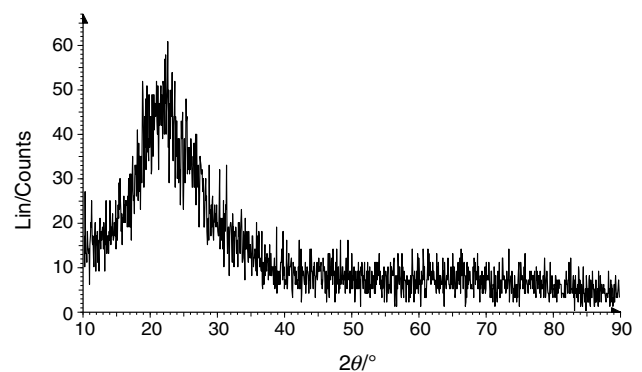
Materials used in preparation of this nano-oil are:

- (1) SAE40 engine oil (base fluid) has been produced by Pars Oil Company, which is a suitable lubricant for diesel engines. The properties of this lubricant are presented in Table 3, which are taken up from the specification of the SAE40 engine oil.
- (2) SiO<sub>2</sub> nanoparticles prepared by AEROSIL Company have been used. The properties of these nanoparticles are presented in Table 4.

To determine the morphology and structure of nanoparticles, XRD and SEM analyses are performed and the results are presented in Figs. 1 and 2. As can be seen in XRD pattern, these nanoparticles do not have crystalline structure and are amorphous.

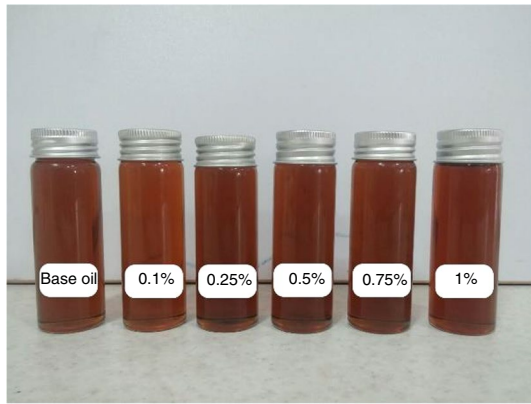
**Table 4** Properties of SiO<sub>2</sub> nanoparticle

Parameter	Value	Units
Density	2100	kg m <sup>-3</sup>
Size	20	nm
Shape	Spherical	–
Purity	99.8%	–
Color	White	–

**Fig. 1** SEM images of SiO<sub>2</sub> nanoparticles**Fig. 2** XRD analysis of SiO<sub>2</sub> nanoparticles

## Nanoparticle dispersion

Nano-lubricants used in this research are prepared using a two-step method. Two-step method is the fastest and



**Fig. 3** Samples after 1-month

**Table 5** Specifications of CAP2000+ viscometer

Parameter	Explanation	units
Measuring range	0.3–1028	cP
Torque range	797–7.970	dyne cm
Speeds	5–1000	RPM
Temperatures	5–75	°C
Accuracy	±2%	–
Repeatability	±5%	–

most economical way of nanofluids production. A digital scale, magnetic stirrer, and ultrasonic homogenizer are used in preparation of this nano-lubricant. First, SiO<sub>2</sub> nanoparticles are added to the base oil and mixed with magnetic stirrer for 30 min. Then, the agglomerations are broken in solution using ultrasonic waves for 40 min with power of 200 W. Then, nanoparticles are completely dissolved in base oil in a way that there is no evidence of sedimentation or change in color of the solution after one month. Figure 3 shows the nano-lubricant samples after one month.

## Specifications of measuring equipment and experimental conditions

### Viscometer

Viscosity measurement of the samples is performed using cone and plate viscometer CAP2000+ manufactured by Brookfield Co (USA) with accuracy of ±2%. The specifications and operational conditions of this device are listed in Table 5.

Nano-lubricants viscosity is measured in six solid volume fractions (0%, 0.1%, 0.25%, 0.5%, 0.75%, and 1%),



**Fig. 4** CAP2000+ viscometer

**Table 6** Specifications of pin-on-disk tribometer

Parameter	Explanation	Units
Pin diameter	6–10	mm
Track Diameter	20–50	mm
Disk Rotation	1–300	RPM
Normal Load	0–100	N
Frictional Force	0–100	N

temperature in the range of 25°C–65 °C, and shear rates up to 13,000 1/s. Figure 4 shows CAP2000+ viscometer.

### Pin-on-disk tribometer

In order to measure tribological properties of nano-lubricant such as friction coefficient and wear rate, a pin-on-disk tribometer is used according to the ASTM G99. Description and operating conditions of this equipment are presented in Table 6.

These experiments are carried out for this nano-lubricant with solid volume fractions of 0%, 0.01%, 0.025, 0.05%, and 0.1% under two different loads of 120 N and 180 N at room temperature. Time for each experiment is 1 h, and speed of

disk rotation is 120 rpm. The disk is made from CK45 steel, and it is replaced with a new one after each measurement. Figure 5 shows a schematic of the test procedure.

## Diesel engine

In order to compare the quality of prepared nano-lubricant with the base oil, two similar one-cylinder diesel engines manufactured by KAMA Motors Company are used. Specifications and operational conditions of two engines are presented in Table 7.

To compare the performance of nano-oil and base oil, these two samples have been tested in operational condition of diesel engines. The operational times of both engines are thirty hours dividing to ten intervals. After thirty hours, both engine oils are drained according to the standard conditions.

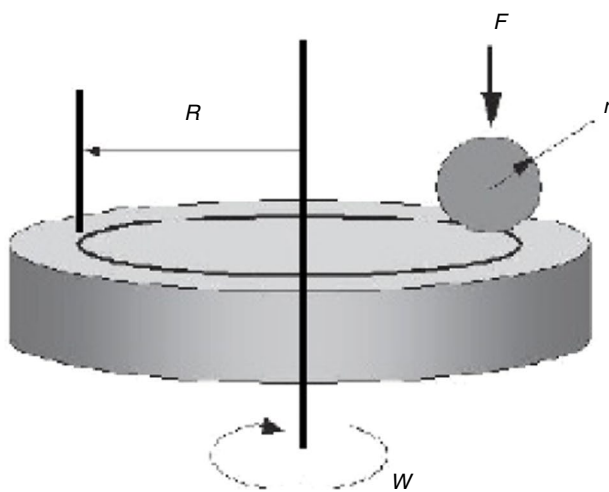
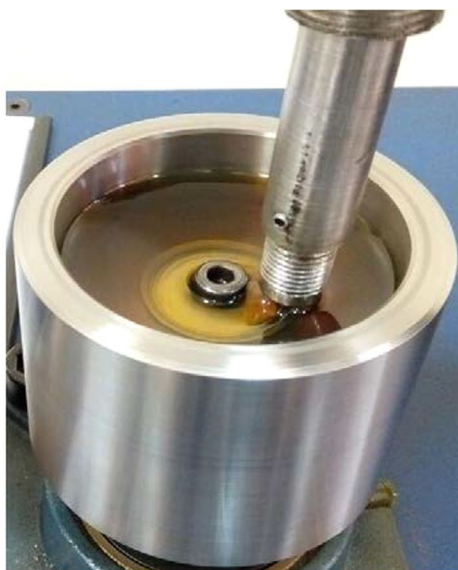


Fig. 5 Pin-on-disk tribometer

Table 7 Specifications of diesel engine

Parameter	Explanation	units
Nominal power	4	KW
Maximum speed	3600	RPM
Fuel	Gasoline	–
Cooling system	Air cooling	–

Analysis of abrasive particles is performed for both samples. Results are discussed in the following section.

## Results and discussion

### Rheological behavior

In order to investigate the rheological behavior of this nano-lubricant, Fig. 6 has been presented which shows viscosity changes versus shear rate in different solid volume fractions. As shown in this figure, in temperatures higher than  $T = 45^\circ\text{C}$ , the slope of the lines is close to zero in all different concentrations. Deviation from zero slopes of lines is increased by increasing solid volume fraction. The pseudoplastic behavior can be perceived, since viscosity is decreased with increasing shear rate. The maximum deviation of the slope belongs to  $\varphi = 1\%$ .

Figure 7 shows shear stress changes versus shear rate in different solid volume fractions and temperatures. This figure also presents one of the methods of investigating the rheological behavior of the fluids. The deviation from the straight line shows nanofluid behavior tendency to non-Newtonian fluid behavior. The presence of nanoparticles causes to not have a linear trend between the shear stress and shear rate.

Different theoretical and experimental models for nano-fluids viscosity have already been proposed by researchers. A brief summary of these models is presented in Table 8. Moreover, the errors of experimental results with these models have been presented by Eq. 1. These values obtained in volume fraction of 0.1%, and two temperatures of  $35^\circ\text{C}$  and  $55^\circ\text{C}$ . As can be seen, the mentioned models do not consider the temperature and therefore cannot predict the viscosity of nano-lubricant accurately.

$$\text{Error}(\%) = \frac{\mu_{\text{exp}} - \mu_{\text{theory}}}{\mu_{\text{theory}}} * 100 \quad (1)$$

Figure 8 shows a comparison between those obtained from previously mentioned models and experimental viscosity data in different solid volume fractions at  $T = 45^\circ\text{C}$  and shear rate of  $5332 \text{ s}^{-1}$ . It can be seen that Einstein, Bachelor, and Wang models have a good approximation of nano-oil

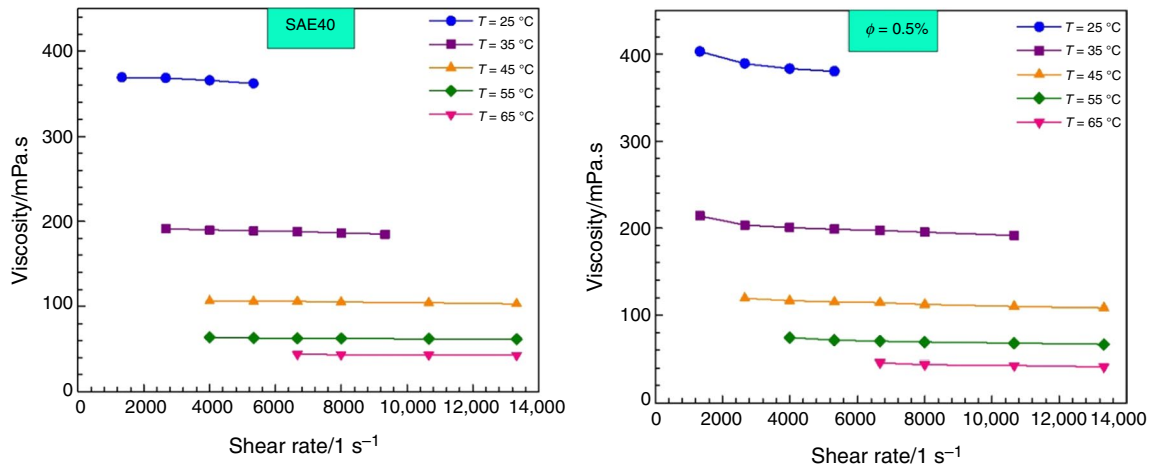


Fig. 6 Viscosity versus shear rate

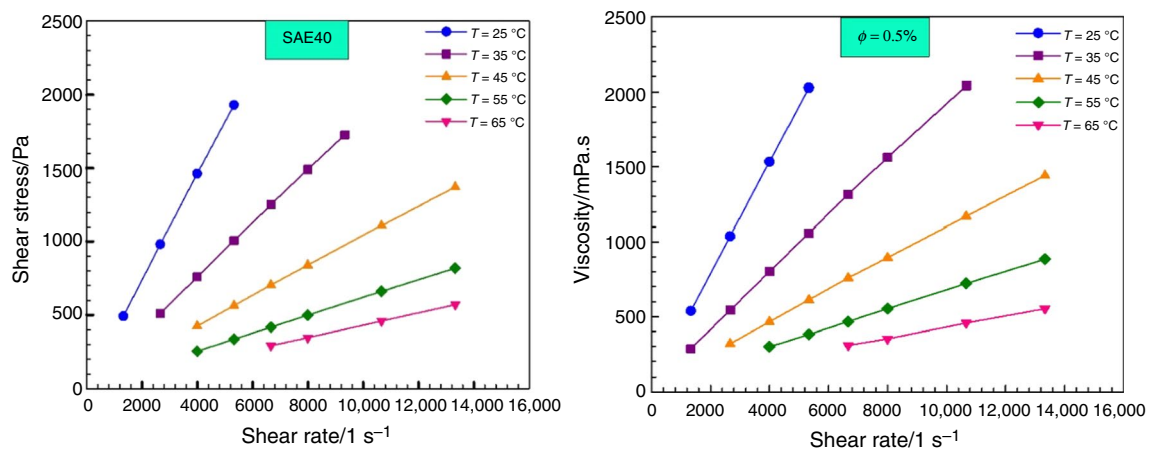


Fig. 7 Shear stress versus shear rate

Table 8 Important models for viscosity of nanofluids

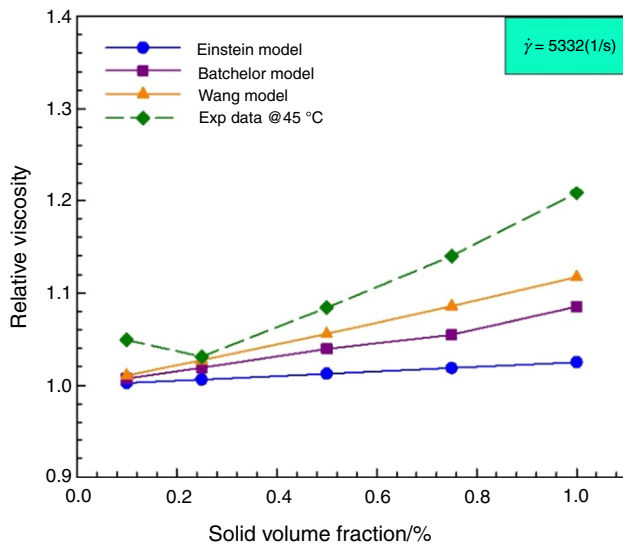
Models	Correlations	Error T=35 °C, $\dot{\gamma} = 5332$ $s^{-1}$	Error T=55 °C, $\dot{\gamma} = 5332$ $s^{-1}$
Einstein [61]	$\frac{\mu_{eff}}{\mu_{bf}} = (1 + 2.5\phi)$	2.1%	7.3%
Saito [62]	$\frac{\mu_{eff}}{\mu_{bf}} = (1 + \frac{2.5\phi}{1-\phi})$	2.1%	7.9%
Brinkman [63]	$\frac{\mu_{eff}}{\mu_{bf}} = \frac{1}{(1-\phi)^{2.5}}$	2.2%	7.6%
Batchelor [64]	$\frac{\mu_{eff}}{\mu_{bf}} = 1 + 2.5\phi + 6.2\phi^2$	2.1%	7.3%
Wang et al. [65]	$\frac{\mu_{eff}}{\mu_{bf}} = 1 + 7.3\phi + 123\phi^2$	1.7%	7.2%
Chen et al. [66]	$\frac{\mu_{eff}}{\mu_{bf}} = 1 + 10.6\phi + (10.6\phi)^2$	1.4%	6.8%

viscosity at concentrations less than 0.5%. More deviation is evident in higher concentrations, as these models do not consider the effects of temperature on the viscosity of

nanofluids. Nevertheless, Wang’s model has higher accuracy between these models with experimental results. So, the presentation of a new experimental model is essential for having a more accurate prediction of viscosity for nano-lubricant containing SiO<sub>2</sub> nanoparticles which are presented in the following sections.

It is expected that fluid viscosity decreases with increasing temperature due to the reduction in intermolecular forces. Figure 9 shows the variations of nano-lubricant viscosity with temperature. It is observed that temperature increment causes a similar reduction in base oil and nano-oil viscosities in all solid volume fractions. According to this figure, the slope of the curve is variable in different temperatures and it decreases with increasing temperature.

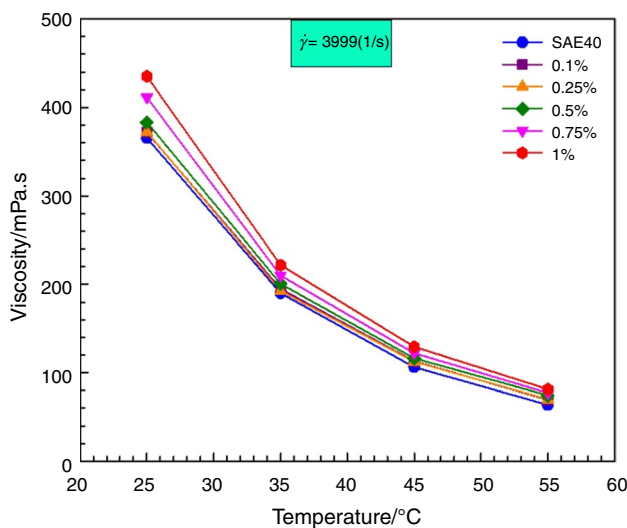
Figure 10 shows relative viscosity changes in different temperatures and solid volume fractions, in the shear rate of 5332 (s<sup>-1</sup>). It is obvious that the viscosity of nano-lubricant increases with increasing concentration. Also, relative



**Fig. 8** Comparison between theoretical models and experimental results at 45 °C

viscosity in  $\phi = 0.25\%$  has experienced a sudden drop in all temperatures. According to these observations,  $\phi = 0.25\%$  would be a proper choice for industrial applications due to the minor changes in its viscosity. On the other hand, a sudden drop can be observed in Fig. 10(b) in  $T = 35\text{ }^\circ\text{C}$  and solid volume fractions of 0.1%, 0.25%, 0.5%, and 0.75%, and after that, it increases with increasing temperature. So,  $T = 35\text{ }^\circ\text{C}$  is a specific temperature in different applications of this nanofluid.

Figure 11 shows the power-law index versus solid volume fraction of nano-oil in different temperatures. According to Eq. 2, if  $n = 1$ , then the nanofluid behavior is Newtonian, if  $n < 1$ , it has pseudoplastic behavior, and if  $n > 1$ , it shows dilatant behavior. It can be observed in this figure that  $n < 1$



**Fig. 9** Viscosity versus temperature

in all solid volume fractions and nano-oil has pseudoplastic behavior. Also, values of  $n$  decrease with increasing temperature. The minimum value of  $n$ , which is about 0.8, corresponds to the  $\phi = 0.25\%$  and  $T = 65\text{ }^\circ\text{C}$ . Hence, it should be careful in using this concentration in lubrication to not pass the allowable viscosity index.

$$\tau = m\dot{\gamma}^n \tag{2}$$

Figure 12 shows the consistency index of nano-oil versus solid volume fraction at different temperatures. The maximum value of this index corresponds to  $T = 25\text{ }^\circ\text{C}$ , and it decreases with increasing temperature. Increasing nanoparticle concentration in the base oil results in an increase in the consistency index except, at  $T = 65\text{ }^\circ\text{C}$ .

The exact values of  $n$  and  $m$  are presented in Table 9.

An accurate correlation is proposed based on experimental data for prediction of viscosity changes due to solid volume fraction and temperature. It is demonstrated in Eq. 3 and is obtained through the ANOVA method.

$$\begin{aligned} \frac{\mu_{nf}}{\mu_{bf}} = & 1.312617 - 0.40743\phi - 0.02201T - 1.0867\phi.T \\ & + 6637.082\phi^2 + 0.000532T^2 + 0.012826\phi.T^2 \\ & - 298214\phi^3 - 0.0000038T^3 \end{aligned} \tag{3}$$

The results of ANOVA analysis for the model of viscosity are presented in Table 10. F value equal to 16.321 shows the considerable effectiveness of regression model. Pvalue of this model is less than 0.05 that shows the significance of model parameters. If the p value of any parameter is higher than 0.05 that parameter would be insignificant. All the insignificant parameters are omitted from the model.

Figure 13 shows a comparison between experimental data and those obtained from the proposed correlation at different temperatures. Little difference between these two data groups indicates the high accuracy of the proposed correlation for the viscosity prediction of this nano-lubricant.

### Tribological behavior

Figures 14 and 15 show the variations of friction coefficient with different solid volume fractions and under loads of 120 N and 180 N. In these figures, it is shown that increasing solid volume fraction of  $\text{SiO}_2$  nanoparticles causes an improvement in lubrication and reduction in friction coefficient. But this reduction does not continue with increasing concentration, since the excessive addition of nanoparticles has an opposite effect on the friction coefficient. The main reason is nanoparticles stick and creating agglomerations in the engine oil in higher concentrations. Furthermore, considering the descending trend of friction coefficient versus time in all solid volume fractions, it can be concluded that this nano-lubricant has a good mending and polishing effect.

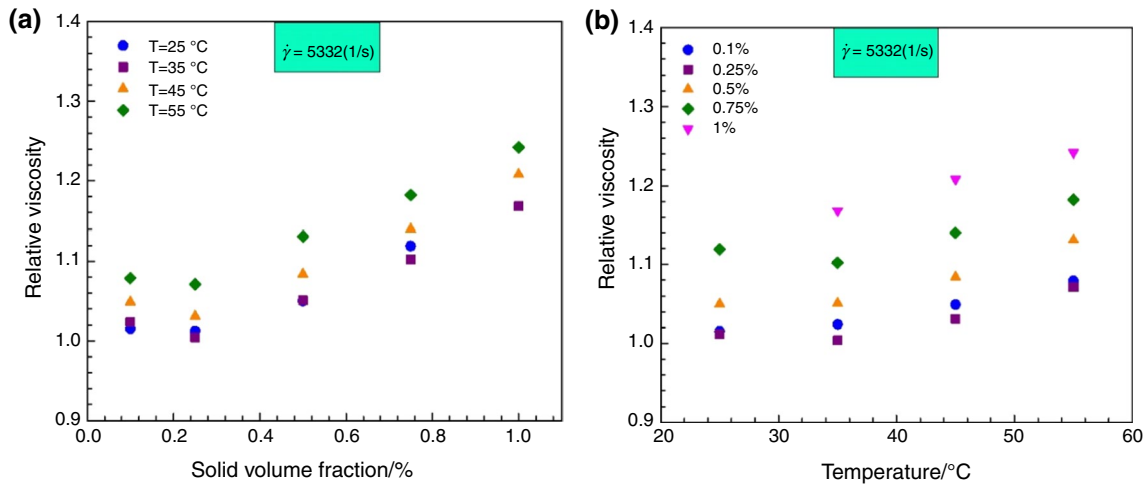


Fig. 10 a Relative viscosity versus solid volume fractions, b relative viscosity versus temperature in shear rate of 5332 s<sup>-1</sup>

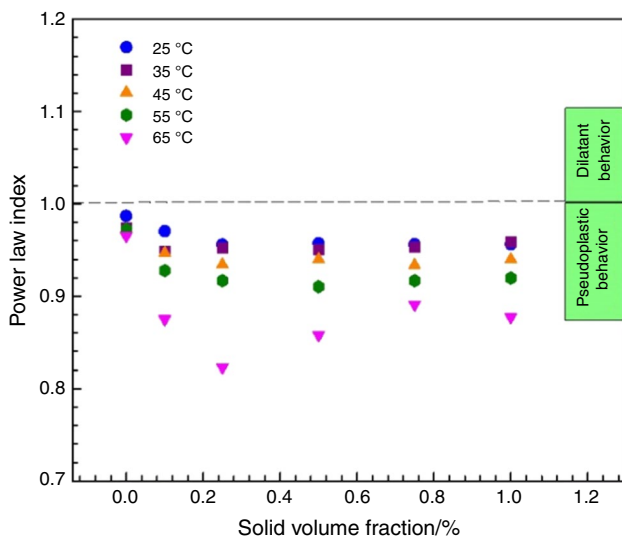


Fig. 11 Power-law index versus solid volume fraction

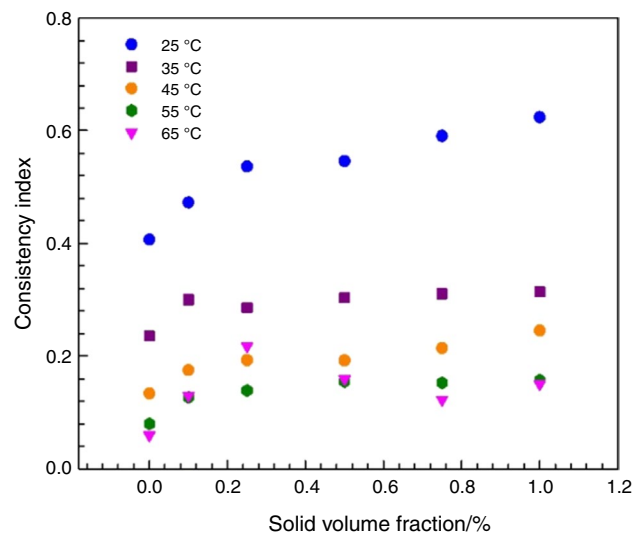


Fig. 12 Consistency index versus solid volume fraction

Figure 16 shows changes in the average friction coefficient in different solid volume fractions under two different loads. The minimum friction coefficient is recorded in  $\phi = 0.1\%$ . In this volume fraction, the friction coefficient decreased by 18.46% and 16.21% under 120 N and 180 N of load, respectively, compared with the base oil.

In addition to the measurement of friction coefficient, the amount of decrease in mass of disks is measured with an accurate scale after each test. The disks are washed completely after each test to remove the remaining oil, and then, the amount of decrease in mass is reported. Equation 3 is used to calculate the wear rate:

$$W_r = \frac{\Delta m}{\rho * l * F} \tag{4}$$

where  $\rho_{\text{Disk}} = 8.908 \text{ g mm}^{-3}$

Figure 17 shows changes in the wear rate of different samples. It can be seen that increasing solid volume fraction reduces the wear rate. The maximum reduction in wear rate, while using nano-lubricant as compared with the base oil is about 50% and is occurred at  $\phi = 0.1\%$  and  $F = 120 \text{ N}$ .

The uncertainty of friction coefficient has been calculated using Eq. 4 [67].

$$\omega_R = \left[ \left( \frac{\partial R}{\partial X_1} \omega_1 \right)^2 + \left( \frac{\partial R}{\partial X_2} \omega_2 \right)^2 + \dots + \left( \frac{\partial R}{\partial X_n} \omega_n \right)^2 \right]^{\frac{1}{2}} \tag{5}$$



**Table 9** n and m values for different volume fractions and temperatures

Concentration	Temperature									
	25 °C		35 °C		45 °C		55 °C		65 °C	
	n	m	n	m	n	m	n	m	n	m
SAE40	0.987	0.4065	0.9742	0.2351	0.9728	0.1338	0.9725	0.0799	0.9654	0.0594
0.1%	0.9704	0.4728	0.9487	0.3	0.9466	0.1753	0.9279	0.1267	0.8752	0.1302
0.25%	0.9559	0.5366	0.9524	0.2857	0.9343	0.1928	0.9168	0.1389	0.823	0.2173
0.5%	0.9574	0.5463	0.9507	0.3031	0.9399	0.192	0.9104	0.1549	0.8578	0.1596
0.75%	0.9563	0.5905	0.9534	0.3106	0.9337	0.2137	0.9169	0.1528	0.8911	0.1227
1%	0.9564	0.6235	0.9591	0.3139	0.9399	0.245	0.9197	0.1574	0.8774	0.1504

**Table 10** ANOVA results for relative viscosity

Source	Adj SS	DF	Adj MS	F	P
Model	0.14	8	0.017	321.16	<0.0001
T	0.005597	1	0.005597	104.92	<0.0001
Ø	0.012	1	0.012	223.64	<0.0001
T. Ø	0.0002441	1	0.0002441	4.58	0.0482
T <sup>2</sup>	0.005604	1	0.070362	105.05	<0.0001
Ø <sup>2</sup>	0.004980	1	0.004980	93.36	<0.0001
T <sup>2</sup> Ø	0.001228	1	0.001228	23.01	0.0002
T <sup>3</sup>	0.001040	1	0.001040	19.49	0.0004
Ø <sup>3</sup>	0.0007115	1	0.0007115	14.46	0.0016
Residual error	0.0008534	16	0.00005334		
Total	0.14	24			

Standard deviation = 0.007303  
 PRESS = 0.001913  
 R<sup>2</sup> = 99.38%, Adjusted R<sup>2</sup> = 99.07%, Predicted R<sup>2</sup> = 95.61%  
 Adequate precision = 62.258

In this equation  $\omega_R$  is the absolute uncertainty, and  $R$  is the function of independent variables ( $X_1, X_2, \dots, X_n$ ). According to Eqs. 5 and 6, the uncertainty of friction coefficient can be calculated by each parameter’s uncertainty.

$$C_f = \frac{F}{N} \tag{6}$$

$$\frac{\omega_{C_f}}{C_f} = \left[ \left( \frac{\omega_F}{F} \right)^2 + \left( \frac{\omega_N}{N} \right)^2 \right]^{\frac{1}{2}} \tag{7}$$

The value of  $\frac{\omega_{C_f}}{C_f}$  is the relative uncertainty of friction coefficient. The uncertainty of each parameter is 2%, and hence, the friction coefficient uncertainty is 2.82%.

To demonstrate the effect of nanoparticles on the lubrication property of the oil on the pin-on-disk tribometer, SEM images are obtained from the worn path created on the disks which can be seen in Fig. 18.

Since minimum friction coefficient and wear rate, in loads of 120 N and 180 N, occur in  $\phi = 0.1\%$ , it can be concluded that using this nano-lubricant with  $\phi = 0.1\%$  can have a considerable effect on the quality of engine oil and also on the operation of internal combustion engines. So, other properties of the oil like flash point and pour point are measured for the base fluid and SiO<sub>2</sub>/SAE40 in  $\phi = 0.1\%$  and are reported in Fig. 19.

The flash point of oil determines an upper limit for its operating temperature. As the flash point is higher, it will be possible for the oil to operate in higher temperatures. As shown in this figure, the addition of SiO<sub>2</sub> nanoparticles to the base oil in  $\phi = 0.1\%$  causes an increase of 3.8% in the flash point of the nano-oil as compared to the base oil. However, there is no change in the pour point by using the nanoparticles. Accordingly, it can be concluded that the addition of nanoparticles to the base oil improves the operational temperature range of the oil.

### Oil test in engine

Since the friction coefficient and the flash point of 0.1%SiO<sub>2</sub>/SAE40 are optimized, this concentration is chosen for comparing these two oils in engine. After thirty hours of operation, both engine oils are drained and abrasive particle analysis is performed. The analysis is performed according to the ASTM D6595, and the results are depicted in Fig. 20. In this experiment, abrasive particles like Fe, Cr, Al, Cu, and Pb are measured. It can be observed that the presence of nanoparticles in the oil has reduced the amount of abrasive particles in nano-oil compared to the base oil. This improves the lubrication and reduces the abrasion of the cylinder wall and piston. These results strongly confirm the anti-wear property of 0.1%SiO<sub>2</sub>/SAE40 nano-lubricant compared with base oil.

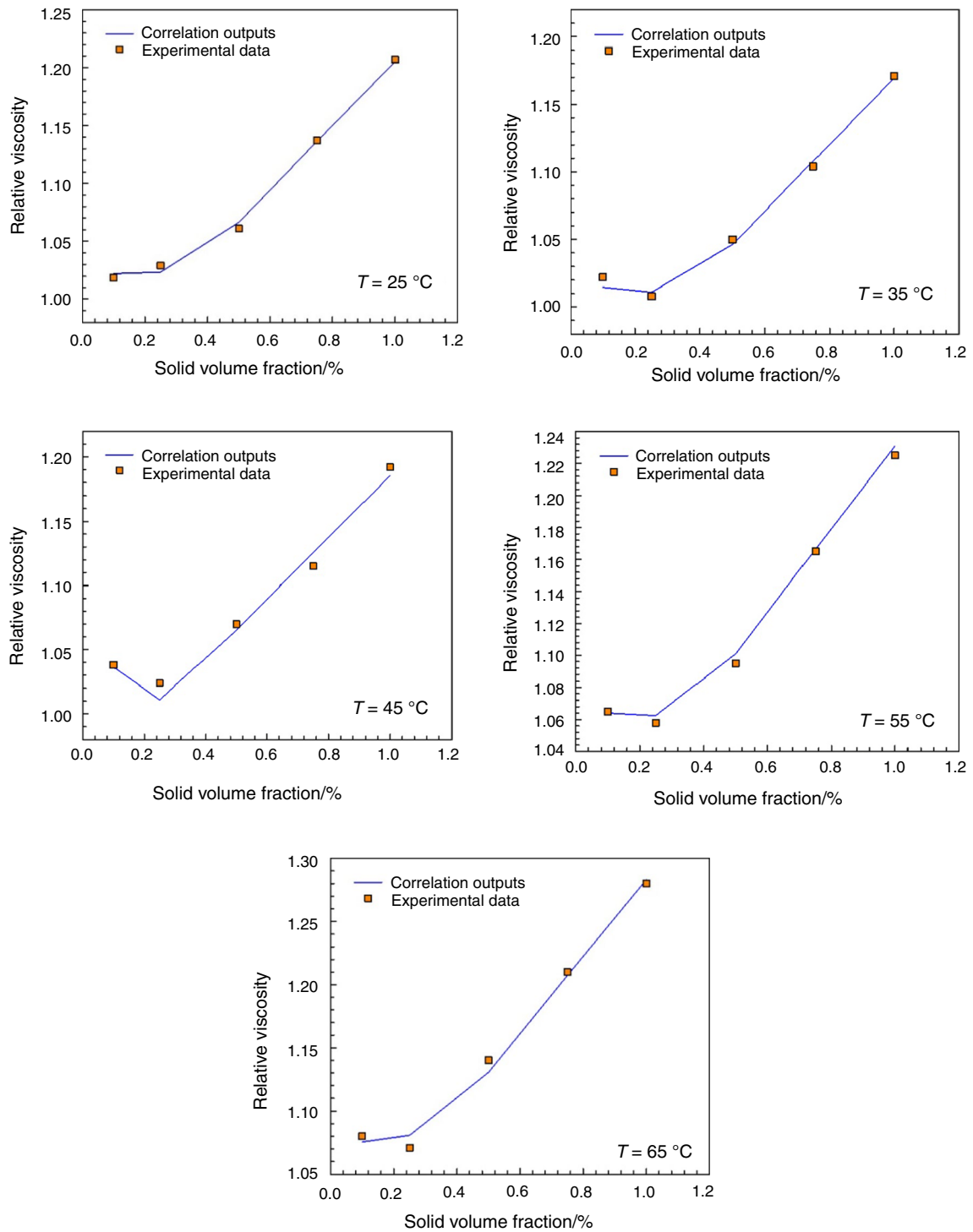


Fig. 13 Comparison between experimental data and correlation outputs

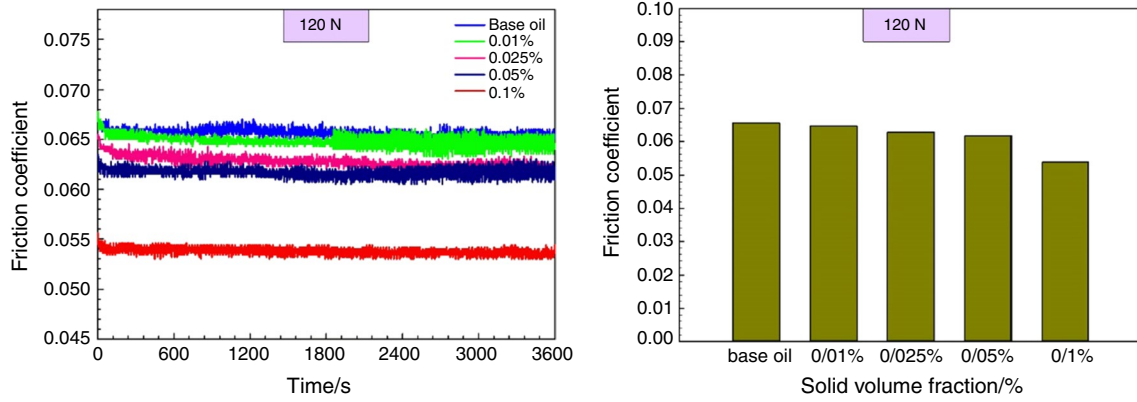


Fig. 14 Friction coefficient in different solid volume fractions at 120 N load

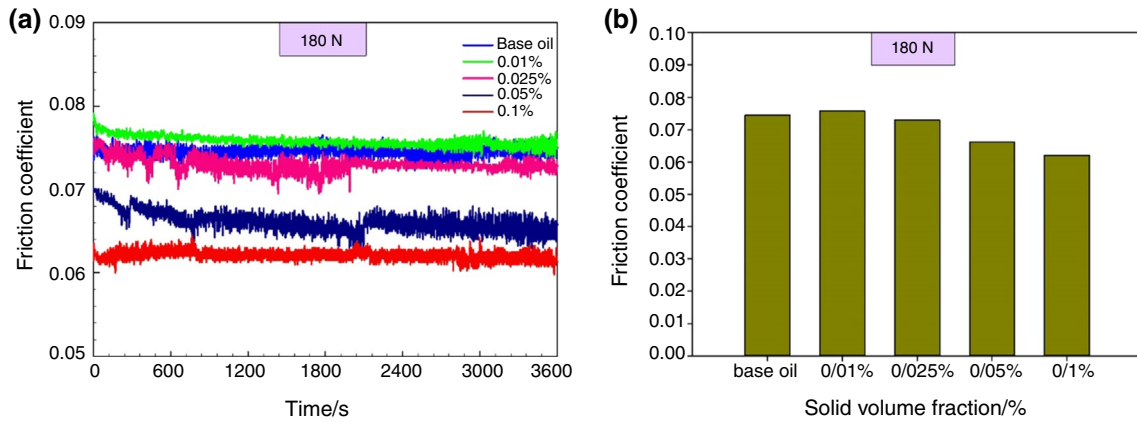


Fig. 15 Friction coefficient in different solid volume fractions at 180 N load

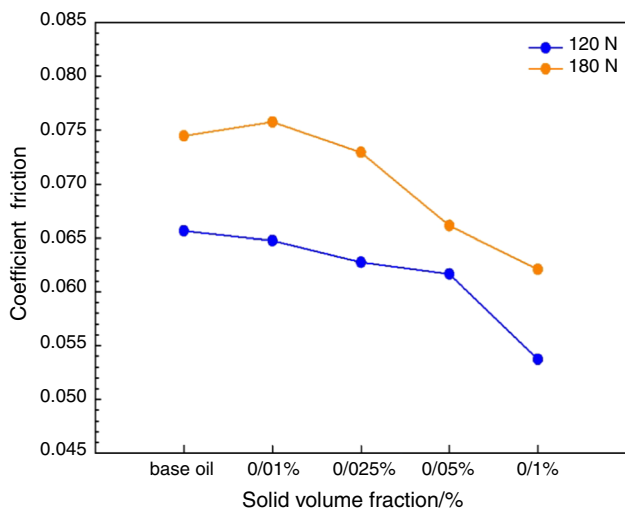


Fig. 16 Average friction coefficient versus different solid volume fractions

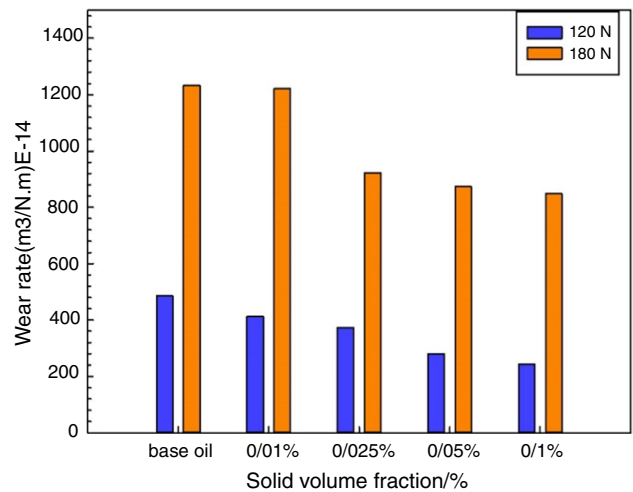
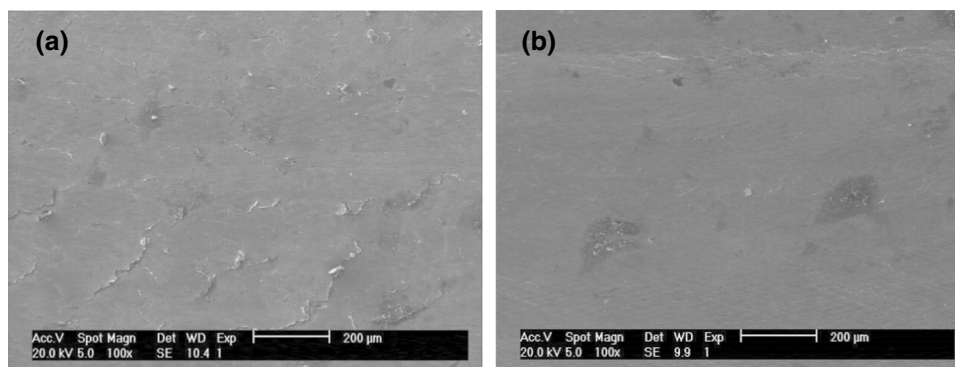
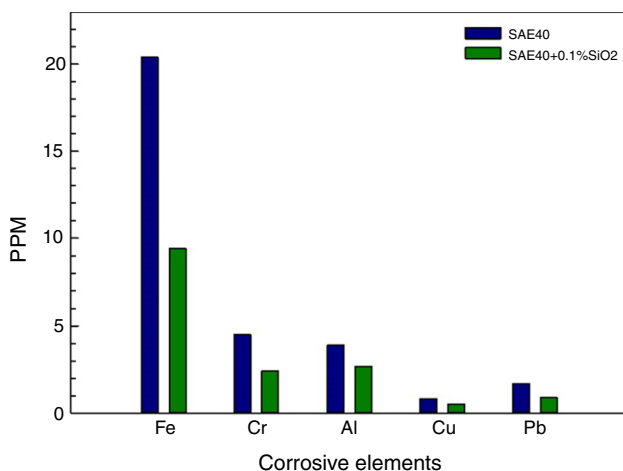
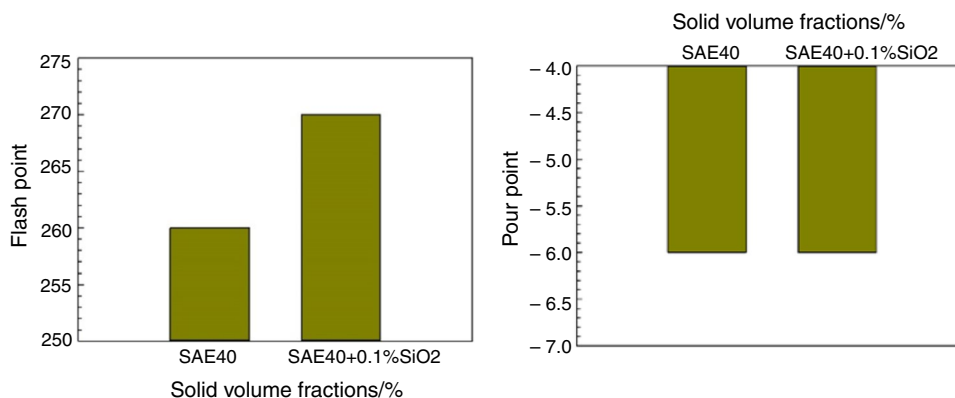


Fig. 17 Wear rate versus solid volume fraction

**Fig. 18** SEM images of abrasion path on the disks in the presence of **a**: base oil **b**: base oil + 0.1%SiO<sub>2</sub>



**Fig. 19** Flash point and pour point versus solid volume fraction



**Fig. 20** Abrasive particle analysis

## Conclusions

In this study, a comprehensive investigation and analysis of important factors of a nano-lubricant including viscosity, coefficient of friction, pour point, and flash point was carried out. The effects of temperature, shear rate, and solid volume

fraction on these parameters were studied. The main results of this experimental study are listed as follows:

- The viscosity has increased with increasing nanoparticle concentration and decreasing temperature. But, two exceptions were observed in nano-lubricant behavior; one in  $\phi = 0.25\%$  in all temperatures and the other in  $T = 35^\circ\text{C}$  in all solid volume fractions.
- Investigation on rheological behavior using the power-law method has shown that the value of the power-law index was less than unity for all samples, which shows pseudoplastic behavior for this nano-lubricant.
- Mean value of friction coefficient in different solid volume fractions and exerted loads indicates that the minimum friction coefficient was recorded in  $\phi = 0.1\%$ . Moreover, the addition of SiO<sub>2</sub> nanoparticles to the base oil in  $\phi = 0.1\%$  causes a 3.8% increase in flash point as compared with the base oil.
- Measuring the amounts of different elements in nano-lubricant and base oil showed that these amounts in nano-lubricant with  $\phi = 0.1\%$  were lower than the base oil. This implies that nano-lubricants can reduce wear between parts of piston and cylinder in internal combustion engines.

**Acknowledgements** Special thanks to the Science and Technology Park of Semnan University, which provided the conditions for this research.

## References

- Lee C-G, Hwang Y-J, Choi Y-M, Lee J-K, Choi C, Oh J-M. A study on the tribological characteristics of graphite nano lubricants. *Int J Precis Eng Manuf.* 2009;10(1):85–90.
- Sarafraz M, Arya A, Nikkiah V, Hormozi F. Thermal performance and viscosity of biologically produced silver/coconut oil nanofluids. *Chem Biochem Eng Q.* 2016;30(4):489–500.
- Salari E, Peyghambarzadeh M, Sarafraz M, Hormozi F. Boiling heat transfer of alumina nano-fluids: role of nanoparticle deposition on the boiling heat transfer coefficient. 2016.
- Izadi M, Mohebbi R, Sajjadi H, Amiri Delouei A. LTNE modeling of Magneto-Ferro natural convection inside a porous enclosure exposed to nonuniform magnetic field. *Phys A: Stat Mecha Appl.* 2019;535:122394.
- Yuan M, Mohebbi R, Rashidi MM, Yang Zh. MHD forced convection of MWCNT–Fe 3 O 4/water hybrid nanofluid in a partially heated  $\tau$ -shaped channel using LBM. *J Therm Anal Calorim.* 2019;136(4):1723–35.
- Delouei AA, Sajjadi H, Mohebbi R, Izadi M. Experimental study on inlet turbulent flow under ultrasonic vibration: Pressure drop and heat transfer enhancement. *Ultrason Sonochem.* 2019;51:151–9.
- Hemmat-Esfe M, Esfandeh S. Investigation of rheological behavior of hybrid oil based nanolubricant-coolant applied in car engines and cooling equipments. *Applied Thermal Engineering.* 2017.
- Alirezaie A, Saedodin S, Hemmat-Esfe M, Rostamian SH. Investigation of rheological behavior of MWCNT (COOH-functionalized)/MgO-Engine oil hybrid nanofluids and modelling the results with artificial neural networks. *J Mol Liq.* 2017;241:173–81.
- Hemmat-Esfe M, Zabihi F, Rostamian H, Esfandeh S. Experimental investigation and model development of the non-Newtonian behavior of CuO-MWCNT-10w40 hybrid nano-lubricant for lubrication purposes. *J Mol Liq.* 2018;249:677–87.
- Hemmat-Esfe M, Tatar A, Ahangar MRH, Rostamian H. A comparison of performance of several artificial intelligence methods for predicting the dynamic viscosity of TiO<sub>2</sub>/SAE 50 nano-lubricant. *Phys E.* 2018;96:85–93.
- Izadi F, Ranjbarzadeh R, Kalbasi R, Afrand M. A new experimental correlation for non-Newtonian behavior of COOH-DWCNTs/antifreeze nanofluid. *Phys E.* 2018;98:83–9.
- Kharabati, S., Saedodin S., and Rostamian S. H. 2021 "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.* 1–15.
- Aghaei A, Khorasanizadeh H, Sheikhzadeh GA. Measurement of the dynamic viscosity of hybrid engine oil-Cuo-MWCNT nanofluid, development of a practical viscosity correlation and utilizing the artificial neural network. *Heat Mass Transf.* 2018;54(1):151–61.
- Saedodin S, Kashefi MH, Bahrami Z. Experimental study on the rheological behavior of nanolubricant-containing MCM-41 nanoparticles with viscosity measurement. *J Therm Anal Calorim.* 2019;137(5):1499–511.
- Sanukrishna S, Prakash MJ. Experimental studies on thermal and rheological behaviour of TiO<sub>2</sub>-PAG nanolubricant for refrigeration system. *Int J Refrig.* 2018;86:356–72.
- Rostamian S.H, Saedodin S, Asghari SA, Salarian AH. 2020 Effect of C60-SiO<sub>2</sub> hybrid nanoparticles on thermophysical and tribological properties of a multigrade engine oil: an experimental study. *Journal of Thermal Analysis and Calorimetry,* 1–13.
- Parvar, M., Saedodin S, Rostamian SH. Experimental study on the thermal conductivity and viscosity of transformer oil-based nanofluid containing ZnO nanoparticles. *Journal of Heat and Mass Transfer Research,* 2020.
- Mohebbi R, Amiri Delouei A, Jamali A, Izadi M, Mohamad AA. Pore-scale simulation of non-Newtonian power-law fluid flow and forced convection in partially porous media: thermal lattice Boltzmann method. *Phys A.* 2019;525:642–56.
- Krishnakumar T, Viswanath S, Varghese SM. Experimental studies on thermal and rheological properties of Al<sub>2</sub>O<sub>3</sub>-ethylene glycol nanofluid. *Int J Refrig.* 2018;89:122–30.
- Hemmat-Esfe M, Arani AAA, Madadi MR, Alirezaie A. A study on rheological characteristics of hybrid nano-lubricants containing MWCNT-TiO<sub>2</sub> nanoparticles. *J Mol Liq.* 2018;260:229–36.
- Sepyani K, Afrand M, Hemmat-Esfe M. An experimental evaluation of the effect of ZnO nanoparticles on the rheological behavior of engine oil. *J Mol Liq.* 2017;236:198–204.
- Nadooshan AA, Hemmat-Esfe M, Afrand M. Prediction of rheological behavior of SiO<sub>2</sub>-MWCNTs/10W40 hybrid nanolubricant by designing neural network. *J Therm Anal Calorim.* 2018;131(3):2741–8.
- Soltani O, Akbari M. Effects of temperature and particles concentration on the dynamic viscosity of MgO-MWCNT/ethylene glycol hybrid nanofluid: experimental study. *Phys E.* 2016;84:564–70.
- Hemmat-Esfe M, Afrand M, Gharekhani S, Rostamian H, Toghraie D, Dahari M. An experimental study on viscosity of alumina-engine oil: effects of temperature and nanoparticles concentration. *Int Commun Heat Mass Transfer.* 2016;76:202–8.
- Vakili-Nezhaad G, Dorany A. Investigation of the effect of multiwalled carbon nanotubes on the viscosity index of lube oil cuts. *Chem Eng Commun.* 2009;196(9):997–1007.
- Afrand M, Najafabadi KN, Sina N, Safaei MR, Kherbeet AS, Wongwises S, et al. Prediction of dynamic viscosity of a hybrid nano-lubricant by an optimal artificial neural network. *Int Commun Heat Mass Transfer.* 2016;76:209–14.
- Chen L, Xie H, Yu W, Li Y. Rheological behaviors of nanofluids containing multi-walled carbon nanotube. *J Dispersion Sci Technol.* 2011;32(4):550–4.
- Hemmat-Esfe M, Afrand M, Rostamian SH, Toghraie D. Examination of rheological behavior of MWCNTs/ZnO-*SAE40* hybrid nano-lubricants under various temperatures and solid volume fractions. *Exp Thermal Fluid Sci.* 2017;80:384–90.
- Shababi K, Firouzi M, Fakhar A 2018 An experimental study on rheological behavior of *SAE50* engine oil. *Journal of Thermal Analysis and Calorimetry* 1–10.
- Asadi A, Asadi M, Rezaei M, Siahmargoi M, Asadi F. The effect of temperature and solid concentration on dynamic viscosity of MWCNT/MgO (20–80)-*SAE50* hybrid nano-lubricant and proposing a new correlation: an experimental study. *Int Commun Heat Mass Transfer.* 2016;78:48–53.
- Asadi M, Asadi A. Dynamic viscosity of MWCNT/ZnO-engine oil hybrid nanofluid: an experimental investigation and new correlation in different temperatures and solid concentrations. *Int Commun Heat Mass Transfer.* 2016;76:41–5.
- Esfe MH, Bahraei M, Hajmohammad MH, Afrand M. Rheological characteristics of MgO/oil nanolubricants: Experimental study and neural network modeling. *Int Commun Heat Mass Transfer.* 2017;86:245–52.
- Dardan E, Afrand M, Isfahani AM. Effect of suspending hybrid nano-additives on rheological behavior of engine oil and pumping power. *Appl Therm Eng.* 2016;109:524–34.

34. Zhou LH, Wei XC, Ma ZJ, Mei B. Anti-friction performance of FeS nanoparticle synthesized by biological method. *Appl Surf Sci.* 2017;407:21–8.
35. Shahnazar S, Bagheri S, Hamid SBA. Enhancing lubricant properties by nanoparticle additives. *Int J Hydro Energy.* 2016;41(4):3153–70.
36. Wan Q, Jin Y, Sun P, Ding Y. Tribological behaviour of a lubricant oil containing boron nitride nanoparticles. *Procedia Eng.* 2015;102:1038–45.
37. Aldana PU, Dassenoy F, Vacher B, Le Mogne T, Thiebaut B. WS<sub>2</sub> nanoparticles anti-wear and friction reducing properties on rough surfaces in the presence of ZDDP additive. *Tribol Int.* 2016;102:213–21.
38. Sgroi M, Asti M, Gili F, Deorsola FA, Bensaid S, Fino D, et al. Engine bench and road testing of an engine oil containing MoS<sub>2</sub> particles as nano-additive for friction reduction. *Tribol Int.* 2017;105:317–25.
39. Wu H, Zhao J, Xia W, Cheng X, He A, Yun JH et al. 2017 A study of the tribological behaviour of TiO<sub>2</sub> nano-additive water-based lubricants. *Tribology International*
40. Rodrigues A, Österle W, Gradt T, Azevedo C. Impact of copper nanoparticles on tribofilm formation determined by pin-on-disc tests with powder supply: Addition of artificial third body consisting of Fe<sub>3</sub>O<sub>4</sub>. *Cu Graph Tribol Int.* 2017;110:103–12.
41. Ingole S, Charanpahari A, Kakade A, Umare S, Bhatt D, Menghani J. Tribological behavior of nano TiO<sub>2</sub> as an additive in base oil. *Wear.* 2013;301(1–2):776–85.
42. Mosleh M, Shirvani KA. In-situ nanopolishing by nanolubricants for enhanced elastohydrodynamic lubrication. *Wear.* 2013;301(1–2):137–43.
43. Demas NG, Erck RA, Lorenzo-Martin C, Ajayi OO, Fenske GR. Experimental evaluation of oxide nanoparticles as friction and wear improvement additives in motor oil. *Journal of Nanomaterials.* 2017
44. Viesca J, Battez AH, González R, Chou R, Cabello J. Antiwear properties of carbon-coated copper nanoparticles used as an additive to a polyalphaolefin. *Tribol Int.* 2011;44(7–8):829–33.
45. Chinas-Castillo F, Spikes H. Mechanism of action of colloidal solid dispersions. *J Tribol.* 2003;125(3):552–7.
46. Hu ZS, Lai R, Lou F, Wang L, Chen Z, Chen G, et al. Preparation and tribological properties of nanometer magnesium borate as lubricating oil additive. *Wear.* 2002;252(5–6):370–4.
47. Liu G, Li X, Qin B, Xing D, Guo Y, Fan R. Investigation of the mending effect and mechanism of copper nano-particles on a tribologically stressed surface. *Tribol Lett.* 2004;17(4):961–6.
48. Zhou J, Yang J, Zhang Z, Liu W, Xue Q. Study on the structure and tribological properties of surface-modified Cu nanoparticles. *Mater Res Bull.* 1999;34(9):1361–7.
49. Rastogi R, Yadav M, Bhattacharya A. Application of molybdenum complexes of 1-aryl-2, 5-dithiohydrazodicarbonamides as extreme pressure lubricant additives. *Wear.* 2002;252(9–10):686–92.
50. Ginzburg B, Shibaev L, Kireenko O, Shepelevskii A, Baidakova M, Sitnikova A. Antiwear effect of fullerene C 6 0 additives to lubricating oils. *Russ J Appl Chem.* 2002;75(8):1330–5.
51. Xiaodong Z, Xun F, Huaqiang S, Zhengshui H. Lubricating properties of Cyanex 302-modified MoS<sub>2</sub> microspheres in base oil 500SN. *Lubr Sci.* 2007;19(1):71–9.
52. Lee J, Cho S, Hwang Y, Lee C, Kim SH. Enhancement of lubrication properties of nano-oil by controlling the amount of fullerene nanoparticle additives. *Tribol Lett.* 2007;28(2):203–8.
53. Nasiri-Khuzani G, Asoodar M, Rahnama M, Sharifnasab H. 2012 Evaluation of engine parts wear using nano lubrication oil in agricultural tractors. *Global Journal of Science Frontier Research* 12(8-D).
54. Jatti VS, Singh T. 2015 Copper oxide nano-particles as friction-reduction and anti-wear additives in lubricating oil. *Journal of Mechanical Science and Technology*
55. Chen S, Liu W. Oleic acid capped PbS nanoparticles: synthesis, characterization and tribological properties. *Mater Chem Phys.* 2006;98(1):183–9.
56. Jiao D, Zheng S, Wang Y, Guan R, Cao B. The tribology properties of alumina/silica composite nanoparticles as lubricant additives. *Appl Surf Sci.* 2011;257(13):5720–5.
57. Koshy CP, Rajendrakumar PK, Thottackkad MV. Evaluation of the tribological and thermo-physical properties of coconut oil added with MoS<sub>2</sub> nanoparticles at elevated temperatures. *Wear.* 2015;330:288–308.
58. Ran X, Yu X, Zou Q. Effect of particle concentration on tribological properties of ZnO nanofluids. *Tribol Trans.* 2017;60(1):154–8.
59. Ahmadi H, Rashidi A, Nouralishahi A, Mohtasebi SS. Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant. *Int Commun Heat Mass Transfer.* 2013;46:142–7.
60. Ahmadi H, Rashidi A, Mohtasebi SS, Alaei M. Experimental evaluation of engine oil properties containing copper oxide nanoparticles as a nanoadditive. *Int J Ind Chem.* 2013;4(1):28.
61. Einstein A. Eine neue bestimmung der moleküldimensionen. *Ann Phys.* 1906;324(2):289–306.
62. Saitô N. Concentration dependence of the viscosity of high polymer solutions I. *J Phys Soc Japan.* 1950;5(1):4–8.
63. Brinkman H. The viscosity of concentrated suspensions and solutions. *J Chem Phys.* 1952;20(4):571–571.
64. Batchelor G. The effect of Brownian motion on the bulk stress in a suspension of spherical particles. *J Fluid Mech.* 1977;83(1):97–117.
65. Wang X-Q, Mujumdar AS. Heat transfer characteristics of nanofluids: a review. *Int J Therm Sci.* 2007;46(1):1–19.
66. Chen H, Ding Y, Tan C. Rheological behaviour of nanofluids. *New J Phys.* 2007;9(10):367.
67. Holman, J.P. *Experimental methods for engineers.* 2001.

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.