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Research Paper

Effect of suspending hybrid nano-additives on rheological behavior of engine oil and pumping power

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HIGHLIGHTS

- Preparing SAE40 based nanofluids containing Al_2O_3-MWCNTs hybrid nano-additives.
- Performing tests in concentration range of 0–1.0% and temperature range of 25–50 °C.
- All hybrid nanofluid samples were Newtonian fluid at all temperatures considered.
- Performing sensitivity analysis for viscosity using experimental findings.
- Proposing a new correlation to predict the viscosity of the hybrid nanofluid.

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ABSTRACT

In this paper, the rheological behavior of engine oil containing various quantities of hybrid nano-additives has been examined. The experiments were performed in the solid volume fraction range of 0–1.0% and temperatures ranging from 25 °C to 50 °C. Viscosity measurements, at the shear rate range of 1333–13,333 s^{-1}, showed that Al_2O_3-MWCNTs/SAE40 hybrid nanofluid had a Newtonian behavior at all solid volume fractions and temperatures considered. Experimental results also indicated that the viscosity of the hybrid nanofluid increased with increasing nano-additives concentration and decreasing temperature. Results of relative viscosity of the hybrid nanofluid showed that the maximum augmentation of the viscosity was about 46%. Results from sensitivity analysis of viscosity revealed that the viscosity sensitivity to temperature variation is minor, while it is more sensitive to the variations of solid volume fraction. Furthermore, an accurate correlation was proposed to predict the viscosity of the hybrid nanofluids for application in thermal engineering. Finally, the effects of nano-additives on the pumping power for the oil flow have been reported.

1. Introduction

Engine oil is a type of lubricant employed in many engineering applications such as engine generators, power cars, bearings and machines including moving parts. In mechanical systems, the friction between the moving parts diminishes the efficiency by altering the kinetic energy to heat. The chief duty of oils is to reduce friction between parts which move contrary to each other. In addition, the engine oil can cool the parts that are heated due to friction.

The thermal conductivity and viscosity of engine oil are two important properties in cooling and lubricating of mechanical systems, respectively. The viscosity also affects the pumping power and oil flow. It is clear that engine oils with enhanced thermal conductivity can improve the heat transfer rate. One of the methods to improve the thermal conductivity is dispersing nano-additives in liquids, called nanofluids [1]. Many researchers reported that suspending the nano-additives to base fluid significantly enhances the thermal conductivity [2–12]. They revealed that the amount of the enhancement depends on various parameters including temperature and concentration.

However, when the nano-additives are suspended in a base fluid to improve its thermal conductivity, the viscosity is also affected. Many analytical and experimental studies on rheological behavior of fluids containing nano-additives have been performed. For example, Batchelor [13], Drew and Passman [14] and Wang et al. [15] suggested analytical models for estimating the viscosity of nanofluids. Moreover, a summary of experimental studies on the viscosity of nanofluids is presented in Table 1. These works have

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Nomenclature

d	tube diameter (m)
f	Fanning friction factor
h	vertical position (m)
K	pressure loss coefficient
m	mass (kg)
P	power (J/s)
T	temperature (°C)
Q	volumetric flow rate (m^3/s)
V	velocity (m/s)

Greek letters

Δp	pressure drop (pa)
φ	solid volume fraction (%)
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)

Subscripts

bf	base fluid
Exp	experimental data
nf	nanofluid
Pred	predicted value
s	solid particles
MWCNTs	multi walled carbon nanotubes
Al_2O_3	alumina
SAE40	engine oil

Table 1
A summary of experimental studies on the viscosity of nanofluids.

Authors	Additives	Base fluid	Temperature (°C)	Concentration (%)
Duangthongsuk and Wongwises [16]	TiO_2	Water	15–35	0.2–2 vol
Sahoo et al. [17]	Al_2O_3	EG-water	(−35)–50	1–10 vol
Kole and Dey [18]	Al_2O_3	Water	10–50	0.1–1.5 vol
Kole and Dey [19]	CuO	Gear oil	10–80	0.5–2.5 vol
Bobbo et al. [20]	SWCNT-TiO_2	Water	10–80	0.01–1 wt
Sundar et al. [21]	Fe_3O_4	EG-water	0–50	0–1 vol
Vakili-Nezhaad and Dorany [22]	SWCNT	Lubricant	25–100	0.01–0.2 wt
Vajjha and Das [23]	Al_2O_3 CuO SiO_2	EG-water	20–90	10 vol 6 vol 10 vol
Yiamsawas et al. [24]	Al_2O_3 TiO_2	EG-water	15–40	0–4 vol
Esfe et al. [25]	MgO	Water	24–60	<1 vol
Esfe and Saedodin [26]	ZnO	EG	25–50	0.25–5 vol
Esfe et al. [27]	MWCNT	Water	25–55	0.05–1 vol
Esfe et al. [28]	DWCNT	Water	27–67	0.01–0.4 vol
Baratpour et al. [29]	SWCNT	EG	30–60	0.0125–0.1 vol
Toghraie et al. [30]	Fe_3O_4	Water	20–55	0.1–3 vol

indicated that the viscosity of nanofluids depends on temperature, size and concentration of nanoparticles.

As mentioned above, improving thermo-physical properties of engine oils is very important for engineering applications. Accordingly, the study of rheological behavior of engine oil has attracted researcher's interest. In this regard, Vakili-Nezhaad and Dorany [31] investigated the influence of temperature and multi-walled carbon nanotube (MWCNT) concentration on the viscosity index of oil theoretically and experimentally. Their experiments were performed under temperatures ranging from ambient to 100 °C and for MWCNT concentrations ranging from 0.01 to 0.2 wt%. They reported that the viscosity increased with an increase in the MWCNT concentration and reducing temperature. Vasheghani et al. [32] added Al_2O_3 nanoparticles to the engine oil and reported that the its viscosity increased about 38%. They also indicated that the nanofluids (up to 3 wt% of the nanomaterial) exhibited a Newtonian behavior. Ettefaghi et al. [33] added different carbon nanostructures to SAE 20W50 engine oil. They evaluated and compare effects of different carbon nanostructures on thermal and rheological properties of engine oil. Their results revealed that the viscosity of oil depended on the type of additive structures. Recently, Cieśliński et al. [34] measured the dynamic viscosity of thermal oil-MWCNT nanofluid. They tested samples with the concentration of 0.001%, 0.005%, 0.01%, 0.05%, and 0.1% by weight. They compared the results with existing models for liquid/solid particles mixtures.

In the continuation of nanofluids research, the researchers have also made effort to use hybrid nanofluid recently, which is prepared by dispersing unlike nano-sized materials either in mixture or composite form. For example, Baghbanzadeh et al. [35] examined the effects of SiO_2-MWCNTs hybrid nano-additives on the thermal conductivity of distilled water. They reported that the maximum and the minimum enhancement of the fluids were related with MWCNTs and SiO_2 nanoparticles, while the enhancement for the hybrid nano-additives was an amount between MWCNTs and SiO_2 nanoparticles. Esfe et al. [36] experimentally investigated the thermal conductivity of hybrid nanofluids by dispersing Cu and TiO_2 nanoparticles in a binary mixture of water/EG (60:40). They measured the thermal conductivity of nanofluid samples in various temperatures ranging from 30 to 60 °C. Their results showed that a maximum enhancement in the thermal conductivity of the nanofluid (45%) was occurred for the sample with solid volume fraction of 2% at temperature of 60 °C. An experimental investigation on the effects of ZnO–TiO_2 hybrid nano-additives on the thermal conductivity ethylene glycol was presented by Toghraie et al. [37]. Their experiments were performed at temperatures ranging from 25 to 50 °C and solid volume fraction range of 0–3.5%. Their results showed that the thermal conductivity of the hybrid nanofluid enhanced up to 35% at solid volume fraction of 3.5%. Esfe et al. [38] also investigated the effects of CNTs–Al_2O_3 hybrid nano-additives on the thermal conductivity of water at various fluid temperatures of at temperatures ranging from 30 to 60 °C. They reported that the thermal conductivity of the hybrid nanofluid enhanced up to 18% at solid volume fraction of 1%.

However, only a few works have been done on viscosity of hybrid nanofluids. In this way, the viscosity of SiO_2-MWCNTs/water nanofluid was investigated by Baghbanzadeh et al. [39]. Their measurements showed that the viscosity of the nanofluid increased with increasing concentration and reducing the temperature. Afrand et al. [40] examined the effects of temperature and nanoparticles concentration on the rheological behavior of Fe_3O_4-Ag/EG hybrid nanofluid. They measured the viscosity of the nanofluid samples at different shear rates in temperature range of 25–50 °C. Their results indicated that the nanofluid samples with solid volume fractions of less than 0.3% showed Newtonian behavior, while the samples with higher solid volume fractions (0.6% and 1.2%) exhibited non-Newtonian behavior. The rheological behavior of MWCNTs-SiO_2/EG-water hybrid nanofluid in concentration range of 0–2% at temperatures ranging from 27.5 °C to 50 °C was examined by Eshgarf and Afrand [41]. They repeated viscosity measurements at various shear rates for each nanofluid samples. Their results revealed that the base fluid exhibits Newtonian behavior and the nano-coolant samples exhibit a pseudoplastic rheological behavior. Recently, Afrand et al. [42] presented an experimental study on the dynamic viscosity of SiO_2-MWCNTs/engine oil hybrid nano-lubricant. They showed that the hybrid nano-lubricant had a Newtonian behavior. Their results also revealed that the dynamic viscosity enhanced with an increase in the concentration and reduced with enhancing temperature.

Some researchers also have investigated the wear effect of nano-additives on the engine parts. For example, Nasiri-Khuzani et al. [43] reported that the use of oil containing nano-additives in agricultural tractor engines would diminish wear in cylinder, shaft, gaskets, and valve mechanisms and gear camshaft by 68%. Zin et al. [44] illustrated the preparation of stable suspensions of single-walled carbon nano-horns (SWCNHs) in engine oil and shows their tribological behavior at different temperatures. They carried out wear tests and observed a reduction in mean wear rate at each temperature, between 25% and 30%. Therefore, it can be found that nano-sized materials revealed the potential to be promising candidates as additives, to develop a new class of lubricants that are suitable and effective in thermal engineering applications.

Regarding the importance of rheological behavior of engine oils, in this work, the rheological behavior of engine oil (SAE40) containing hybrid nano-additives composed of alumina (Al_2O_3) and multi-walled carbon nanotubes (MWCNTs) is examined for the first time. The effects of temperature and concentration of hybrid nano-additives on the viscosity of nanofluids are examined by a Viscometer. The measured viscosities of nanofluids also are compared with those obtained from the existing studies. Finally, to indicate that how much the viscosity is sensitive to the changes of concentration of hybrid nano-additives and temperature, a sensitivity analysis is performed.

2. Experimental procedure

2.1. Samples preparation

Stable and homogeneous samples with the solid volume fractions of 0.0625%, 0.125%, 0.25%, 0.5% and 0.75% and 1% were prepared by suspending 75 vol% alumina nanoparticles and 25 vol% MWCNTs in SAE40 engine oil. It should be noted that, at higher solid volume fraction than 1%, clustering phenomenon was observed, which leaded to deposition and sedimentation of nanoparticles and nanofluids was unsuspended. Properties of alumina nanoparticles, MWCNTs and SAE40 engine oil are presented in Tables 2 and 3.

Table 2
Characteristics of MWCNTs and Al_2O_3 nanoparticles.

Characteristic	Value	
	MWCNTs	Al_2O_3
Purity	>97%	>99%
Color	Black	White
Size	Outer diameter: 5–15 (nm) Inner diameter: 3–5 (nm) Length: 50 (μm)	20 (nm)
True density	~2.1 (g/cm^3)	3.89 (g/cm^3)
Specific surface area (SSA)	233 (m^2/g)	>138 (m^2/g)

Table 3
Characteristics of engine oil (SAE40).

Characteristic	Value
Kinematic viscosity @ 100 °C	0.155 (m^2/s)
Viscosity Index (VI)	85 (High)
Flash point	235 (°C)
Pour point	−12 (°C)
Total base number (TBN)	4 (mg KOH/g)
Density @ 15 °C	0.895 (g/cm^3)

The quantities of MWCNTs and Al_2O_3 nanoparticles needed for various solid volume fractions were gained from the following equation,

$$\varphi = \left[\frac{\left(\frac{m}{\rho}\right)_{MWCNTs} + \left(\frac{m}{\rho}\right)_{Al_2O_3}}{\left(\frac{m}{\rho}\right)_{MWCNTs} + \left(\frac{m}{\rho}\right)_{Al_2O_3} + \left(\frac{m}{\rho}\right)_{SAE40}} \right] \times 100 \tag{1}$$

where φ is the solid volume fraction in%, ρ is the density in kg/m^3 and m is the mass in kg. The masses of nano-additives used for the preparing a volume of 200 ml of each nanofluid samples were determined and presented in Table 4.

In this work, in order to produce stable samples, first by magnetic stirrer devices, nano-additives and engine oil were mixed for two hours. Then, to prevent agglomeration of nano-additives, the samples obtained in the previous step were exposed to magnetic waves by ultrasonic processor (manufactured by Hielscher Company with a power of 400 W and a frequency of 24 kHz) for five to six hours. According to past experiences, after making nano-fluid at different volume fractions, each sample was monitored for three days visually. During this period, deposition, settling and agglomeration were not observed. The photographs of Al_2O_3 nanoparticles, MWCNTs, SAE40 and hybrid nanofluid samples are displayed in Fig. 1.

2.2. Viscosity measurement

The CAP 2000+ Viscometer, supplied by Brookfield engineering laboratories of the USA, was used to measure the viscosities of nanofluid samples under a temperature range of 25–50 °C. The Viscometer is medium to high shear rate instrument with Cone Plate geometry and integrated temperature control of the test sample material (Fig. 2). Measurements were carried out at the shear rate range of 1333–13,333 s^{-1}. The range of accuracy and repeatability of the Viscometer are respectively ±2.0% and ±0.5% of the full scale range (FSR). According to CAP 2000+ Viscometer manual [45], ±1% of measured viscosity should be added to accuracy of the Viscometer. CAP-01 spindle on High Torque has been used to perform the present experiments, which was calibrated with viscosity standard fluid (Fluid Part Number: CAP1L) at 25 °C before the measurements.

Based on the measurements, “relative viscosity” is defined as the ratio of the viscosity of hybrid nanofluids to viscosity of the oil (SAE40).

Table 4
Masses of nano-additives used for the preparing a volume of 200 ml of nanofluid.

Solid volume fraction (%)	Mass [±0.001] (g)	
	MWCNTs	Al_2O_3
0.0625	0.066	0.365
0.125	0.131	0.729
0.25	0.263	1.459
0.5	0.525	2.917
0.75	0.788	4.376
1	1.050	5.835

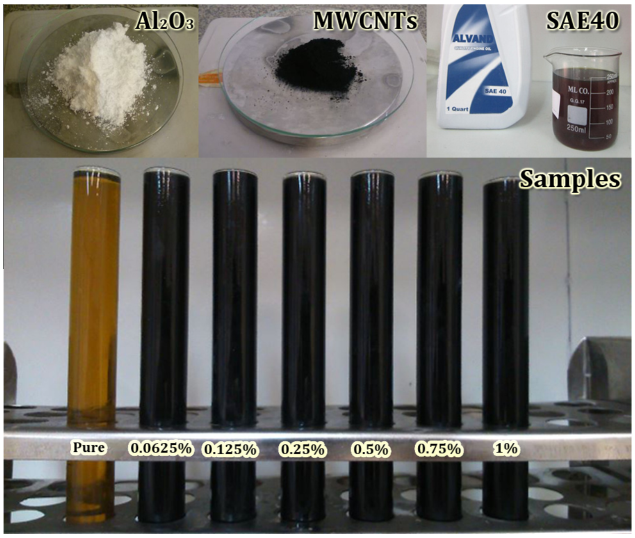

Fig. 1. Photographs of Al_2O_3 nanoparticles, MWCNTs, SAE40 and hybrid nanofluid samples.

Fig. 2. Brookfield CAP 2000+ Viscometer.

3. Results and discussion

3.1. Rheological evaluation

The viscosity affects the Prandtl and Reynolds numbers. Hence, the rheological behavior of nanofluids is very important for the pumping power, heat and mass transfer. In order to evaluate the rheological behavior of Al_2O_3-MWCNTs/SAE40 hybrid nanofluids, the viscosities of the pure SAE40 and nanofluid samples with solid volume fractions of 0.0625%, 0.125%, 0.25%, 0.5%, 0.75% and 1% were measured. Experiments were performed at temperatures ranging from 25 °C to 50 °C and the shear rate range of 1333–13,333 s^{-1}.

The viscosity of SAE40 versus shear rate at various temperatures is depicted in Fig. 3. As can be seen, the viscosity of SAE40 is almost constant with shear rate changes, which means that it is independent of the shear rate. Therefore, SAE40 has Newtonian behavior at all temperatures considered.

Fig. 4 shows the viscosity of all nanofluid samples versus shear rate at various temperatures. It can be observed that, at all temperatures and solid volume fractions, the viscosity is almost constant with shear rate changes. It is found from this figure that there is a little decrease in viscosity with an increase in shear rate. This change is not so much that can be claimed the samples are non-Newtonian. This behavior may be due to shear heating considerations which occur in high shear rates. Thus, it can be argued that all samples behave as a Newtonian fluid at all temperatures considered.

3.2. Effects of temperature and solid volume fraction

Fig. 5 shows the viscosity of the hybrid nanofluid versus solid volume fraction at different temperatures. It can be seen that the viscosity of the hybrid nanofluid augments with increasing nano-additives concentration. The viscosity effect is to withstand the relative movement of the liquid. In fact, it plays a main role in the momentum transfer between the layers of liquid, which acts long as there are movements between the layers. This phenomenon is because of the van der Waals forces between the molecules. Therefore, the dispersion of nano-additives in SAE40 would increase its viscosity as a result of the interactions between them. By increasing the amount of nano-additives in a specific amount of SAE40, larger nano-clusters arise due to the van der Waals forces between them, which can prevent the movement of oil layers on each other. It may lead to higher augmentation in viscosity.

The viscosity of the hybrid nanofluid samples versus temperature is illustrated in Fig. 6. It is obvious from Fig. 6 that the viscosity of the hybrid nanofluid diminishes with an increase in temperature. This is due to the fact that, with enhancing temperature, the intermolecular interactions between the molecules become feeble and consequently the viscosity diminishes.

Fig. 7 shows the relative viscosity of the hybrid nanofluid as a function of solid volume fraction and temperature. As seen in this figure, relative viscosities have slight changes with the tempera-

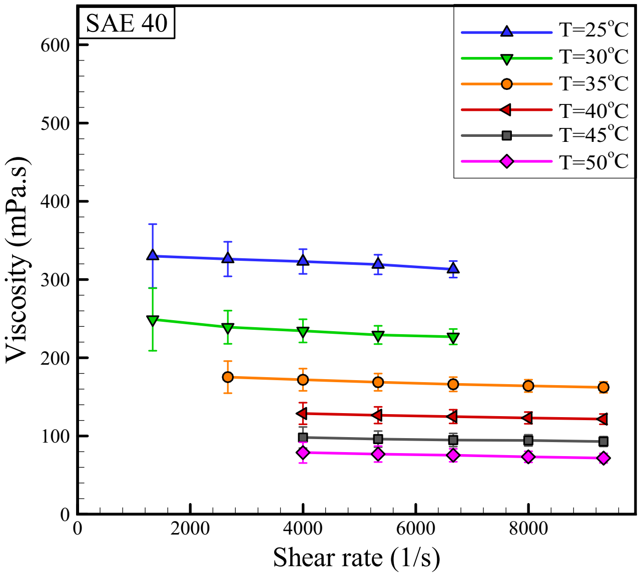

Fig. 3. Viscosity of SAE40 versus shear rate at various temperatures.

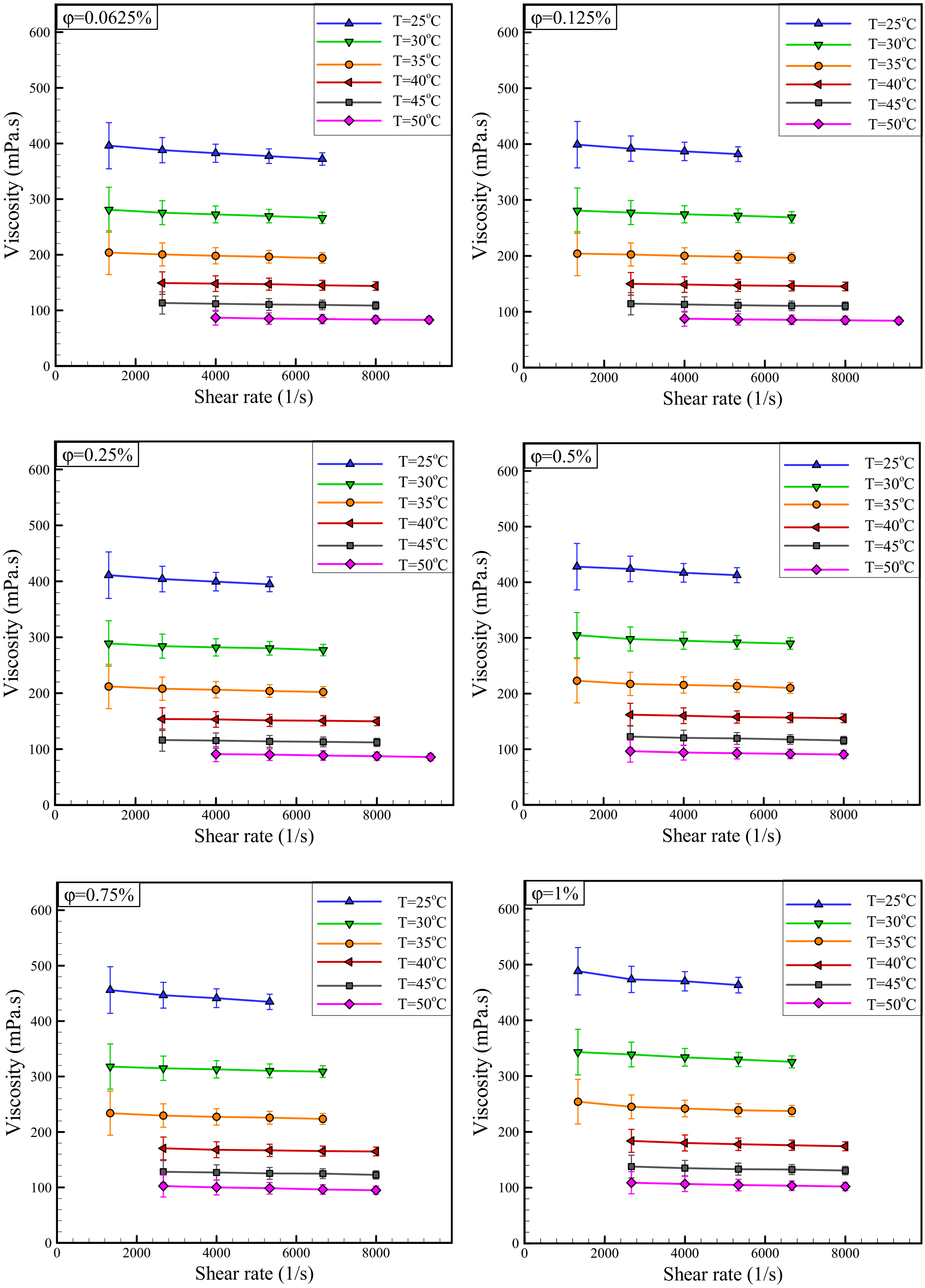

Fig. 4. Viscosity of all nanofluid samples versus shear rate at various temperatures.

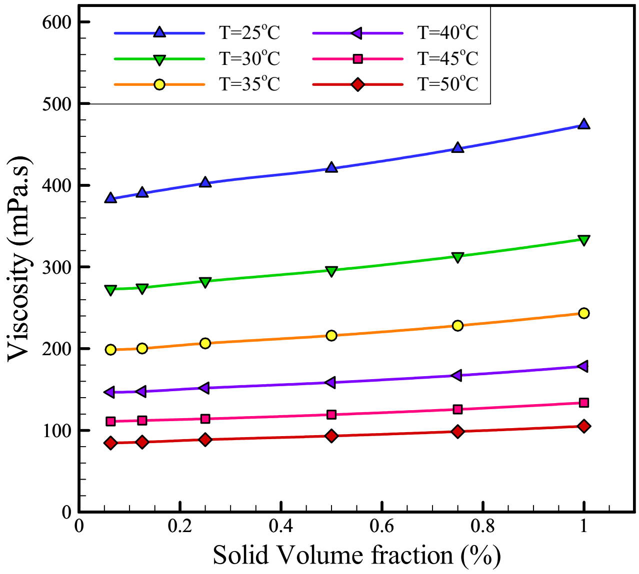

Fig. 5. Viscosity of the hybrid nanofluid versus solid volume fraction at different temperatures.

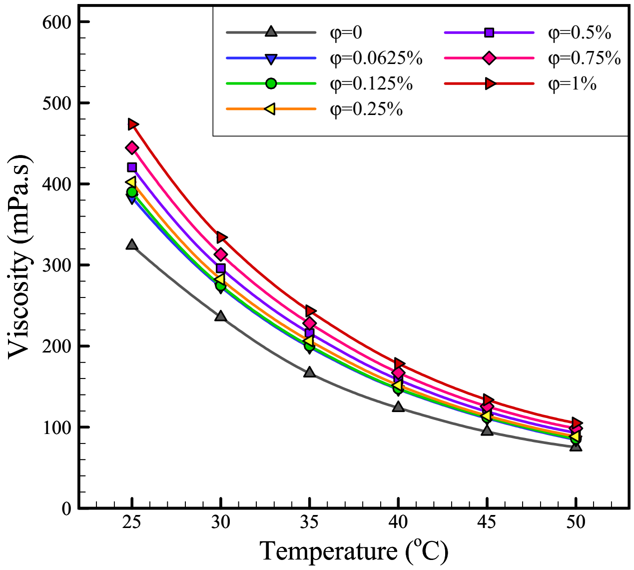

Fig. 6. Viscosity of the hybrid nanofluid samples versus temperature.

ture variation. The maximum deviations of relative viscosity between temperatures of 25 °C and 50 °C are 7% for all hybrid nanofluid samples. However, the deviation in relative viscosity between solid volume fractions of 0.0625% and 1% is approximately 28% for all temperatures considered. Calculations for the relative viscosity of the hybrid nanofluid show that the maximum augmentation of the viscosity is about 46%. Moreover, as seen in Fig. 7, there is a dip at 30 °C. In fact, with increasing temperature from 25 °C to 30 °C, the movement of nano-additives enhances; consequently, nanotubes would be arranged along the flow direction, and this provides to a lower viscosity. By increasing the temperature from 30 °C to 35 °C, the relative viscosity is increased. The reason may be related to this fact that nanotubes would be arranged perpendicular to the flow direction, and this provides to a higher viscosity.

3.3. Comparison between experimental findings and previous data

Fig. 8 shows a comparison of the relative viscosity with respect to solid volume fraction for experimental findings and predicted values from Batchelor [13] and Wang et al. [15] models. As shown in Fig. 3, both existing models are unable to predict the viscosity of Al_2O_3-MWCNTs/SAE40 hybrid nanofluids correctly. However, the present relative viscosity of the hybrid nanofluid is much higher than those predicted by both existing models. This significant difference shows the fact that adding the compound of alumina nanoparticles and multi-walled carbon nanotubes unexpectedly increases the viscosity. The reason may be related to the large surface area per unit volume of nanotubes, which causes interface to rise, and in turn, lead to an increase in nanofluid viscosity compared to the values predicted by the existing models.

In order to provide general insights about effect of type of additive structure on viscosity in the current study, a comparison between the relative viscosity of Al_2O_3-MWCNTs/SAE40 and that of different nanofluids (SiO_2/SAE40, MWCNTs/SAE40 and SiO_2-MWCNTs/SAE40) at temperatures of 25 °C and 50 °C is shown in Fig. 9. It can be established that the relative viscosity of MWCNTs/SAE40 is meaningfully greater than that of the other nanofluids. In fact, cylindrical shape and large length of MWCNTs reduces the capability of their movement between the oil layers. In the case of SiO_2/SAE40 nanofluid, the spherical shape of silica nanoparticles would raise viscosity of the oil marginally as a result of their easier movement between oil layers [42]. As can be observed in this figure, the relative viscosity of hybrid nanofluids (Al_2O_3-MWCNTs/SAE40 and SiO_2-MWCNTs/SAE40) is between those values for both mono nanofluids (SiO_2/SAE40 and MWCNTs/SAE40) at temperatures of 25 °C and 50 °C. The cause may be associated to the fact that MWCNTs have been tightly surrounded by oxide nanoparticles in the cases of hybrid nanofluids. This phenomenon avoids the formation of larger nano-clusters of MWCNTs and subsequently a sharp increase in viscosity. TEM and SEM images of the hybrid nano-additives presented by Baghbanzadeh et al. [39] also confirmed the presence of spherical nanoparticles in between the MWCNTs.

It can be found from Fig. 9 that the general behavior of all nanofluids is similar. However, the relative viscosity of Al_2O_3-MWCNTs/SAE40 is significantly more than that of SiO_2-MWCNTs/SAE40. This comparison can be important with the knowledge that the lower viscosity causes easier oil pumping and draining back to the crankcase, while higher viscosity causes an increase in bearing load capability [42]. Consequently, Al_2O_3-MWCNTs/SAE40 can support a higher load at the bearing compared with SiO_2-MWCNTs/SAE40 and this leads to an increase in mechanical systems durability.

Previous studies conducted by Ettefaghi et al. [33,46] have shown that adding nanoparticles to the oil leads to dramatically improve its thermal properties. Moreover, CNTs have a high thermal conductivity, low specific gravity, and high aspect ratio as compared to metal oxide nanoparticles. However, as observed in Fig. 9, CNTs dramatically increase the viscosity of oil as well as needed pumping power. On the other hand, despite low thermal conductivity of oxide nanoparticles (e.g., SiO_2 and Al_2O_3) compared to CNTs, they can be easily dispersed in oil. Therefore, the simultaneous use of Al_2O_3 and CNTs nano-additives can lead to stable compounds with special thermal properties and a reasonable increase in viscosity.

3.4. Sensitivity analysis

In order to show that how much the viscosity of hybrid nanofluid is sensitive to the variation of volume fraction of nano-additives and temperature, a sensitivity analysis has been applied.

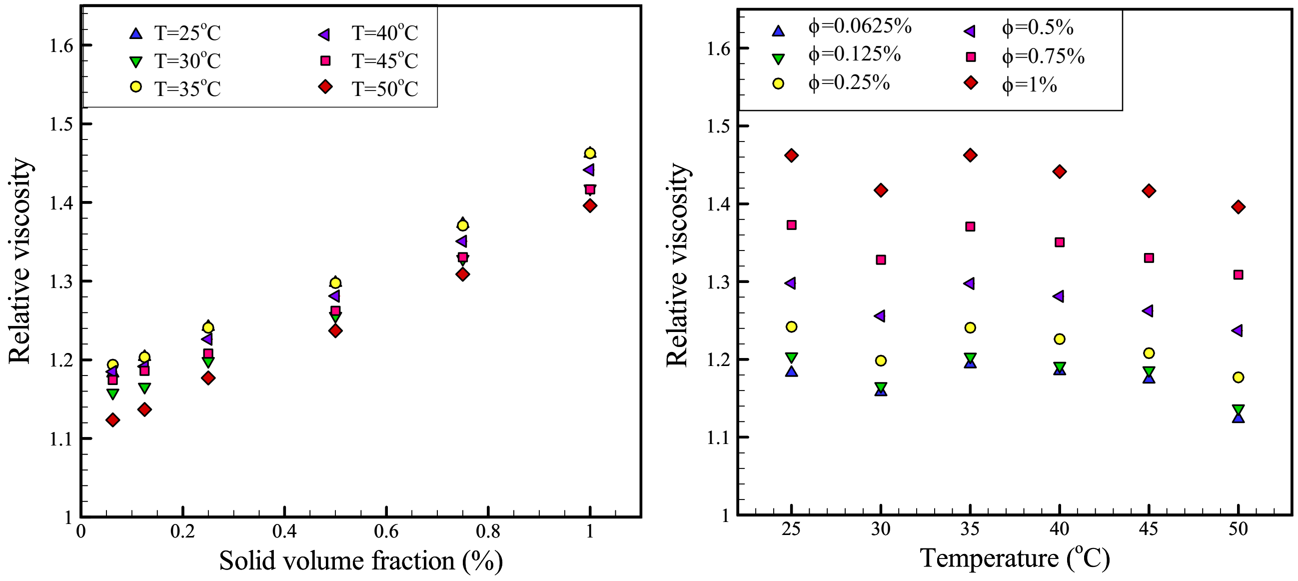

Fig. 7. Relative viscosity of the hybrid nanofluid as a function of solid volume fraction and temperature.

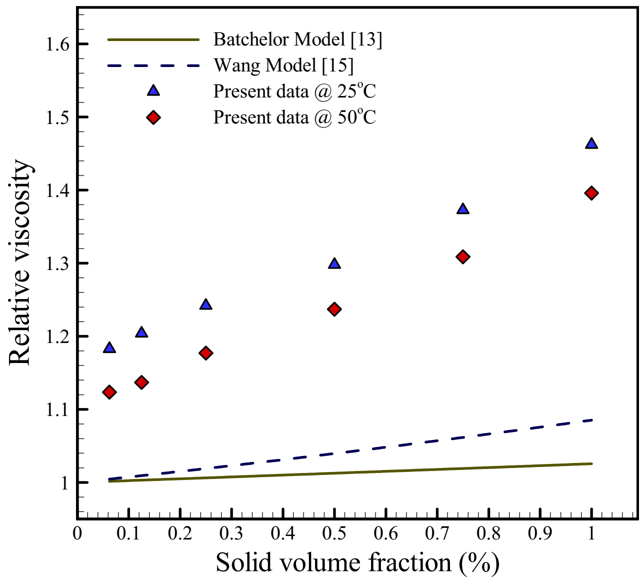

Fig. 8. Comparison of the relative viscosity with respect to solid volume fraction for experimental findings and predicted values from existing models.

For this purpose, the solid volume fractions of 0.0625%, 0.125%, 0.25%, 0.5% and 0.75% were presumed as the base conditions. Then, it must be investigated that how much the viscosity increases with 10% variation in volume fraction of nano-additives. The sensitivity of viscosity can be determined as follows:

$$Sensivity\ of\ Viscosity = \left[\frac{(\mu_{nf})_{After\ \ Changes} - (\mu_{nf})_{Base\ \ Condition}}{(\mu_{nf})_{Base\ \ Condition}}\right] \times 100(\%) \tag{2}$$

Fig. 10 presented the sensitivity of viscosity of the hybrid nanofluid at various temperatures. By comparing the results at different temperatures, it can be found that the viscosity sensitivity to temperature variation is minor. However, it is clear that the viscosity of the hybrid nanofluid is more sensitive to the variations of solid volume fraction from 0.0625% to 1%, which shows the importance of adding nano-additives in high volume fractions.

3.5. Proposed correlation

As shown in Figs. 8 and 9, previous models were incapable to predict the viscosity of Al_2O_3-MWCNTs/SAE40 hybrid nanofluids correctly. Regarding the importance of estimating the viscosity of this nanofluid, the efforts were made to provide a new correlation to predict the viscosity of the hybrid nanofluid. To attain a precise equation, the curve-fitting has been performed by using the Marquardt-Levenberg algorithm [47] for obtaining the coefficients of the independent variables (solid volume fraction and temperature) that give the best fit between the equation and the experimental relative viscosity. This algorithm searches the parameters values that minimize the sum of the squared differences between the values of the experimental results and predicted relative viscosities (see Eq. (3)).

$$S = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{3}$$

In which, S is the sum of the squared differences between the experimental and predicted values. Moreover, y_i and $\hat{y}_i$ are respectively the experimental and the predicted values of the relative viscosity.

The obtained correlation, which is a function of solid volume fraction and temperature, is presented in Eq. (4). This is valid for solid volume fractions ranging from 0.0625% to 1% and temperature range of 25–50 °C, and it can be used to predict the viscosity of the hybrid nanofluid in several applications as easily as possible.

$$\frac{\mu_{nf}}{\mu_{bf}} = 1.123 + 0.3251\varphi - 0.08994T + 0.002552T^2 - 0.00002386T^3 + 0.9695\left(\frac{T}{\varphi}\right)^{0.01719} \tag{4}$$

In Eq. (4), μ is the viscosity and φ is the solid volume fraction. Moreover, the subscripts of *nf* and *bf* indicate nanofluid and base fluid, respectively.

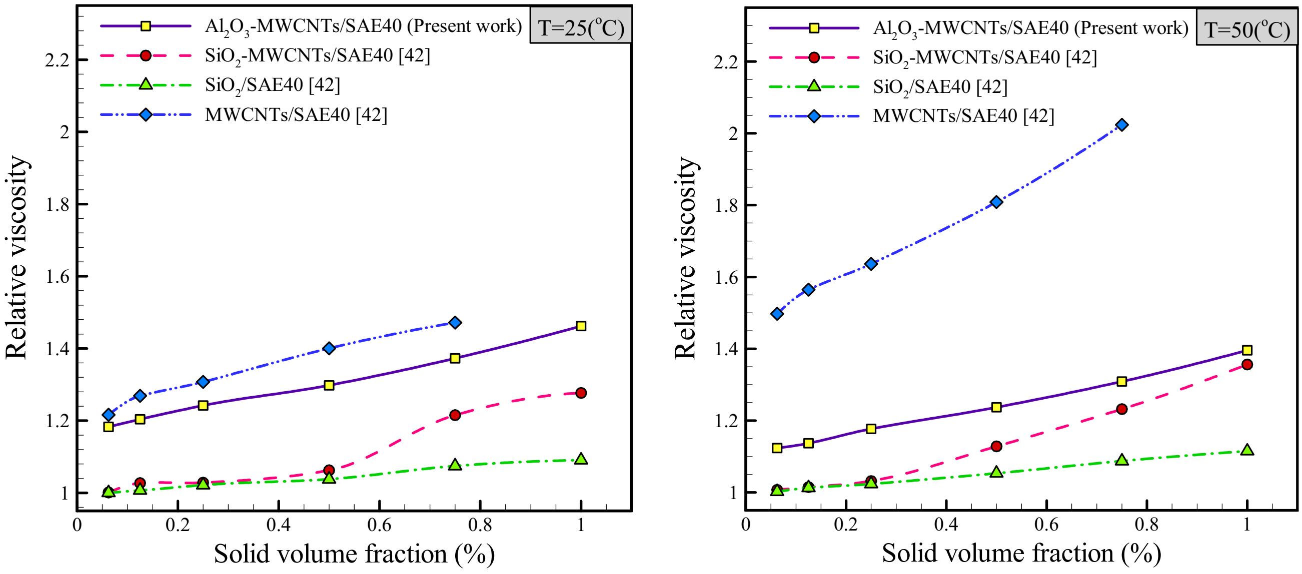

Fig. 9. Relative viscosity of various nano-lubricant versus solid volume fraction at T = 25 °C and T = 50 °C.

In order to assess the accuracy of this correlation, deviation analysis of the relative viscosity was implemented. The deviation between experimental findings and predicted values from the correlation can be calculated as follows:

$$\text{Margin of deviation} = \left[\frac{\left(\frac{\mu_{nf}}{\mu_{bf}}\right)_{Pred} - \left(\frac{\mu_{nf}}{\mu_{bf}}\right)_{Exp}}{\left(\frac{\mu_{nf}}{\mu_{bf}}\right)_{Exp}}\right] \times 100(\%) \tag{5}$$

where the subscripts of Pred and Exp indicate predicted value and experimental data, respectively.

Fig. 11 shows a comparison between relative viscosities measured by experiments and those predicted values from the correlation. It can be seen that most of the data are near the equality line or on it, which is not a significant distance. The maximum of deviation margin is also illustrated in this figure in the form of two bands. As can be observed, the maximum value of deviation margin is 2%. It is understood from this figure that, there is an excellent agreement between the experimental data and the correlation outputs, leading to the fact that the proposed correlation could be useful for engineering applications.

3.6. Effects of nano-additives on the pumping power

In this section, the effects of nano-additives and temperature on the pumping power are illustrated. The pumping power for a fluid can be obtained by using the following equation:

$$P_{pumping} = Q \cdot \Delta p \tag{6}$$

where Q is the volumetric flow rate and Δp is the pressure drop.

For a continuous flowing system, the pressure drop commonly includes the static head (ρgh), pressure losses caused by fittings ($\rho K V^2/2$) and the friction pressure drop as a function of the friction factor and length ($2\rho f\, V^2 L/d$). By expressing the component pressure losses in terms of the component inlet velocity, the pumping power for a turbulent fluid flow can be calculated from the following equation [48]:

$$P_{pumping} = \rho Q\left[gh + K\frac{V^2}{2} + 2f\frac{L}{d}V^2\right] \tag{7}$$

where L, h, d and V are length, vertical position, circular tube diameter and velocity respectively. Moreover, K is the pressure loss coefficient and f is the Fanning friction factor. For a turbulent fluid flow, Fanning friction factor can be estimated by Eq. (8) (Blasius equation [49]):

$$f = 0.0791\left(\frac{\mu_{nf}}{\rho_{nf} V d}\right)^{0.25} \tag{8}$$

in which, ρ is density and can be calculated by the following equation:

$$\rho_{nf} = \varphi \rho_s + (1 - \varphi)\rho_{SAE40} \tag{9}$$

where s indicates the solid particles.

Since that density affected by nano-additives, "density ratio" should be defined as the ratio of the density of the nano-lubricant, calculated from Eq. (9), to density of SAE40. In order to evaluate of the effects of nano-additives on the pumping power for the oil flow, Fanning friction factor is investigated for comparing between the pumping power in case of nano-lubricant and that in case of SAE40. In this way, the "Fanning friction factor ratio (FFFR)" is defined as the ratio of the friction factor of the nano-lubricant, calculated from Eq. (8), to friction factor of SAE40 (See Eq. (10)).

$$FFFR = \frac{f_{nf}}{f_{SAE40}} = \frac{0.0791\mu_{nf}^{0.25}(\rho_{nf} V d)^{-0.25}}{0.0791\mu_{SAE40}^{0.25}(\rho_{SAE40} V d)^{-0.25}} = \left[\left(\frac{\rho_{SAE40}}{\rho_{nf}}\right)\left(\frac{\mu_{nf}}{\mu_{SAE40}}\right)\right]^{0.25} \tag{10}$$

Fig. 12 shows density ratio versus solid volume fraction at temperature of 15 °C. It can be observed that the maximum density growth is less than 3%. This means that the pumping power is increased by increasing the nano-additives; nonetheless, this increase is not impressive. Fig. 13 illustrates FFFR versus solid volume fraction at various temperatures. As seen in this figure, when solid volume fraction is increased up to 1%, FFFR is augmented up to 10%. This figure also shows that the effect of variation of temperature on the pumping power is not significant.

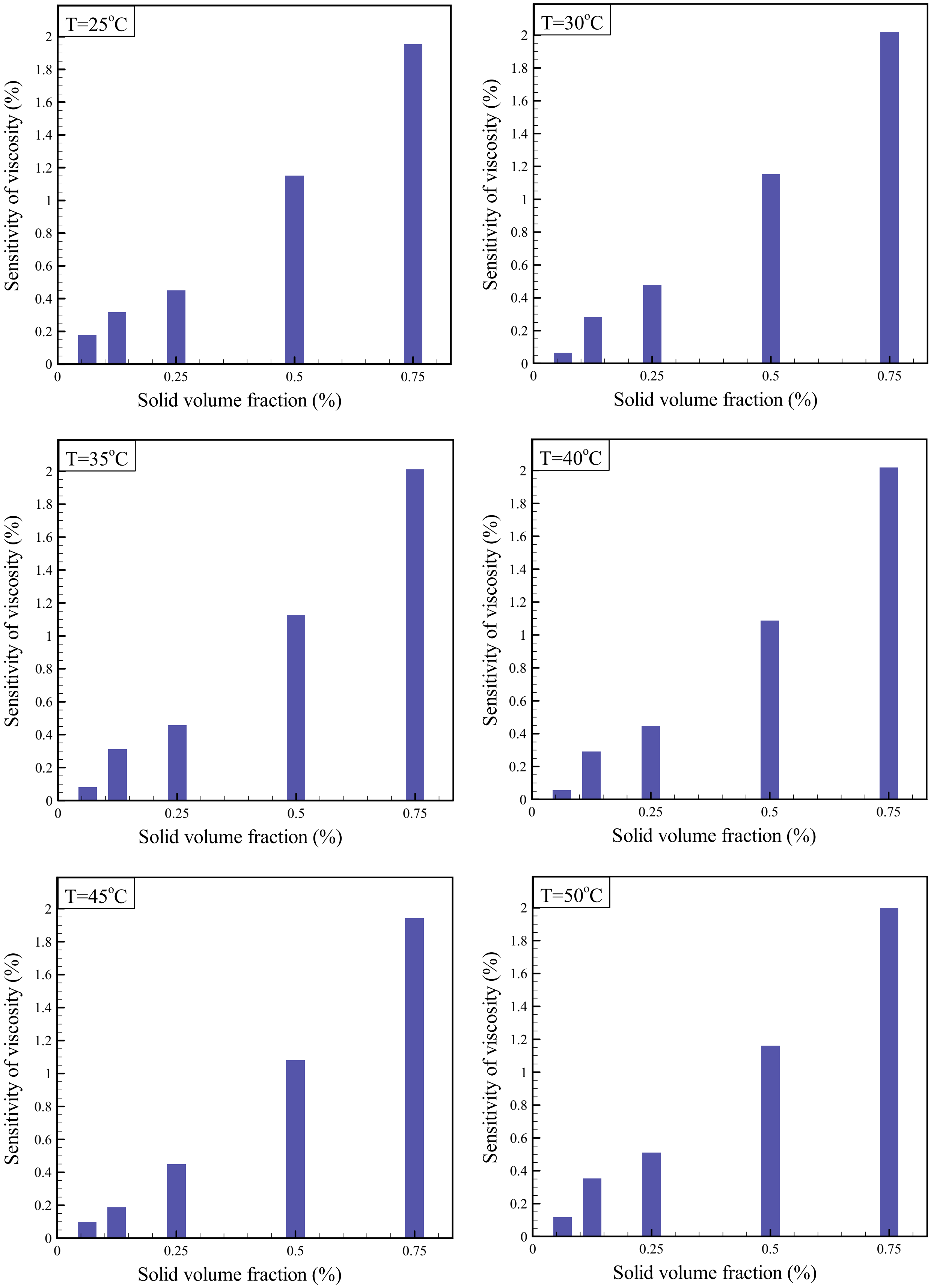

Fig. 10. Sensitivity of viscosity of the hybrid nanofluid at different temperatures.

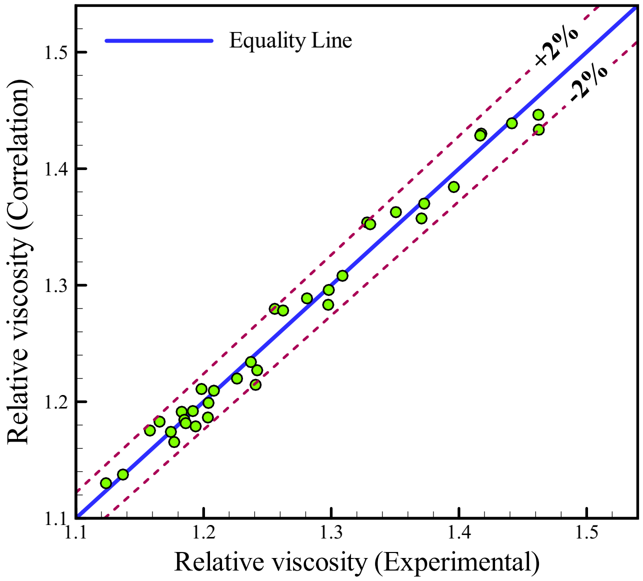

Fig. 11. Comparison between experimental data and correlation outputs.

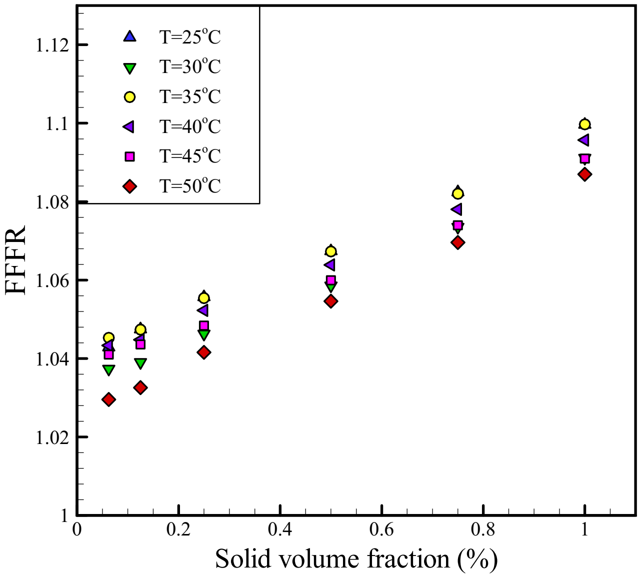

Fig. 13. FFFR versus solid volume fraction at various temperatures.

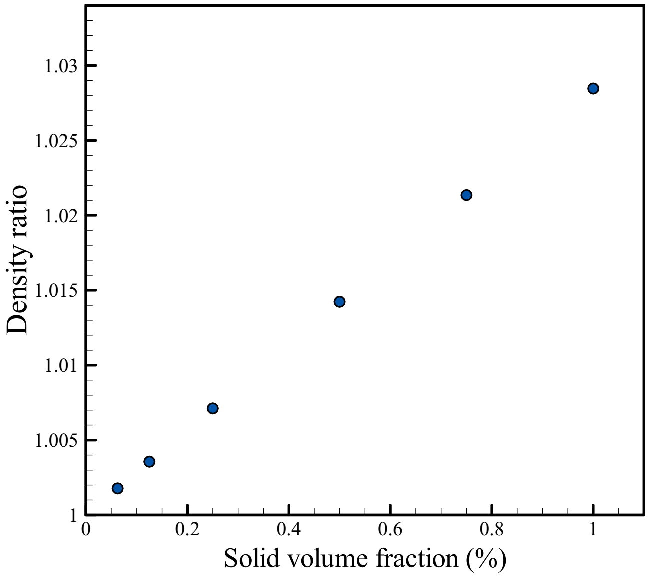

Fig. 12. Density ratio versus solid volume fraction at temperature of 15 °C.

4. Conclusion

In the present study, the viscosities of the pure SAE40 and nanofluid samples with solid volume fractions of 0.0625%, 0.125%, 0.25%, 0.5%, 0.75% and 1% were measured. Experiments were performed at temperatures ranging from 25 °C to 50 °C and the shear rate range of 1333–13,333 s^{-1}. Viscosity measurements showed that all samples of the hybrid nanofluid had Newtonian behavior. Experiments also indicated that the viscosity of the hybrid nanofluid augmented with increasing nano-additives concentration and decreasing temperature. Performing the sensitivity analysis at various temperatures showed that the viscosity sensitivity to temperature variation is minor. Calculations for the relative viscosity of the hybrid nanofluid showed that the maximum augmentation of the viscosity was about 46%. Regarding the importance of estimating the viscosity of the hybrid nanofluid and the incompatibility of previous models and present data, a new correlation was proposed to predict the viscosity of the hybrid nanofluid using experimental findings. The maximum value of deviation margin was 2%, which showed that there was an excellent agreement between the experimental data and the correlation outputs.

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