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Research Paper

Effects of temperature and solid volume fraction on viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluid as a coolant and lubricant in heat engines

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HIGHLIGHTS

- Preparing the stable SiO_2-MWCNTs/SAE40 hybrid nanofluids by the two-step method.
- Measuring the viscosity for various concentrations under different temperatures.
- Comparing the nanofluid viscosity with the existing well-known models.
- Viscosity enhances with increasing the solid volume fraction.
- Proposing an accurate correlation to predict the viscosity of the hybrid nanofluid.

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ABSTRACT

In this study, an experimental investigation on the effects of temperature and concentration of nanoparticles on the dynamic viscosity of SiO_2-MWCNTs/engine oil (SAE40) hybrid nanofluid is presented. The experiments were performed in the solid volume fraction range of 0–1.0% and temperature ranging from 25 °C to 60 °C. Viscosity measurements showed that SiO_2-MWCNTs/SAE40 hybrid nanofluid behaves as a Newtonian fluid at all considered solid volume fractions and temperatures. Experimental results also revealed that the dynamic viscosity enhances with an increase in the solid volume fraction and decreases with increasing temperature. Moreover, results indicated that the maximum enhancement of viscosity of the hybrid nanofluid was 37.4%. Finally, an accurate correlation with maximum deviation of 0.75% has been proposed to predict the dynamic viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluids.

1. Introduction

Engine oil is a type of lubricant and coolant used in internal combustion engines such as engine generators, lawn mowers, power cars and many other machines. In this type of engine, there are several parts which move against each other. The friction between the moving parts reduces the efficiency by changing the kinetic energy to heat. The main duty of engine oil is to diminish friction in moving parts. It also inhibits corrosion, improves sealing and cleans the engine. Another important duty of the engine oil is cooling it by removing heat away from the moving parts. Hence, the use of suitable engine oil can lead to higher efficiency, lower fuel consumption and higher durability of the engine.

The viscosity and thermal conductivity of engine oil are two important parameters in lubricating and cooling of engines. Lower viscosity causes easier oil pumping and draining back to the crankcase, while higher viscosity causes an increase in bearing load capability. Therefore, engine oils with a high viscosity can support a greater load at the bearing on the crankshaft and this leads to an increase in engine durability. On the other hand, engine oils with enhanced thermal conductivity can improve the heat transfer rate. This phenomenon also improves the engine life and fuel consumption. Hence, engineers always look for methods to improve the thermal conductivity. One of these methods is the use of solid nanoparticles in common fluids such as water, ethylene glycol (EG) and oil, called nanofluids [1]. Many researchers showed that adding the nanoparticles to base fluid dramatically increases the thermal conductivity [2–11].

However, the viscosity of the fluids is changed by adding solid nanoparticles to the base fluid. Many studies have been conducted on the viscosity of nanofluids. A summary of such studies for the

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Nomenclature

A, B, C, D	constant values
d	diameter (nm)
m	mass (kg)
T	temperature (°C)

Greek letters

ϕ	solid volume fraction (%)
γ	shear rate (1/s)
μ	dynamic viscosity (kg/ms)
μ_r	relative viscosity (μ_{nf}/μ_{bf})
ρ	density (kg/m^3)
τ	shear stress (Dyne/cm^2)

Subscripts

bf	base fluid
Exp	experimental data
nf	nanofluid
Pred	predicted value
r	relative parameter
MWCNT	multi walled carbon nanotubes
SiO_2	silica
SAE40	engine oil

viscosity of nanofluids is presented in Table 1. The mentioned works [12–22] have shown that the viscosity of nanofluids is a function of shape and size of nanoparticles, temperature and concentration. Moreover, in some of these works, the measured viscosities of nanofluids were compared with existing well-known models [23–25].

In recent years, growing attention has been paid to use innovative nanofluids combined of various nanoparticles to improve the thermo-physical properties of common fluids. This class of nanofluids, called hybrid nanofluids, has been experimentally considered by many researchers. In some works, the combination of metallic and metal-oxide nanoparticles was used as suspending nanoparticles in the base fluid. For example, thermo-physical properties of hybrid nanofluids such as Al_2O_3-Cu/water [26], Cu-TiO_2/water [27] and Ag–MgO/water [28] have been reported. Because of the unique thermal properties of carbon nanotubes (CNTs), they have been attached to metal-oxide nanoparticles by some researchers. In this regard, Baghbanzadeh et al. [29] investigated the effect of MWCNT-silica hybrid nanostructures on the thermal conductivity of distilled water. Munkhbayar et al. [30] reported a significant enhancement in the thermal conductivity of Ag–MWCNT/water hybrid nanofluid, and Chen et al. [31] investigated the thermal conductivity of Fe_2O_3-MWCNTs/water nanofluid. Esfe et al. [32] studied the thermal conductivity of CNTs-Al_2O_3/water nanofluid. Recently, Eshgarf and Afrand [33] examined the rheological behavior of MWCNTs-SiO_2/EG-water nanofluid. Moreover, Soltanimehr and Afrand [34] reported thermal conductivity enhancement of COOH-functionalized MWCNTs/ethylene glycol–water nanofluid.

Due to numerous applications of engine oil, improving engine oil thermo-physical properties is one of the key factors in saving energy. Accordingly, the study of rheological behavior of engine oil has attracted researcher's interest. However, only a few works have been done on thermo-physical properties of engine oils [35–39].

According to the above works, it was observed that researchers focused on evaluating and comparing the effects of different nanoparticles on thermo-physical properties of various base fluids. As mentioned earlier, the dynamic viscosity of engine oil is an important property for energy saving and durability of heat engines. Therefore, many researchers measured the dynamic viscosity of nanofluids containing various kinds of metal or nonmetal nanoparticles. However, the analysis of SiO_2-MWCNTs/SAE40 hybrid nanofluid as a coolant and lubricant in heat engines has not been investigated.

In this work, SiO_2-MWCNTs/SAE40 hybrid nanofluid was prepared at various solid volume fractions, and its structural properties were measured by using XRD pattern. The effects of temperature and concentration of nanoparticles on the dynamic viscosity of nanofluids were examined by a Viscometer. The measured viscosities of nanofluids also are compared with those obtained from the existing models [24,25]. Moreover the viscosity of hybrid nanofluid is compared with SiO_2/SAE40 and MWCNTs/SAE40 mono nanofluids. Finally, using experimental data, for engineering applications, a new correlation is proposed to estimate the dynamic viscosity of SiO_2-MWCNTs/SAE40 hybrid nano-lubricant as a coolant in heat engines.

2. Experimentation

2.1. Nanofluid preparation

In this work, SiO_2-MWCNTs/SAE40 hybrid nanofluids with solid volume fractions of 0.0625%, 0.125%, 0.25%, 0.5%, 0.75% and 1.0%

Table 1
A summary of such studies for the viscosity of nanofluids based on considered parameters and proposed correlations.

Correlation	Dispersed particles	Size (nm)	Base fluid	T (°C)	ϕ (%)	Ref.
$\mu_r = A + B\varphi + C\varphi^2$	TiO_2	21	Water	15–35	0.2–2	[12]
$\mu_r = 1.005 + 0.497\varphi - 0.1149\varphi^2$	Ag	<100	Di water	50–90	0.3–0.9	[13]
$\mu_r = A\exp(B\varphi)$	CuO	40	Gear oil	10–80	0.5–2.5	[14]
$\mu_r = (1+\varphi)^{1.205}$	Fe_3O_4	5–70	EG:Water	0–50	0–1	[15]
$\mu_{nf} = \mu_{bf}(1 + 1.59\varphi - 16.36\varphi^2 + 50.4\varphi^3)$	SWCNT	2 × (5–10 µm)	Lubricant	25–100	0.01–0.2 wt	[16]
$\mu_{nf} = A\varphi^B T^C \mu_{bf}^D$,	Al_2O_3	120	EG:Water	15–40	0–4	[17]
$\mu_{bf} = 0.0003T^2 - 0.0461T + 2.3775$	TiO_2	21				
$\mu_r = 1 + 11.6\varphi + 109\varphi^2$	MgO	40	Water	24–60	<1	[18]
$\mu_r = 0.911\exp(5.49\varphi - 1.359\times10^{-5}T^2) + 0.0303Ln(T)$	ZnO	18	EG	25–50	0.25–5	[19]
$\mu_r = 38.158\varphi - 0.0017357T + 1.1296$	MWCNT	N/A	Water	25–55	0.05–1	[20]
$\mu_r = 1 + 3.575\varphi + 6032.93\varphi^2 - 1{,}153{,}669\varphi^3$	DWCNT	(2–4) × 50 µm	Water	27–67	0.01–0.4	[21]
$\mu_r = 1.089 + \left[-7.722\times10^{-9}\left(\frac{T}{\varphi}\right)^2 + 1.1917T^{0.298}\varphi^{0.4777}\right]\times\exp\left(19{,}457T^{-0.453}\varphi^{3.219}\right)$	SWCNT	N/A	EG	30–60	0.0125–0.1	[22]

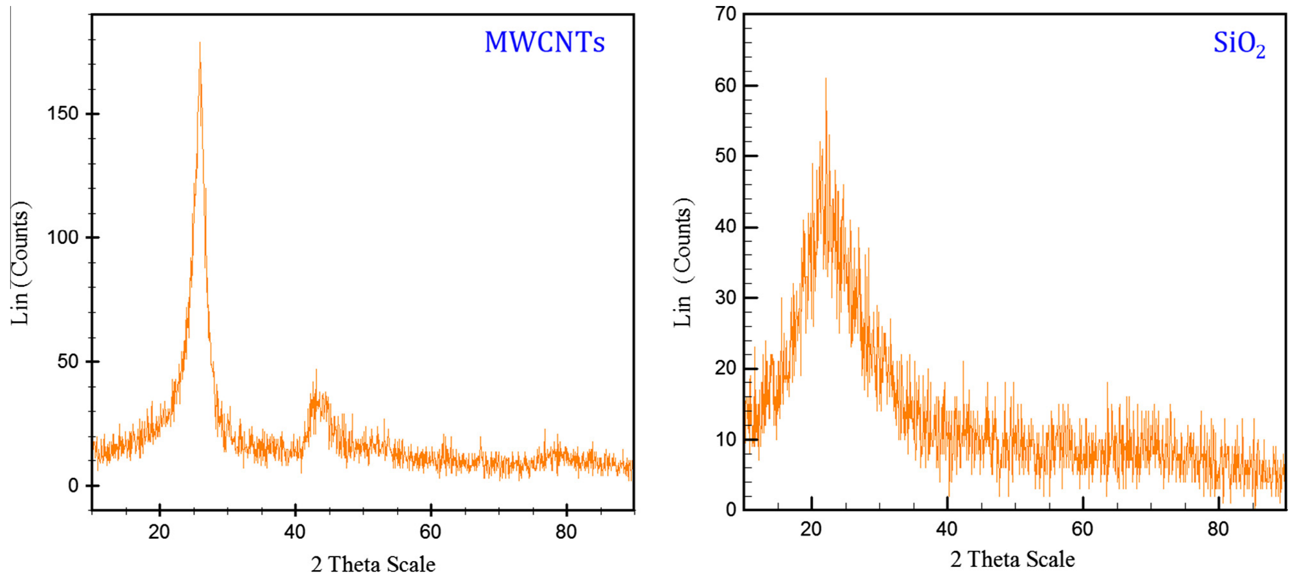

Fig. 1. XRD pattern for MWCNTs and SiO_2 nanoparticles.

were prepared using a two-step method. First, to obtain a characterization of the particles, the structural properties of the dry MWCNTs and SiO_2 nanoparticles were measured by using X-ray diffraction as shown in Fig. 1.

The quantity of MWCNTs and SiO_2 nanoparticles needed for different solid volume fractions can be determined using the following equation [40],

$$\varphi = \left[\frac{\left(\frac{m}{\rho}\right)_{MWCNT} + \left(\frac{m}{\rho}\right)_{SiO_2}}{\left(\frac{m}{\rho}\right)_{MWCNT} + \left(\frac{m}{\rho}\right)_{SiO_2} + \left(\frac{m}{\rho}\right)_{SAE40}} \right] \times 100 \tag{1}$$

where φ is the percentage of solid volume fraction, ρ is the density and m is the mass. The masses of MWCNTs, SiO_2 nanoparticles and engine oil were determined by using a sensitive electronic balance with an accuracy of 1 mg. An equal volume of multi-walled carbon nanotubes (MWCNTs) and silica (SiO_2) nanoparticles were dispersed into a specified amount of engine oil (SAE40-Iranol product, Iran). The characteristics of SAE40, MWCNTs and SiO_2 are presented in Tables 2 and 3.

Since the first important step in the experiments is the preparation of nanofluids, the nanoparticles must be dispersed appropriately in the oil. Therefore, to prepare stable nanofluid samples, after magnetic stirring for 2.5 h, the suspensions were exposed to an ultrasonic processor (Hielscher Company, Germany) with the power of 400 W and a frequency of 24 kHz for 6–7 h. The photographs of MWCNTs, SiO_2 nanoparticles, SAE40 and SiO_2-MWCNTs/SAE40 hybrid nanofluid are displayed in Fig. 2. Visual observations showed that nanofluid samples exhibit good stability after 15 days and no obvious sedimentation is observed.

Table 3
Characteristics of MWCNTs and SiO_2 nanoparticles.

Characteristic	Value	
	MWCNTs	SiO_2
Purity	>97%	>99%
Color	Black	White
Size	Outer diameter: 5–15 (nm) Inner diameter: 3–5 (nm) Length: 50 (μm)	20–30 (nm)
Thermal conductivity	1500 (W/m K)	1.3 (W/m K)
Bulk density:	0.27 (g/cm^3)	<0.10 (g/cm^3)
True density	~2.1 (g/cm^3)	2.4 (g/cm^3)
Specific surface area (SSA)	233 (m^2/g)	180–600 (m^2/g)

2.2. Dynamic viscosity measurement

The viscosity of the hybrid nanofluids with the solid volume fractions of 0.0625%, 0.125%, 0.25%, 0.5%, 0.75% and 1.0% were measured at a temperature range of 25–60 °C. The CAP 2000+ Viscometer, supplied by Brookfield engineering laboratories of the USA, was employed to measure the viscosities of nanofluids. The Viscometer is medium to high shear rate instrument with Cone Plate geometry and integrated temperature control of the test sample material. Experiments were performed at the shear rate range of 667–6667 s^{-1}. The range of accuracy and repeatability of the Viscometer are respectively ±2.0% and ±0.5% of the full scale viscosity range. Before the measurements, the Viscometer was calibrated with the engine oil (SAE40) at room temperature. In order to make sure of the Viscometer repeatability, all experiments were repeated at different shear rates for each solid volume fraction and temperature.

Table 2
Characteristics of engine oil (SAE40).

Characteristic	Descriptions	Value
Kinematic viscosity @ 100 °C	The ratio of the dynamic viscosity to the fluid density	0.155 (m^2/s)
Viscosity Index (VI)	A formal measure for the change of viscosity with temperature variations	85 (High)
Flash point	The lowest temperature at which a liquid can form an ignitable mixture in air	235 (°C)
Pour point	The temperature at which oil becomes semi-solid	−12 (°C)
Total base number (TBN)	A measure of a reserve alkalinity of a lubricant	4 (mg KOH/g)
Density @ 15 °C	–	0.895 (g/cm^3)

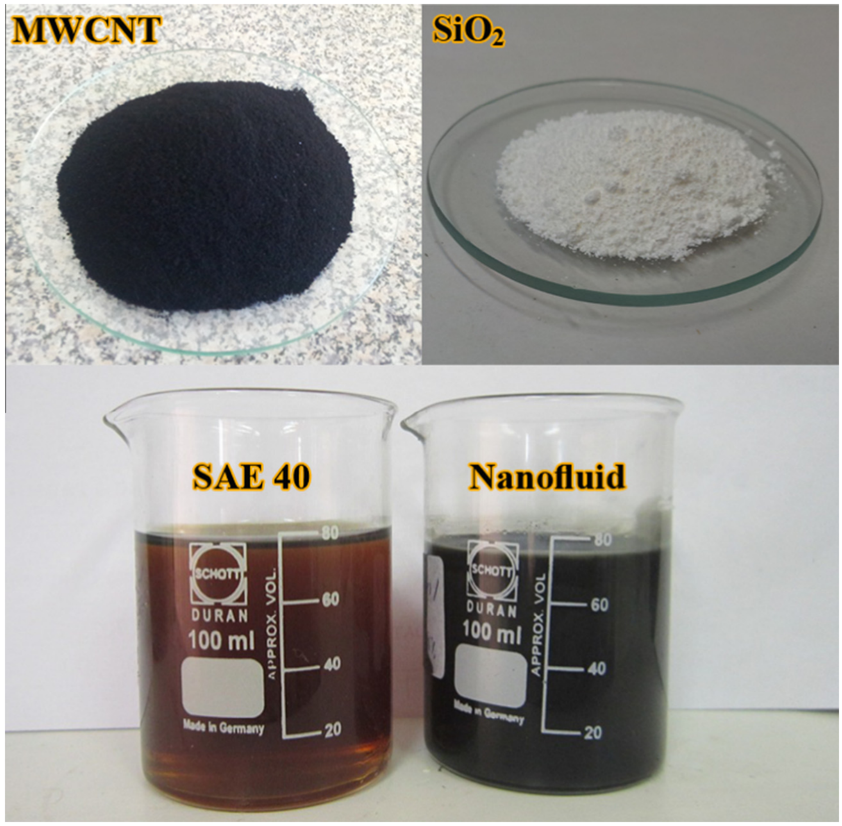

Fig. 2. Photographs of MWCNTs, SiO_2 nanoparticles, SAE40 and SiO_2-MWCNTs/SAE40 hybrid nanofluid.

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

3. Results and discussion

At the beginning of this section, measured viscosities are compared with some theoretical models. Moreover, rheological behavior (Newtonian or non-Newtonian) of hybrid nanofluids is investigated. Then, the effects of temperature and nanoparticles volume fraction on viscosity of hybrid nanofluid are examined. Finally, a new accurate correlation is proposed to predict the relative viscosity using experimental data. The nanofluid samples consist of engine oil (SAE40) and an equal volume of multi-walled carbon nanotubes (MWCNTs) and silica (SiO_2) nanoparticles. The measurements are performed at temperature ranges from 25 °C to 60 °C for various suspensions at volume fraction of 0.0625%, 0.125%, 0.25%, 0.5%, 0.75% and 1.0%.

3.1. Comparison between experimental data and theoretical models

Fig. 3 shows a comparison of the relative viscosity with respect to solid volume fraction for measuring values and predicted values from available models. As shown in Fig. 3, neither of the theoretical models are able to predict the viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluids accurately. In previous works [12,20], it was shown that the relative viscosities of TiO_2/water and ZnO/EG nanofluids agree with the Wang model [25]. However, the measured data of the hybrid nanofluid are much higher than both theoretical models. These differences show the fact that adding the combination of multi-walled carbon nanotubes and silica particles greatly increases the viscosity. In fact, nanotubes have a large surface area per unit volume, which causes interface to increase, and in turn, lead to an increase in nanofluid viscosity compared to the quantities predicted by classical models.

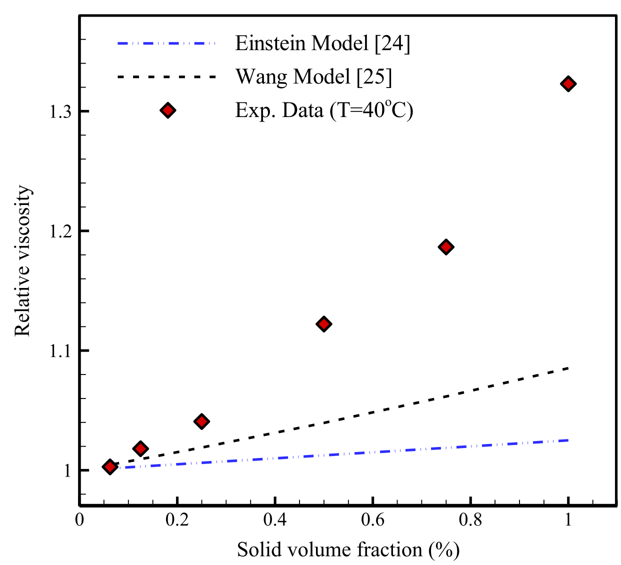

Fig. 3. Comparison between theoretical models and experimental data.

3.2. Newtonian behavior

The viscosity of nanofluid affects the Prandtl and Reynolds number. Therefore, it is an essential thermophysical property for the pumping power, lubrication and convective heat transfer. To evaluate the rheological characteristics of SiO_2-MWCNTs/SAE40

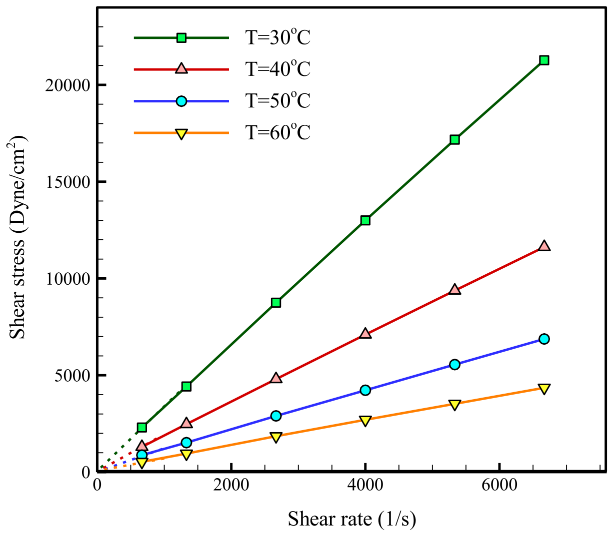

Fig. 4. Shear stress as a function of shear rate for SiO_2-MWCNTs/SAE40 hybrid nanofluid at the solid volume fraction of 1% at various temperatures.

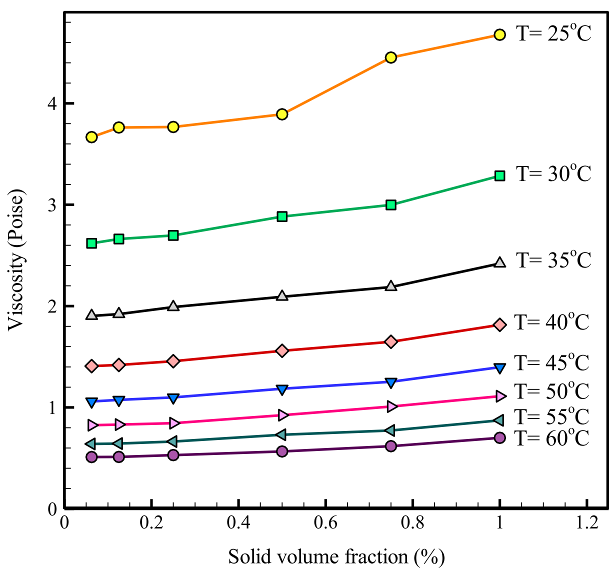

Fig. 5. Variations of dynamic viscosity with solid volume fraction at different temperatures.

hybrid nanofluid, the viscosity of nanofluids was measured at different shear rates. The equation of Newtonian behavior of a fluid is given by,

$$\tau = \mu\gamma \tag{2}$$

where τ is the shear stress, γ is the shear strain and μ is the dynamic viscosity. According to this equation, when the shear stress is a linear function of shear rate, fluid is Newtonian. Fig. 4 depicts the shear stress as a function of shear rate for the hybrid nanofluid at the solid volume fraction of 1% and various temperatures. It can be seen that the hybrid nanofluid behaves as a Newtonian fluid. This is a vital criterion for the use of this nanofluid in thermal applications such as convective heat transfer.

3.3. Effects of temperature and solid volume fraction on dynamic viscosity

Fig. 5 shows the variations of dynamic viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluids with solid volume fraction at

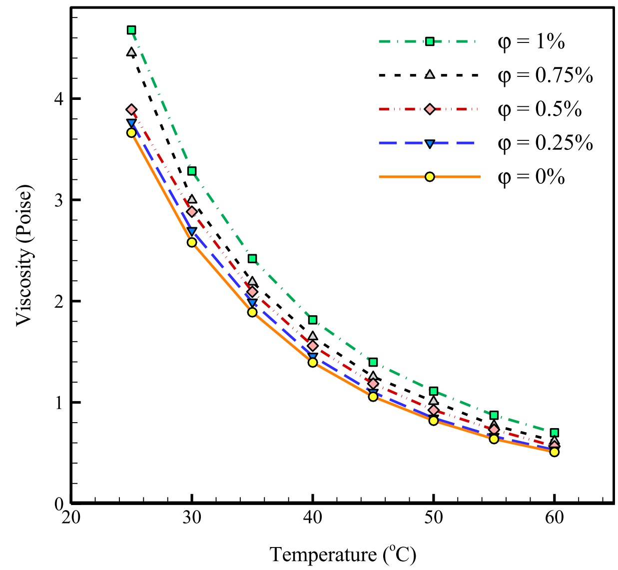

Fig. 6. Variations of dynamic viscosity with temperature at different solid volume fractions.

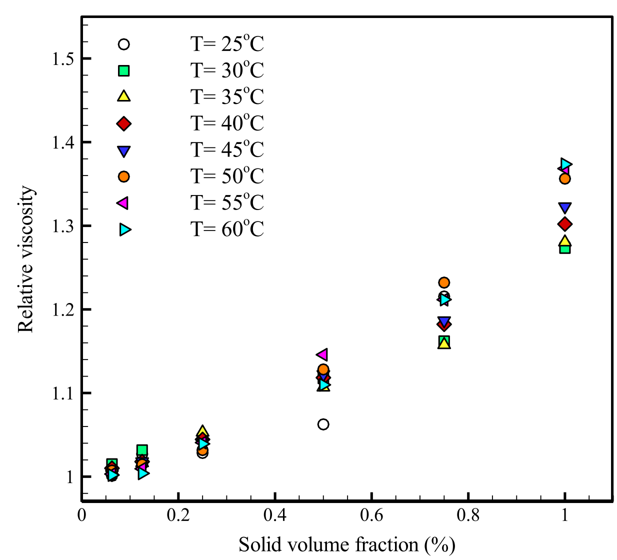

Fig. 7. Variations of relative viscosity with solid volume fraction at different temperatures.

different temperatures. It can be observed that the viscosity of the hybrid nanofluid enhances with increasing solid volume fraction. The effect of viscosity is to resist relative motion of the fluid. In fact, it plays a key role in momentum transfer between the layers of fluid, and it acts when there are movements between those layers. In liquids, it is due to the van der Waals forces between the molecules [41,42]. Hence, the adding nanoparticles and nanotubes into engine oil would increase its viscosity as a result of the interactions between the particles and oil molecules. By increasing the quantity of solid particles in a specific amount of a fluid, larger nano-clusters arise due to van der Waals forces between the particles. These nano-clusters prevent the movement of oil layers on each other, leading to a higher increment in viscosity. The viscosity results can suggest that this nanofluid can be useful for engineering applications in which pressure drop is not a subject.

As we know, if oil viscosity changes with temperature were lower, then engine oil would be more suitable for thermal

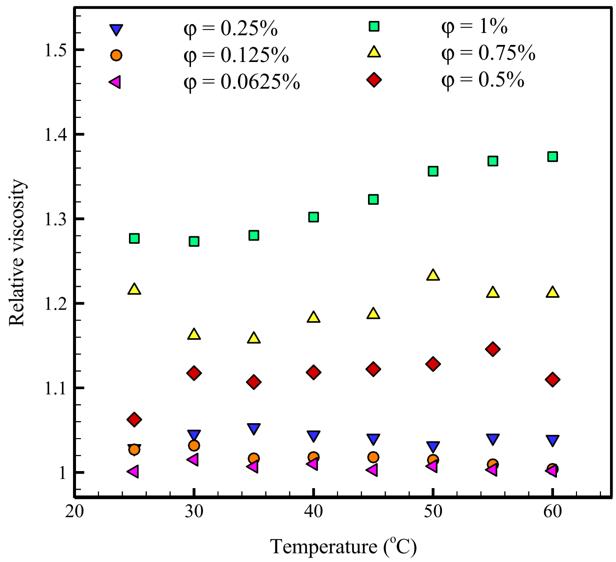

Fig. 8. Variations of relative viscosity with temperature at different solid volume fractions.

applications. In order to understand the nanofluid viscosity changes with temperature, the variations of viscosity with temperature at different solid volume fractions are presented in Fig. 6. It is clear from Figs. 5 and 6 that the viscosity of nanofluid decreases with an increase in temperature. This is due to the fact that, with increasing temperature, the intermolecular interactions between the molecules become weak and therefore the viscosity decreases. The results indicate that for higher volume fractions (e.g. 0.75% and 1.0%), the effect of temperature on the viscosity of nanofluids is more tangible. In fact, at higher volume fractions, the agglomeration of solid particles is more probable; hence, the temperature effect on interactions between the solid particles is more impact.

As can be seen in Fig. 5, the trend for the temperature of 25 °C is different from the rest ones. In fact, at higher solid volume fractions ($\varphi > 0.5\%$), the number of MWCNTs increases and consequently the formation of clusters becomes more probable. However, at temperature of 25 °C, the nano-clusters, which prevent the movement of oil layers on each other, are due to the very strong van der Waals interactions between MWCNTs. This phenomenon increases the viscosity dramatically. This increase is more gentle at higher temperatures (T > 30 °C). This is due to the fact that rising temperature helps the particles to overcome the attractive van der Waals forces.

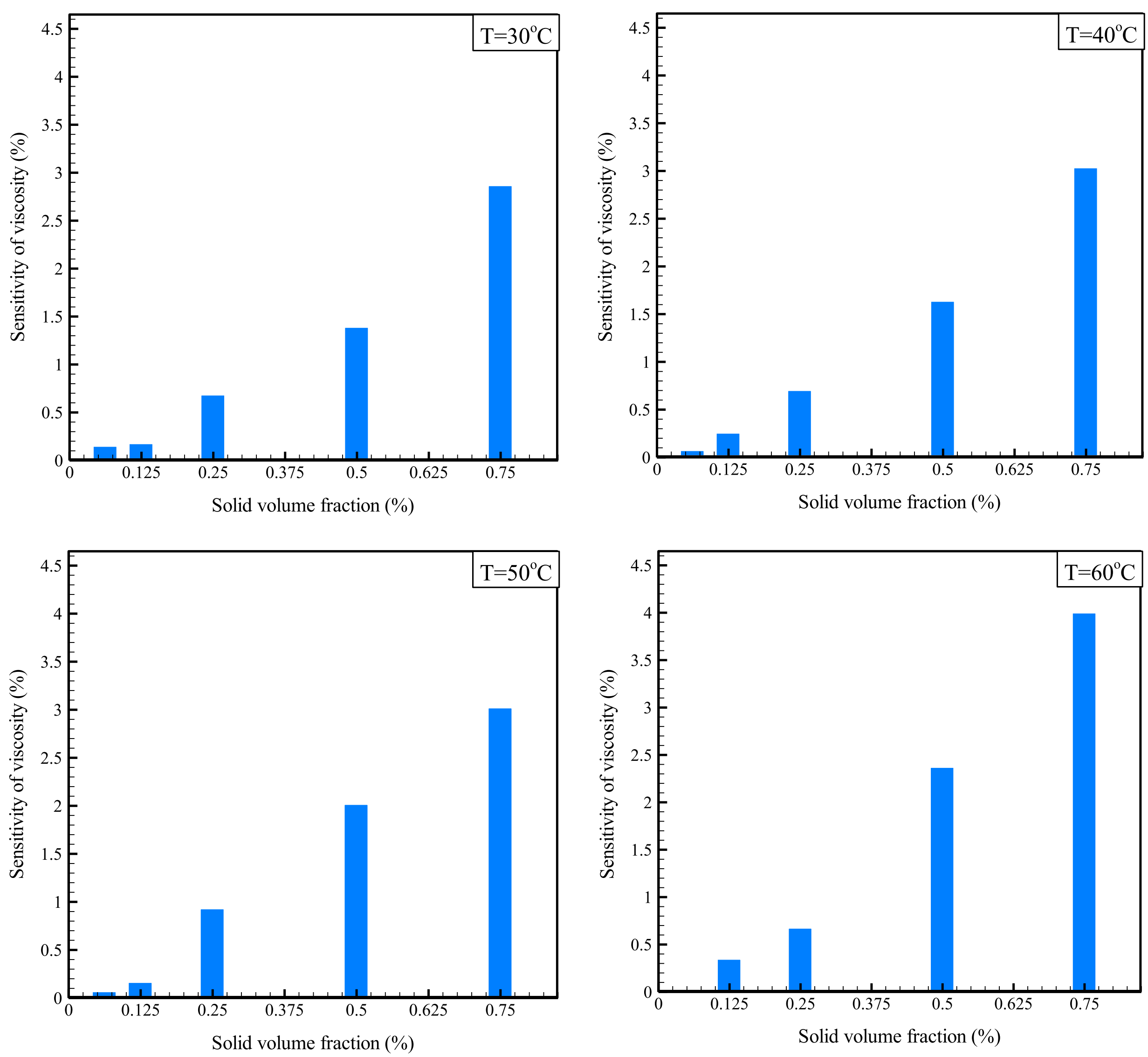

Fig. 9. Results of sensitivity analysis for viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluid at different temperatures.

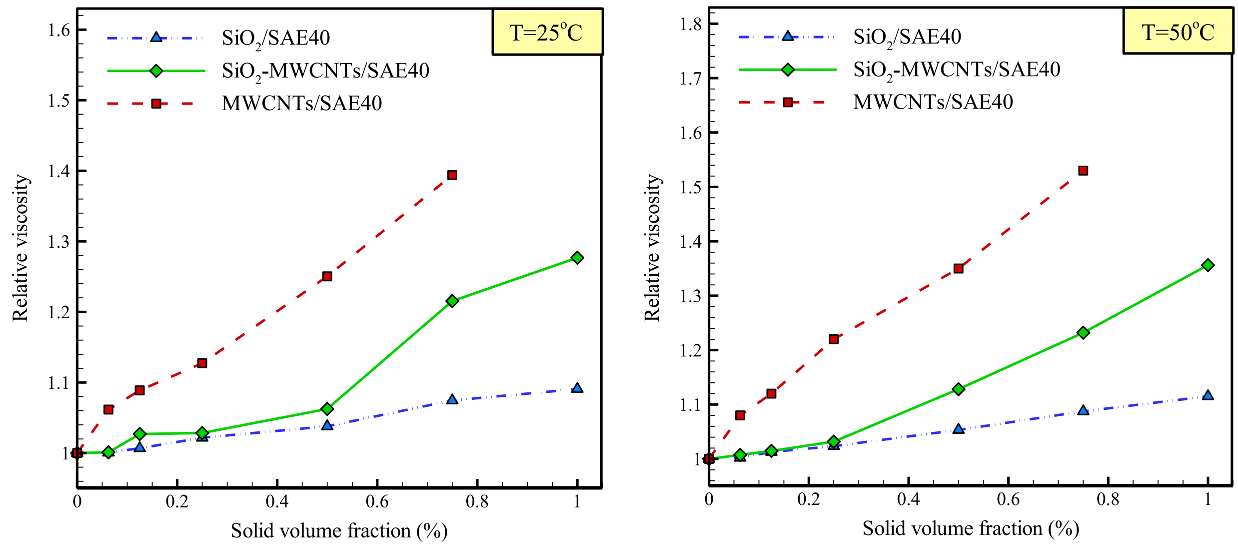

Fig. 10. Relative viscosity variations of various nanofluids with solid volume fraction at different temperatures.

Table 4
Constants values of proposed correlation at different temperatures.

T (°C)	a_0	a_1	a_2	a_3	a_4
25	0.9566	0.9841	−4.4687	7.8779	−4.0731
30	1.023	−0.1613	1.6674	−2.6513	1.3953
35	0.9956	0.1194	0.7286	−1.5119	0.9488
40	1.0133	−0.1316	1.5444	−2.326	1.2019
45	1.007	−0.1187	1.6253	−2.5437	1.3528
50	1.0182	−0.2347	1.593	−1.7341	0.7139
55	1.0224	−0.471	3.3185	−5.047	2.5453
60	0.9952	0.0305	0.7167	−0.8848	0.5161

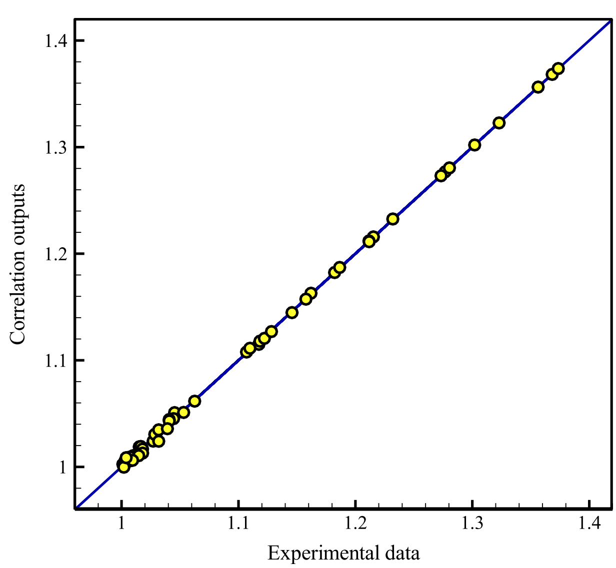

Fig. 11. Comparison between experimental data and correlation outputs.

Figs. 7 and 8 illustrate the relative dynamic viscosity as a function of solid volume fraction and temperature. It is obvious from Fig. 7 that the relative viscosity increases with an increase in solid volume fraction. This trend has been confirmed in the previous works [12–22]. As seen in Fig. 8, relative viscosities have a slight increase with the temperature enhancement and it becomes noticeable as the higher solid volume fractions. The maximum deviations of relative viscosity between temperatures of 25 °C

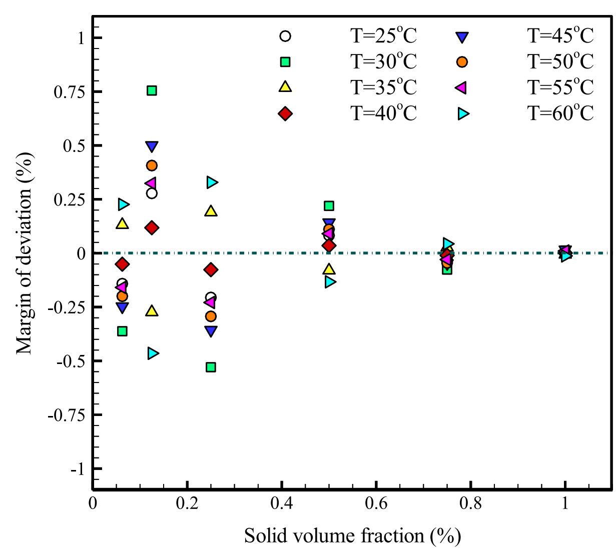

Fig. 12. Measured margin of deviation for all data.

and 60 °C are 1.4%, 2.9% and 2.5% at the solid volume fractions of 0.0625%, 0.125% and 0.25%, respectively. This behavior indicates that, at lower solid volume fractions, the relative viscosity is almost constant at different temperatures, which means that it is not temperature dependent. The maximum deviations of relative viscosity are 8.3%, 7.4% and 10.0% at the solid volume fractions of 0.5%, 0.75% and 1%, respectively. However, the maximum deviations in relative viscosity between solid volume fractions of 0.0625% and 1% are 27.6% and 37.4% at temperatures of 25 °C and 60 °C, respectively.

In order to show that how much the viscosity is sensitive to the changes of solid volume fraction and temperature, a sensitivity analysis is implemented. In this way, the solid volume fractions of 0.0625%, 0.125%, 0.25%, 0.5% and 0.75% are assumed as the base conditions. Then, it should be investigated that how much the viscosity increases with 10% change in solid volume fraction. The sensitivity of viscosity can be calculated as follows:

$$Sensitivity\ of\ Viscosity = \left[\frac{(\mu_{nf})_{After\ Changes} - (\mu_{nf})_{Base\ Condition}}{(\mu_{nf})_{Base\ Condition}}\right] \times 100\ (\%) \tag{3}$$

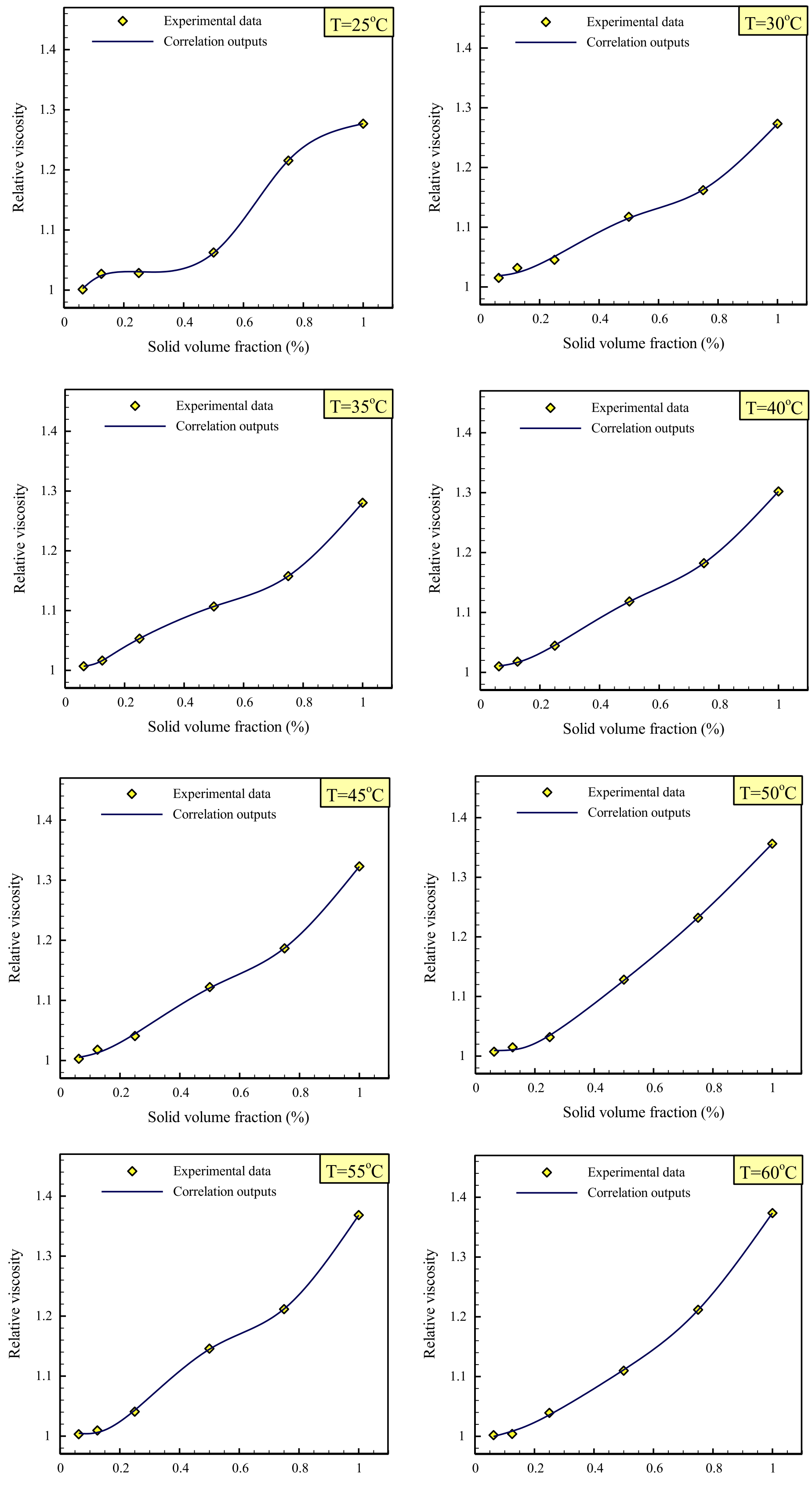

Fig. 13. Curve fitting on experimental data (proposed model) at different temperatures.

Fig. 9 shows the results of the sensitivity analysis at various temperatures where different volume fractions are selected as the base condition. As it is observed, the sensitivity of viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluid to temperature variation is small. Moreover, it is found that at higher temperatures, viscosity is more sensitive to the changes in solid volume fraction. As known, the changes of viscosity are important in engineering applications. Since, at higher temperatures, sensitivity increases with increasing temperature, the engineers should be more careful to increase the solid volume fraction. Moreover, it is observed that the sensitivity increases significantly when the volume fraction increases from 0.0625% to 1%, which shows the importance of adding solid particles in high volume fractions.

3.4. Comparison of hybrid nanofluid with mono nanofluids

In order to provide general insights for the hybrid nanofluid viscosity, some experiments were performed for determination of the viscosity of SiO_2/SAE40 and MWCNTs/SAE40 mono nanofluids at temperatures of 25 °C and 50 °C. Fig. 10 shows the comparison between the relative viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluid and two mono nanofluids, including SiO_2/SAE40 and MWCNTs/SAE40. It should be noted that early experimentations showed that MWCNTs/SAE40 exhibited a non-Newtonian behavior at higher solid volume fractions ($\varphi > 0.75\%$). As can be seen in this figure, the relative viscosity of hybrid nanofluid is between those quantities for both mono nanofluids at temperatures of 25 °C and 50 °C. It can also be found that the relative viscosity of MWCNTs/SAE40 is significantly greater than that of SiO_2-MWCNTs/SAE40 and SiO_2/SAE40 nanofluids. In fact, cylindrical shape and large length of MWCNTs diminishes the capability of their movement between the oil layers. Therefore, the viscosity of MWCNTs/SAE40 nanofluid increases dramatically. In the case of SiO_2/SAE40 nanofluid, the spherical shape of SiO_2 nanoparticles would increase viscosity of the oil slightly as a result of their easier movement between oil layers.

The behavior of SiO_2-MWCNTs/SAE40 hybrid nanofluid, at lower solid volume fractions ($\varphi < 0.5\%$), is similar to behavior of SiO_2/SAE40 nanofluid. By considering the characteristics of MWCNTs and SiO_2, presented in Table 3, it was found that there is one nanotube per 250 particles of SiO_2 in nanofluid samples approximately. Therefore, at lower solid volume fractions, the number of MWCNTs is not very noticeable, which means that the hybrid nanofluid behaves like the SiO_2 nanofluid. However, at higher solid volume fractions ($\varphi > 0.5\%$), the number of MWCNTs increases and consequently the formation of clusters becomes more probable. Hence, for SiO_2-MWCNTs/SAE40 hybrid nanofluid, the viscosity increment happens with a higher slope at higher solid volume fractions. Nevertheless, this increment is not significant compared with that of MWCNTs/SAE40 nanofluids. The reason may be related to the fact that MWCNTs have been tightly enclosed by SiO_2 nanoparticles in the case of SiO_2/SAE40 nanofluid. This phenomenon prevents the formation of larger nano-clusters of MWCNTs and consequently a sharp increase in viscosity. TEM and SEM images of the carbon nanotube–nanoparticle hybrids presented by Baghbanzadeh et al. [32] and Li et al. [43] also confirmed the presence of nanoparticles in between the nanotubes.

3.5. Proposed correlation

As mentioned in Section 3.1, theoretical models were unable to predict viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluids accurately. Regarding the importance of estimating the dynamic viscosity of this nanofluid, the correlations have been proposed separately at different temperatures. These correlations are accurate, and they can be used to predict dynamic viscosity of the hybrid nanofluid in several applications as easily as possible. The general form of the correlations is as follows:

$$\frac{\mu_{nf}}{\mu_{bf}} = a_0 + a_1\varphi + a_2\varphi^2 + a_3\varphi^3 + a_4\varphi^4 \tag{4}$$

where μ is the dynamic viscosity and ϕ is the solid volume fraction. Moreover, the subscripts of *nf* and *bf* indicate nanofluid and base fluid, respectively. a_0, a_1, a_2, a_3 and a_4 are constant values, which are presented for each temperature in Table 4.

In order to evaluate the accuracy of this correlation, deviation analysis of the relative viscosity was performed. The deviation between experimental results and predicted data can be calculated as follows:

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

Fig. 11 shows a comparison between experimental results and correlation outputs. It can be seen that most of the data are near the bisector or on it, which is not a noteworthy distance.

Fig. 12 illustrates the measured margin of deviation for all experiments according to Eq. (4). As can be observed, the maximum value of deviation margin is 0.75%. Figs. 11 and 12 indicate the excellent agreement between the experimental data and the correlation outputs.

In order to show the deviation margin at each experimental measurement, Fig. 13 presents the data related to curve fitting of the experimental data at various temperatures. As can be seen, in most measurement data, the points corresponding to the experimental results and correlation overlap each other or show a small deviation, which reveals that the proposed correlations have an acceptable accuracy.

4. Conclusion

In the present study, the dynamic viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluid at temperatures ranging from 25 °C to 60 °C for various suspensions at solid volume fraction of 0.0625%, 0.125%, 0.25%, 0.5%, 0.75% and 1.0% have been examined. Viscosity measurements showed that the hybrid nanofluid behaves as a Newtonian fluid. Experimental results also revealed that the dynamic viscosity enhances with an increase in the solid volume fraction, and decreases with increasing temperature. Based on experimental data, calculations for relative viscosity indicated that the maximum enhancement of viscosity of the hybrid nanofluid was 37.4%, which occurred at solid volume fraction of 1.0% and temperature of 60 °C. Moreover, a comparison between measured viscosities and theoretical models outputs revealed that previous theoretical models are unable to predict the viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluids accurately. Therefore, using experimental results, the correlation has been proposed to predict the dynamic viscosity of the hybrid nanofluids. Deviation analysis showed that the maximum value of margin of deviation was 0.75%. Comparison between the experimental results and the correlation outputs indicated that the proposed model can be employed to predict the relative viscosity of SiO_2-MWCNTs/SAE40 hybrid nanofluids at solid volume fractions ranging from 0.0125% to 1.0% for the temperature range of 25–60 °C.

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