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Experimental evaluation of dynamic viscosity of ZnO–MWCNTs/engine oil hybrid nanolubricant based on changes in temperature and concentration

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Abstract

In this work, an experimental investigation on the effects of temperature and concentration of nanoparticles on the viscosity of ZnO–MWCNTs/engine oil (SAE 10W40) hybrid nanolubricant is presented. The experiments were repeated at volume fractions of 0.05%, 0.1%, 0.2%, 0.4%, 0.6%, and 0.8%, temperature range of 5–55 °C, and shear rates from 666.5 to 13,330 s^{-1}. The viscosity of hybrid nanolubricant was measured using the Brookfield digital viscometer (CAP2000). We found that the nanofluid has a Newtonian behavior at all volume fractions and temperatures. Also, by increasing the volume fraction of nanoparticles and nanotubes at a constant temperature the nanofluid viscosity is increased. Nanofluid viscosity decreases with increasing the temperature at a constant volume fraction.

Keywords Dynamic viscosity · Engine oil · Temperatures · Solid volume fractions · Experimental

Introduction

Engine oils are used in many industrial systems as coolant and lubricant. As we know, the thermal conductivity of engine oils is less than 0.2 W m^{-1} K^{-1}. Therefore, it can be noted that this fluid has low thermal conductivity for processes related to heat exchange. As we know, thermal conductivity of solid particles is much higher compared to conventional fluids. For example, thermal conductivity of copper is about 400 W m^{-1} K^{-1}, aluminum is about 200 W m^{-1} K^{-1}, and zinc is about 120 W m^{-1} K^{-1}. Therefore, the researchers believed that suspending solids in common fluids could lead to improved thermal properties of fluids. However, the major drawback of the use of solid particles was that the large size of solid particles caused the formation of sediment and the formation of eclipse in narrow tubes. Therefore, with the advancement of technology that led to the creation of nano-sized particles, the problems associated with the collapse of the channel were overcome, and the surface-to-volume ratio that increased the heat transfer increased. Since then, many researchers have used nano-sized solid particles in common fluids to increase the thermal conductivity and called them nanofluids [1–25].

However, the increase in nanoparticles into fluids to increase thermal conductivity can lead to side effects like increased viscosity. Therefore, the researchers also looked at the rheological behavior of nanofluids and presented different reports. A review of reported work related to the rheological behavior of nanofluids is presented in Table 1.

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Table 1 A review of reported work related to the rheological behavior of nanofluids

References	Nano-additives	Base fluid	Behavior
Sepyani et al. [13]	ZnO	SAE50	Newtonian
Baratpour et al. [15]	SWCNTs	Ethylene glycol	Newtonian
Afshari et al. [19]	MWCNTs	Water	Newtonian
Yu et al. [21]	ZnO	Ethylene glycol	Newtonian and Non-Newtonian
Shahsavani et al. [23]	MWCNTs	Ethylene glycol–Water	Non-Newtonian
Meng et al. [25]	MWCNTs	Ethylene glycol	Newtonian

As seen in Table 1, mono nano-additives have been used for preparing these nanofluids. It was also understood that some nanofluids show Newtonian behavior, while others are non-Newtonian. Recently, a new type of nano-additives called "hybrid nano-additives" has been used. These nano-additives are a combination of two or more nanoscale materials that are used for the simultaneous use of the unique properties of several materials. Researchers have also been working on these nanofluids and have presented various reports of their behavior. Table 2 provides a summary of the rheological behavior of the hybrid nanofluids.

Since oils are the most widely used fluids for lubricating and cooling in various industries, some researchers have suspended nano-additives into the oils. For example, Afrand et al. [36] presented an experimental study on the dynamic viscosity of SiO_2–MWCNTs/SAE40 hybrid nanolubricant. They prepared nanolubricant samples with the solid volume fractions up to 1.0% and took viscosity measurements under different temperatures up to 60 °C. Their experiments showed that all nanolubricant samples had Newtonian behavior. They also reported 37.4% increase in viscosity compared to SAE40 using nano-additives. They finally presented a set of correlations for predicting the viscosity of the nanolubricant. Moreover, Hemmat Esfe et al. [37–39] applied a hybrid nano-additive containing MWCNTs and ZnO in various oils. They dispersed MWCNTs–ZnO nano-additives into 10W40 engine oil and reported a non-Newtonian behavior [37]. It should be noted that MWCNTs and ZnO nano-additives were used with ratio of 45% and 55%, respectively. In another work, they added MWCNTs–ZnO nano-additives into 5W50 engine oil and reported non-Newtonian behavior [38]. Hemmat Esfe et al. [39] also used MWCNTs–ZnO hybrid nano-additives with combination of 10–90% to improve the properties of SAE40 engine oil. Asadi et al. [40] also used the same combination of hybrid nano-additives (MWCNTs–ZnO) for changing the properties of 10W40 engine oil. The ratio of MWCNTs and ZnO was 15% and 85% in their study, respectively. They reported a Newtonian behavior for this nanolubricant. However, the use of hybrid nano-material to change the properties of oils was not limited to the above-mentioned researches. In the same way, Asadi et al. [41–44], Hemmat Esfe et al. [45–49], Ahmadi Nadooshan et al. [50, 51], Dardan et al. [52] and [53–60] used some nanoparticles for changing the properties of different engine oils.

As understood from a review of previous studies, oils have attracted the attention of nanoscience researchers because they have important applications in various industries. Due to the fact that Hemmet et al. [37] and Asadi et al. [40] used different volumetric combinations of MWCNTs and ZnO nano-additives to improve the

Table 2 A summary of the rheological behavior of the hybrid nanofluids

References	Nano-additives	Base fluid	Behavior
Eshgarf et al. [26]	SiO_2–MWCNTs	Ethylene glycol–water	Non-Newtonian
Afrand et al. [27]	Fe_3O_4–Ag	Ethylene glycol	Newtonian and Non-Newtonian
Bahrami et al. [28]	Fe–CuO	Ethylene glycol–water	Newtonian and Non-Newtonian
Megatif et al. [29]	CNTs–TiO_2	Water	Newtonian
Suresh et al. [30]	Al_2O_3–Cu	Water	Newtonian
Sundar et al. [31]	MWCNTs–Fe_3O_4	Water	Newtonian
Yarmand et al. [32]	GNP–Ag	Water	Newtonian
Balla et al. [33]	CuO–Cu	Water	Newtonian
Esfe et al. [34]	Ag–MgO	Water	Newtonian
Soltani and Akbari [35]	MWCNTs–MgO	Ethylene glycol	Newtonian

properties of 10W40 engine oil, in this study, a different volume composition of MWCNTs and ZnO nano-additives was selected to improve the properties of 10W40 engine oil. Here, the hybrid nano-additive is composed of 25% MWCNTs and 75% ZnO and thus the results can be compared with their works [37, 40]. To the author's knowledge, there is no comprehensive and thorough investigation to predict the viscosity of the supposed nanofluid.

Specifications of materials

The following materials were used to prepare the nanofluid for this experiment:

A. Base fluid: four season engine oil SAE10W40 produced by Behran Super Pishtaz, Behran oil company, Iran (specifications are presented in Table 3).
B. Nano-additives: multi-walled carbon nanotubes (MWCNTs) and zinc oxide (ZnO) nanoparticles produced by US Research nanomaterials, Inc (specifications are listed in Table 4).

Dried samples of the multi-walled carbon nanotube and zinc oxide nanoparticles were tested to ensure the desired structure and size of nanoparticles. The size and structure of the nanoparticles and nanotubes were obtained through X-ray diffraction (XRD) diagram and Debye–Scherrer equation [28]. The XRD patterns and TEM of nanoparticles and nanotubes are presented in Fig. 1. As can be seen, both XRD diagrams have several peaks. The highest peaks are related to the carbon nanotubes and ZnO nano-additives, and other peaks are related to impurities.

The required amounts of carbon nanotube and zinc oxide nanoparticles at different volume fractions can be calculated using Eq. 1, in which φ is volume fraction, ρ is density, and w is mass.

Table 3 Specification of SAE10W40 engine oil (Behran Co.)

Specification	Values
Kinematic viscosity at 100 °C/cst	15.5
Density at 15 °C/kg m^{-3}	869
Viscosity index	160
Pour point/°C	− 33
Flare point/°C	224

$$\varphi = \left[\frac{\left(\frac{w}{\rho}\right)_{\mathrm{ZnO}} + \left(\frac{w}{\rho}\right)_{\mathrm{MWCNTs}}}{\left(\frac{w}{\rho}\right)_{\mathrm{ZnO}} + \left(\frac{w}{\rho}\right)_{\mathrm{MWCNTs}} + \left(\frac{w}{\rho}\right)_{\mathrm{SAE10W40}}}\right] \times 100 \qquad (1)$$

Table 5 shows the required amount of MWCNTs and ZnO nanoparticles (25:75 vol.%) at different volume fractions.

Experimental

Nanolubricant preparation

The first step in testing nanofluids is to prepare them. To perform more precise experiments, nanofluid should be stabilized and homogenized. In other words, settling and deposition should not occur if the nanofluid remains stagnant for a short while. Therefore, producing a stable and homogenous sample is a very important stage in the experiment. In this study, a two-step method was used for nanofluid preparation. To produce a stable ZnO–MWCNT/engine oil (SAE 10W40) nanofluid, the solution was first mixed in a magnetic stirrer (Model: HPMA 700) for 2.5 h. Then, to break up the agglomerated particles and dissolve nanoparticles completely in the base fluid, the ultrasonic process was applied for 7 h at a power of 400 W and frequency of 24 kHz (Model: UP400St manufactured by Hielscher). During the sonication period, for 30 min of sonication, a 30-min stop was considered to maintain the temperature of the samples. The optimum duration of ultrasonic process is 5 h and 15 min, which was obtained by examining the stability of the samples.

Based on previous trials, after producing samples at various volume fractions, each nanolubricant was monitored for 5 days visually. Through this time, deposition, settling and agglomeration were not detected.

Viscosity measurement and error calculation

The viscosity of ZnO–MWCNT/engine oil (SAE 10W40) nanofluid was measured using the Brookfield digital viscometer (CAP2000). During the experiment, the sample temperature was adjusted by a highly accurate water bath circulator, installed on the device. Therefore, the sample temperature remained constant during the viscosity measurement. The experiment was repeated at volume fractions of 0.05%, 0.1%, 0.2%, 0.4%, 0.6%, and 0.8%, temperature range of 5–55 °C, and shear rate of 666.5–13,330 s^{-1}. It is worth noting that the accuracy and repeatability of the

Table 4 Specification of MWCNTs and ZnO (US Research nanomaterials, Inc)

Specification	Values	
	MWCNTs	ZnO
Purity/%	> 97	> 99
Color	Black	Milky white
Size	Outer diameter = 5–15/nm	35–45/nm
	Inner diameter = 3–5/nm	
	Length = 50/μm	
Density/kg m^{-3}	~ 2100	5600
Specific surface area/m^2 g^{-1}	233	65

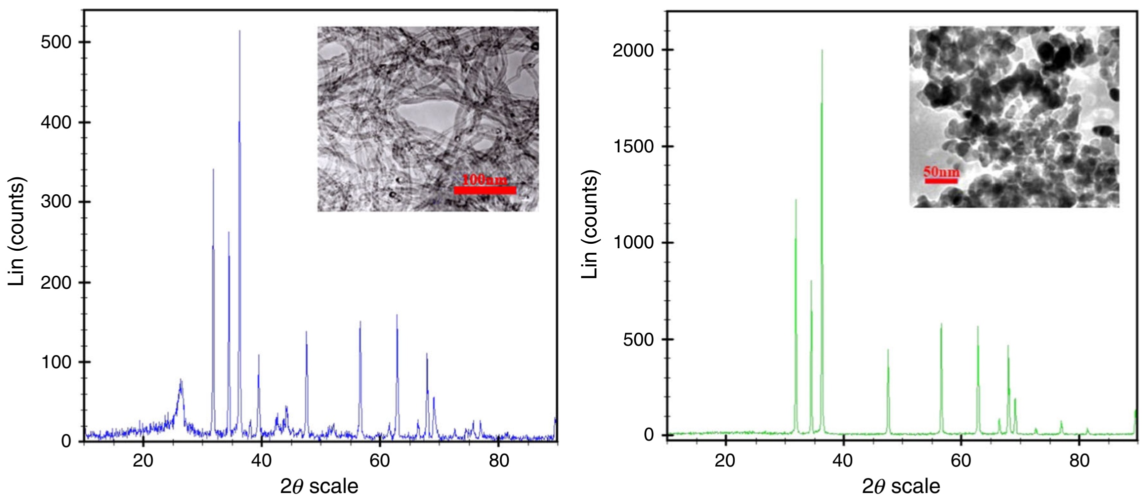

Fig. 1 XRD pattern and TEM for MWCNTs (left) and ZnO nanoparticles (right)

Table 5 Amounts of MWCNTs and ZnO nanoparticles (25:75 vol.%) at different volume fractions

Mass/g		Density/gm^{-3}		Solid volume fraction/%
MWCNT	ZnO	MWCNTs	ZnO	
0.158	0.420	2.1	5.6	0.05
0.315	0.840			0.1
0.630	1.680			0.2
1.260	3.360			0.4
1.890	5.040			0.6
2.520	6.72			0.8

Brookfield viscometer were ± 2% and ± 0.5% in full-scale range (FSR), respectively. In the experiments, CAP-01 spindle on High Torque was employed to implement the present measurements. In order to ensure the accuracy of the results, the viscometer was calibrated with viscosity standard fluid (Fluid Part Number: CAP1L) at 25 °C before the experiments. Moreover, having viscosity at 100 °C (from Table 1), the viscosity of the base oil was measured with the viscometer at this temperature, difference of which was less than 2%.

According to the device manual [16], the measurement error was equal to 2% of the measurement range plus 1% of measured viscosity. The measurement range can be calculated as follows:

$$\text{Full scale viscosity range [cP]} = \frac{1875}{\langle \text{rpm} \rangle} \times 100 \qquad (2)$$

The full-scale range depends only on the number of rounds and is equal to (at 300 rpm):

Table 6 Error and FSR values at volume fraction of 0.8% and temperature of 35 °C

Rotational speed/rpm	FSR/cP	Error/Pa
200	937.5	19.73
300	625	13.34
400	438.8	10.24
500	375	8.33
600	312.5	7.06

$$\mathrm{FSR}\,[\mathrm{cP}] = \frac{1875}{\langle \mathrm{rpm} \rangle} \times 100 = \frac{1875}{\langle 300 \rangle} \times 100 = 625\,\mathrm{cP} \quad (3a)$$

$$\begin{aligned}\mathrm{Error} &= 0.02 \times \mathrm{FSR}[\mathrm{cP}] + 0.01 \times \mu[\mathrm{cP}] \\ &= 12.5 + 0.01 \times 83.8 = 13.34\,\mathrm{cP}\end{aligned} \quad (3b)$$

Table 6 shows the values of the full-scale range and error in different rotational speeds.

Table 7 presents a measurement sample at volume fraction of 0.2% and temperature of 35 °C. The spindle used in this experiment had the shear rate constant (SRC) of 13.33.

Results and discussion

As mentioned in previous sections, nanofluid samples were prepared and measured at volume fractions of 0.05%, 0.1%, 0.2%, 0.4%, 0.6%, and 0.8%, temperature range of 5–55 °C, and shear rates from 666.5 to 13,330 s^{-1}. In the current section, results obtained from investigations into the effect of volume fraction and temperature on viscosity of ZnO–MWCNT/engine oil (SAE 10W40) hybrid nanofluid, along with results from data analysis, are presented by diagrams and tables.

Rheological behavior of nanofluid

In a Newtonian fluid, viscosity is constant at different shear rates. In other words, a linear relationship between shear stress and shear rate indicates that the fluid is Newtonian. This conclusion can be made according to Figs. 2 and 3. Based on these figures, the base fluid has a Newtonian behavior. Figures 4 and 5 indicate, respectively, relationships of shear stress and viscosity with shear rate at volume fractions of 0.05%, 0.1%, 0.2%, 0.4%, 0.6%, and 0.8%. As observed in these figures, there are linear relationship between shear stress and shear rate, and viscosity is approximately constant at different shear rates. However, slight changes that are observed with increasing shear rate in viscosity can be due to friction heat. Therefore, it can be

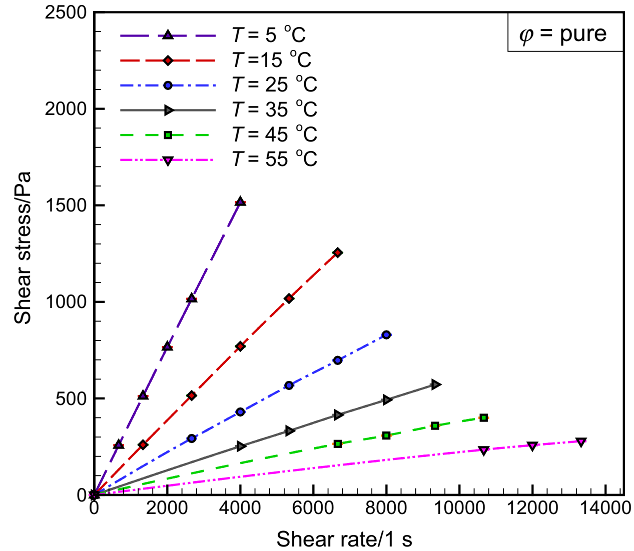

Fig. 2 Shear stress–shear rate dependency for the base fluid at different temperatures

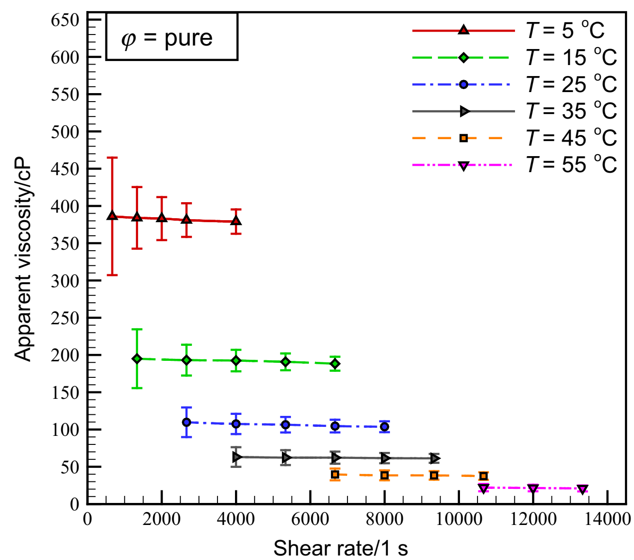

Fig. 3 Viscosity–shear rate dependency for the base fluid at different temperatures

Table 7 A measurement sample at volume fraction of 0.2% and temperature of 35 °C

Rotational speed/rpm	Viscosity/cP	Shear rate/s^{-1}	Shear stress/Pa
200	74.3	2666	198.1
300	73.4	3999	293.5
400	73.3	5332	690.8
500	72.6	6655	483.9
600	72.2	7998	577.5

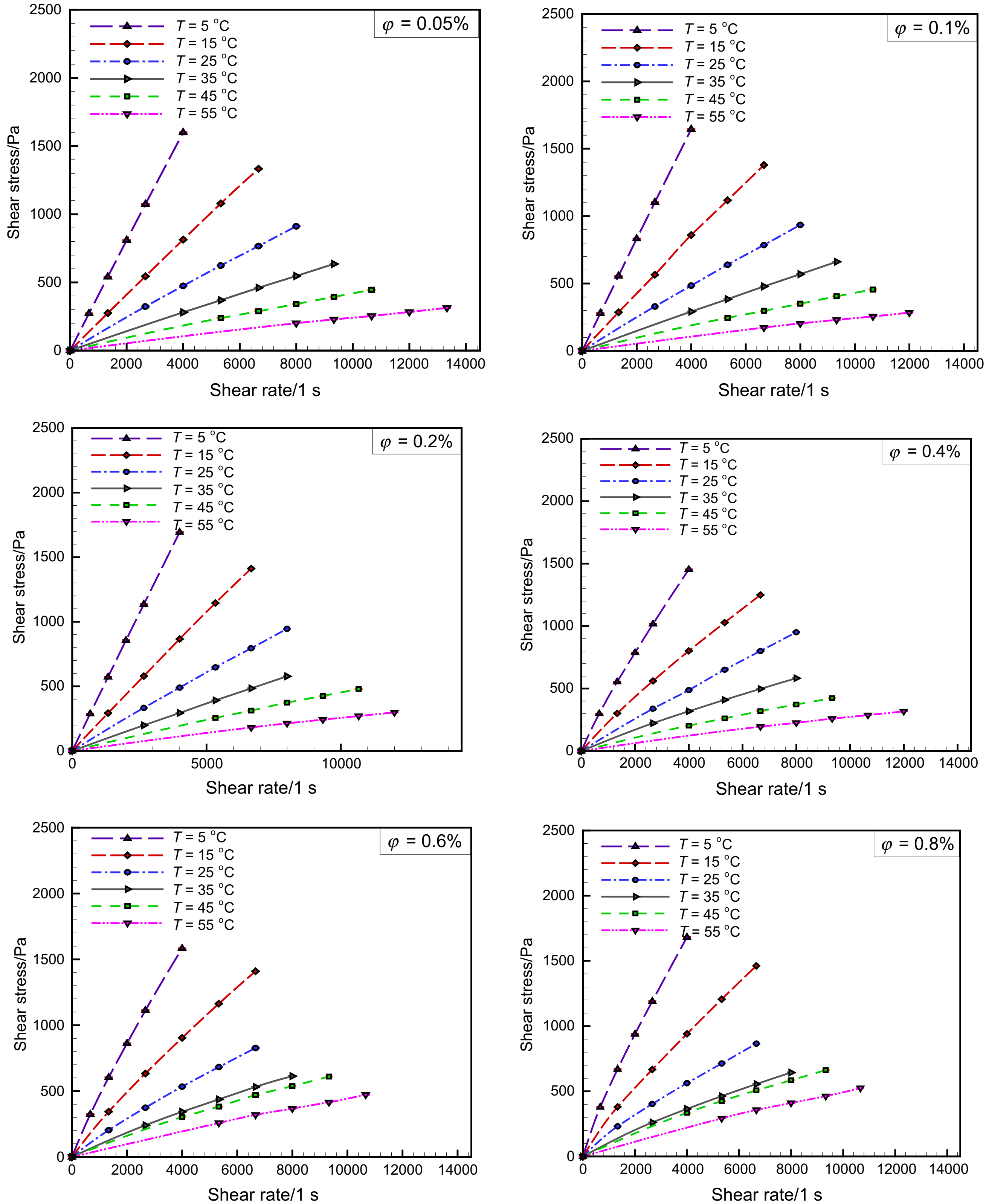

Fig. 4 Shear stress–shear rate dependency for all nanofluid samples fluid at different temperatures

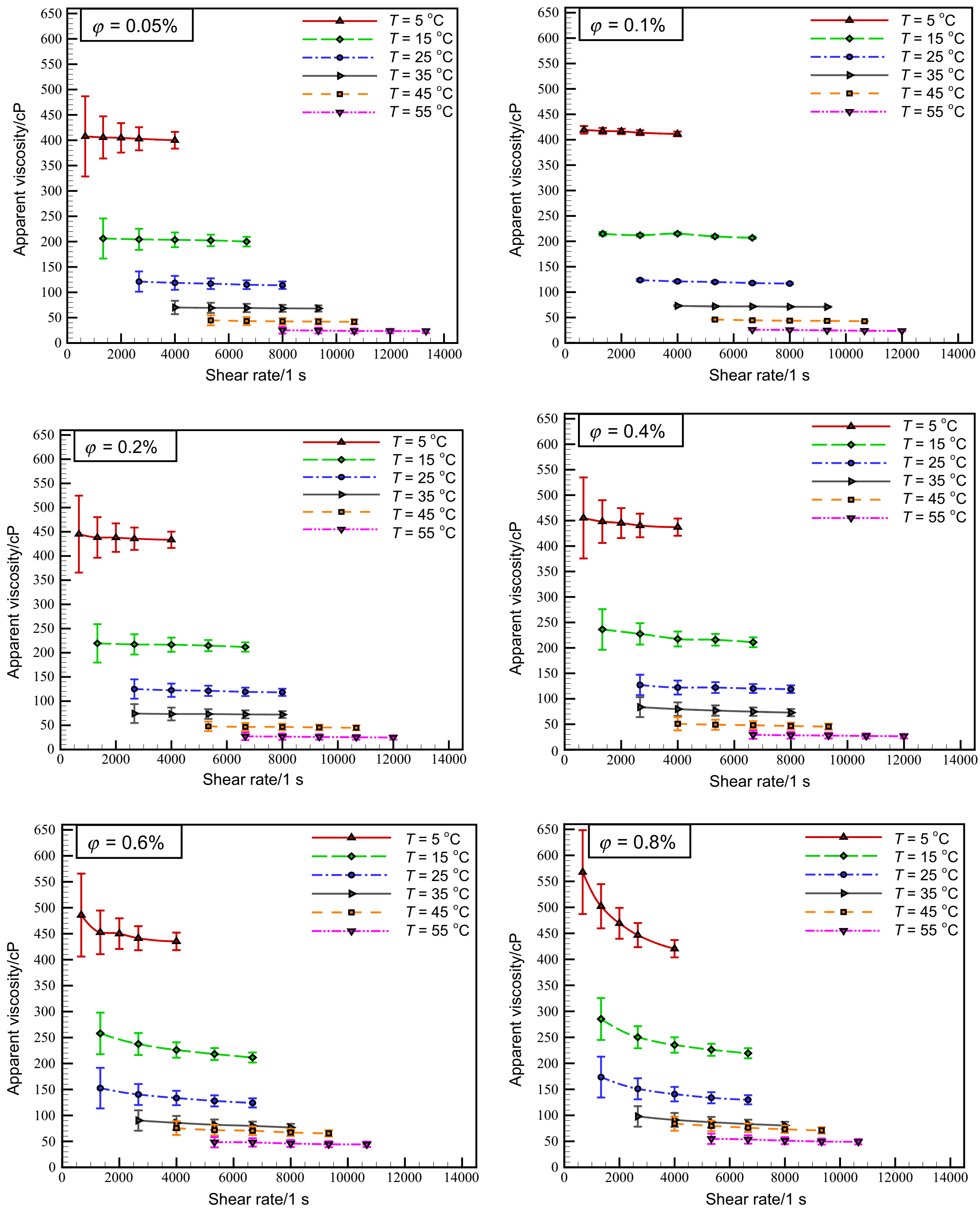

Fig. 5 Viscosity–shear rate dependency for all nanofluid samples fluid at different temperatures

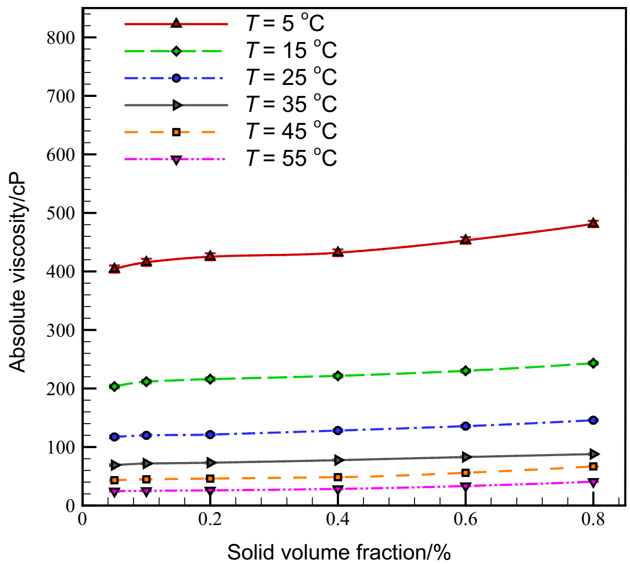

Fig. 6 Effect of volume fraction on nanofluid viscosity at different temperatures

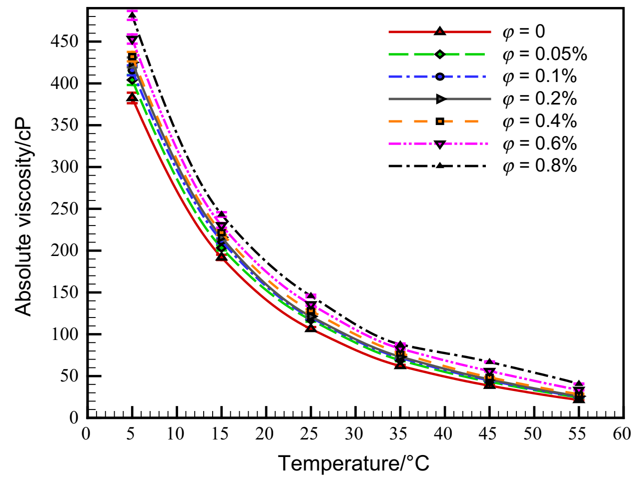

Fig. 7 Viscosity variation versus temperature for all samples

claimed that similar to the base fluid, the nanolubricant has a Newtonian behavior. In conclusion, the experimented nanofluid has a Newtonian behavior at all studied volume fractions and different temperatures.

Effect of volume fraction of nanoparticles and temperature on nanofluid viscosity

Figure 6 shows the effect of volume fraction on nanofluid viscosity at different temperatures. As it was expected, increased volume fraction of nanoparticles and nanotubes at a constant temperature increased the nanofluid viscosity. The same results were obtained in many experiments conducted by other researchers. According to Fig. 6, viscosity of the base fluid was 383 cP at 5 °C, which increased to 404, 453, and 481 cP by adding nanoparticles and reaching volume fractions of 0.05%, 0.6%, and 0.8%, respectively. At these volume fractions, nanofluid viscosity increased by 5, 16, and 20% of the base fluid, respectively. Comparison of nanofluid viscosity between 25 and 55 °C at the same volume fractions showed that at the latter temperature, the nanofluid viscosity reached 24, 46, and 51 cP at volume fraction of 0.05, 0.6, and 0.8%, respectively. As a result, nanofluid viscosity increases with increasing volume fraction at the same temperature. The highest increase in nanofluid viscosity, as compared to the base fluid, was observed at 55 °C and volume fraction of 0.8%. Nanofluid viscosity increased with increasing the volume fraction of nanoparticles at a constant temperature.

Figure 7 shows the effect of temperature on nanofluid viscosity at different volume fractions. According to this figure, nanofluid viscosity is 216, 121, and 73 cP at volume fraction of 0.2% and temperatures of 15 °C, 25 °C, and 35 °C, respectively. Nanofluid viscosity decreases with increasing the temperature at a constant volume fraction. As we know, viscosity is caused by the adhesive forces between liquid molecules. In fact, molecules are affected by a greater amount of energy at higher temperature and can overcome the adhesive forces. As a result, the energized molecules can move more freely. This greater frequency of molecular collision per unit volume and per unit time results in higher resistance against the flow. Reduced intermolecular forces driven by increased temperature lowers resistance to the flow. As a result, viscosity of Newtonian nanofluid decreases with increasing temperature. Another reason of changing the viscosity with the temperature and volume fraction is associated with

Table 8 Constant coefficients corresponding to each temperature

Temperature/°C	a_1	a_2	a_3	a_4
5	1.289	− 5.116	8.556	− 4.589
15	1.403	− 5.169	8.220	4.287
25	1.606	− 5.837	9.710	− 5.251
35	2.230	− 8.863	1.539	− 8.735
45	2.549	− 1.113	2.025	− 1.109
55	2.665	− 1.120	2.072	− 1.141

Brownian motion. The effect of Brownian motion of nanoparticles on the viscosity of nanofluid after increasing temperature is justifiable. Nanoparticles and the base fluid have free molecular movements, and the chance of intermolecular collision is lower in nanoparticles with the rise of temperature. Moreover, the intermolecular distance between nanoparticles and the base fluid increases with the rise of temperature, thereby reducing the resistance to the flow and viscosity.

Proposed correlation for nanofluid lubricant

To facilitate the calculation of viscosity of the nanofluid lubricant [ZnO–MWCNT/engine oil (SAE 10W40) hybrid nanofluid] at different temperatures and volume fractions, the below equation with constants specific to each temperature (six temperatures within the experiment's range) were developed.

$$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 1 + a_1\varphi + a_2\varphi^2 + a_3\varphi^3 + a_4\varphi^4 \quad (4)$$

This equation was obtained through fitting the curve on experimental data. According to Table 8, nanofluid viscosity within the temperature range of 25–55 °C is calculated based on their corresponding coefficients. In this equation, volume fraction is in percentage.

Figure 8 shows a complete agreement between values derived from the mathematical equation with the experimental results. Accordingly, this equation can be used as a suitable predictive model for estimation of viscosity of the given hybrid nanofluid. This equation has a good compliance with experimental results within specified ranges of volume fraction and temperature.

The margin of deviation between the experimental and experimental results was defined as follows:

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

Figure 9 shows the calculated margin of deviation between experimental results and empirical equations at different volume fractions and temperatures. According to this figure, the majority of points are located on the bisector or close to it, indicating good accuracy of this equation. Moreover, the maximum margin of deviation (0.86%) is shown in this diagram. This value is acceptable for an empirical equation. The Rsqr value for each equation is close to 0.997, which is desirable for equations obtained from curve fitting. The Rsqr value of each equation is at higher order than 0.997, which is desirable for equations obtained from curve fitting (Fig. 10).

According to Fig. 10, the maximum and minimum values of Rsqr were obtained at 55 °C and 25 °C, respectively. This finding indicates good compliance between experimental and empirical results.

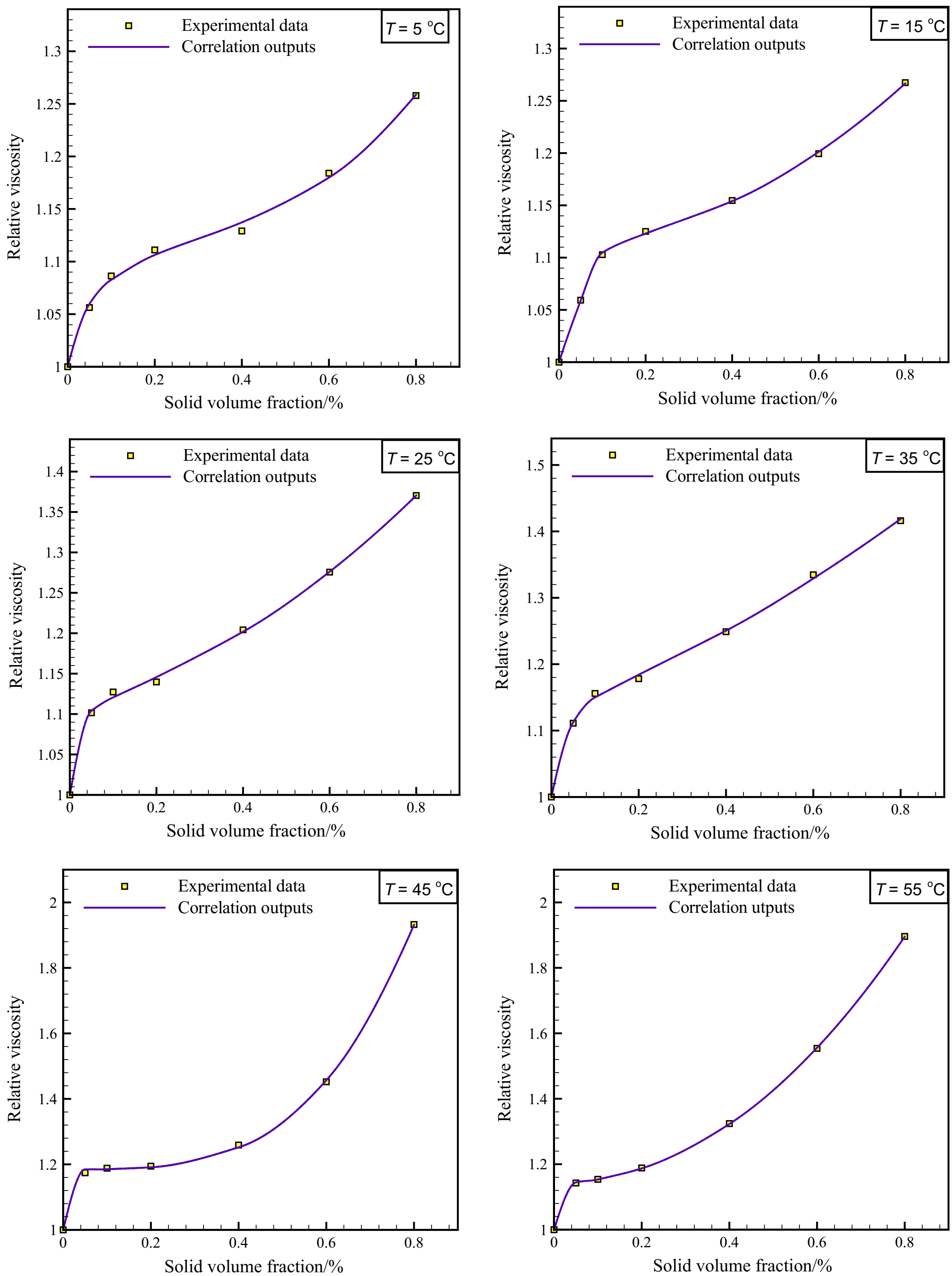

Fig. 8 Comparisons between values derived from the mathematical equation with the experimental data

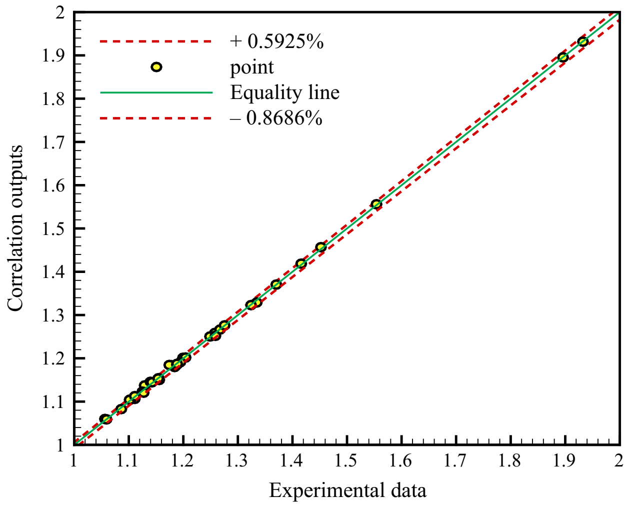

Fig. 9 A comparison between experimental results and empirical equations based on margin of deviation

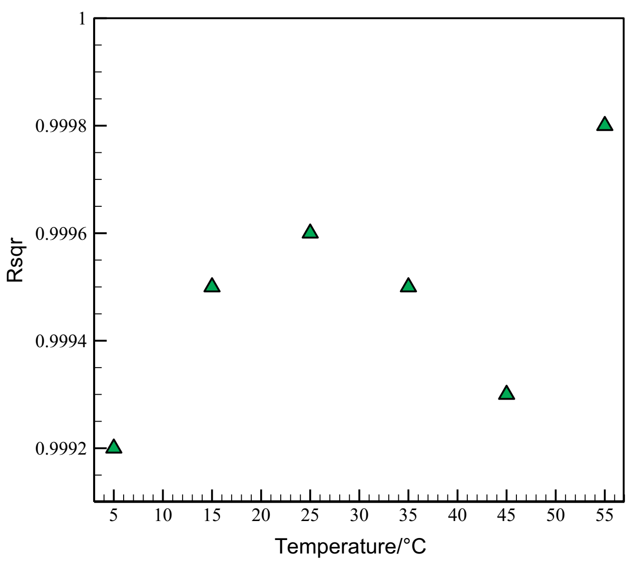

Fig. 10 Rsqr values for the proposed correlation

Conclusions

In this paper, the effect of volume fraction and temperature on viscosity of a hybrid nanofluid, i.e., ZnO–MWCNT/engine oil (SAE 10W40), is presented. The following results can be deduced from our simulation:

- The nanofluid has a Newtonian behavior at all volume fractions and temperatures.
- At highest concentrations and low temperatures, the nanolubricant exhibited a slight shear-thinning behavior can be due to friction heat.
- Increased volume fraction of nanoparticles and nanotubes at a constant temperature increased the nanofluid viscosity up to about 100%.
- Nanofluid viscosity decreases with increasing the temperature at a constant volume fraction. For example, by increasing the temperature from 5 to 55 °C, the viscosity decreases from about 500 cP to about 50 cP.
- A new correlation presented for predicting the relative viscosity of the nanolubricant.

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