A new generation of hybrid-nanofluid: thermal properties enriched lubricant fluids with controlled viscosity amount

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Abstract

The experimental rheological behavior study on Multi-Wall Carbon Nanotube (MWCNT)-TiO₂ (40:60)/SAE50 hybrid nanofluid (NF) is the main subject of present work. The experiment conditions are temperature range of 25–50 °C and solids volume fractions of 0–1% at a shear rate (SR) range of 666.5–9331 s⁻¹. The results show that at an SR of 3999 S⁻¹, the viscosity decreases by 76% when increasing the temperature at a concentration of 1%. Based on the results, NFs exhibit non-Newtonian behavior in all concentrations. Since the power-law index is less than 1 at all temperatures and volume fractions, its behavior is of pseudoplastic type. The results show that hybrid NFs at all solid volume fractions (SVFs) less than 0.5% has a viscosity lower than the base fluid. The sensitivity analysis and economic evaluation of using hybrid NFs are the other analyzed parameters in present study. The sensitivity analysis achieves its maximum value at SVF of 1% and the temperature of 50 °C, and its minimum value at SVF of 0.0625% and the temperature of 25 °C. In addition, to predict the viscosity of hybrid NFs, this study propose a three variable novel experimental model with a coefficient of determination (R²) of 0.9882. Also investigation on hybrid NF effect on rheological behavior of NFs is another question in present study that is answered completely.

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Graphic abstract

Nano particles :

- 1- MWCNTs
- 2- CuO

Base fluid :

- 1- SAE50

1-Equipments :

Brookfield Viscometer

2- prepared
Nanofluids at different
solid volume fractions

Viscosity of the
hybrid nanofluid
versus temperature

Comparison
between Viscosity
enhancement and
price of the various
hybrid nanofluids.

Application

Keywords Hybrid-nanofluid · Viscosity · Sensitivity · Rheological behavior · MWCNT-TiO₂/SAE50

List of symbols

k_{nf}	Thermal conductivity of nanofluid
k_f	Thermal conductivity of base fluid
T	Temperature
T_h	Hot temperature (K)
T_c	Cold temperature (K)

Abbreviation

MOD	Margin of deviation
SVF	Solid volume fraction
SR	Shear rate
SSA	Specific surface area
PPF	Price performance factor
BET	Brunauer-Emmett-Teller
TEM	Transmission electron microscope
TGA	Thermo gravimetric analysis

Greek letters

τ	Shear stress (Pa)
$\dot{\gamma}$	Shear rate (1/sec)
M	Consistency index
N	Power law index
φ	Volume fraction (%)
k	Porosity coefficient
ρ	Density (kgm ⁻³)
μ	Dynamic viscosity (kgm ⁻¹ s ⁻¹)
θ	Dimensionless temperature

Subscripts

f	Base fluid
nf	Nanofluid

1 Introduction

The selection of an appropriate working fluid for heat transfer in different industries has been addressed by many researchers and engineers. In the past decade, NFs have been considered as working fluids that increase heat transfer in different thermal-based applications

and instruments such as thermal and hydraulic analysis of microchannels [1–9] and pool boiling heat transfer [10]. Many scientists have also studied the physical and chemical properties of NPs, including type, concentration, size, shape of NPs and also base fluids [11–28]. A comprehensive view about heat transfer of nanofluids and its fundamental and concepts can be found in hybrid nanofluids for convection heat transfer book [29].

Next to heat transfer properties of fluids and nanofluids, viscosity is the fluid resistance to flow when no external force is acting on it. However, by adding particles to fluid, the particles hinder the movement of the layers over each other. Viscosity is one of the most significant thermophysical properties of NFs due to its effect on pumping, pressure drop, and heat transfer. The viscosity of NFs is influenced by different factors such as temperature, SVF, SR, and size/shape of solid particles. In this regard, some researchers investigated the impact of the mentioned parameters on the NF viscosity [30–42]. Investigation on the viscosity of NFs requires several experiments that need equipment tests, time, and expenses. To solve this problem, the researchers provided a few models with high precision to predict the viscosity of NPs with the help of different software tools [43–50]. Soltani et al. [51] investigated the rheological behavior of MWCNT-MgO/EG nanofluid at SVFs of 0–1% and the temperature range of 30–60 °C. They also developed a model to predict viscosity. In this case, good results can be achieved by saving time and money. Other researchers have also investigated the simultaneous heat transfer and viscosity of nanofluids [52–55]. Some past studies on the viscosity of NFs are summarized in Table 1. The history of nanofluids could be divided in to two parts. The first main step was nanofluids introduction by Choi et al. [56] and the second part started after the year of 2010 that Hemmat Esfe research group [57–59] was one of top three main groups that developed new age of nanofluids known as hybrid nanofluids. Also Hemmat Esfe research group proposed new combinations of additives to control the viscosity and viscosity index [60–62].

Hemmat Esfe et al. [68] investigated the rheological behavior of MWCNT-SiO₂ (3:7)/EG nanofluid at SVFs of

Table 1 A summary of the equations developed for estimating the viscosity of the nanofluids

Authors	NP	BF	Correlation	Deviation
Abdolbaqi et al. [63]	SiO ₂	Bio Glycol/water	$\mu_{nf} = \left[0.906 \exp \left(10.975\varphi + 0.169 \frac{T}{80} \right) \right] \mu_{bf}$	< 3%
Hemmat Esfe et al. [64]	Mg (OH) ₂	ethylene glycol	$\mu_{nf} = (15.89 + 614.4\Phi - 14526\Phi^2)$	< 2
Aberoumand et al. [65]	Ag	oil	$\mu_{nf} = (1.15 + 1.061\varphi - 0.542\varphi^2 + 0.181\varphi^3) \mu_{bf}$	1
Abdollahi [66]	MWCNT-CuO (30–70)	SAE40	$\mu_{nf} = (1.017 + 0.6471\varphi \exp(\varphi) - 1.886\varphi^2 + 0.4045\varphi^3) \mu_{bf}$	< 2.1
Abdolbaqi et al. [67]	TiO ₂	BioGlycol/water	$\mu_{nf} = \left[0.918 \exp \left(14.496\varphi + 0.161 \frac{T}{80} \right) \right] \mu_{bf}$	< 5%

0.025% and 0.6586 and the temperature range of 30–50 °C. They also developed a model to predict viscosity with $R^2 = 0.997$.

In addition, Moghaddam and Motahari [66] have examined the rheological changes of the hybrid nanolubricant containing CuO nanoparticles and MWCNTs in SAE40 motor oil with different temperatures and SVFs. They measured the changes in NFs viscosity at the SVF range of 0.0625–1% and a temperature range of 25–50 °C with different SRs. By viscosity measurements, they found that the viscosity of the nano-lubricant was 29.27% higher than that of the base fluid at a volume fraction of 1%. They also provided a new model based on the temperature and SVF parameters to predict the nano-lubricant viscosity.

TiO₂ is a main semiconducting material that has been applied as photo-catalyst and photosensitive active material due to its excellent physical and chemical features, nontoxic nature, high surface area, low cost, and anticorrosive. The MWCNT-TiO₂ nanoparticles with high current density, easy oxidation, electromagnetic protection, solar cells, and magnetic agglomeration are widely used in heat transfer, wave-absorbing field [69, 70]. Next to above mentioned experimental works, in numerical studies researchers analyzed the effect of using nanoparticles as additive in flooding fluid of EOR process. based on results nanoparticles improved the EOR process and enhanced the recovered oil compared to conventional flooding fluids [71, 72].

In this study, the rheological behavior of MWCNT-TiO₂ (40:60)/SAE50 hybrid NF is experimentally investigated. Understanding the reduction of NF viscosity relative to the base fluid with a certain concentration of NPs (less than 0.5%) is one of the very important findings in the present study. The application of this finding in heat transfer is very significant due to the great increase in thermal conductivity by adding fewer carbon nanotubes to the base fluid. In this study, at first step the process of preparing NF and measuring viscosity are presented and then the NF behavior and the effects of temperature, SR, and SVF on NF viscosity are analyzed. Comparison NF viscosity behavior of MWCNT-TiO₂ (40:60)/SAE50 as representative for hybrid NF and TiO₂/SAE50 as a type of conventional NF and their economic analysis and sensitivity analysis of viscosity related to MWCNT-TiO₂ (40:60)/SAE50 NF are also provided at different temperatures and VF. In fact finding the effect of using MWCNT next to the TiO₂ on viscosity behavior and price change of conventional NF is the main goal of present work.

2 Experimental

2.1 Nanofluid preparation

In this study, a NF containing MWCNT and TiO₂ nanoparticles was prepared with a volume ratio of 40:60 in SAE50 oil, with SVFs of 0%, 0.0625%, 0.125%, 0.25%, 0.5%, 0.75%, and 1% using a two-step method and Eq. 1. The specifications of MWCNT and TiO₂ were listed in Table 2.

$$\varphi\% = \frac{\left(\frac{w}{\rho}\right)_{MWCNT} + \left(\frac{w}{\rho}\right)_{TiO_2}}{\left(\frac{w}{\rho}\right)_{MWCNT} + \left(\frac{w}{\rho}\right)_{TiO_2} + \left(\frac{w}{\rho}\right)_{SAE50}} \quad (1)$$

NPs were prepared in two steps. First, the MWCNT and TiO₂ nanoparticles were mixed in SAE50 oil with a magnetic stirrer for 2 h. The resulting mixture was exposed to ultrasonic waves for 4 h in an ultrasonic agitator of 1200 watts with a frequency of 20 kHz (Ultrasonic Homogenizer, Development of Ultrasonic Technology, Iran). The samples prepared with SAE50 oil are shown in Fig. 1.

The X-ray diffraction (XRD) was used to identify the morphological properties and dimensions of NPs. The XRD of TiO₂ and MWCNT nanoparticles are shown in Fig. 2.

2.2 Viscosity measurement

To determine the hybrid NF viscosity, a Brookfield viscometer cap 2000+ was used. This viscometer has an accuracy of $\pm 1\%$ and a repeatability of $\pm 0.2\%$. The viscometer characteristics were listed in Table 3. Viscosity was measured at the temperatures between 5 and 55 °C with the SRs of 666.5–11,997 s⁻¹. To obtain accurate results, the instrument was calibrated with pure oil, every single test was repeated three times, and then, the mean value of results was reported.

Table 2 Specification of NPs [73]

Nanoparticle	MWCNTs	Titanium oxide nanopowder
Parameter	Value	Value
Purity	> 95 wt% (carbon nanotubes) (from TGA & TEM) > 97 wt% (carbon content)	+ 99.9%
Outside diameter	5–15 nm (from HRTEM, Raman)	30 nm
Inside diameter	3–5 nm	
Length	50 µm (TEM)	–
SSA	233 m ² /g (BET)	~ 35–60 m ² /g
Color	Black	White
Tap density	0.27 g/cm ³	0.25 g/cm ³
True density	~ 2.1 g/cm ³	4.23 g/cm ³

Fig. 1 Prepared nanofluids at different SVF **Fig. 2** The X-ray diffraction images of MWCNT and TiO_2 [73]**Table 3** Viscometer characteristics

Model	CAP 2000+
Meets Industry Standards	ASTM D4287, ISO 2884 and BS 3900
Range	0.2–15,000 Poise
speed of rotation	5–1000 RPM
SR	10–13,000 s^{-1}
Temperature range	5–75 °C
SR constant	13.33 N

3 Results

In this study, the rheological behavior of MWCNT- TiO_2 (40:60)/SAE50 hybrid NF has been investigated empirically. The experiments were carried out at the temperature range of 25–50 °C with SVFs of 0%, 0.0625%, 0.125%, 0.25%, 0.5%, 0.75%, and 1% at SRs of 666.5–9331 s^{-1} .

3.1 Nanofluid behavior

In terms of rheological fluids, fluids are classified into non-Newtonian and Newtonian fluids depending on their response to the shear stress. Equation 2 known as the power-law equation that is derived from the curve fitting of the shear stress according to SR.

$$\tau = m\dot{\gamma}^n \quad (2)$$

Figure 3 shows the consistency index changes versus temperature. Figure 4 shows the power-law index changes versus temperature at different SVFs. Figure 4 shows that the power-law index is less than 1 at all temperatures, indicating a non-Newtonian (pseudoplastic) fluid.

The resistance of the fluid inner layers to the external force is named viscosity that affects fluid pumping. Therefore, NF viscosity must be investigated seriously. Figure 5 shows the changes in the SAE50 viscosity versus SR at different temperatures. The viscosity versus SR represents the non-Newtonian behavior of the oil-based fluid. It also shows that the temperature increase has a significant effect in reducing the viscosity of base oil. As the temperature increases, the intermolecular force thus the viscosity decrease. Regarding the lower gradient of viscosity changes at higher temperatures, Fig. 5 shows that an increase in temperature leads to a reduction in the non-Newtonian NFs behavior.

Fig. 3 Consistency index versus temperature at different SVFs

Fig. 5 The viscosity of base fluid versus SR at different temperatures

Fig. 4 Power law index versus temperature at different SVFs

Figure 6 shows the changes in the hybrid NF viscosity versus SR at different SVFs. The NFs viscosity changes show a decreasing trend by increasing temperature. Low viscosity changes at higher temperatures are evident at all SVFs. At SVF of 0.5% and 5 °C, the most significant decrease (−13%) is observed, indicating the NFs behavior is closer to non-Newtonian behavior at lower temperatures.

3.2 Impact of temperature and SVF on NF viscosity

The changes in temperature and concentration directly affect the viscosity of fluids. By increasing temperature, the molecular force decreases, and the disconnection of molecular bonds occurs more easily. Figure 7 shows the viscosity versus temperature at different SVFs. At high temperatures, the viscosity changes are lesser than low temperatures. By increasing the temperature, the Van der Waals forces weaken between the molecules, resulting in the simplest intermolecular bonds breakdown and decreased viscosity. The results show that at an SR of 3999 s^{-1} , the viscosity decreases by 76% as the temperature increases at a concentration of 1%.

Figure 8 shows the NF viscosity versus concentration at different temperatures. By adding NPs to the base fluid, the number of NPs encounters an increase in base fluid molecules that subsequently increases the fluid viscosity. In addition, adding NPs to the base fluid causes larger nano-clusters that prevent the movement of fluid layers over each other, and increase the NF viscosity. As can be seen in Fig. 8, contrary to what we expected, the NF viscosity decreases at lower SVFs. The viscosity gradually increases with the addition of NPs. Lower SVFs make the layers easier to slip over each other; thereby it reduces friction and the NFs viscosity. In other word, at the beginning of the nanoparticles addition, a decrease in viscosity was

Fig. 6 The viscosity of all nanofluid samples versus shear rate at different temperatures

Fig. 7 The viscosity of hybrid NF versus temperature at different SVFs

Fig. 8 The viscosity of hybrid NF versus SVF at different temperatures

observed, due to the presence of nanoparticles, the layers move more easily, reducing the viscosity and decreasing their intermolecular forces. As more nanoparticles are

added, the intermolecular forces become stronger and the layers move harder together, which increases the viscosity. This phenomena cause minimum points in Fig. 8 curves.

Figure 9 shows the relative viscosity versus SR at different SVFs and temperatures. At the lower SVFs, the relative viscosity is less than 1, representing the NF viscosity is less than the base fluid. For concentrations up to 0.5%, the NF viscosity is less than the base fluid. If more NPs are added, i.e. concentrations of 0.75% and 1%, the NF viscosity is greater than the base fluid. Therefore, viscosity reduction at low SVFs can be guaranteed in the case of using MWCNT-TiO₂ (40:60)/SAE50. This means that the engineers are capable of developing a fluid with a lower viscosity (lower pumping cost) and a higher thermal conductivity coefficient. Finding an optimal point for these changes will result in a fluid development that can play a significant role in the future heat transfer processes. To ensure the experimental data in low concentrations, tests were repeated at least 5 times using two different viscometers that led to similar results.

The relative viscosity versus temperature at different SVFs is shown in Fig. 10 according to which as the temperature increases from 25 to 50 °C, the relative viscosity decreases. This means that the NF viscosity decreases more than the base fluid viscosity by increasing temperature.

Based on the figure, in SVFs less than 0.5%, the NF viscosity is less than the base fluid viscosity and in a concentration greater than 0.5%, the NF viscosity is greater than the base fluid viscosity.

Figure 11 shows the percent viscosity enhancement of MWCNT-TiO₂ (40:60)/SAE50 versus SVF at different temperatures. In concentrations less than 0.5%, viscosity decreases and in SVFs greater than 0.5% an increase in NFs viscosity is observed. Figure 11 shows that the highest viscosity reduction (– 22%) is observed at 50 °C and SVF of 0.0625%. Nevertheless, as the presence of NPs in the fluid increases, the increase in some of the particles collides prevents the movement of liquid layers over each other, which increases the NF viscosity. The highest viscosity enhancement (15%) is observed at 25 °C and SVF of 1%.

3.3 Comparison

A comparison is shown in Fig. 12 between the viscosities of hybrid MWCNT-TiO₂ (40:60)/SAE50 nanofluid and Non-hybrid TiO₂/SAE50 nanofluid (Hemmet et al. [74]) at the different temperatures, SVFs, and SRs. The hybridfluid

Fig. 9 The relative viscosity of hybrid NF versus shear rate at different SVFs and temperatures

Fig. 10 The relative viscosity of hybrid NF versus temperature at different SVFs

Fig. 11 Viscosity enhancement of hybrid NF versus SVF at different temperatures

viscosity drop at SVFs of 0.0625%, 0.125%, 0.25%, and 0.5% is significant compared to $\text{TiO}_2/\text{SAE50}$. This can be due to the positive effect of the CNT presence on the better

movement of NF layers over each other. Of course, with an increase in carbon nanotubes, the viscosity of hybrid NF moves toward the viscosity of $\text{TiO}_2/\text{SAE50}$. At SVE of 0.75%, the viscosity of both NFs is the same and at SVF of 1%, the viscosity of hybrid MWCNT-TiO_2 (40:60)/SAE50 NF is greater than $\text{TiO}_2/\text{SAE50}$. So, MWCNT-TiO_2 (40:60)/SAE50 NFs with concentrations lower than 0.5% is more suitable for engineering applications.

Figure 13 shows the percent viscosity enhancement in two different NFs. The highest percentage of viscosity increase for MWCNT-TiO_2 (40:60)/SAE50 is 15% at 25 °C with a concentration of 1%, and the highest percentage of viscosity reduction (−22%) is for SVF of 0.0625% at the temperature of 45 °C. Thus, they can be used for different purposes concerning the application type of NF.

3.4 Evaluation of economic value

For the analysis of NFs, viscosity changes along with NF usage costs can be considered as a suitable measure for the application of NFs on an industrial scale. In this section, a comparison has been made between the viscosity and the cost of using MWCNT-TiO_2 (40:60)/SAE50 nanofluid and the results of Hemmat Esfe et al. [74] on $\text{TiO}_2/\text{SAE50}$ at 50 °C. The cost of NF is base on the price announced by Kimia Nano-Danesh. Figure 14 shows the viscosity enhancement, as well as the cost of using the two mentioned NFs at the temperature of 50 °C and SR of 3999 s^{-1} . The cost of using two NFs is almost the same, but the percent increase and percent decrease in the viscosity of two NFs are very different, which can be used as a measure to select the appropriate NF. If NF is used in a system that requires less viscosity, the NF concerned in this study is a more appropriate option.

The cost and power of fluid pumping can be reduced using MWCNT-TiO_2 (40:60)/SAE50 nanofluids. In addition, it will save energy and increase productivity in different items. This nanofluid does not lead to an unnecessary increase in viscosity compared to $\text{TiO}_2/\text{SAE50}$ nanofluid at 50 °C. Due to the presence of MWCNTs, these nanofluids have high thermal properties.

3.5 Proposed correlation

The classical models are not able to provide a model for predicting the hybrid NF viscosity. To achieve an appropriate mathematical correlation for a precise prediction of

Fig. 12 The viscosity of different hybrid nanofluids versus SVF and temperature

Fig. 13 Viscosity enhancement of different hybrid nanofluids versus SVF and temperature

Fig. 14 A comparison between viscosity enhancement and cost of different hybrid nanofluids

the viscosity of MWCNT-TiO₂ (40:60)/SAE50, modeling was conducted base on the empirical data and finally, a novel correlation (Eq. 3) was proposed based on the temperature, SVF, and SR.

$$\begin{aligned} \mu_{nf} = & 2081.17 + 212.77\varphi - 103.04T - 0.068\dot{\gamma} \\ & - 14.78\varphi T + 0.0055\varphi\dot{\gamma} + 0.0023T\dot{\gamma} + 385.06\varphi^2 \\ & + 1.88T^2 + 2.93 \times 10^{-6}\dot{\gamma}^2 - 2.32 \times 10^{-5}\varphi T\dot{\gamma} - 0.0076\varphi^2 T \\ & - 0.0032\varphi^2\dot{\gamma} + 0.15\varphi T^2 - 7.91 \times 10^{-8}\varphi\dot{\gamma}^2 - 2.85 \times 10^{-5}T^2\dot{\gamma} \\ & + 1.33 \times 10^{-8}T\dot{\gamma}^2 - 227.42\varphi^3 - 0.011T^3 - 2 \times 10^{-10}\dot{\gamma}^3 \end{aligned} \quad (3)$$

Tables 4 and 5, show the significance of each parameter and the accuracy of Eq. 3, respectively. Due to the high coefficient of determination (R^2) of the proposed model (0.9882), the accuracy of the obtained results can be assured. The values greater than 0.1000 indicate that the model terms are not significant. Therefore, Eq. 4 is obtained by ignoring them in Eq. 3.

$$\begin{aligned} \mu_{nf} = & 2081.17 + 212.77\varphi - 103.04T - 14.78\varphi T \\ & + 385.06\varphi^2 + 1.88T^2 - 0.0032\varphi^2\dot{\gamma} + 0.15\varphi T^2 \\ & - 2.85 \times 10^{-5}T^2\dot{\gamma} - 227.42\varphi^3 - 0.011T^3 - 2 \times 10^{-10}\dot{\gamma}^3 \end{aligned} \quad (4)$$

Figure 15 shows the comparison between experimental data of MWCNT-TiO₂/SAE50(40:60) with the data obtained from the above-mentioned correlation. According to the figure, the viscosity data are well predicted by the proposed correlation, indicating its high precision.

The margin of deviation with respect to SVF is represented in Fig. 16. The average percentage of MOD was determined using Eq. 5.

$$MOD(\%) = \left[\frac{\left(\frac{\mu_{nf}}{\mu_{bf}} \right)_{Exp} \left(\frac{\mu_{nf}}{\mu_f} \right)_{Pred}}{\left(\frac{\mu_{nf}}{\mu_f} \right)_{Exp}} \right] \times 100 \quad (5)$$

3.6 Sensitivity analyze

The sensitivity analysis of the viscosity of MWCNT-TiO₂ (40:60)/SAE50 is shown in Fig. 17 in terms of temperature and SVF. By the use of Eq. 6, viscosity changes were applied to calculate sensitivity with respect to an increase in SVF by 10%. It was found that in the concentration of 1% and 50 °C, the sensitivity reaches its maximum value. In addition, at SVF of 0.0625% and 25 °C, the sensitivity is at the lowest level. Therefore, the preparation of NFs at high temperatures and SVFs should be considered more.

Table 4 Analysis of suggested correlations factors

Source	Sum of squares	df	Mean square	F Value	P value Prob > F
Model	3,198,588	19	168,346.7	810.4341	< 0.0001 significant
A-phi	16,478.88	1	16,478.88	79.33058	< 0.0001
B-T	166,193.8	1	166,193.8	800.0696	< 0.0001
C-SR	17.58094	1	17.58094	0.084636	0.7714
AB	12514.34	1	12514.34	60.24499	< 0.0001
AC	19.67333	1	19.67333	0.094709	0.7586
BC	1291.168	1	1291.168	6.215784	0.0135
A ²	1062.32	1	1062.32	5.114089	0.0249
B ²	64799.92	1	64799.92	311.9518	< 0.0001
C ²	5.986049	1	5.986049	0.028817	0.8654
ABC	1.604124	1	1.604124	0.007722	0.9301
A ² B	0.005543	1	0.005543	2.67E-05	0.9959
A ² C	61.26074	1	61.26074	0.294914	0.5877
AB ²	1531.258	1	1531.258	7.371595	0.0073
AC ²	1.52504	1	1.52504	0.007342	0.9318
B ² C	787.4641	1	787.4641	3.790913	0.0531
BC ²	8.300152	1	8.300152	0.039958	0.8418
A ³	5995.985	1	5995.985	28.86513	< 0.0001
B ³	3349.852	1	3349.852	16.12645	< 0.0001
C ³	288.8619	1	288.8619	1.390603	0.2398
Residual	38013.52	183	207.7242		
Cor Total	3236601	202			

The Model F-value of 810.43 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case, A, B, AB, BC, A², B², AB², A³, B³ are significant model terms. Values greater than 0.1000 indicate the model terms are not significant

If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model

Table 5 Analysis of variance for proposed correlation

SD	14.41264	R-Squared	0.988255
Mean	241.3089	Adj R-Squared	0.987036
C.V. %	5.972693	Pred R-Squared	0.985783
PRESS	46014.49	Adeq Precision	108.9135

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 108.913 indicates an adequate signal. This model can be used to navigate the design space

$$\text{Sensitivity} = \left(\frac{(\mu_{nf})_{\text{After Change}}}{(\mu_{nf})_{\text{Base Condition}}} - 1 \right) \times 100 \quad (6)$$

Fig. 15 A comparison between results from proposed correlation and experiment

Fig. 16 Margin Of Deviation percentage versus SVF

Fig. 17 SVF sensitivity at SR = 3999(1/sec)

4 Conclusion

In this study, the thermophysical properties of MWCNT-TiO₂ (40:60)/SAE50 NF were investigated. Experiments were performed at temperature range of 25–50 °C and SVFs of 0–1% with SRs of 666.5–9331 s⁻¹, to study the effect of those three parameters on viscosity changes. The nanofluid showed non-Newtonian behavior (pseudo plastic) based on viscosity dependency on SR. The main research questions were comparing the rheological behavior of hybrid NF with conventional NFs behavior available in literature that have the same base fluid (SAE 50) and same nanoparticle (TiO₂). Also the price analysis between hybrid and conventional NFs is the second main research question. The major finding of present work is negative relative viscosity for hybrid NF in some low SVFs. Based on

results viscosity of hybrid NFs with SVF of less than 0.25% was lower than the base fluid viscosity at all temperature that it could reduce the pumping power waste in a heat cycles. The stated decreasing viscosity behavior after adding the nanoparticles is not happened for conventional NF containing TiO₂. Surely the limitation of present work are expanding the temperature range and also the range of SR to have more information about the hybrid NF behavior that could be considered in future works. According to our studied range, the hybrid NFs are more efficient than the conventional NF if we look at their price and viscosity behavior simultaneously.

An economic study of the two NFs showed that costs were equal approximately, but the difference in viscosity increase was significant, and one should be selected based on the application considerations. In order to predict the viscosity, the relationship presented in terms of SR and VF and temperature has $R^2 = 0.9882$ and therefore the predicted values agree well with the experimental values. Investigation of sensitivity analysis showed that the sensitivity analysis reaches its maximum value at SVF of 1% and the temperature of 50 °C, and its minimum value at SVF of 0.0625% and the temperature of 25 °C.

Compliance with ethical standards

Conflict of interest All authors have declare that they have no conflict of interest.

References

1. Sarafraz MM, Arjomandi M (2018) Demonstration of plausible application of gallium nano-suspension in microchannel solar thermal receiver: experimental assessment of thermo-hydraulic performance of microchannel. *Int Commun Heat Mass Transfer* 94:39–46
2. Sarafraz MM, Arya H, Arjomandi M (2018) Thermal and hydraulic analysis of a rectangular microchannel with gallium-copper oxide nano-suspension. *J Mol Liq* 263:382–389
3. Safaei MR, Gooarzi M, Akbari OA, Shadloo MS, Dahari M (2016) Performance evaluation of nanofluids in an inclined ribbed microchannel for electronic cooling applications. In: *Electronics cooling*, p 832
4. Zhao H, Wang JX, Wang QA, Chen JF, Yun J (2007) Controlled liquid antisolvent precipitation of hydrophobic pharmaceutical nanoparticles in a microchannel reactor. *Ind Eng Chem Res* 46(24):8229–8235
5. Wagner J, Kirner T, Mayer G, Albert J, Köhler JM (2004) Generation of metal nanoparticles in a microchannel reactor. *Chem Eng J* 101(1–3):251–260
6. Wunsch R, Fichtner M, Görke O, Haas-Santo K, Schubert K (2002) Process of applying Al₂O₃ coatings in microchannels of completely manufactured microstructured reactors. *Chem Eng Technol Ind Chem Plant Equip Process Eng Biotechnol* 25(7):700–703
7. Hung LH, Lee AP (2007) Microfluidic devices for the synthesis of nanoparticles and biomaterials. *J Med Biol Eng* 27(1):1

8. Chamkha AJ, Molana M, Rahnama A, Ghadami F (2018) On the nanofluids applications in microchannels: a comprehensive review. *Powder Technol* 332:287–322
9. Karami E, Rahimi M, Azimi N (2018) Convective heat transfer enhancement in a pitted microchannel by stimulation of magnetic nanoparticles. *Chem Eng Process Process Intensif* 126:156–167
10. Sarafraz MM, Pourmehran O, Yang B, Arjomandi M, Ellahi R (2020) Pool boiling heat transfer characteristics of iron oxide nano-suspension under constant magnetic field. *Int J Therm Sci* 147:106131
11. Koca HD et al (2018) Effect of particle size on the viscosity of nanofluids: a review. *Renew Sustain Energy Rev* 82:1664–1674
12. Shiriny A, Bayareh M, Nadooshan AA (2019) Nanofluid flow in a microchannel with inclined cross-flow injection. *SN Appl Sci* 1(9):1015
13. Murshed SS, Estellé PJR, Reviews SE (2017) A state of the art review on viscosity of nanofluids. *Renew Sustain Energy Rev* 76:1134–1152
14. Sheikholeslami M, Shehzad SA (2017) Magnetohydrodynamic nanofluid convection in a porous enclosure considering heat flux boundary condition. *Int J Heat Mass Transf* 106:1261–1269
15. Alimohammadi Z, Akhijahani HS, Salami P (2020) Thermal analysis of a solar dryer equipped with PTSC and PCM using experimental and numerical methods. *Sol Energy* 201:157–177
16. Banisharif A, Aghajani M, Van Vaerenbergh S, Estellé P, Rashidi A (2020) Thermophysical properties of water ethylene glycol (WEG) mixture-based Fe₃O₄ nanofluids at low concentration and temperature. *J Mol Liq* 302:112606
17. Alshaheen AAS, Kianifar A, Rahimi AB (2019) Experimental study of using nano-(GNP, MWCNT, and SWCNT)/water to investigate the performance of a PVT module. *J Therm Anal Calorim* 25:1–13
18. Khan SA, Nie Y, Ali B (2020) Multiple slip effects on MHD unsteady viscoelastic nano-fluid flow over a permeable stretching sheet with radiation using the finite element method. *SN Appl Sci* 2(1):66
19. Ali A, Ali Y, Marwat DK, Awais M, Shah Z (2020) Peristaltic flow of nanofluid in a deformable channel with double diffusion. *SN Appl Sci* 2(1):100
20. Ogunseye HA, Mondal H, Sibanda P, Mambili-Mamoundou H (2020) Lie group analysis of a Powell-Eyring nanofluid flow over a stretching surface with variable properties. *SN Appl Sci* 2(1):115
21. Esfe MH, Rejvani M, Karimpour R, Arani AAA (2017) Estimation of thermal conductivity of ethylene glycol-based nanofluid with hybrid suspensions of SWCNT–Al₂O₃ nanoparticles by correlation and ANN methods using experimental data. *J Therm Anal Calorim* 128(3):1359–1371
22. Ramzan M, Bilal MJOML (2016) Three-dimensional flow of an elastico-viscous nanofluid with chemical reaction and magnetic field effects. *J Mol Liq* 215:212–220
23. Esfe MH, Saedodin S, Wongwises S, Toghraie D (2015) An experimental study on the effect of diameter on thermal conductivity and dynamic viscosity of Fe/water nanofluids. *J Therm Anal Calorim* 119(3):1817–1824
24. Nithiyanantham U, González-Fernández L, Grosu Y, Zaki A, Igartua JM, Faik A (2020) Shape effect of Al₂O₃ nanoparticles on the thermophysical properties and viscosity of molten salt nanofluids for TES application at CSP plants. *Appl Therm Eng* 169:114942
25. Timofeeva EV, Routbort JL, Singh D (2009) Particle shape effects on thermophysical properties of alumina nanofluids. *J Appl Phys* 106(1):014304
26. Munyalo JM, Zhang X (2018) Particle size effect on thermophysical properties of nanofluid and nanofluid based phase change materials: a review. *J Mol Liq* 265:77–87
27. Esfe MH, Nadooshan AA, Arshi A, Alirezaie A (2018) Convective heat transfer and pressure drop of aqua based TiO₂ nanofluids at different diameters of nanoparticles: data analysis and modeling with artificial neural network. *Physica E Low Dimens Syst* 97:155–161
28. Esfe MH, Esforjani SSM, Akbari M, Karimipour A (2014) Mixed-convection flow in a lid-driven square cavity filled with a nanofluid with variable properties: effect of the nanoparticle diameter and of the position of a hot obstacle. *Heat Transf Res* 45(6):563–578
29. Ali H (2020) Hybrid nanofluids for convection heat transfer, 1st edn. eBook ISBN: 9780128192818
30. Sheikholeslami M, Shehzad SA (2017) CVFEM for influence of external magnetic source on Fe₃O₄-H₂O nanofluid behavior in a permeable cavity considering shape effect. *Int J Heat Mass Transf* 115:180–191
31. Liu X, Mohammed HI, Ashkezari AZ, Shahsavari A, Hussein AK, Rostami S (2020) An experimental investigation on the rheological behavior of nanofluids made by suspending multi-walled carbon nanotubes in liquid paraffin. *J Mol Liq* 300:112269
32. Tian Z, Rostami S, Taherialekouchi R, Karimipour A, Moradikazerouni A, Yarmand H, Zulkifli NWBM (2020) Prediction of rheological behavior of a new hybrid nanofluid consists of copper oxide and multi wall carbon nanotubes suspended in a mixture of water and ethylene glycol using curve-fitting on experimental data. *Stat Mech Appl Physica A* 79:124101
33. Sharma AK, Tiwari AK, Dixit ARJR, Reviews SE (2016) Rheological behaviour of nanofluids: a review. *Renew Sustain Energy Rev* 53:779–791
34. Shoghli SN, Jamali J, Moraveji MKJET, Science F (2016) Electrical conductivity, viscosity, and density of different nanofluids: an experimental study. *Exp Therm Fluid Sci* 74:339–346
35. Mabood F, Shateyi S, Rashidi M, Momoniat E, Freidoonimehr NJAPT (2016) MHD stagnation point flow heat and mass transfer of nanofluids in porous medium with radiation, viscous dissipation and chemical reaction. *Adv Powder Technol* 27(2):742–749
36. Esfe MH, Kamyab MH (2019) Viscosity analysis of enriched SAE50 by nanoparticles as lubricant of heavy-duty engines. *J Therm Anal Calorim* 140:79–93
37. Esfe MH, Ahangar MRH, Rejvani M, Toghraie D, Hajmohammad MH (2016) Designing an artificial neural network to predict dynamic viscosity of aqueous nanofluid of TiO₂ using experimental data. *Int Commun Heat Mass Transfer* 75:192–196
38. Namburu PK, Kulkarni DP, Misra D, Das DK (2007) Viscosity of copper oxide nanoparticles dispersed in ethylene glycol and water mixture. *Exp Thermal Fluid Sci* 32(2):397–402
39. Kole M, Dey TK (2010) Viscosity of alumina nanoparticles dispersed in car engine coolant. *Exp Thermal Fluid Sci* 34(6):677–683
40. Nadooshan AA, Esfe MH, Afrand M (2017) Evaluation of rheological behavior of 10W40 lubricant containing hybrid nanomaterial by measuring dynamic viscosity. *Physica E Low Dimens Syst* 92:47–54
41. Attari H, Derakhshanfard F, Darvanjooghi MHK (2017) Effect of temperature and mass fraction on viscosity of crude oil-based nanofluids containing oxide nanoparticles. *Int Commun Heat Mass Transfer* 82:103–113
42. Abdollahi A, Darvanjooghi MHK, Karimipour A, Safaei MR (2018) Experimental study to obtain the viscosity of CuO-loaded nanofluid: effects of nanoparticles' mass fraction, temperature and basefluid's types to develop a correlation. *Meccanica* 53(15):3739–3757
43. Esfe MH, Reiszadeh M, Esfandeh S, Afrand M (2018) Optimization of MWCNTs (10%)–Al₂O₃ (90%)/5W50 nanofluid viscosity using experimental data and artificial neural network. *Physica A Stat Mech Appl* 512:731–744

44. Pourmehran O, Sarafraz MM, Rahimi-Gorji M, Ganji DD (2018) Rheological behaviour of different metal-based nano-fluids between rotating discs: a new insight. *J Taiwan Inst Chem Eng* 88:37–48
45. Alirezaie, A., Saedodin, S., Esfe, M. H., & Rostamian, S. H. (2017). Investigation of rheological behavior of MWCNT (COOH-functionalized)/MgO-engine oil hybrid nanofluids and modelling the results with artificial neural networks. *Journal of Molecular Liquids*, 241, 173–181
46. Ghahdarijani AM, Hormozi F, Asl AHJCIH, Transfer M (2017) Convective heat transfer and pressure drop study on nanofluids in double-walled reactor by developing an optimal multilayer perceptron artificial neural network. *Int Commun Heat Mass Transf* 84:11–19
47. Esfe, M. H., Motahari, K., Sanatizadeh, E., Afrand, M., Rostamian, H., & Ahangar, M. R. H. (2016). Estimation of thermal conductivity of CNTs-water in low temperature by artificial neural network and correlation. *International Communications in Heat and Mass Transfer*, 76, 376–381
48. Esfe MH, Saedodin S, Biglari M, Rostamian H (2015) Experimental investigation of thermal conductivity of CNTs- Al_2O_3 /water: a statistical approach. *Int Commun Heat Mass Transf* 69:29–33
49. Sheikholeslami M (2019) Numerical approach for MHD Al_2O_3 -water nanofluid transportation inside a permeable medium using innovative computer method. *Comput Methods Appl Mech Eng* 344:306–318
50. Esfe, M. H., Arani, A. A. A., Badi, R. S., & Rejvani, M. (2018). ANN modeling, cost performance and sensitivity analyzing of thermal conductivity of DWCNT-SiO₂/EG hybrid nanofluid for higher heat transfer. *Journal of Thermal Analysis and Calorimetry*, 131(3), 2381–2393
51. Soltani Omid, Akbari Mohammad (2016) Effects of temperature and particles concentration on the dynamic viscosity of MgO-MWCNT/ethylene glycol hybrid nanofluid. *Physica E Exp Study* 84:564–570
52. Aberoumand S, Jafarimoghaddam A (2017) Experimental study on synthesis, stability, thermal conductivity and viscosity of Cu-engine oil nanofluid. *J Taiwan Inst Chem Eng* 71:315–322
53. Sarafraz MM, Arya A, Nikkhar V, Hormozi F (2016) Thermal performance and viscosity of biologically produced silver/coconut oil nanofluids. *Chem Biochem Eng Q* 30(4):489–500
54. Esfe MH, Hajmohammad MH (2017) Thermal conductivity and viscosity optimization of nanodiamond- Co_3O_4 /EG (40: 60) aqueous nanofluid using NSGA-II coupled with RSM. *J Mol Liq* 238:545–552
55. Garoosi F (2020) Presenting two new empirical models for calculating the effective dynamic viscosity and thermal conductivity of nanofluids. *Powder Technol* 59:963
56. Eastman JA, Choi US, Li S, Thompson LJ, Lee S (1996) Enhanced thermal conductivity through the development of nanofluids. In: *MRS online proceedings library archive*, p 457
57. Esfe MH, Wongwises S, Naderi A, Asadi A, Safaei MR, Rostamian H, Karimipour A (2015) Thermal conductivity of Cu/TiO₂-water/EG hybrid nanofluid: experimental data and modeling using artificial neural network and correlation. *Int Commun Heat Mass Transf* 66:100–104
58. Esfe MH, Arani AAA, Rezaie M, Yan WM, Karimipour A (2015) Experimental determination of thermal conductivity and dynamic viscosity of Ag-MgO/water hybrid nanofluid. *Int Commun Heat Mass Transf* 66:189–195
59. Esfe MH, Yan WM, Akbari M, Karimipour A, Hassani M (2015) Experimental study on thermal conductivity of DWCNT-ZnO/water-EG nanofluids. *Int Commun Heat Mass Transf* 68:248–251
60. Esfe MH, Esfandeh S, Arani AAA (2019) Proposing a modified engine oil to reduce cold engine start damages and increase safety in high temperature operating conditions. *Powder Technol* 355:251–263
61. Esfe MH, Arani AAA, Esfandeh S, Afrand M (2019) Proposing new hybrid nano-engine oil for lubrication of internal combustion engines: preventing cold start engine damages and saving energy. *Energy* 170:228–238
62. Esfe MH, Arani AAA, Esfandeh S (2018) Improving engine oil lubrication in light-duty vehicles by using of dispersing MWCNT and ZnO nanoparticles in 5W50 as viscosity index improvers (VII). *Appl Therm Eng* 143:493–506
63. Abdolbaqi MK et al (2016) Experimental investigation and development of new correlation for thermal conductivity and viscosity of BioGlycol/water based SiO₂. *Int Commun Heat Mass Transf* 56:463
64. Esfe MH, Saedodin S, Asadi A (2014) An empirical investigation on the dynamic viscosity of Mg (OH) 2-ethylene glycol in different solid concentrations and proposing new correlation based on experimental data. *Int J Nat Eng Sci* 5(3):29–34
65. Aberoumand S, Jafarimoghaddam A, Moravej M, Aberoumand H, Javaherdeh K (2016) Experimental study on the rheological behavior of silver-heat transfer oil nanofluid and suggesting two empirical based correlations for thermal conductivity and viscosity of oil based nanofluids. *Appl Therm Eng* 101:362–372
66. Moghaddam MA, Motahari K (2017) Experimental investigation, sensitivity analysis and modeling of rheological behavior of MWCNT-CuO (30–70)/SAE40 hybrid nano-lubricant. *Appl Therm Eng* 123:1419–1433
67. Abdolbaqi MKh et al (2016) An experimental determination of thermal conductivity and viscosity of BioGlycol/water based TiO₂ nanofluids. *Int Commun Heat Mass Transf* 77:22–32
68. Esfe MH, Esfandeh S, Rejvani M (2018) Modeling of thermal conductivity of MWCNT-SiO₂ (30: 70%)/EG hybrid nanofluid, sensitivity analyzing and cost performance for industrial applications. *J Therm Anal Calorim* 131(2):1437–1447
69. Seo MH, Na KH, Yang WH, Song TH, Choi WY (2020) Characterization of a TiO₂/multi-wall carbon nanotube core-shell nanocomposite synthesized by a hydrothermal method. *J Nanosci Nanotechnol* 20(6):3582–3587
70. Zhang J, Wang L, Lyu S, Ye W, Xu BB, Qiu H, Chen L, Gu J (2020) Fabrication and investigation on ternary heterogeneous MWCNT@TiO₂-C fillers and their silicone rubber wave-absorbing composites. *Compos A Appl Sci Manuf* 129:105714
71. Esfe MH, Esfandeh S (2020) 3D numerical simulation of the enhanced oil recovery process using nanoscale colloidal solution flooding. *J Mol Liq* 301:112094
72. Esfe MH, Hosseiniadeh E, Esfandeh S (2020) Flooding numerical simulation of heterogeneous oil reservoir using different nanoscale colloidal solutions. *J Mol Liq* 302:111972
73. <https://www.us-nano.com/>
74. Esfe MH, Rostamian H (2017) Non-Newtonian power-law behavior of TiO₂/SAE 50 nano-lubricant: an experimental report and new correlation. *Molliq*. <https://doi.org/10.1016/j.molliq.2017.02.014>

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