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Curve-fitting on experimental thermal conductivity of motor oil under influence of hybrid nano additives containing multi-walled carbon nanotubes and zinc oxide

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HIGHLIGHTS

- Experimental investigation on thermal conductivity of ZnO-MWCNT/SAE 10W40 hybrid nanofluid.
- Thermal conductivity ratio enhances with increasing the solid volume fraction and temperature.
- Curve-fitting on test measurements as a function of volume fraction and temperature.
- Deviation analysis of the thermal conductivity ratio.
- Good agreement between experimental results and correlations outputs.

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ABSTRACT

Hybrid nanofluids has been attracted lots of attention due to simultaneous take advantage of the properties of two or more kinds of nanoparticles in the base fluid. Carbon Nanotubes (CNTs) are utilized widely attached to metal oxide nanoparticles due to significant thermal characteristics. This study aims to assess experimentally the thermal conductivity of the hybrid nanofluid of Zinc Oxide (ZnO) and Multi-Wall CNT (MWCNT) in Engine oil (SAE 10W40). The influences of nanoparticles concentration as well as fluid's temperature are evaluated. The experiments performed at the temperature between 25 °C and 50 °C and nanoparticles volume fraction from 0.05 to 0.8 %. The experimental results showed that a higher ratio of nano-lubricant thermal conductivity is achieved for a higher volume fraction and temperature of nanoparticles. According to the absence of an exact relationship to determine the thermal conductivity of ZnO-MWCNT/Engine oil, a correlation is developed based on the test measurements presented in terms of volume fraction and temperature using a curve-fitting method. A deviation

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analysis is also performed on the ratio of thermal conductivity achieved from the developed correlation and experimental data showing a reasonable agreement

1. Introduction

In order to modify the rate of heat transfer, nanofluids has been widely used in recent years which are manufactured from the suspension of nanoparticles in a base fluid and many applications have been reported for them [1–10]. By adding solid nanoparticles to the base fluid, the characteristics of the nanofluid such as the thermal conductivity are modified. The effective thermal conductivity can be determined approximately based on the Maxwell theory [1]. Lots of researches has been studied the thermophysical properties of nanofluids [11–33]. Recently, new nano-additives containing two or more nanoparticles have been used by researchers. This group of nano-additives is called hybrid nano-additive. Table 1 presents an overview of the previous researches on hybrid nanofluids.

Here, the details of some works performed on hybrid nanofluids are briefly reviewed. Execution on the effective thermal conductivity of hybrid nanofluid including Magnesium Oxide (MgO) and Functionalized Multi-walled CNTs (FMWCNTs) in ethylene glycol (EG) was investigated experimentally by Afrand [34]. His research was arranged for solid volume fractions range from 0% to 0.6% and various temperatures range from 25 °C to 50 °C. He showed that the thermal conductivity of nanofluids supremely boosts by enhancing solid volume fractions of nano-particles in the base fluid. Furthermore, the thermal conductivity of EG raises by raising the temperature at the modified set up; even though, the thermal conductivity of hybrid nanofluid enhances marginally. At the concentration of 0.6% and temperature of 25 °C, the supremum augmentation is 21.3%. Finally, he reached an accurate correlation in order to calculate the thermal conductivity in terms of solid volume fractions and temperatures. Rostami et al. [35] studied experimentally on the preparation and determination of the thermal conductivity of a novel hybrid nanofluid which was prepared by the Two-step method. They employed the hybrid nanofluid including antifreeze as the base fluid with Copper Oxide (CuO) and Graphene oxide (GO). The surface and atomic structure of the nano-additives, respectively, were classified by XRD and FESEM examinations. They evaluated different volume fractions of 0.1%, 0.2%, 0.4%, 0.8%, 1.6% and different temperatures range from 25 °C to 50 °C. They showed an improvement in the thermal conductivity of nanofluid for a higher concentration of nanoparticles using KD2-Pro analyzer. The maximum amplification of thermal conductivity of the proposed nanofluid was 43.4%. Safaei et al. [36] performed an experimental analysis of a hybrid nanofluid including Zinc Oxide (ZnO) and Titanium Oxide (TiO_2) in EG. They achieved variable functions, using the curve-fitting method to calculate the thermal conductivity. They showed thermal conductivity increment using the produced hybrid nanofluid compared with the base fluid. Furthermore, the finest transfer correlation for training the artificial neural network was carefully chosen in terms of volume fraction and temperature of the ZnO-TiO_2/EG hybrid nanofluid. They have proved that the neural network is capable to foretell the nanofluid's thermal conductivity extension because the ANN consequences and examined data comparison had great accuracy. Hemmat Esfe et al. [37] investigated a hybrid nanofluid in which SWCNT-MgO particles were suspended in EG. They studied different volume fractions of 0.015%, 0.025%, 0.05%, 0.1%, 0.2%, 0.35%, 0.45% and 0.55% at different temperatures range from 25 °C to 50 °C for the nanofluid. They presented that the thermal conductivity amplification is depended on the amount of nanoparticles and temperature. Furthermore, in 0.55% volume fraction, there was an unexpected growth up to 35% in the thermal conductivity. They showed that the thermal conductivity of nanofluids is highly affected by temperature growing. Additionally, the cost of nanofluid could be diminished by adding MgO nanoparticles. They have achieved a correlation for the thermal conductivity of hybrid nanofluid showing a great agreement based on the experimental data. Aparna et al. [38] investigated on the thermal conductivity of Al_2O_3/Ag (50:50) vol% as a hybrid nanofluid with the base fluid of distilled water experimentally. The stability was prepared by applying Polyvinylpyrrolidone. Particularly, surface properties, the particle size and the surface charge were analyzed using X-ray diffraction, dynamic light scattering and zetapotential, respectively. Their experiments were accomplished for particle loading range from 0.005 vol% to 0.1 vol%. The transient hot-wire method was used to measure the thermal conductivity of nanofluid. Their results exhibited that this especial hybrid nanofluid called Al_2O_3/Ag has a greater increment in thermal conductivity than Al_2O_3. They suggested a correlation in which they were capable to determine the thermal conductivity.

The aim of this paper is to examine the nano-lubricant thermal conductivity created by ZnO-MWCNT/Engine oil (SAE 10W40) experimentally. The influences of nanoparticles concentration and fluid's temperature on the thermal conductivity are studied. A correlation is developed to determine the thermal conductivity of nano-lubricant. To the best of author's knowledge, for the proposed nano-lubricant, no comprehensive study and no developed correlation has been shown in the literature.

2. Material specification

The specifications of nano-additives are presented in Tables 2 and 3.

Table 1
A brief review of the hybrid nanofluids studies.

Ref.	Base fluid	Nano particles	Volume concentration (%)	Temperature (°C)	Enhancement in thermal conductivity (%)
[39]	EG	ZnO-TiO_2	0.1–3.5	25–50	32
[40]	Water	ZnO-Ag	0.125-2	25–50	26
[41]	waterand EG (60:40)	DWCNTs-ZnO	0.025-1	25–50	33
[42]	waterand EG (50:50)	ZnO-MWCNTs	0.02-1	30–50	28.1
[43]	water and EG (40:60)	SWCNTs-ZnO(30:70)	0.05–1.6	26–50	45
[44]	Thermal Oil	Al_2O_3-MWCNTs(85–15)	0.125–1.5	25–50	45
[34]	EG	MgO-FMWCNTs	0-0.6	25–50	21.3
[45]	EG	FMWCNTs-Fe_3O_4	0-2.3	25–50	30
[46]	Water	TiO_2-MWCNTs	0.02–0.08	36–60	13.71
[47]	Water	Ag-MWCNTs	0.1	20–50	20.4

Table 2
Engine oil specifications (Behran Super Pishtaz SAE 10W40 Oil).

Viscosity (100 °C)	15.5 cst
Density (15 °C)	869 kg/m^3
Viscosity Index	160
Flash Point	224 °C
Pour Point	−33 °C

Table 3
MWCNTs and ZnO_2 specifications.

Specifications	Multi-walled carbon nanotubes (MWCNT)	Zinc Dioxide (ZnO)
Purity (%)	>97%	>99%
Color	Black	Milky white
Size <nm>	20–30	25–35
Density <gr/cm^3>	2.1	5.6
Specific area <m^2/gr>	110	35–50

Table 4
The required MWCNT and ZnO nanoparticles mass at different concentrations.

No.	Volume fraction(%)	Density (gr/cm^3)		Mass (gr)	
		ZnO	MWCNT	ZnO	MWCNT
1	0.05			0.42	0.158
2	0.1			0.84	0.315
3	0.2	5.6	2.1	1.68	0.63
4	0.4			3.36	1.26
5	0.6			5.04	1.89
6	0.8			6.72	2.52

The Two-step procedure was used for nano-lubricant preparation for different nanoparticles volume fractions. The required amounts of nanoparticles and base fluid for preparation of different volume fractions is determined based on:

$$\phi = \left[\frac{\left(\frac{w}{\rho}\right)_{ZNO} + \left(\frac{w}{\rho}\right)_{MWCNTs}}{\left(\frac{w}{\rho}\right)_{ZNO} + \left(\frac{w}{\rho}\right)_{MWCNTs} + \left(\frac{w}{\rho}\right)_{SAE\,10W40}} \right] \times 100 \tag{1}$$

The required amount of ZnO and MWCNT (75:25) is shown in Table 4 at different concentrations.

3. Preparing the nanofluid

In order to make the nano-lubricant at various volume fractions based on Two-stage method, the masses required for making desirable volume fractions were employed according to Table 4. Then, the nanoparticles were poured into the base fluid and stirred for 2.5 h by a magnetic stirrer. Next, the mixture was sonicated at 24 kHz for 6 h using a 400 W ultrasonic device (Hielscher, Germany) to break the aggregates and fully suspend the nanoparticles in the base fluid. The produced nano-lubricant offers desirable stability, showing no sign of precipitation or sedimentation before the experiment. The structure and size of the dried MWCNTs and ZnO nanoparticles were examined by X-ray diffraction. The

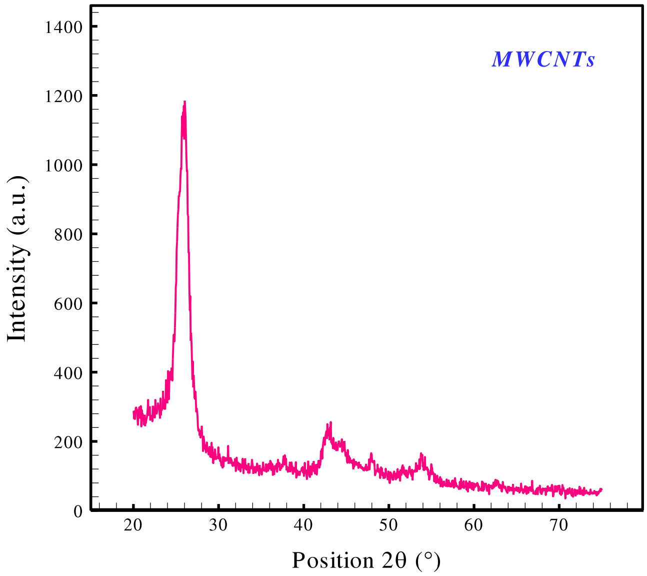

Fig. 1. XRD of MWCNTs.

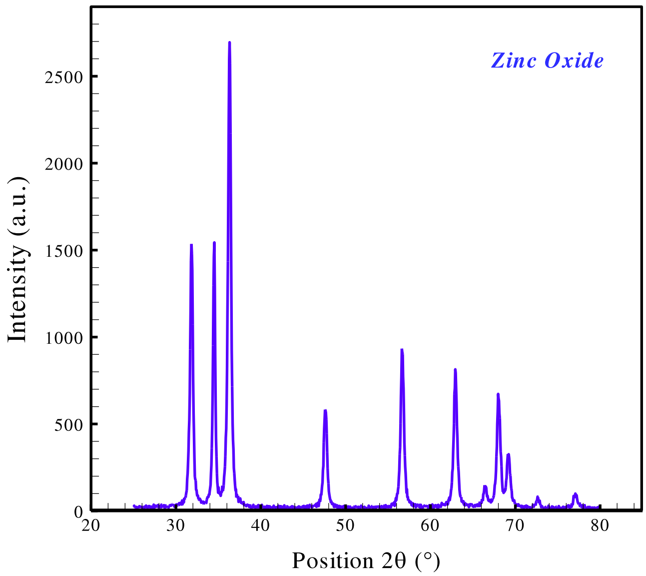

Fig. 2. XRD of ZnO nanoparticles.

size and structure of the nanoparticles were verified by XRD diagrams. The XRD results of the nanotubes and nanoparticles are presented in Figs. 1 and 2, respectively.

4. Measuring thermal conductivity

KD2-Pro device is employed for thermal conductivity measurement of the hybrid nano-lubricant. The device mainly operates using the transient hot-wire method as one of the best precise methods. The KS-1 sensor of the device with a maximum precision of 5% is used in this test.

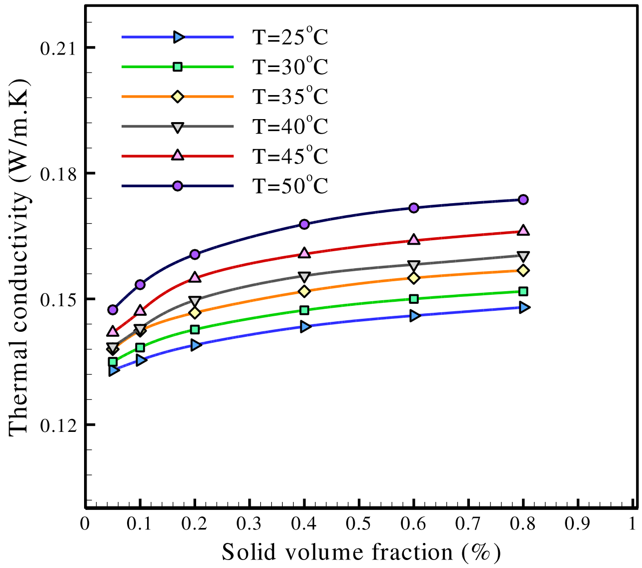

Fig. 3. K_{eff} against the volume fraction at different temperatures.

Table 5
K_{eff} versus temperature and volume fraction.

T(°C) / φ(%)	25	30	35	40	45	50
0	0.132	0.133	0.135	0.136	0.137	0.139
0.05	0.133	0.135	0.138	0.140	0.142	0.146
0.1	0.135	0.137	0.141	0.143	0.147	0.152
0.2	0.141	0.144	0.148	0.151	0.156	0.162
0.4	0.143	0.146	0.151	0.156	0.160	0.165
0.6	0.146	0.150	0.155	0.159	0.163	0.171
0.8	0.148	0.152	0.156	0.160	0.167	0.174

5. Results and discussion on thermal conductivity

5.1. Volume fraction effect

The thermal conductivity of hybrid nano-lubricant (K_{eff}) in terms of volume fraction is illustrated in Fig. 3 at various temperatures. Considering the data presented at T = 25 °C, K_{eff} rises from 0.133 W/m°C to 0.148 W/m°C when the volume fraction increments from 0.05 to 0.8, with the highest K_{eff} corresponds to the largest volume fraction. At T = 30 °C, increasing the volume fraction of nanoparticles from 0.05 to 0.8 results in a higher K_{eff} obtained from 0.135 W/m°C to 0.152 W/m°C. Increasing the volume fraction to 0.05 at T = 35 °C results in a higher K_{eff} by almost 2.22% compared with the base fluid. At the same temperature, a higher nanoparticles volume fraction implies an increase in K_{eff}. The largest increase in K_{eff} corresponds to the volume fraction of 0.8, for which K_{eff} enhances by almost 13.46% at T = 35 °C. Similarly, increasing the volume fraction of the nanofluid to 0.05 at T = 40 °C results in an enhancement of K_{eff} by almost 2.9%, while increasing the volume fraction up to 0.8, enhances K_{eff} by 17.6% at the same temperature. It is also deduced from the data that temperature increment of the base fluid from 25 °C to 40 °C, and the addition of nanoparticles at a volume fraction of 0.8 increases K_{eff} by 8.10%. At T = 45 °C and 50 °C, increasing the volume fraction enhances K_{eff}. Furthermore, increasing the temperature at any volume fraction enhances K_{eff}. At T = 50 °C, K_{eff} at $\varphi = 0.05$ is 5% higher than the base fluid with at the same temperature, and increasing the volume fraction up to 0.8 enhances K_{eff} by 25.1% compared with the base fluid at the same temperature, showing the considerable contribution of temperature and volume fraction in K_{eff}. At higher volume fractions, particles form larger clusters which help further increase in K_{eff} by transporting heat more efficiently. Increasing temperature leads to a higher intensity of nanoparticles Brownian motion and more collisions between the fluid molecules and nanoparticles results in a higher K_{eff}.

Table 5 presents the changes in K_{eff} for different temperatures and concentrations. It is evident that the enhancement of the temperature and the volume fraction enhance K_{eff}. Furthermore, the volume fraction is more effective than the temperature. The impact of temperature is low at small volume fractions and becomes more effective for a higher volume fraction.

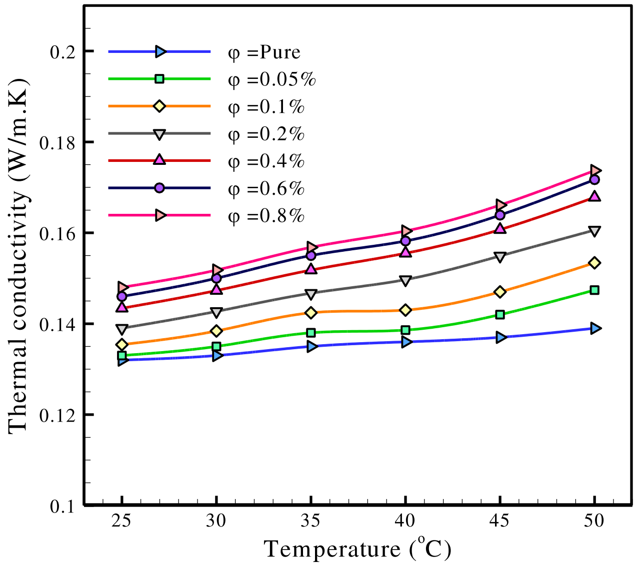

Fig. 4. The variation of K_{eff} in terms of temperature for different volume fractions.

Table 6
Variation of K_{eff} for different temperature and volume fraction.

T(°C) φ(%)	25	30	35	40	45	50
0.05	0.75	1.48	2.17	2.86	3.52	4.79
0.1	1.48	1.46	2.13	2.10	3.40	3.95
0.2	4.26	1.86	2.73	2.30	5.77	6.17
0.4	1.40	1.37	1.99	3.21	2.50	1.82
0.6	2.05	1.67	2.58	1.89	1.84	3.51
0.8	1.35	1.32	0.64	0.63	2.40	1.72

5.2. Temperature effect

Fig. 4 shows the variation of K_{eff} against temperature for different concentrations. For $\varphi = 0$, temperature increment from 25 °C to 50 °C results in the enhancement of K_{eff} by 5.03%. The highest increase in K_{eff} happens at T = 50 °C. At $\varphi = 0.05\%$ and T = 50 °C, K_{eff} is 4.79% higher than that for the base fluid. At $\varphi = 0.1\%$, temperature increment from 25 °C to 50 °C enhances K_{eff} by 2.22%–8.55% compared with the base fluid; put differently, the addition of 0.1% nanoparticles enhances K_{eff} by 8.55% compared with the base fluid. At $\varphi = 0.2\%$, increasing the temperature from 25 °C to 50 °C enhances K_{eff} by 6.38% to 14.19% compared with the base fluid. At $\varphi = 0.4\%$, by increasing the temperature from 25 °C to 50 °C, K_{eff} enhances by 7.60% to 15.75% compared with the base fluid. At $\varphi = 0.6\%$, increasing the temperature from 25 °C to 50 °C enhances K_{eff} by 9.58% to 18.71% compared with the base fluid, while the same increase in the temperature at $\varphi = 0.8\%$ enhances K_{eff} by 10.81% to 21.46% compared with the base fluid. Nanoparticles motion is promoted at higher temperatures, enhancing K_{eff} as a result of more impacts between the nanoparticles atoms surface and the fluid molecules. The enhancement of K_{eff} with increasing the temperature and volume fraction corresponds to the weakened intermolecular bonds at fluid layers and also the increased Brownian motion and impacts between the nanoparticles. Simultaneously, by increasing the temperature and volume fraction, the effects of the Brownian motion and particle clustering are combined, considerably enhancing K_{eff}. Given that the Brownian motion is more effective at higher temperatures, the impact of the volume fraction on the thermal conductivity is amplified at higher temperatures.

5.3. Sonication time effect

Three different durations of sonication are tried for each volume fraction at various temperatures. Interestingly, the sonication time is found not to have any impact on K_{eff}, which is due to the nanoparticles being oxides (See Table 6).

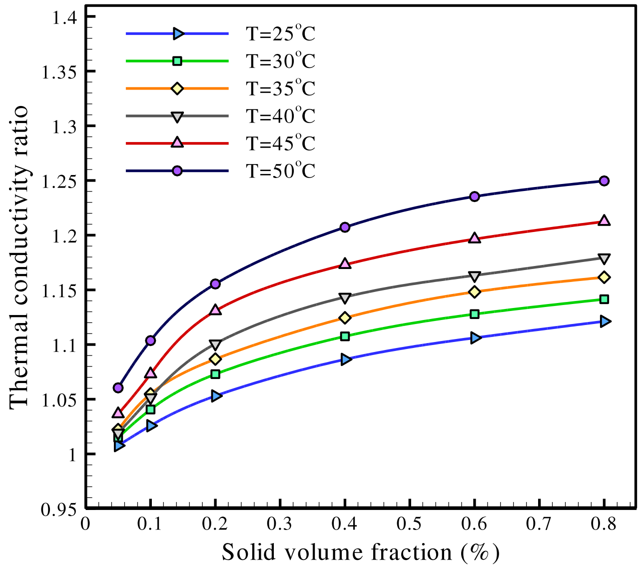

Fig. 5. Thermal conductivity ratio in terms of volume fraction at various temperatures.

6. Results and discussion on thermal conductivity ratio

6.1. Volume fraction effect

Fig. 5 shows the variation of thermal conductivity ratio at different temperatures of 30 °C, 35 °C, 40 °C, 45 °C, and 50 °C. A higher thermal conductivity ratio is achieved for a higher volume fraction and the largest thermal conductivity ratio corresponds to $\varphi = 0.8\%$ and T = 50 °C. Increasing the volume fraction impacts clustering while increasing the temperature affects the Brownian motion and the fluid layer mixture, enhancing the thermal conductivity. The temperature becomes more effective as the volume fraction increases, given a higher Brownian random motion of nanoparticles. The highest increase corresponds to the largest volume fraction. It is deduced that increasing the nanoparticle concentration enhances the thermal conductivity ratio. Note that nanoparticles concentration is not to be increased to the point where it results in sedimentation and precipitation.

6.2. Temperature effect

Thermal conductivity ratio is plotted in Fig. 6 against temperature at different volume fractions. At any volume fraction, increasing the temperature is associated with increased Thermal conductivity ratio. Temperature enhancement influences the Brownian motion and nanoparticles clustering in nano-lubricant, amplifying the influence of temperature. The enhancement of thermal conductivity ratio with increased temperature is negligible at low volume fractions as a result of limited Brownian motion at such volume fractions. However, clustering takes place at larger volume fractions given that more nanoparticles are available in the fluid. This allows for a more efficient heat transport through the solid phase, enhancing the thermal conductivity. Nanoparticles motion is promoted at higher temperatures, enhancing the thermal conductivity ratio due to more collisions between the atoms surface and the fluid molecules. Therefore, the maximum Thermal conductivity ratio was observed at T = 50 °C and $\varphi = 0.8\%$.

6.3. Develop a new model

As mentioned, the existed analytical equations cannot estimate K_{eff} of the proposed nano-lubricant at different volume fractions and temperatures. Therefore, an equation is developed to determine K_{eff} of ZnO-MWCNT/Engine oil (SAE 10W40) nano-lubricant as a function of temperature range from 25 °C to 50 °C and volume fraction range from 0.05% to 0.8%. The equation is developed based on curve fitting method in Sigma Plot 12.3 as:

$$\frac{k_{nf}}{k_{bf}} = 1.5085 + ((-0.8377) + \phi^{(-0.0135)}) \times ((-0.2879) + T^{(0.0273)}) \times \exp((\phi^{(-1.3715)}) - (\phi^{(-1.3716)}) + (T^{(0.2744)})) \quad (2)$$

The R_{sqr} value of the obtained correlation is almost 0.98.

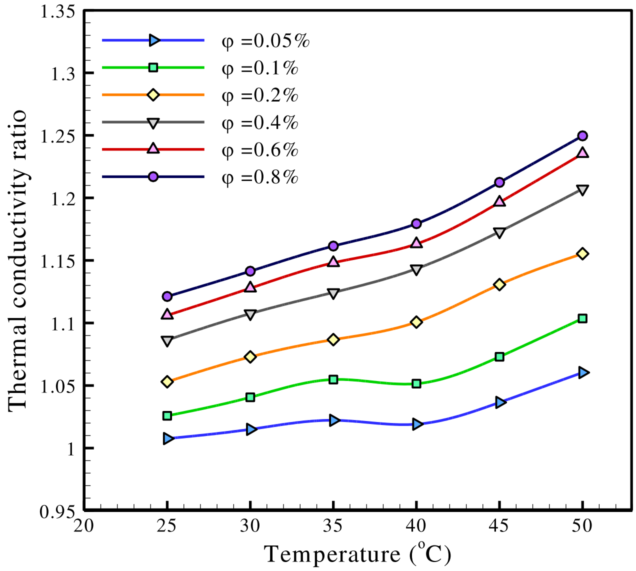

Fig. 6. The variation of thermal conductivity ratio as a function of temperature for different volume fractions.

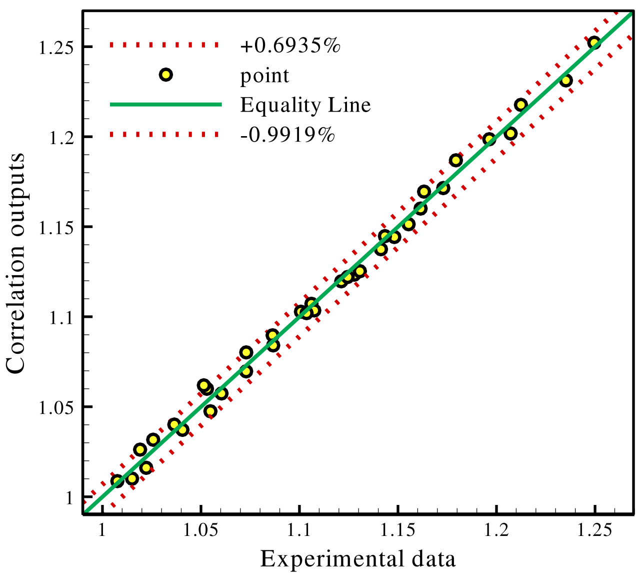

Fig. 7. The calculated Dev between the correlated and experimental data for different volume fractions and temperatures.

To evaluate the developed equation, the margin of deviation between the results of experimental data and the developed equation is obtained using the following equation:

$$Dev = \left[\frac{k_{Exp} - k_{Pred}}{k_{Exp}}\right] \times 100\% \tag{3}$$

Fig. 7 illustrates the calculated Dev between the experimental data and the output results from Eq. (2) for different produced volume fractions and temperatures. As shown, all the points are located close to the developed line, showing the satisfying accuracy of the relationship. Moreover, maximum Dev is less than 1%.

6.4. Comparison of the experimental data with the outputs of the developed correlation

Fig. 8 compares the results of model outputs with experimental data at each temperature. The advantage of these diagrams is to specify the difference between the model outputs and experimental results in every test.

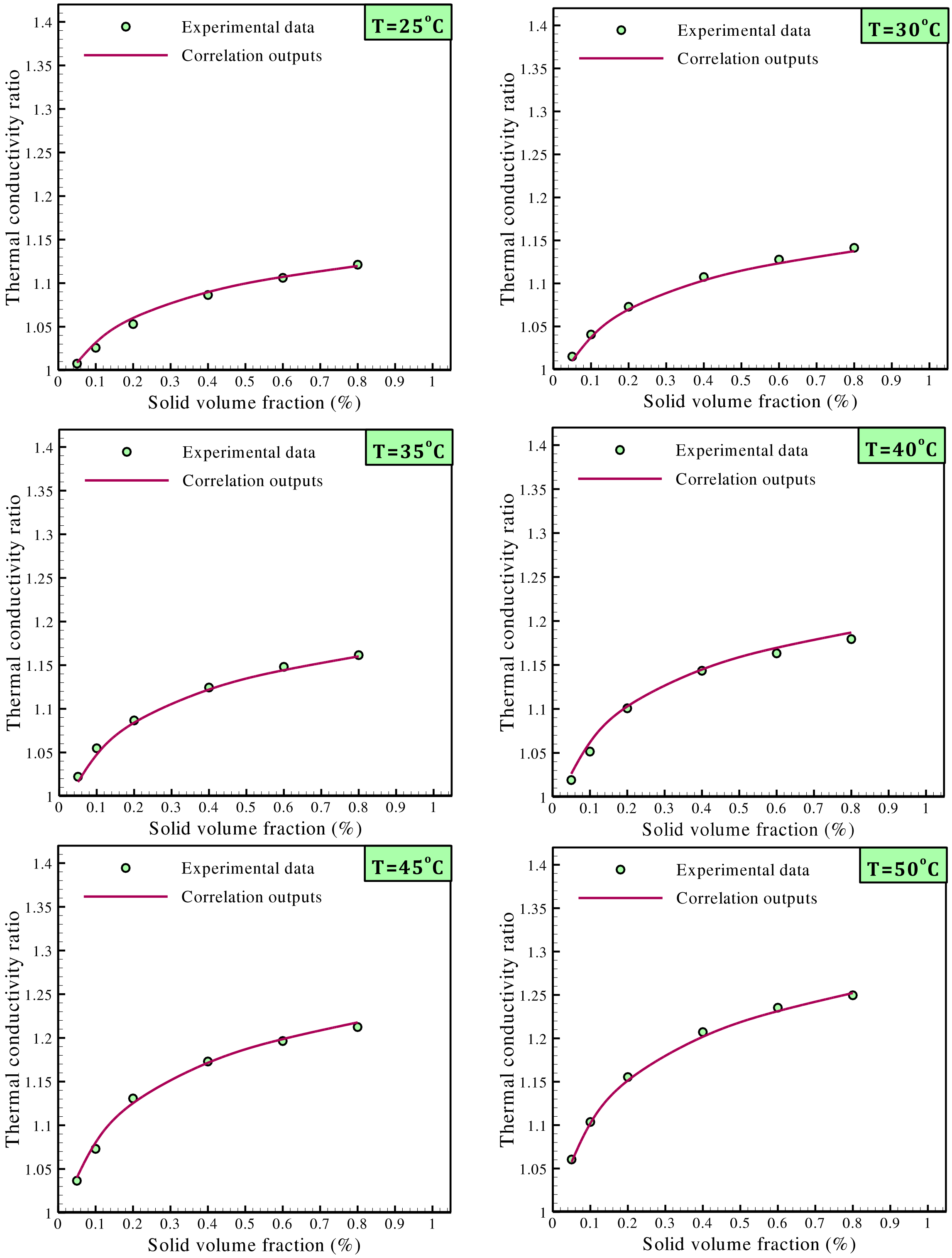

Fig. 8. Comparison of experimental data with the results of the developed correlation at different temperatures.

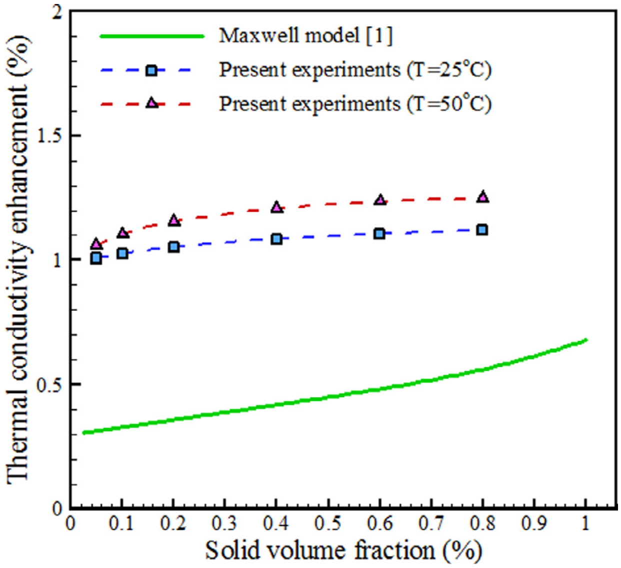

Fig. 9. Comparison between the thermal conductivity of the nanofluid and the Maxwell model [1].

6.5. Comparison with theoretical models

As mentioned earlier, the Maxwell relationship, based on the effective medium theory [1], is one of the most applied relationships for K_{eff} prediction of nanofluids containing spherical particles. Fig. 9 shows a comparison between the thermal conductivity of the proposed nanofluid and the Maxwell equation [1]. As displayed, the Maxwell equation is not capable to determine the thermal conductivity of ZnO-MWCNT/Engine oil showing a significant disagreement since the Maxwell equation was proposed for fluids containing micrometer or millimeter scale particles which shows the importance of developing a new correlation.

7. Conclusion

Thermal conductivity of a novel hybrid nano-lubricant, i.e. ZnO-MWCNT/Engine oil (SAE 10W40), was evaluated at different volume fractions and temperatures experimentally to develop a prediction correlation. The results obtained from this study are as follows:

- A higher Thermal conductivity is achieved for a higher volume fraction and temperature.
- The maximum thermal conductivity ratio produced in 0.8% Vol and 50 °C temperature.
- A new relationship was developed to determine the thermal conductivity of the proposed nano-lubricant.
- The maximum deviation margin between the outputs of the developed relationship and the experimental outputs was less than 1%.
- Maxwell model is not able to forecast the thermal conductivity of the proposed nano-lubricant given the substantial difference.
- The results of this study according to the previous works [15–59] provide guidelines for engineers for simulation of nanofluids.

Acknowledgments

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