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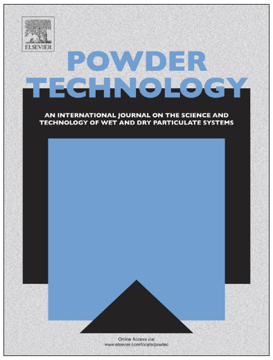

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Heat transfer performance of two oil-based nanofluids containing ZnO and MgO nanoparticles; A comparative experimental investigation

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Abstract

The major objective of the present study is to experimentally investigate the thermophysical properties and heat transfer capability of ZnO- and MgO-engine oil nanofluid as a coolant and lubricant in various engineering applications. The viscosity and thermal conductivity measurements have been performed in different temperatures (ranging from 15 °C to 55 °C) and solid concentrations (ranging from 0.125 % to 1.5 %). The nanofluids showed Newtonian behavior over the studied range of temperatures, and solid concentrations. Furthermore, the results revealed that the samples containing ZnO cause more increase in the dynamic viscosity compared to the samples containing MgO. The thermal conductivity has also been measured over the same range of temperatures and solid concentrations. The maximum enhancement of just over 28 % and 32 % at the temperature of 55 ºC and solid concentration of 1.5 % has been observed for the ZnO- and MgO-engine oil nanofluid, respectively. Furthermore, the heat transfer performance of the nanofluids has been evaluated based on different figures-of-merit, and it is revealed that using the MgO-engine oil nanofluid is advantageous just in laminar flow regimes while the ZnO-engine oil nanofluid would be advantageous in a limited range of temperatures.

Keywords: Thermal Oil; Rheological behavior; Thermophysical properties; Heat transfer performance; ZnO and MgO nanoparticles.

1. Introduction

One of the widely used thermal fluid in heat transfer applications is thermal oils. Thermal oils can be used in a vast range of engineering applications and industries, on which high temperature is the main barrier, such as automotive, aerospace, marine and military industries as well as internal combustion engines, compressors, gears, processing equipment and so forth. Heat transfer oils are available in various types on the market such as circulating coolant, chiller fluids, and refrigerant which are used as a cooling media in machinery, process equipment, and combustion engines.

Since for the first time Choi [1] introduced the nanofluid as a suspension of nano-sized particles in conventional fluids such as water, ethylene glycol, and oil, many researchers have paid careful attention to this new type of fluids [2-12]. Moreover, the contribution of various nanofluids in different applications has been reviewed by researchers; employing nanofluids in microchannel heatsinks [13], Cooling of electronics [14], pool boiling [15], and responsible mechanism to improve the heat transfer of nanofluids [16]. There are also some papers that reviewed the results of different papers on thermophysical properties and heat transfer performance of various nanofluids [17-21].

The principal duty of engine oils is to decrease or even diminish the friction among the moving segments and on the other hand cooling the moving segments by removing the heat away from them [22]. Since engine oils vary regarding kinematic and dynamic viscosity, operating temperatures, thermal conductivity, pour point, flash point, boiling point, and so forth, many factors must take into consideration in selecting an engine oil for heat transfer applications. Lower viscosity in engine oils means lower pumping power and pressure drop while higher thermal conductivity means higher heat transfer performance. Thus, having an appropriate thermal oil might result in improving the efficiency and energy management of engines. To this end, there is a limited number of published literature on thermophysical properties of oil-based nanofluids [23-26]. A summary of the published literature on oil-based nanofluids has been presented in Tab. 1.

One of the most important features of nanofluids is their rheological behaviors. In this ground, Hemmat et al. [44] conducted an experimental study on the effect of temperature and solid concentration on dynamic viscosity of Al_2O_3-engine oil nanofluid. Their results indicated that the dynamic viscosity of the nanofluid decreased as the temperature increased while it showed an increasing trend as the solid concentration increased. Asadi and Asadi [45] investigated the rheological behavior of MWCNT-ZnO/engine oil hybrid nanofluid in various temperatures and solid concentrations. They proposed a new correlation to predict the dynamic viscosity of the nanofluid. In another experimental investigation, the rheological behavior of MWCNT-SiO_2/SAE40 hybrid nanofluid has been studied by Afrand et al. [22]. Their results revealed that the dynamic viscosity of the nanofluid increased as the solid concentration increased. Ettefaghi et al. [46] conducted an experimental study on thermal and rheological properties of oil-based nanofluids with various carbon nanostructures. In another study, the effect of temperature and solid concentration on dynamic viscosity of MWCNT-SiO_2 (20-80)/SAE40 hybrid nanofluid has been experimentally investigated by Hemmat et al. [47]. Their results showed that the dynamic viscosity of the nanofluid increased as the solid concentration increased while it showed a decreasing trend as the temperature increased. In another experimental investigation, Asadi et al. [35] studied the rheological behavior of MWCNT/MgO (20-80)-SAE50 hybrid nanofluid in different solid concentrations and temperature. They proposed a new correlation to predict the dynamic viscosity of the studied nanofluid regarding solid concentration and temperature.

Another crucial parameter is, undoubtedly, the thermal conductivity of the nanofluids. Many researchers have investigated the thermal conductivity of different nanofluids [48-52], but there are just limited numbers of published literature on the thermal conductivity of oil-based nanofluids [53-55]. Aberoumand and Jafarimoghaddam [56] investigated the thermal conductivity of Cu engine oil-based nanofluid in a limited range of solid concentrations. Their results indicated that the thermal conductivity of the nanofluid gradually increased as the temperature increased. This trend was similar in all the three studied solid concentrations. The thermal properties of the MWCNT-engine oil nanofluid have been experimentally investigated by Ettefaghi et al. [57]. They just conducted the experiments at the temperature of 20 ºC and in low solid concentrations (0.1, 0.2, and 0.5 wt %). Their results showed the maximum thermal conductivity enhancement of 22.7 % at the solid concentration of 0.5 wt %. In another experimental investigation, which is done by Aberoumand et al. [58], the thermal conductivity of the silver-engine oil nanofluid has been investigated. Based on the experimental results, they proposed a new correlation to predict the thermal conductivity of the nanofluid in the studied range of solid concentrations and temperatures. Recently, a review of the affected mechanism of thermal conductivity for both the normal and hybrid nanofluids has been published by Das [59].

From what has been discussed, it can be concluded that improving the thermophysical properties of engine oils is of paramount importance to their industrial applications. However, there are only a limited number of studies on the rheological behavior of oil-based nanofluids. Furthermore, to the best of the authors' knowledge, there is a limited number of studies on the heat transfer performance of oil-based nanofluids to investigate the capability of using this new generation of coolant and lubricant in heat transfer applications both in internal laminar and turbulent flow regimes. Quiet the recently, Asadi et al. [39] investigated the possibility of using $Mg(OH)_2$-MWCNT/thermal oil nanofluid in heat transfer applications. They conducted the study on different temperatures (25-60 ℃) and solid concentrations (0.25-2 %). They reported the maximum thermal conductivity enhancement of 50 %. Moreover, their results showed that using the studied nanofluid instead of base fluid would be advantageous in heat transfer application in both the internal laminar and turbulent flow regimes. In another experimental investigation, the capability of Al_2O_3-MWCNT/thermal oil as a heat transfer fluid has been studied by Asadi et al. [42]. Their results showed that using the studied nanofluid is pretty advantageous in internal lamina flow regime as a heat transfer fluid although it showed different behavior in internal turbulent flow regime.

In the present investigation, the effect of temperature and solid concentration on dynamic viscosity and thermal conductivity of ZnO- and MgO-engine oil nanofluid have been experimentally studied. The experiments have been conducted in different temperatures (15 °C, 25 °C, 35 °C, 45 °C, and 55 °C) and solid concentrations (0.125 %, 0.25 %, 0.5 %, 0.75 %, 1 %, and 1.5 %). The stability of the prepared samples has been investigated over the period of fifteen days after preparation using Zeta potential analysis. Furthermore, two new correlations to predict the dynamic viscosity and thermal conductivity of the nanofluids have been proposed based on the experimental data. The deviation analysis has also been performed to investigate the accuracy of the proposed correlation. Moreover, the heat transfer performance of the nanofluid has been evaluated in both the internal laminar and turbulent flow regimes.

2. Materials and methods

2.1. Sample preparation

It is known that the most crucial step towards using different nanofluids in heat transfer applications is, undoubtedly, the preparation of long-time stable samples. Applying two-step method and without using any surfactant, the ZnO- and MgO-engine oil nanofluid have been prepared as the experimental sample in six different solid concentrations (0.125 %, 0.25 %, 0.5 %, 0.75 %, 1 %, and 1.5 %). The average diameter of ZnO and MgO nanoparticles is 40 nm. To produce a long-time stable nanofluid (at least two weeks), the nanoparticles have been dispersed into the mentioned solid concentration. After that, a magnetic stirrer has been employed for 3 hours. Then, the suspension was subjected to 1 h ultrasonic processor (20 kHz, 400 W) to break down the probable cluster of nanoparticles and achieve a nanofluid with superb dispersion. In this manner, a long-time stable nanofluid has been prepared, and no sedimentation has been observed by the naked eyes. Figure 1 shows a TEM image of the ZnO and MgO nanoparticles and the specification of the nanoparticles has been presented in Tab. 2.

2.2.Stability measurement:

Investigating the stability of the prepared samples, different methods have been employed by researchers thus far. The most usual method is the visual observation which is widely done by researchers. However, this method is not that precise especially for the nanofluids which have a dark color such as CNTs-based or oil-based nanofluid. In such cases, the most reliable method is, undoubtedly, Zeta potential analysis [39, 42]. Thus, in the present paper, the Zeta potential analysis has been done on the prepared samples in four different time periods; right after preparation, after 5 days, after 10 days, and after 15 days of preparation. It is known that a sample with Zeta potential values under 30 mV is considered as bad/unacceptable stability, between 30 and 45 mV possess moderate stability, and above 45 mV shows good stability with possible sedimentation [60, 61]. The results of the Zeta potential analysis of the prepared samples have been clearly presented in Fig. 2. As can be seen, the prepared samples showed good stability even after 15 days of preparation.

2.3.Dynamic viscosity measurement

Measuring the dynamic viscosity of the ZnO- and MgO-engine oil nanofluid in different temperatures and solid concentrations, a Brookfield Cone and Plate viscometer (CAP 2000+, USA) has been employed. The detailed information of the viscometer has been presented in Tab. 3. It must be noted that the calibration of the viscometer has been tested by measuring the viscosity of the base fluid (pure oil 10W40) and comparing the results with those available in the literature [45]. The maximum deviation between the measured data in the present study with those of literature was less than 1 %.

2.4.Thermal conductivity measurement

In the present study, to determine the thermal conductivity of the samples, a KD2 Pro thermal property analyzer (Decagon Devices Inc., USA) has been employed. The device works based on the transient hot-wire method. It can measure the thermal conductivity in the range of 0.02 to 2 W/m. ºC with the maximum deviation of 5 % and the accuracy of ±0.001. First, the device has been calibrated using the glycerol supplied by the manufacturer, and then the thermal conductivity of the samples has been measured. A hot water bath temperature has been employed to set the temperature during the measurement. Fig. 3 depicts a schematic view of the experimental thermal conductivity set up.

To investigate the repeatability of the experiments, all the samples have been tested three times, and the mean values have been recorded. More detailed information about the KD2 pro thermal analyzer has been presented in Tab. 4.

To investigate the accuracy of the KD2 Pro device, the calibration of the device has been tested by measuring the thermal conductivity of water in different temperatures and comparing the results with those available in ASHRAE handbook [62]. Fig. 4 shows the comparison between the experimental results with the data available on the ASHRAE handbook. As can be seen, the maximum deviation between the experimental results and ASHRAE data is less than 1 %, which shows the accuracy of the KD2 Pro thermal analyzer.

3. Results and discussion:

3.1.Dynamic viscosity

3.1.1. Newtonian behavior

The behavior of the nanofluid to determine whether it is Newtonian or non-Newtonian has been investigated over the range of the studied temperatures (15 °C, 25 °C, 35 °C, 45 °C, and 55 °C) and solid concentrations (0.125 %, 0.25 %, 0.5 %, 0.75 %, 1 %, and 1.5 %). Fig. 5 demonstrates the dynamic viscosity of the studied nanofluids concerning rotational speed (shear rate) in different temperatures and solid concentrations of 0.5 % and 0.75 % for MgO- and ZnO-engine oil, respectively. As can be seen, there is a negligible decrease in the dynamic viscosity of the nanofluid as the rotational speed increases. Thus it can be concluded that the viscosity of the nanofluid is independent of the rotational speed. This means that the nanofluid shows Newtonian behavior over the studied range of temperatures and solid concentrations.

3.1.2. Theoretical models:

There are many theoretical models to predict the dynamic viscosity of the suspensions containing nanoparticles, which are widely used by researchers. Among many models, three commonly used models, Einstein [63], Wang et al. [64] and Batchelor [65] have been selected to examine whether they can predict the dynamic viscosity of the studied nanofluid within the acceptable range of accuracy or not. These models are as follows:

$$\mu_{nf,Einstein} = (1+2.5\varphi)\mu_{bf} \tag{1}$$

$$\mu_{nf,Wang} = (1+7.3\varphi+123\varphi^2) \tag{2}$$

$$\mu_{nf,Batchelor} = (1+2.5\varphi+6.2\varphi^2) \tag{3}$$

where μ_{nf}, μ_{bf} and φ represent dynamic viscosity of nanofluid, the dynamic viscosity of the base fluid, and solid concentration, respectively. The comparison between the theoretical models and measured data have been presented in Fig. 6. Based on this figure, it can be inferred that neither of the models is able to predict the dynamic viscosity of the nanofluids in the acceptable range of accuracy.

3.1.3. Dynamic viscosity in different temperatures and solid concentrations

In the present investigation, the effect of temperature and solid concentration on dynamic viscosity of ZnO- and MgO-engine oil nano-lubricant has been precisely investigated. Fig. 7 shows the variations of the dynamic viscosity of the nanofluids versus solid concentration in different temperatures. It can be seen that the increase in the dynamic viscosity of the nanofluids by increasing the solid concentration, in all the studied temperatures, is not that noticeable. However, this increase is more noticeable at lower temperatures (15 °C and 25 °C) compared to those higher. The variations of the dynamic viscosity of the nanofluid versus temperature in all the studied solid concentrations have also been presented in Fig. 7. As can be seen, the dynamic viscosity of the nanofluid significantly decreased as the temperature increased in all the studied solid concentrations, which is in accordance with the previously published papers [22, 35, 45, 66].

Fig. 8 shows the percentage of enhancement in dynamic viscosity of the studied nanofluids concerning temperature in different solid concentrations. As can be seen, for the ZnO-engine oil nanofluid, the minimum increase in dynamic viscosity of the nanofluid with respect to the base fluid, took place at the temperature of 45 °C and solid concentration of 0.125 % by approximately 27.5 % while the maximum increase took place at the temperature of 55 °C and the solid concentration of 1.5% by 124.3 %. Furthermore, it can be seen that in all the solid concentrations, the minimum increase in dynamic viscosity took place at the temperature of 45 °C. Thus the temperature of 45 °C can be taken into account as a critical temperature of this nanofluid in which the nanofluid can be used instead of the base fluid (engine oil) experiencing the minimum enhancement in dynamic viscosity. Minimum enhancement in viscosity means that the increase in the pressure drop and pumping power is at the lowest rate which can be taken into account as a paramount finding of the present study. As for the MgO-engine oil nanofluid, the maximum and minimum increase has been occurred at the temperatures of 15 °C and 55 °C and solid concentrations of 0.125 % and 1.5 % by just over 30 % and 75 %, respectively. It is interesting to note that the MgO nanoparticles showed less impact on increasing the dynamic viscosity of the base fluid compared to ZnO nanoparticles while it has higher thermal conductivity, which is in accordance with the finding of Xie et al. [67].

3.1.4. Proposed model

It has been proofed in section (3.1.2) that the commonly used theoretical models are not able to predict the dynamic viscosity of nanofluids, due to the fact that suspensions of different nanoparticles in different base fluids show different rheological behavior. On the other hand, several correlations to predict the dynamic viscosity of different nanofluids have been presented by different researchers thus far. But these proposed correlations are for the nanofluids with different base fluids and solid particles which none of them can predict the dynamic viscosity of different suspensions of nanoparticles in working fluids. Thus, in the present study, a new precise experimental correlation has been proposed to predict the dynamic viscosity of ZnO- and MgO-engine oil nanofluids. The general form of the correlations is as follows:

$$\mu_{nf} = A + B\varphi \tag{4}$$

Where $\boldsymbol{\mu_{nf}}$ and $\boldsymbol{\varphi}$ represent the dynamic viscosity of the nanofluid and solid concentration, respectively. ***A*** and ***B*** are constant values which are listed for the respective temperatures in Tab. 5 and 6.

Fig. 9 proofs the capability of this correlation (Eq. 4) in predicting the dynamic viscosity of the ZnO- and MgO-engine oil nano-lubricant over the studied range of temperatures and solid concentrations with high accuracy.

Proofing the accuracy of the proposed correlation, deviation analysis has been performed using the following equation:

$$Dev = \left[\frac{\left(\mu_{nf}\right)_{Exp.} - \left(\mu_{nf}\right)_{\mathrm{Pr}ed.}}{\left(\mu_{nf}\right)_{Exp.}} \right] \times 100(\%) \tag{5}$$

The maximum deviation of the proposed correlation is just under 3 % and 4 % for the ZnO- and MgO-engine oil nanofluid, respectively, which are clearly shown in Fig. 10.

3.2.Thermal conductivity

3.2.1. Effects of temperature and solid concentration

Fig. 11 presents the thermal conductivity of the studied nanofluids in various temperatures and solid concentrations. As can be seen, the thermal conductivity of both the nanofluids showed increasing trend as the temperature increased, which is in accordance with the previously published literature [58, 61] while the base fluid showed decreasing trend as the temperature increased. This decreasing trend is also in accordance with the previously published investigations conducted by Aberomand et al. [37, 56] and Asadi et al. [39, 42, 66]. This increasing trend has been observed in all the solid concentrations. Increasing the collisions between the nanoparticles and increasing the Brownian motions could be the main causes of increasing the thermal conductivity by increasing temperature. The thermal conductivity behavior of the studied nano-lubricant by increasing the solid concentration has also been presented in the Fig. 11. As can be seen, the thermal conductivity of the nanofluids showed an increasing trend as the solid concentration increased. This increasing trend has been observed in all the studied temperatures. This figure also proofed that adding nanoparticles to the base fluid definitely leads to enhancing the thermal conductivity of the base fluid, which has been reported widely in the literature. Since one of the main missions of the engine oils is to cool down the different parts of an engine, using these nano-coolants in the solid concentration of 1.5 % could be recommended in cooling applications.

Fig. 12 demonstrates the thermal conductivity enhancement of the two studied nanofluids. As can be seen, the maximum enhancement in thermal conductivity of the ZnO-engine oil nanofluid is just over 28 % which took place at the temperature of 55 ºC and solid concentration of 1.5 % while for the MgO-engine oil nanofluid, the maximum enhancement is just over 32 % which has been occurred at the same temperature and solid concentration.

3.2.2. Proposed correlation

There are several parameters affecting the thermal conductivity behavior of nanofluids such as the solid concentration of particles, temperature, and the nanoparticles' material. On the other hand, predicting the thermal conductivity of the nanofluids are important to pre-assessment of using nanofluids instead of conventional cooling fluids such as water, ethylene glycol, oil, etc. To this end, several correlations have been proposed by researchers so far [68-72]. But, it is crystal clear that it is not possible to have a single theoretical model to predict the thermal conductivity of various suspensions due to the aforementioned affecting parameters. Thus, in the present study, based on the experimental data, two new accurate correlations to predict the thermal conductivity of the ZnO- and MgO-engine oil nanofluids in the studied range of temperature and solid concentration have been proposed. The proposed correlations have been presented in table 6 and 7.

Fig. 13 shows a comparison between the experimental data and the output of the proposed correlations for the thermal conductivity of the nanofluids.

Furthermore, using the Eq. 6, the deviation analysis has also been performed to evaluate the accuracy of the proposed correlation. The results of the deviation analysis have been presented in Fig. 14. The maximum deviation of well under 1 % has been achieved for the proposed correlation of both the studied nanofluids.

$$Dev. = \left[\frac{(k_{nf})_{Exp.} - (k_{nf})_{\mathrm{Pred.}}}{(k_{nf})_{Exp.}} \right] \times 100(\%) \tag{6}$$

3.3.Assessment of heat transfer performance

In the previous sections, the viscosity increase and thermal conductivity enhancement of the ZnO- and MgO-engine oil nanofluids have been precisely studied. Having the value of these two important parameters, it is possible to investigate the advantage of using nanofluid instead of conventional fluids in heat transfer applications in both the laminar and turbulent flow regimes. For the laminar flow regime, the assessment of heat transfer performance can be done based on the ratio of viscosity increase and thermal conductivity enhancement which is presented by Prasher et al. [73] as follows:

$$\frac{C_{\mu}}{C_k} = \frac{(\mu_{nf} - \mu_{bf}) / \mu_{bf}}{(k_{nf} - k_{bf}) / k_{bf}} \tag{7}$$

Using nanofluids instead of base fluids could always be considered as advantageous for the ratios of less than 4 ($C_{\mu}/C_k<4$) in heat transfer applications [73]. Fig. 15 depicts the results of this assessment. As can be clearly seen, for the ZnO-engine oil nanofluid, at the temperature of 45 ºC and in all the studied solid concentrations, using this nanofluid is better than the base fluid as a heat transfer fluid. However, at the temperature of 25 ºC and the solid concentration of 1.5 % and at the temperature of 35 ºC and the solid concentrations greater than 0.75 %, using this nanofluid can be advantageous as well. But for the MgO-engine oil nanofluid, the trend is totally different. Using this nanofluid is highly advantageous in all the temperatures and solid concentrations except the temperature of 15 ºC and solid concentrations less than 0.75 %. It is known that most of the flows in the practical situation are turbulent and the laminar flow regime is just encountered when the highly viscous fluids, i.e., oil, flow in narrow passages and small pipes [74]. Since in automotive applications the oils mostly used as coolant and lubricant among different moving parts of engines and in most cases there is only a narrow gap among these moving parts, thus the flow regime in this region is laminar. Therefore, from what has been discussed in this section, it can be concluded that regarding the higher thermal conductivity of

MgO-engine oil nanofluid compared to that of the base fluid (engine oil), using this nanofluid is highly advantageous although it possesses higher viscosity.

As for the turbulent flow regime, based on the Mouromtseff number [75], the advantage of using nanofluid as a heat transfer fluid can be evaluated as follows:

$$Mo = \frac{\rho^{0.8} k^{0.67} c_p^{0.33}}{\mu^{0.47}} \tag{8}$$

Where $\boldsymbol{C_p}$ represents the specific heat capacity and $\boldsymbol{\rho}$ is the density, $\boldsymbol{\mu}$ is dynamic viscosity, and $\boldsymbol{k}$ is thermal conductivity. The thermal conductivity and dynamic viscosity of the studied nanofluids and the respective base fluids (oil) have been measured, and the results were reported in the previous sections. As for the specific heat capacity and density of the nanofluid, the values have been calculated using the following correlations presented by Pak and Cho [71]:

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_{Particle} \tag{9}$$

$$C_{p,nf} = (1-\varphi)C_{p,bf} + \varphi C_{p,\mathrm{P}article} \tag{10}$$

Generally, the higher the ***Mo*** number, the better the nanofluid for heat transfer applications. Moreover, the nanofluid considered advantageous for heat transfer applications for the ratios of ***Mo*** number higher than 1 ($Mo_{nf}/ Mo_{bf}>1$). Figure 16 shows the results of heat transfer performance of ZnO- and MgO-engine oil nanofluids in different temperatures and solid concentrations. As can be seen, using neither of these two nanofluids can be advantageous in turbulent flow regimes.

4. Concluding remarks

In the present investigation, the thermal and rheological properties of the ZnO- and MgO-engine oil nanofluid has been experimentally investigated. The samples have been prepared using the two-step method in various temperatures (ranging from 15 °C to 55 °C) and solid concentrations (ranging from 0.125 % to 1.5 %). The Zeta potential analysis has been performed to investigate the stability of the prepared samples over the period of fifteen days after preparation. Furthermore, the heat transfer performance of the studied nanofluids has been investigated based on different figures of merit for both the internal laminar and turbulent flow regimes. Based on the measurements, the conclusion can be drawn as follows:

- The studied nanofluids exhibit Newtonian behavior at different rotational speeds (shear rates).
- It has been proofed that the commonly used theoretical models to predict the dynamic viscosity and thermal conductivity of nanofluids are not able to predict the viscosity, and thermal conductivity of the studied nanofluids accurately.
- There is a slight increase in the dynamic viscosity of the nanofluid at a constant temperature as the solid concentration increased. The maximum increase in dynamic viscosity of the nanofluids took place at the temperature of 55 °C and the solid concentration of 1.5% by just over 124 % and 75 % for ZnO- and MgO-engine oil nanofluid, respectively.
- The thermal conductivity of the nanofluids showed increasing trend as the temperature, and solid concentration increased. The maximum enhancement was just over the 28 % and 32 % for ZnO- and MgO-engine oil nanofluid, respectively.
- Based on the experimental measurements, two new correlations to predict the dynamic viscosity and thermal conductivity of the studied nanofluid have been proposed with the maximum deviation of less than 4 % and 1 %, respectively.
- The evaluation of heat transfer performance of the nanofluid revealed that while using MgO-engine oil nanofluid is advantageous at all the temperatures and solid concentrations except the temperature of 15 ºC and solid concentrations less than 0.75 % in laminar flow regime; the ZnO-engine oil nanofluid recommended to use in a very limited range of temperatures. It has also found that neither of these two nanofluids is suitable to use instead of the base fluid in turbulent flow regime.

Nomenclature	**Subscripts**
K: Thermal conductivity	bf: Base fluid
C_p: Specific heat capacity	nf: Nanofluid
Mo: Mouromtseff number	p: Particle
φ : nanoparticles volume fraction	
Greeks	

ρ : Density τ : Shear stress γ : Shear strain μ : Dynamic viscosity	

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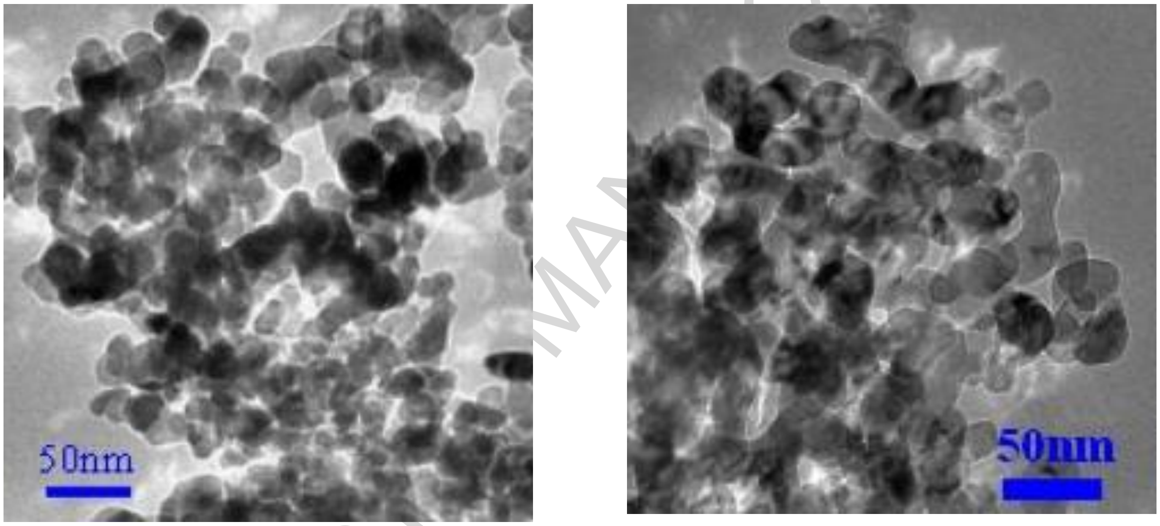
Figures:



A B

Fig. 1 TEM image of A) ZnO, and B) MgO nanoparticles.

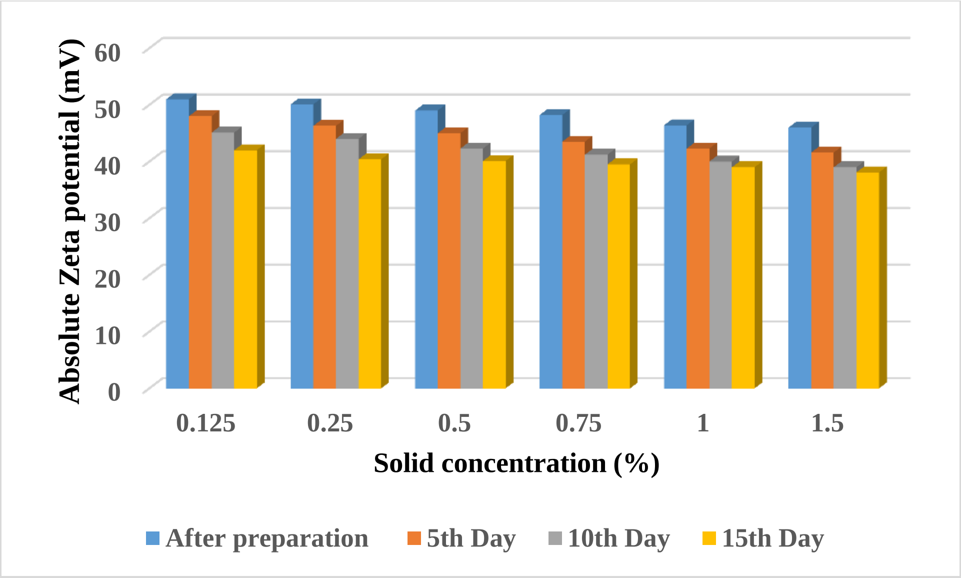


Fig. 2 Absolute Zeta Potential values of the prepared samples in four different times; After preparation, after 5 days, after 10 days, and after 15 days of preparation.

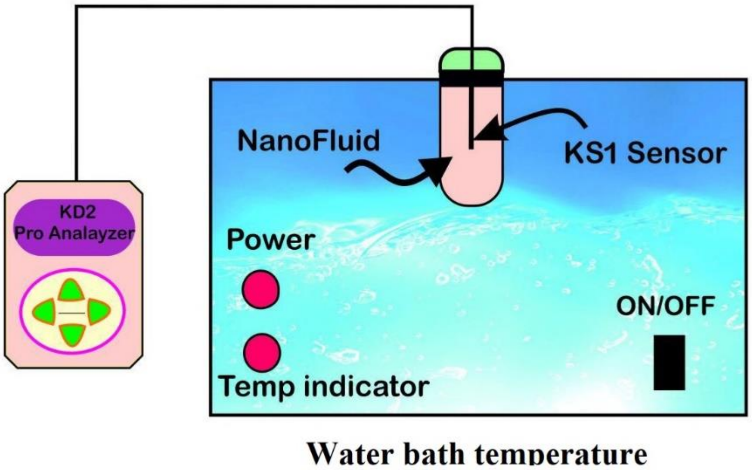


Fig. 3 A schematic view of the thermal conductivity set up.

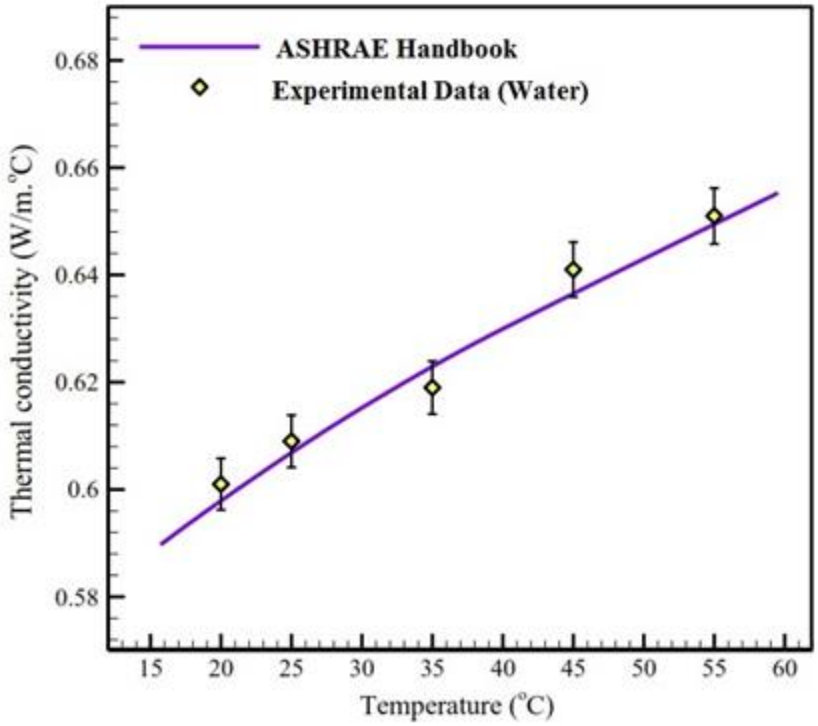
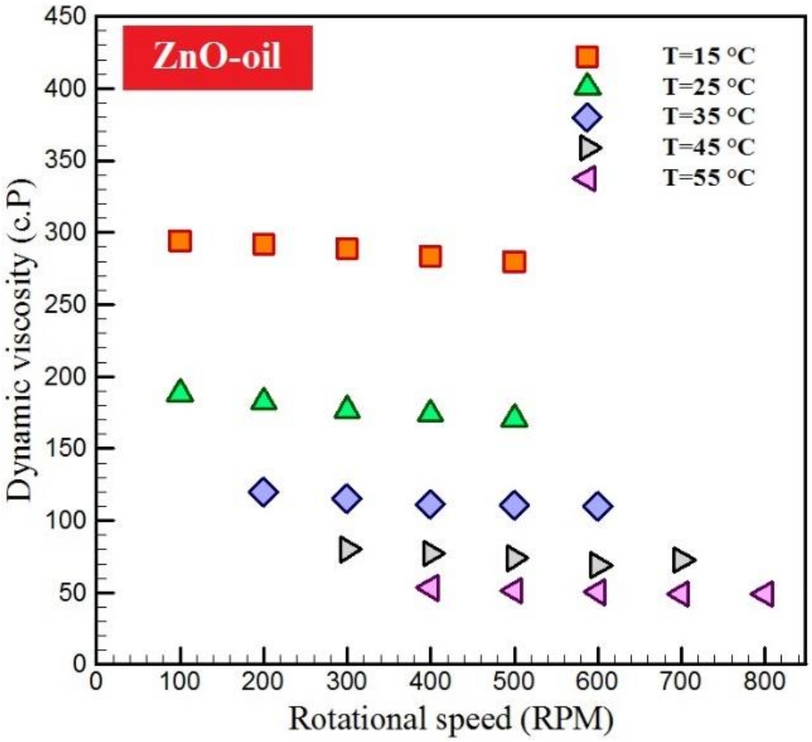


Fig. 4 Comparison between the experimental results of thermal conductivity of water of the present investigation with the data available in ASHRAE handbook.

A



B

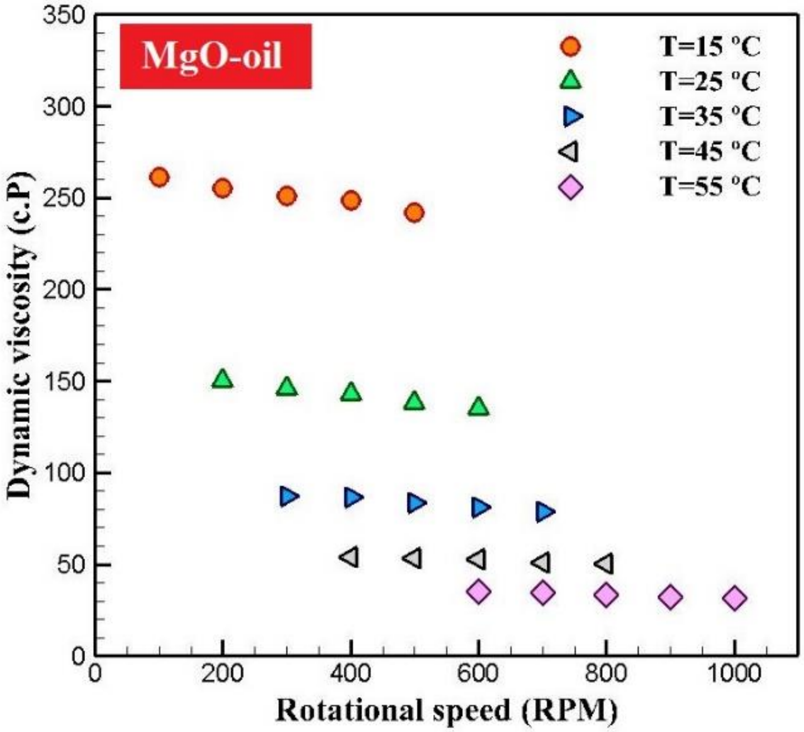
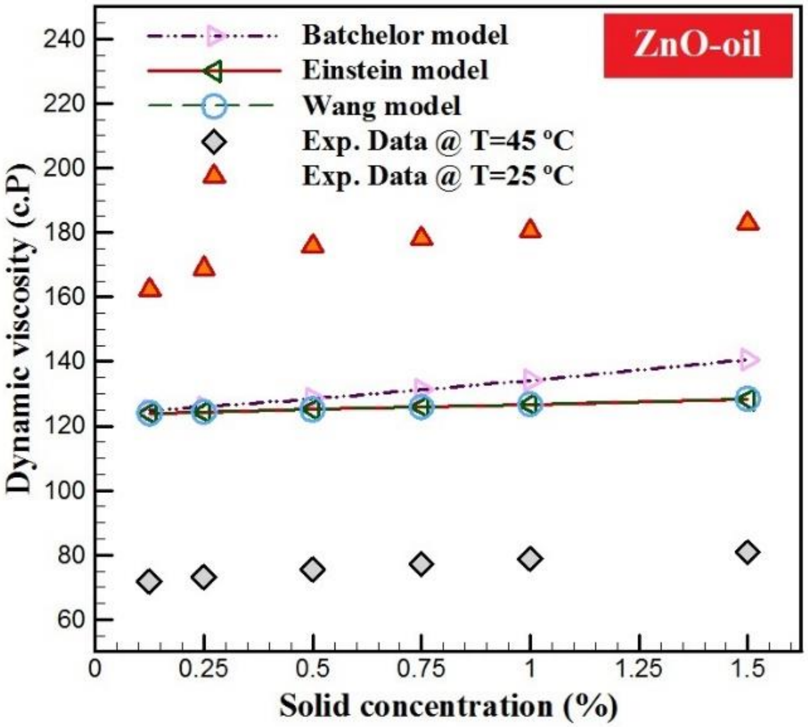


Fig. 5 Dynamic viscosity concerning the rotational speed in various temperature and at the solid concentration of A) 0.75 %, and B) 0.5 %



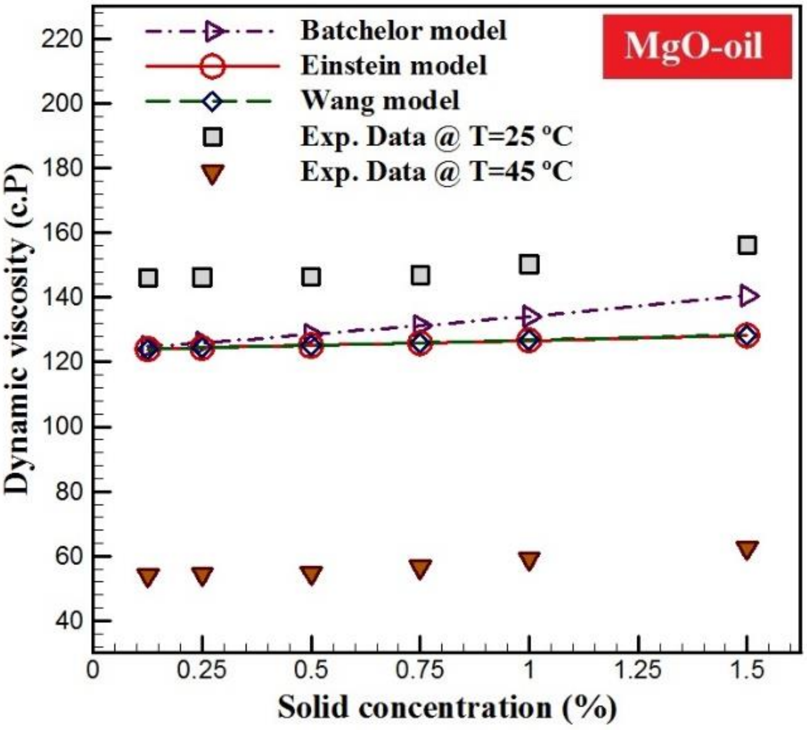
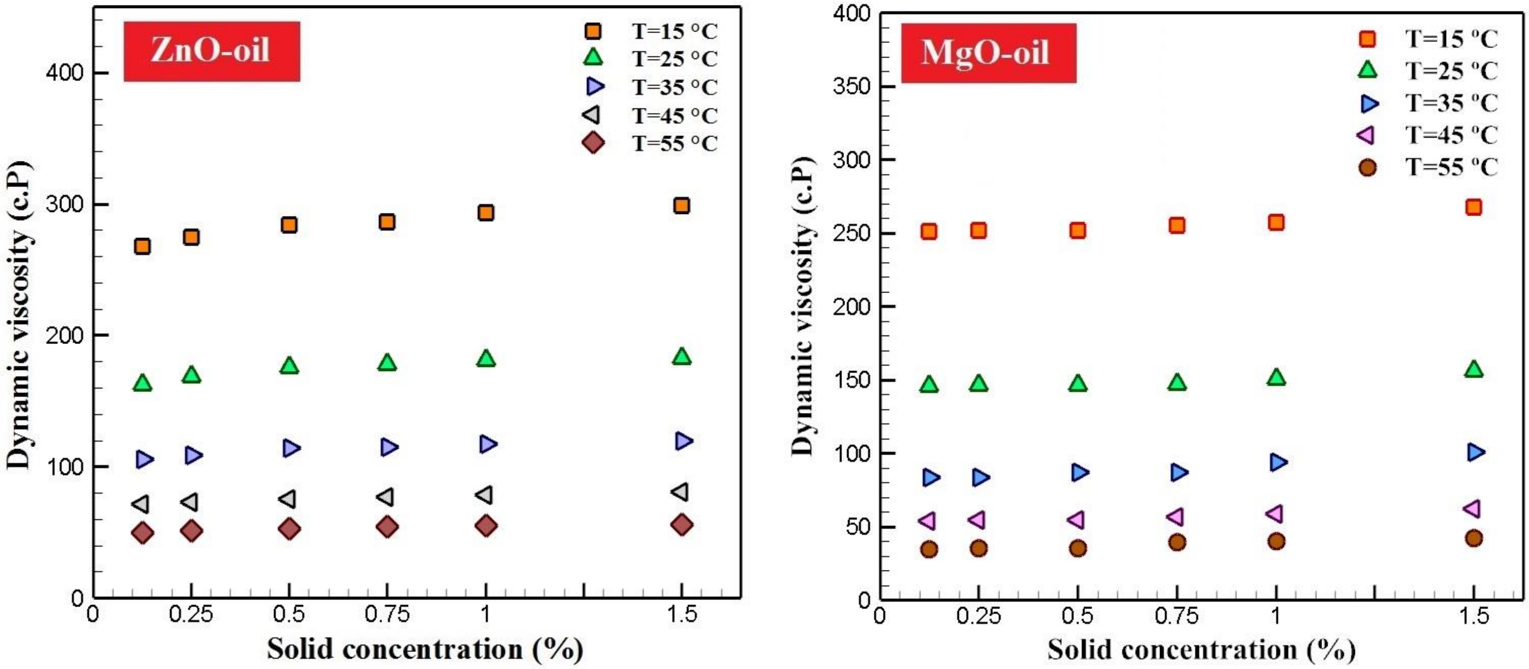


Fig. 6 Comparison between the output of the theoretical models and the measured data.



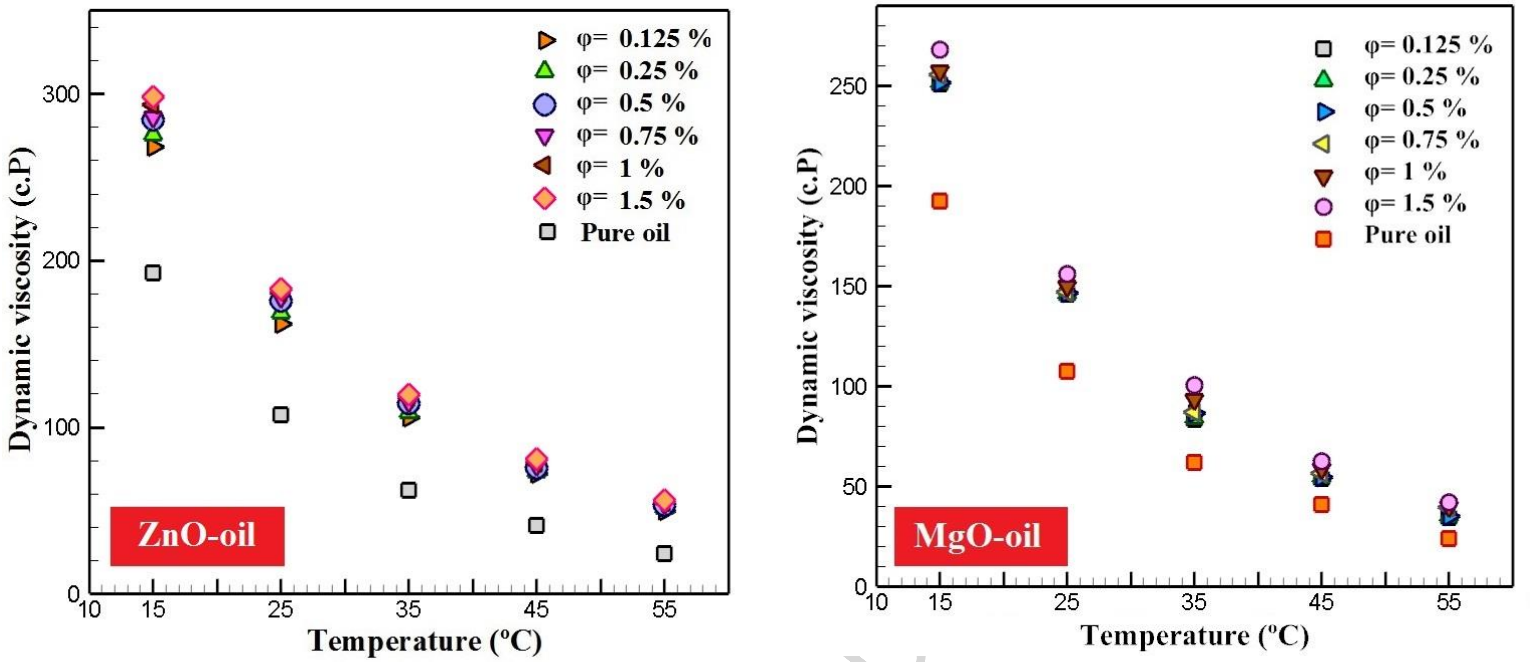
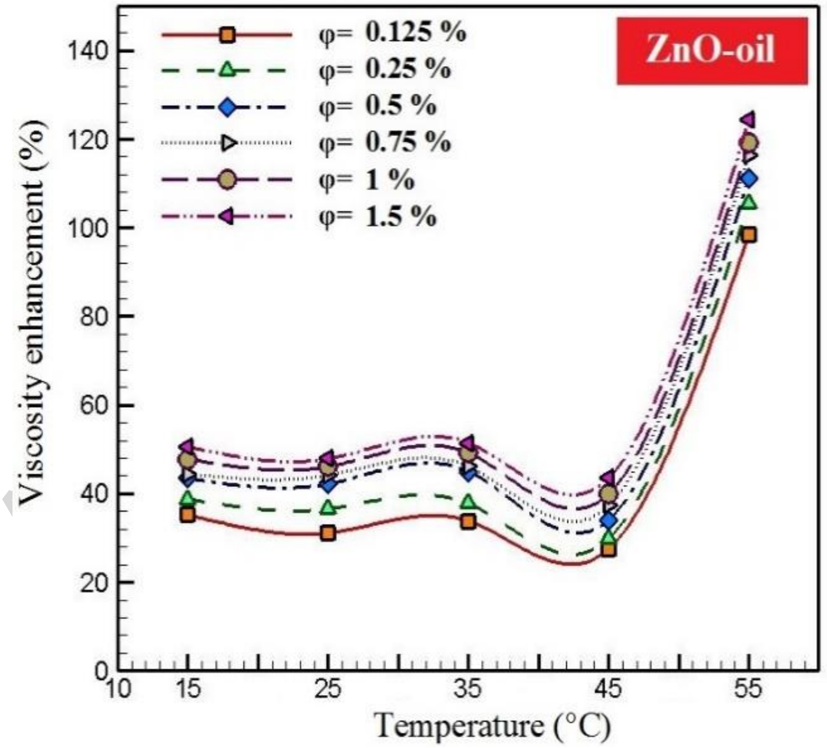


Fig. 7 Dynamic viscosity of the ZnO- and MgO-engine oil nanofluids in different solid concentrations and temperatures.



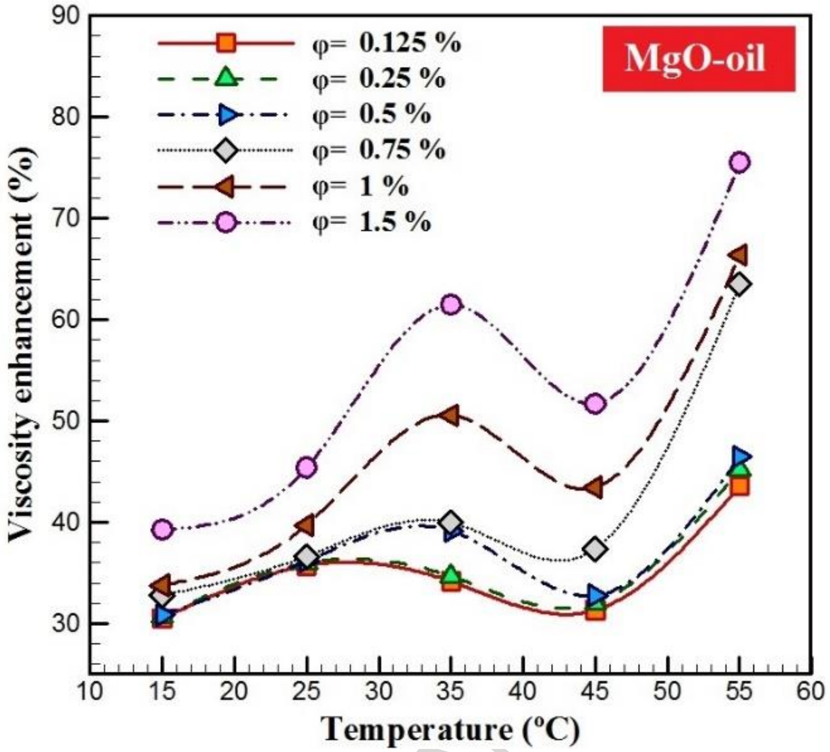


Fig. 8 Dynamic viscosity enhancement versus temperature in different solid concentrations.

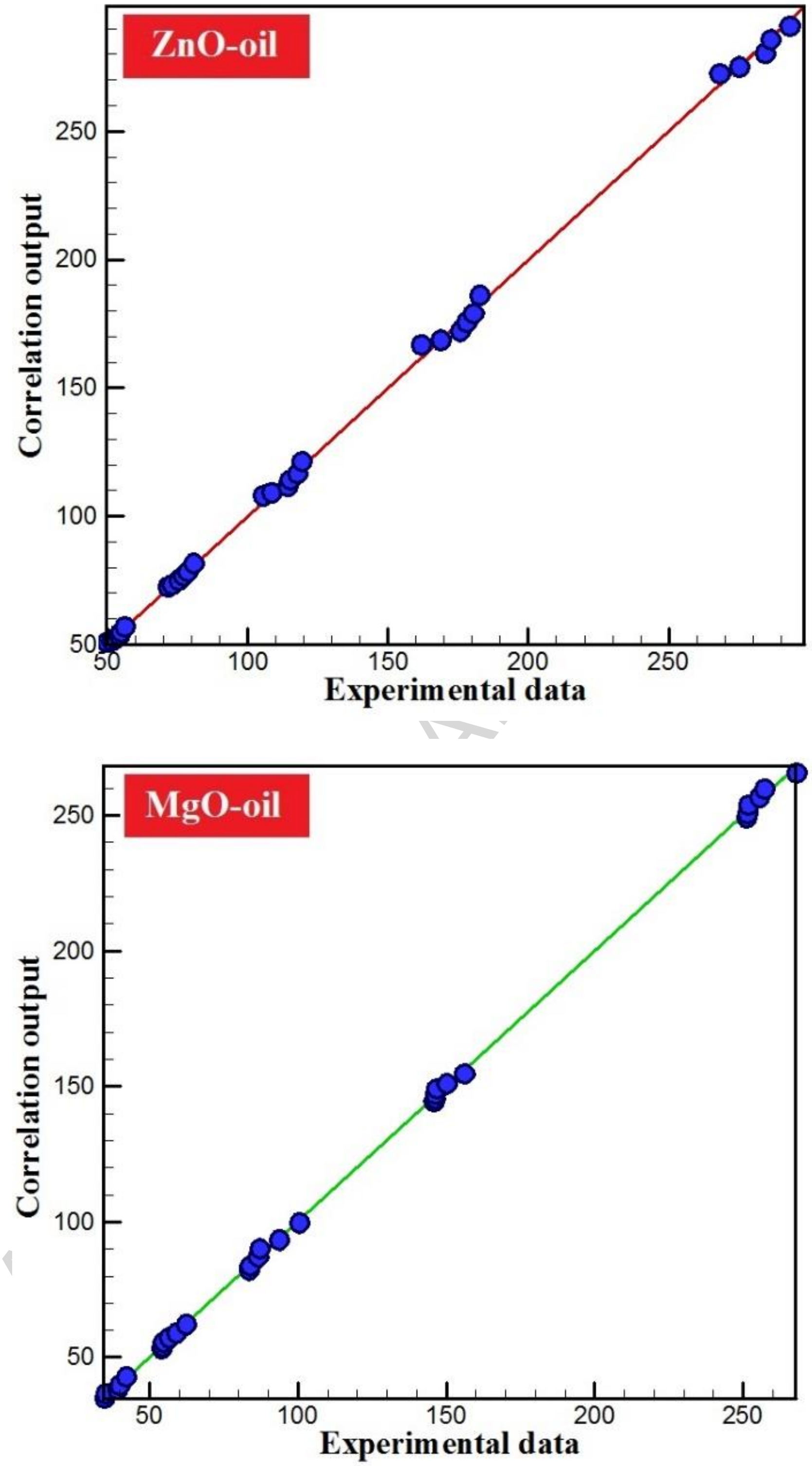


Fig. 9 Comparison between the correlation output and experimental data.

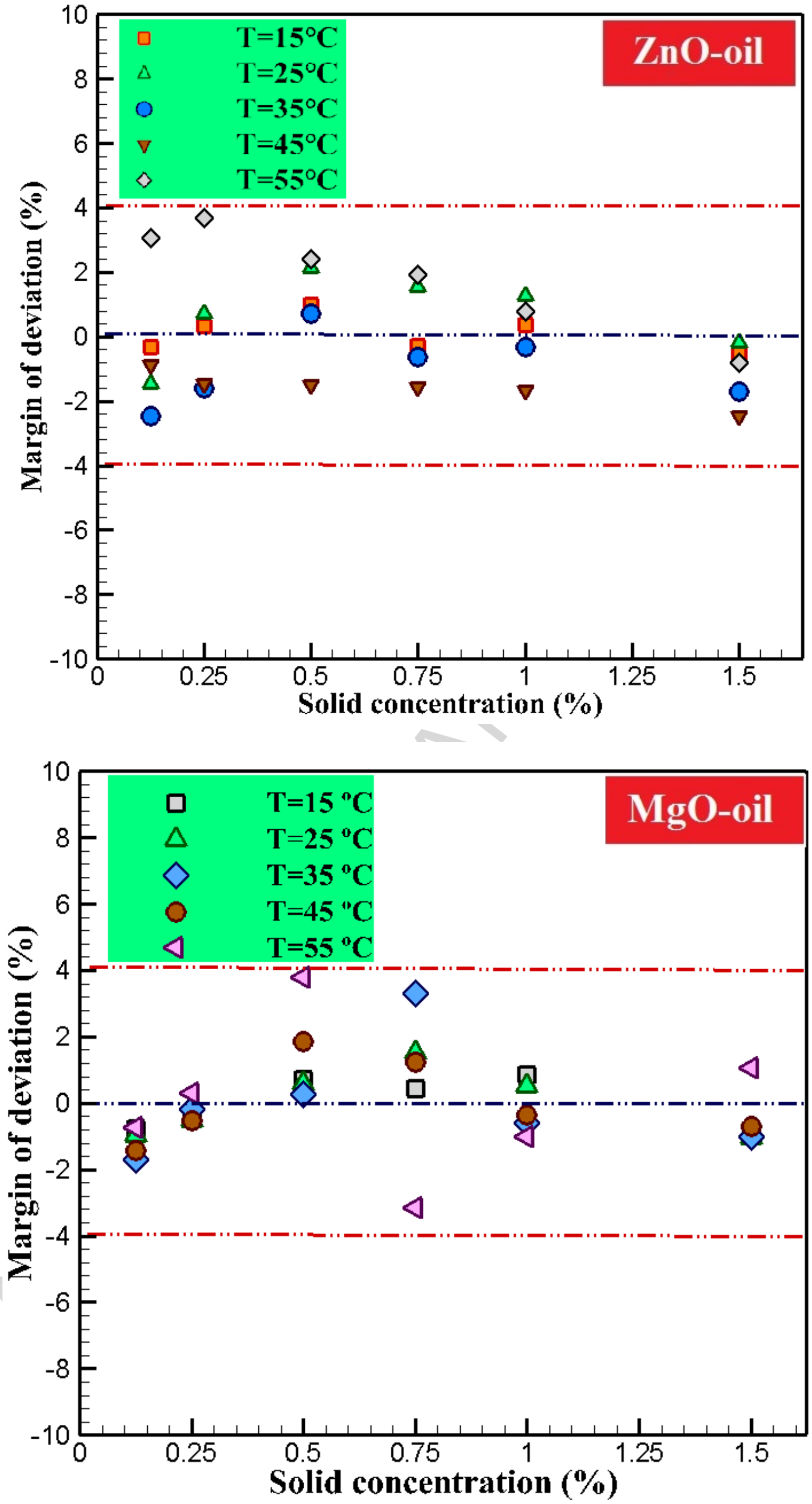


Fig. 10 Margin of deviation for the proposed correlations.

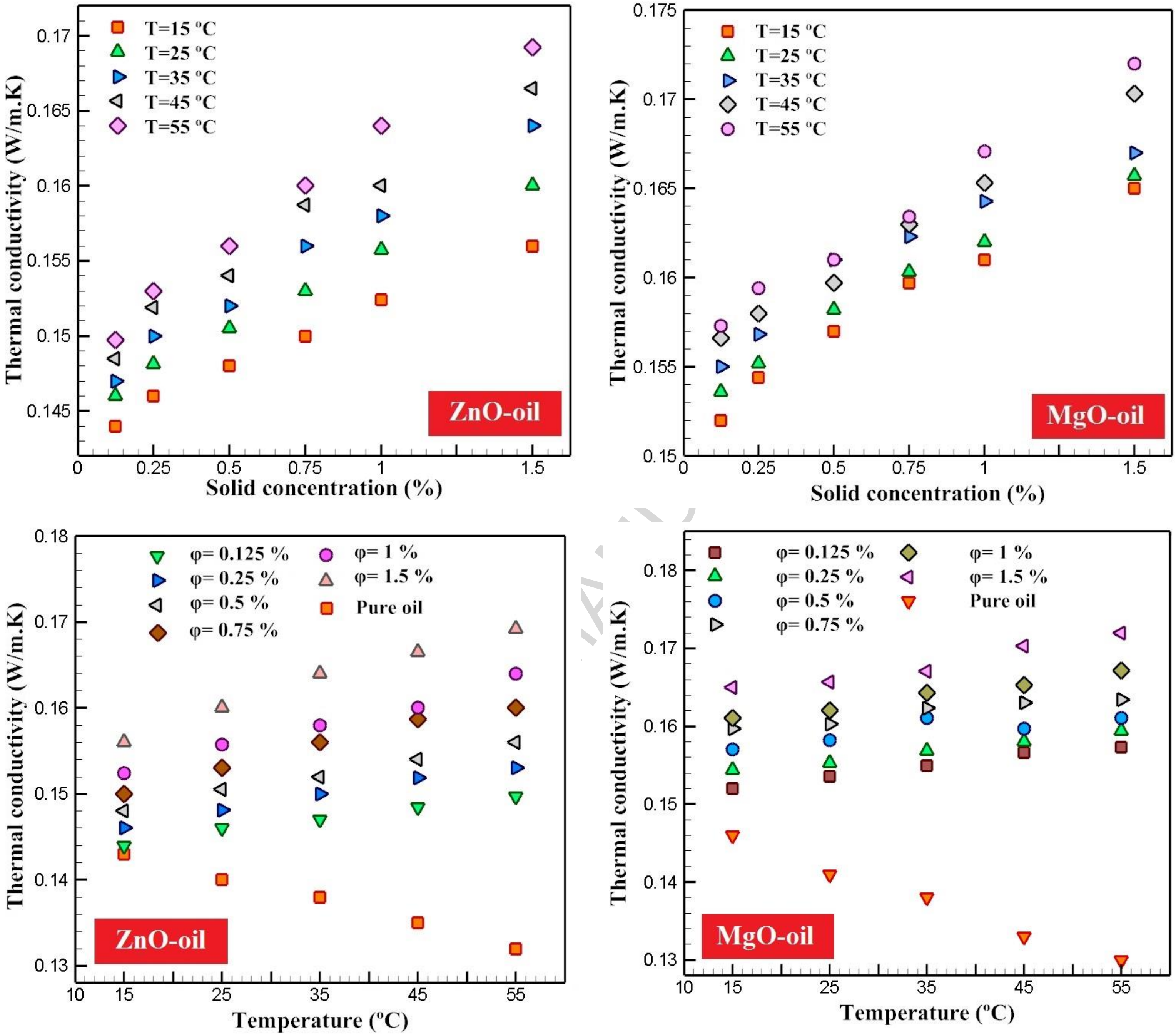


Fig. 11 Thermal conductivity of ZnO and MgO-engine oil nano-lubricant in different solid concentrations and temperatures.

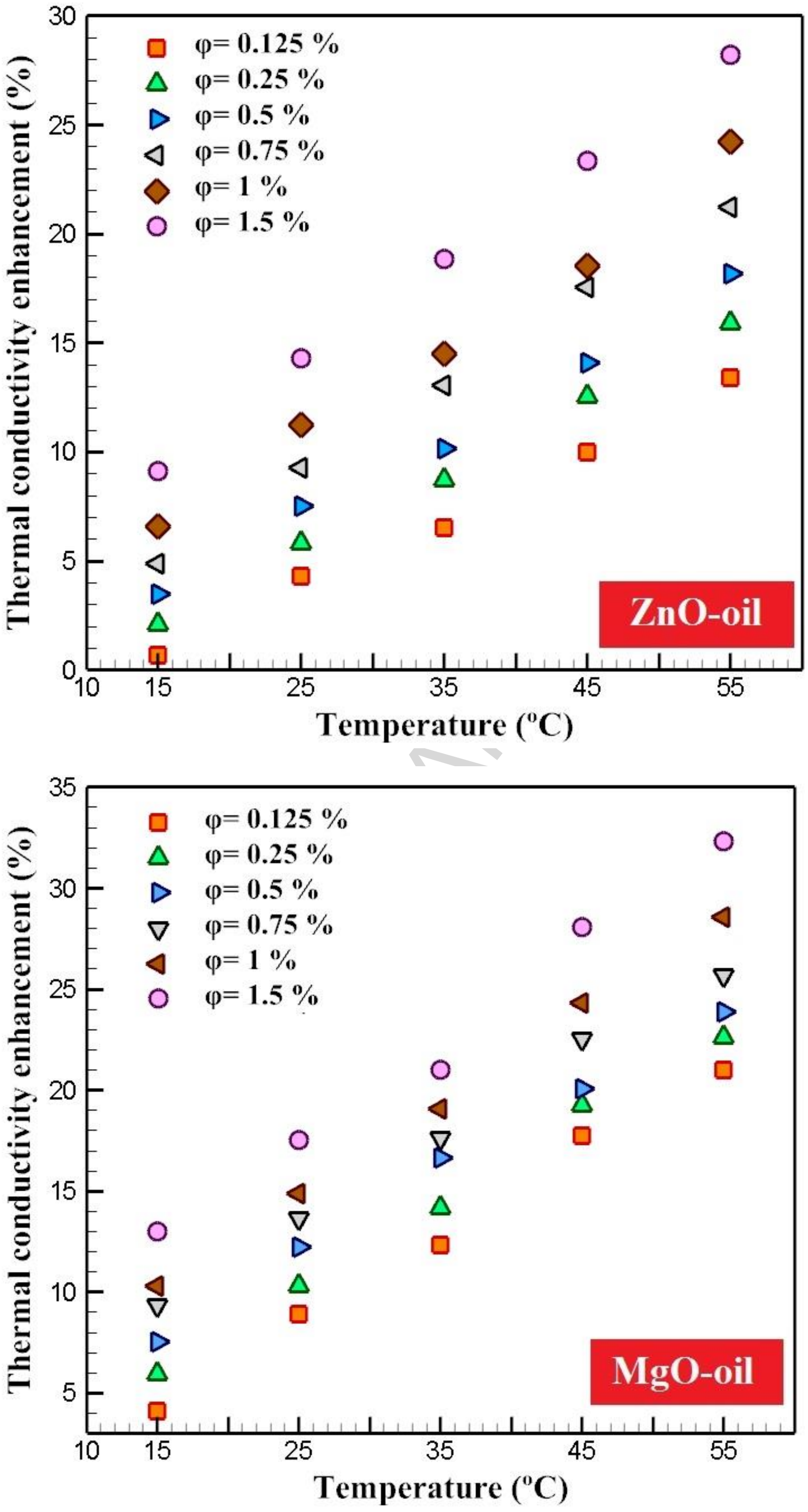


Fig. 12 Thermal conductivity enchantment.

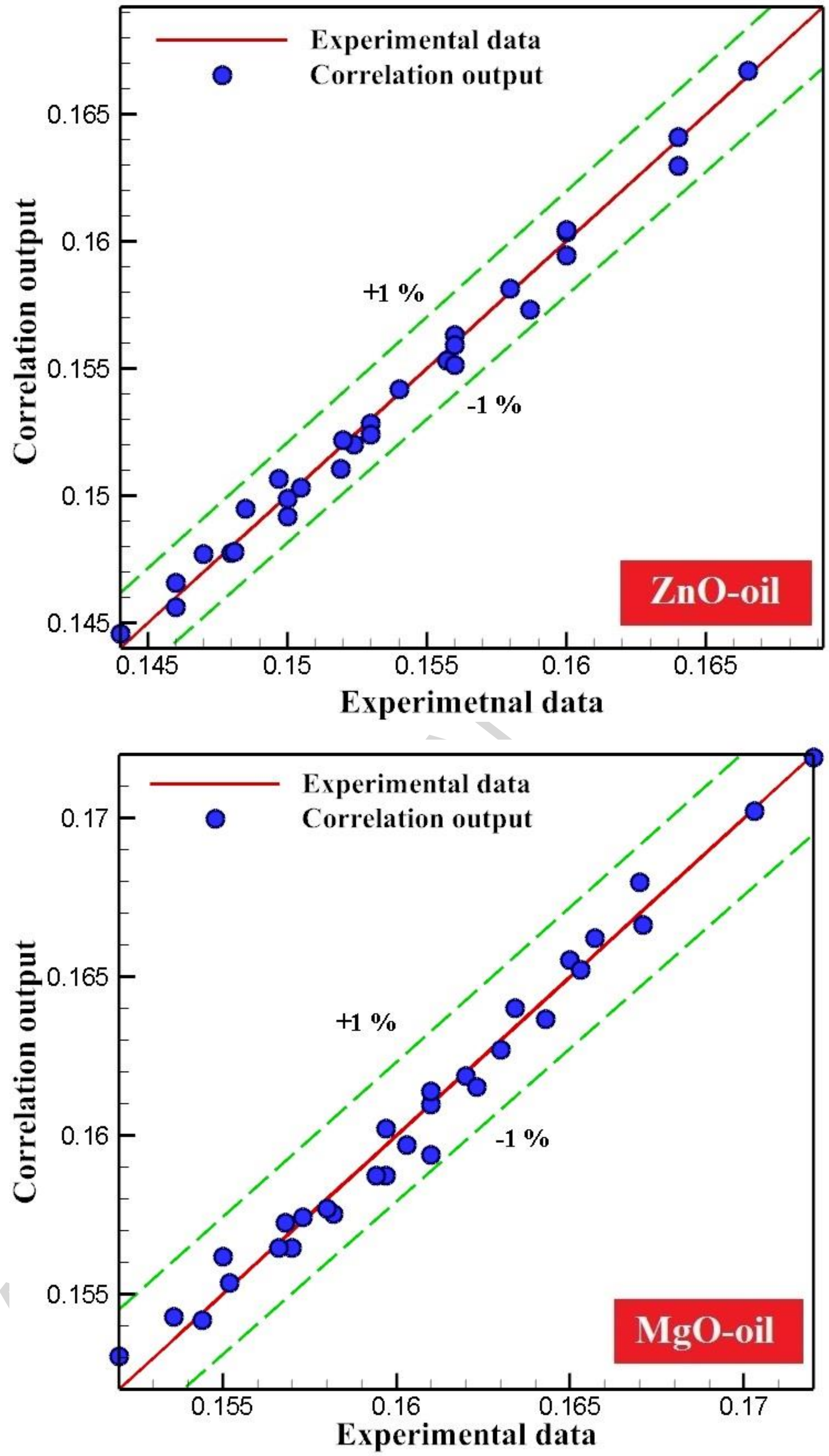


Fig. 13 comparison between correlation output and experimental data.

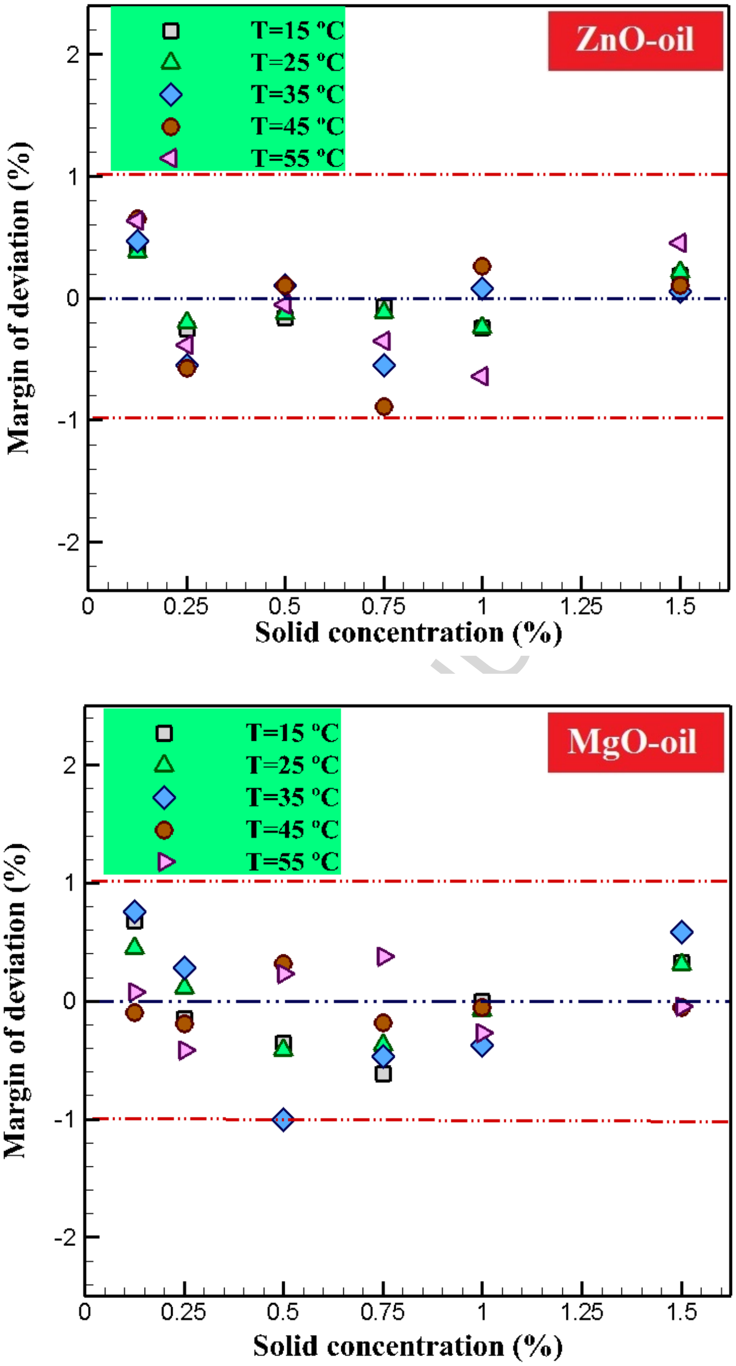


Fig. 14 Margin of deviation for the proposed correlation to predict the thermal conductivity.

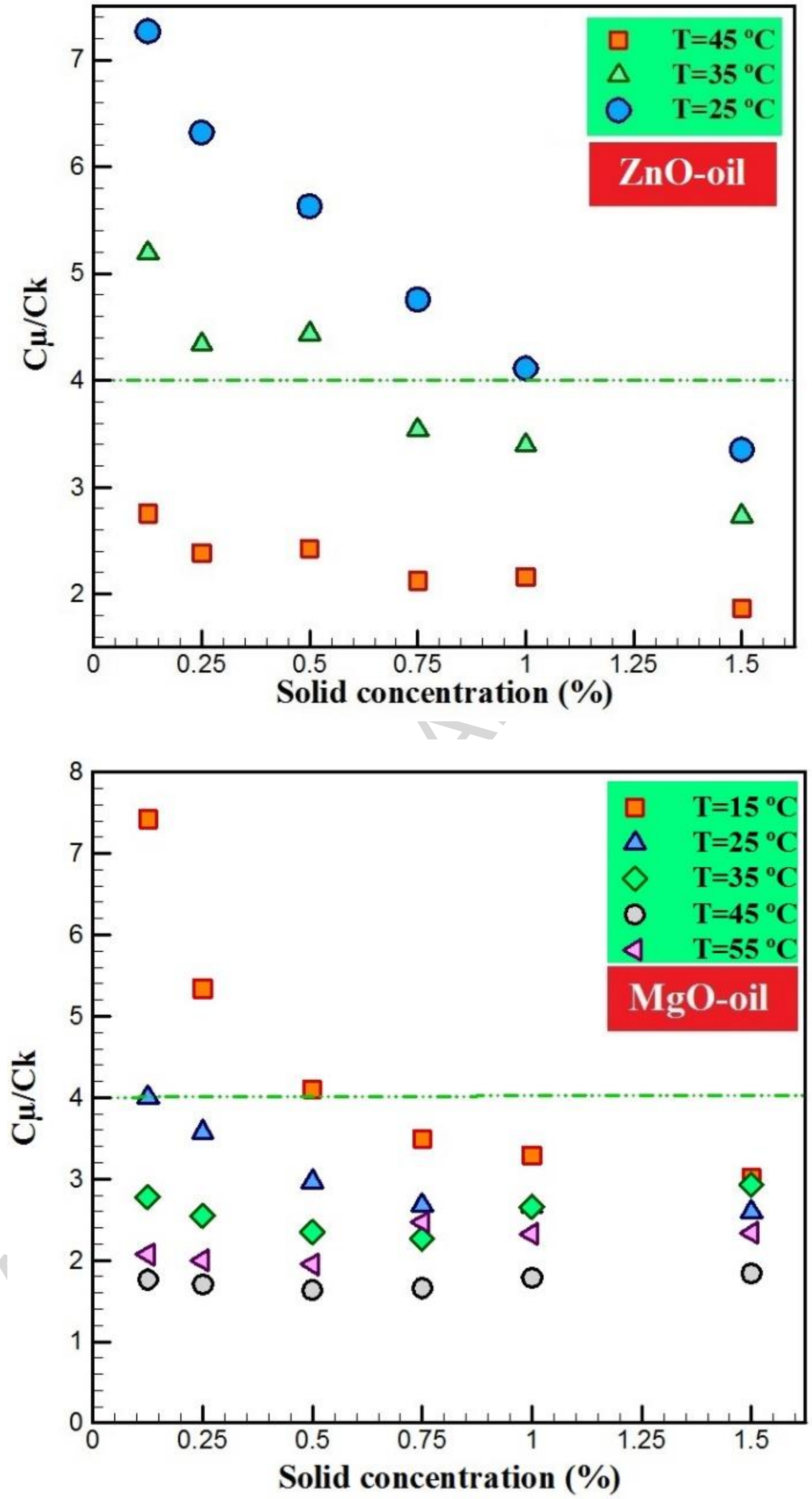
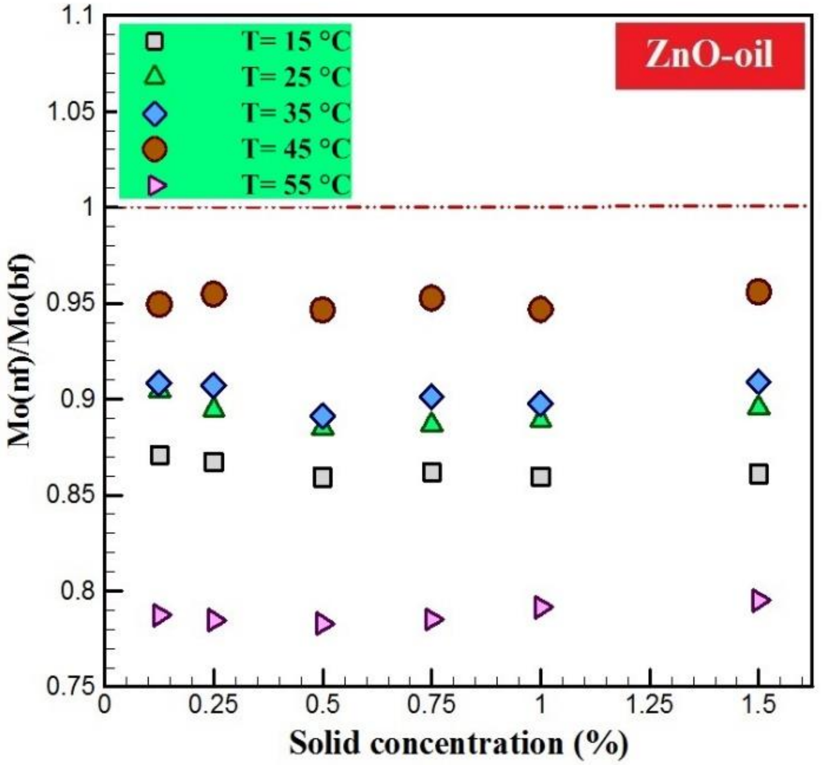


Fig. 15 Evaluation of heat transfer performance of ZnO and MgO-engine oil nanofluid for laminar flows.



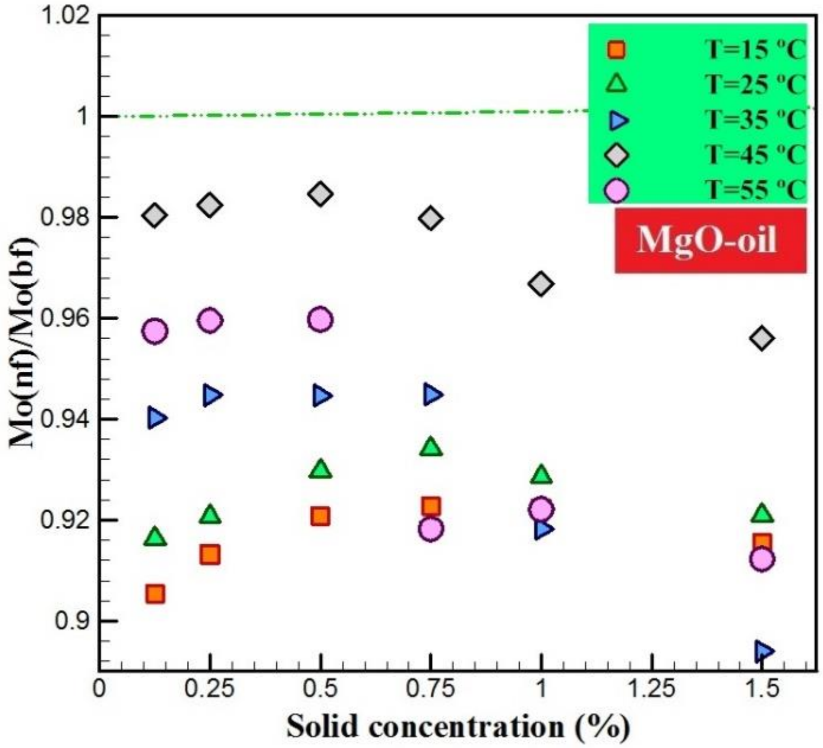


Fig. 16 Evaluation of heat transfer performance of ZnO- MgO-engine oil nanofluid for turbulent lows

Tables:

Table 1 A summary of the recently published literature on oil-based nanofluids

Reference	Studied nanofluid	Solid concentrations	Temperatures	Measured parameters
Saeedinia et al. **[27]**	CuO-oil	0.2-2 wt%	20-70 ℃	Viscosity, thermal conductivity, density, and specific heat capacity
Pakdaman et al. **[28]**	MWCNT/ oil	0.1, 0.2, and 0.4 wt %	40-100 ℃	Viscosity, thermal conductivity, density, and specific heat capacity
Hemmat et al. [29]	MWCNT-TiO2/oil	0.0625-1 %	25-50 ℃	Viscosity
Asadi [30]	MWCNT-ZnO/oil	0.125-1 %	15-55 ℃	Viscosity, thermal conductivity, and heat transfer performance
Dardan et al. **[31]**	Al_2O_3-MWCNT/engine oil (SAE40)	0.0625 % to 1 %	25-50 ℃	Viscosity
Hemmat Esfe et al. **[32]**	MWCNT-SiO_2/ engine oil (SAE40)	0.0625-2 vol.%	25-50 ℃	Viscosity
Afrand et al. **[33]**	MWCNT-SiO_2/ engine oil (SAE40)	0-1 vol.%	25-60 ℃	Viscosity
Li et al. **[34]**	SiC/diathermic oil	0.2-0.8 vol.%	25-60 ℃	Viscosity and thermal conductivity
Asadi et al. **[35]**	MWCNT-MgO/ engine oil (SAE50)	0.25-2 vol. %	25-50 ℃	Viscosity and thermal conductivity
Hemmat Esfe et al. **[36]**	MWCNT-ZnO/ engine oil (SAE40)	0.05-1 vol. %	25-60 ℃	Viscosity
Aberoumand et al. **[37]**	Ag/oil	0.12, 0.36, and 0.72 wt %	25 to 60 ℃	Viscosity and thermal conductivity
Goodarzi et al. [38]	MWCNT-ZnO/ engine oil	0.05-0.8 %	5-55 ℃	Viscosity
Asadi et al. **[39]**	MWCNT-Mg(OH)2/engine oil	0.25 to 2 vol. %	25 to 60 ℃	Viscosity and thermal conductivity
Li et al. **[23]**	SiC/waste cooking oil	0.05 and 1 vol. %	25-65 ℃	Viscosity and thermal conductivity

	TiO_2/waste cooking oil			
Asadi and Asadi **[40]**	MWCNT-ZnO/engine oil (10W40)	0.125-1 vol. %	5-55 ℃	Viscosity and thermal conductivity
Wei et al. **[41]**	SiC-TiO2/diathermic oil	0-1 vol. %	25-60 ℃	Viscosity and thermal conductivity
Asadi et al. **[42]**	MWCNT-Al2O3/engine oil	0.125 to 1.5 vol. %	25 to 50 ℃	Viscosity and thermal conductivity
Motahari et al. **[43]**	MWCNT-SiO2/engine oil (20W50)	0.05 to 1 vol. %	40 to 100 ℃	Viscosity

Tab. 2 Specification of the studied nanoparticles

Characteristic	ZnO	MgO
Purity	99 + %	99 + %
Size (nm)	35-45	40
Specific surface area (SSA) (m^2/g)	> 60	> 60
Color	White	White
True Density (ρ) (g/m^3)	5.606	3.58
Specific heat capacity (C_p) (KJ/Kg. K)	0.514	0.937
Thermal Conductivity (W/m. K)	29	54.9

Tab. 3 Detailed information of the viscometer.

Working Temperature Range	Speeds	Accuracy	Repeatability	Measuring range	Torque range
5-75°C	5-1000 RPM	±2%	±5%	0.3-1028 c.P	797-7, 970 dyne.cm

Tab. 4 Specifications of KD2 Pro thermal analyzer device

Measurement speed	2 min
Accuracy	±5 % Thermal conductivity
Operating environment	Controller: 0 to 50 ºC Sensor: -50 to 150 ºC
Range of measurement	0.02 to 2 W/m. k
Sensor	Needle length: 6 cm Needle diameter: 1.3 mm

Tab. 5 Constant values of the proposed correlation to predict the dynamic viscosity of ZnO-engine oil nanofluid in different temperatures

Temperature (ºC)	A	B
15	269.85	2110.65
25	165.17	1387.78
35	106.85	971.49
45	71.69	657.72
55	50.27	444.55

Tab. 6 Constant values of the proposed correlation to predict the dynamic viscosity of MgO-engine oil nanofluid in different temperatures

Temperature (ºC)	A	B
15	247.72	1200.95
25	143.57	738.2
35	80.59	1265.62
45	52.52	636.16
55	33.58	610.77

Tab. 7 proposed correlation to predict the thermal conductivity of ZnO-engine oil nanofluid.

Temperature (ºC)	Proposed Correlation
15	$k_{nf} = 0.1435 + 0.8526\varphi$
25	$k_{nf} = 0.1453 + 1.0026\varphi$
35	$k_{nf} = 0.1462 + 1.1928\varphi$
45	$k_{nf} = 0.1479 + 1.2522\varphi$
55	$k_{nf} = 0.1489 + 1.405\varphi$

Tab. 8 proposed correlation to predict the thermal conductivity of MgO-engine oil nanofluid.

Temperature (ºC)	Proposed Correlation
15	$k_{nf} = 0.1519 + 0.909\varphi$
25	$k_{nf} = 0.1532 + 0.867\varphi$
35	$k_{nf} = 0.1551 + 0.858\varphi$
45	$k_{nf} = 0.1552 + 1.0007\varphi$
55	$k_{nf} = 0.1561 + 1.05\varphi$

- The prepared samples of both the nanofluids showed Newtonian behavior
- ZnO nanofluid showed higher viscosity increase compare to MgO
- MgO nanofluid showed higher thermal conductivity enhancement compare to ZnO
- MgO nanofluid is favorable to use as heat transfer fluid in internal laminar flow
- ZnO nanofluid is recommended as heat transfer fluid in limited temperatures