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Experimental determination of thermal conductivity and dynamic viscosity of Ag–MgO/water hybrid nanofluid☆

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ABSTRACT

The main goal of this experimental work is to investigate the effect of nanoparticle volume fraction on thermal conductivity and dynamic viscosity of Ag–MgO/water hybrid nanofluid with the particle diameter of 40(MgO) and 25(Ag) nm and nanoparticle volume fraction (50% Ag and 50% MgO by volume) range between 0% and 2% and presenting new correlations. Several existing theoretical and empirical correlations for thermal conductivity (four correlations) and dynamic viscosity (five correlations) of nanofluids have been examined for their accuracy in predicting the value of thermodynamics properties by comparing the predicted values with experimental data. The examined correlations were found to present inaccuracies (under predictions) in the range of nanoparticle volume fraction under study. Predictions of the new developed correlations by comparing the predicted values with experimental data showed that the new correlations are within a very good accuracy.

1. Introduction

Convection heat transfer that occurs through a fluid may be influenced by many factors such as geometry, boundary conditions and thermodynamics properties (thermal conductivity, dynamics viscosity, special heat capacitance and specific mass of the fluid). It is well known that the suspension of solid particles in a fluid may increase the convection heat transfer due to enhancement of thermal conductivity of suspension. This subject is originated by Maxwell [1] and developed by a large number of researchers. In 1995 Choi [2] proposed suspension of fluid and ultrafine solid particle (nano particles) with very low quantity called nanofluid. Nanofluid has exciting properties, such as larger relative surface area of particles, better stability of suspension, reduce erosion of channels or conduits, higher heat transfer enhancement and so on compared to suspension of fluid and micro size particles that proposed by Maxwell [1]. Keblinski et al. [3] presented a complete review on the properties of the nanofluids.

It is well known that the properties of nanofluids depend on the size of nanoparticles [4–7], quantity of nanoparticles (volume fraction) [8–10], shape of nanoparticles, ultrasonication time to prepare nanofluids [10], use or non-use of surfactant in nanofluids [6,11], pH value of nanofluids [12] and temperature of nanofluids [7,9,12,13]. A benchmark study [14] related the heat transfer enhancement of nanofluid to several mechanisms such as Brownian motion of nanoparticles that developed a micro convection in nanofluids influencing energy transport, cluster formation of particles and forming a high thermal conductivity layer around the particles. Clustering formation of particles can enhance or reduce the thermal conductivity depending on the size of clusters [14–17].

Several theories have been presented by a number of researchers in order to explain the thermal conductivity enhancement, such as heat transfer due to Brownian motion of particles in nanofluids [4,5,18] and formation of interfacial layer around the nanoparticles [6]. But there is a lack of agreement between these different theories and experimental data. Due to an existing large number of factors that have a non negligible effect on the thermodynamics properties proposing an accurate model for thermodynamics properties (thermal conductivity, dynamics viscosity …) of nanofluids has been a difficult task. There are two groups of model, theoretical and empirical. As an example of theoretical models one referred to Murshed et al. [6], Maxwell [1], Jeffrey [19], Yu and Choi [20], Koo and Kleinstreuer [21], Xie et al. [22], Bruggeman [23] and Nan et al. [24] for thermal conductivity and Brinkman [25], Lundgren [26], Batchelor [27] and Guo et al. [16] for dynamic viscosity. Barbe's et al. [4], Mintsa [28], and Hemmat Esfe et al. [5] are the empirical correlations for thermal conductivity and Masoumi et al. [29] for dynamic viscosity.

Maxwell [1] proposed his thermal conductivity model based on heat conduction through a stationary random suspension of sphere particles. Yu and Choi [20] presented a new thermal conductivity model that was

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Nomenclature

k	thermal conductivity (W/m K)
Pr	Prandtl number
Re	Reynolds number

Greeks

μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)
δ	uncertainty
φ	nanoparticle volume fraction

Subscripts

f	base fluid
nf	nanofluid
p	particles

a modified version of Maxwell model. Yu and Choi [20] model accounted the effect of nano-layer. Koo and Kleinstreuer [21] thermal conductivity model is based on the consideration of the Brownian motion effect in determining the effective thermal conductivity. Xie [22] proposed another thermal conductivity model that is used from Fourier's law of heat conduction for low volume concentration and nanolayer effects. Burggeman [23] conducted a study and presented a thermal conductivity model for high nanoparticle volume fraction. Nan et al. [24] proposed a thermal conductivity model considering the effects of nanoparticle shape and interfacial resistance. The existed empirical correlations are based on curve fitting through experimental data in the range of their study. Empirical model for thermal conductivity are a functions of nanoparticle volume fraction, size and temperatures. Thermal conductivity model of Hamilton and Crosser [30] was presented for the system having two heterogeneous sub-parts. Prasher et al. [31] presented a thermal conductivity model considering the effect of Brownian motion of nanoparticles as the main factor for increasing the thermal conductivity.

There are a few works on presenting a dynamic viscosity model (correlation) for nanofluids. Dynamic viscosity model of Brinkman [25] was a new version of Einstein model for higher concentration. Lundgren [26] dynamic viscosity model was another version of Einstein model based on the Taylor series on concentration that comprised the second or higher order terms. Batchelor [27] proposed a dynamic viscosity model considering the Brownian motion effect of spherical nanoparticles. A new version of Batchelor model was presented by Guo et al. [16] considering the nanoparticle diameter effect for suspensions at low concentration. Dynamic viscosity model of Graham [32] based on account of the effect of minimum separation distance between two nanospheres for low concentrations. Masoumi et al. [29] dynamic viscosity model was presented taking into account the thermodynamic properties of nanoparticles and base fluid. Wang et al. [9] presented a new correlation that was based on the experimental data. Maiga et al. [33] performed a curve fitting on data of Wang et al. [9] by the least-square curve fitting method. Chen et al. [34] conducted an experimental study on thermal conductivity and dynamic viscosity for carbon nanotube without presenting any correlation.

The main idea in producing hybrid nanofluids is to obtain better properties of product (hybrid nanofluids) such as better thermal conductivity compared to individual nanofluids, chemical stability, physical strength, mechanical resistance and so on. It is worth to say that in real practical applications, it is required to trade-off between several properties and that is where the use of hybrid nanofluid comes. Another important point about newer models (correlations) is their accuracy and reliably. Hence, one of the main objectives of this research work is to investigate the accuracy of the existing thermal conductivity and dynamic viscosity models (correlations) by comparing the presented data of this work with values predicted by existing models for Ag–MgO/water hybrid nanofluids in order to develop new correlation. Up to now there are no studies about thermal conductivity and dynamic viscosity of Ag–MgO/water hybrid nanofluid. In this work we have used water as a base fluid. Some correlations have been presented for calculating thermal conductivity and dynamic viscosity of nanofluid as a function of nanoparticle volume fraction (50% Ag and 50% MgO by volume) in the range of 0 to 2% nanoparticle volume fraction.

2. Preparation of nanofluid

The first part of preparation is dispersing the nanoparticles in the base fluid and the next part is stabilizing the suspension. For dispersing nanoparticles there are two methods; single step and two steps. There are three methods for stabilizing the suspension: addition of surface activators (surfactants), changing the pH value, and using ultrasonic vibrations. In this work, distilled water was used as a base fluid and the average diameter of the Ag and MgO provided by the US Research Nanomaterial Inc. (Fig. 1) was 25 nm and 40 nm, respectively. XRD was used to determine the size of nanoparticles (Fig. 1).

For breaking down the agglomeration of nanoparticles in water an ultrasonic vibrator was used about 3 h. Cetyl Trimethyl Ammonium Bromide (CTAB) was used to ensure better stability and proper dispersion without affecting nanofluids' thermophysical properties since the surfactant concentrations used in the experiments were very low. After preparing the nanofluid with the different volume concentrations, pH was measured and the value was 5.74. Our observation showed that the suspensions were stable for several hours (days).

3. Experiments

3.1. Thermal conductivity measurement

Transient hotwire method was used for determining the thermal conductivity of nanofluids. This method was first presented in 1931 to determine the absolute thermal conductivity and improved by contribution of many authors. With a proper theoretical basis and using modern electronic instrument, transient hotwire method is a most accurate technique of determining the thermal conductivity of fluids [35,36]. The thermal conductivity of Ag–MgO/water hybrid nanofluid was measured by using a KD2 Pro Thermal Properties Analyzer (Decagon Devices, Inc., USA). This device has the standard of ASTM D5334 and IEEE 442-1981 regulations. This method has been used effectively for nanofluids by numerous authors [28,37–39]. It consists of a readout unit and a single-needle sensor that must be inserted into the medium (fluid sample) one desires to measure. The thermal probe, having 1.27 mm diameter and 60 mm length contains a heating element and a thermoresistor. It should be inserted into the sample fluid vertically in order to avoid the inducing convection. Obtaining the data is done by heating the probe within the fluid sample and monitoring the temperature change of probe simultaneously. The thermistor measures the temperature change and the microprocessor stores the data.

The thermal conductivity of fluid is computed by plotting the temperature difference versus time data using parameter-corrected version of the temperature model presented by Carslaw and Jaeger [40] obtained for an infinite line heat source. It must be noted that the accuracy of the probe was checked before analysis of the nanofluid samples. In fact the sensor needle was calibrated by measuring the thermal conductivity of glycerin, ethylene glycol and pure water. The measurement values were in agreement with the literature value within ±5% accuracy. At each point at least four measurements were done. The uncertainty of the calculated (measured) thermal conductivity was calculated from the uncertainty value of experimental data and was estimated to be lower than 5%. The thermal conductivity calculated from experimental

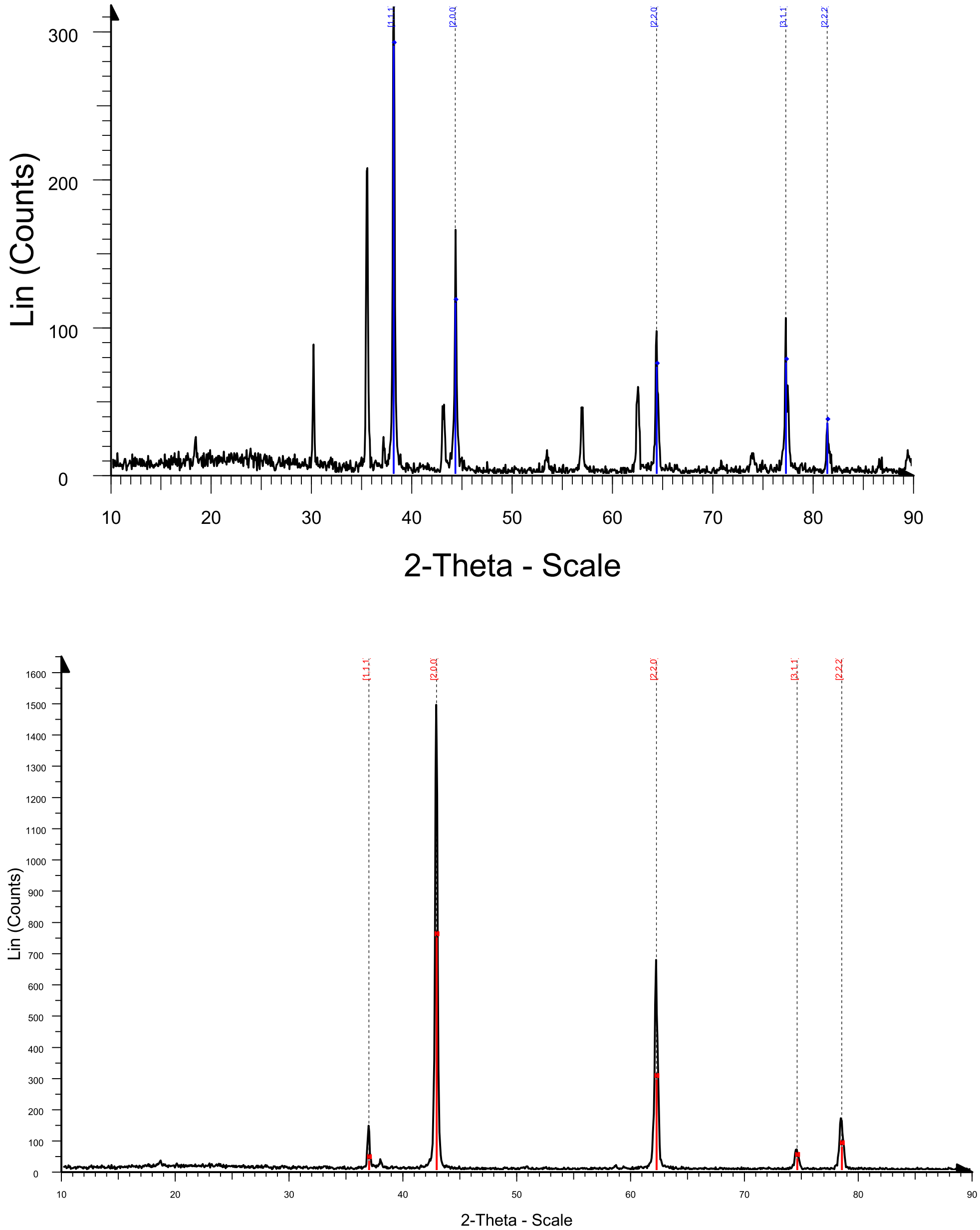

Fig. 1. XRD patterns of Ag and MgO nanoparticles.

data was based on several assumption such as the long heat source treated as an infinitely long heat source and the medium is homogeneous, isotropic, and at uniform initial temperature.

3.2. Viscosity measurement

The viscosity of the Ag–MgO/water hybrid nanofluid was measured by Brookfield cone and plate viscometer. This apparatus is equipped with a 2.4 cm 0.8^0 cone supplied by Brookfield engineering laboratories of USA. The cone is connected to the spindle drive and the plate is mounted in the sample cup. Spindle used was CPE-40 which is designed for measuring the viscosity in the range of 0.3–1028 cP. In order to maintain the gap between the cone and plate an electronic gap adjusting was used. This feature that was provided with the viscometer, makes it possible to maintain a gap of 0.013 mm between the cone and the plate. As the spindle is rotated, the viscous drag of the fluid against the spindle is measured by the deflection of the calibrated spring.

4. Proposed correlations

4.1. Thermal conductivity correlation

According to Fig. 2, through curve fitting on experimental data for thermal conductivity of nanofluid at different volume fractions, Eq. (1) was attained for calculating the thermal conductivity. Fig. 2 shows a good correspondence between experimental data and proposed model.

$$k_{nf} = \left(\frac{0.1747\times10^5+\varphi_p}{0.1747\times10^5-0.1498\times10^6\varphi_p+0.1117\times10^7{\varphi_p}^2+0.1997\times10^8{\varphi_p}^3}\right)k_f \quad 0\le\varphi_p\le0.03 \tag{1}$$

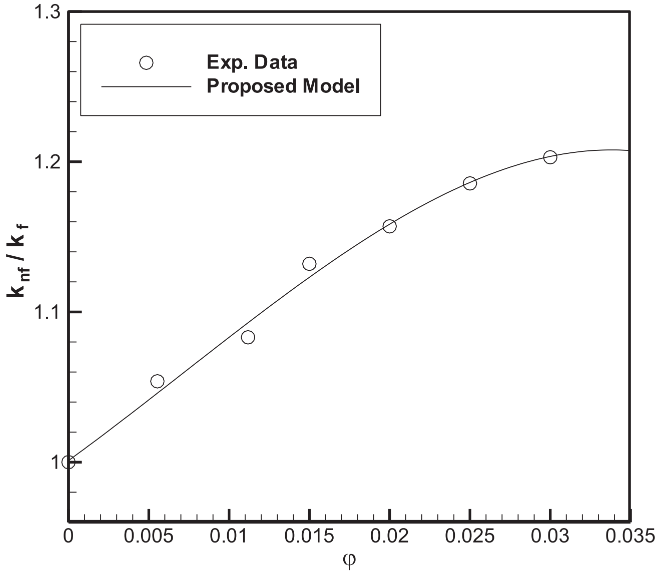

Fig. 2. Curve fitting on experimental data of nanofluid thermal conductivity.

4.2. Dynamic viscosity model

Eq. (2) was obtained for calculating the nanofluid dynamic viscosity by curve fitting on experimental data for different nanoparticle volume fractions shown in Fig. 3.

According to this figure there is a good correspondence between experimental data and proposed model.

$$\mu_{nf} = \left(1 + 32.795\varphi_p - 7214\varphi_p^2 + 714600\varphi_p^3 - 0.1941\times10^8\varphi_p^4\right)\mu_f \quad 0\le\varphi_p\le0.02 \qquad (2)$$

5. Results and discussion

The ratio of nanofluid thermal conductivity to thermal conductivity of base fluid at volume fractions between 0 and 2% was calculated from different equations and shown in Fig. 4.

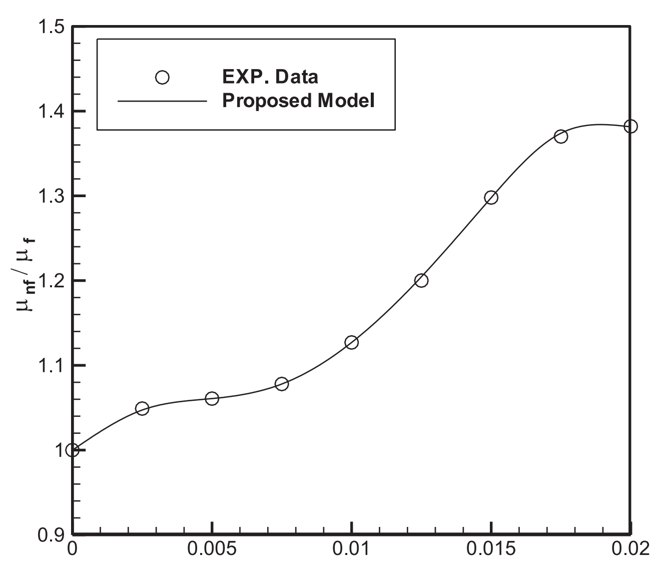

Fig. 3. Curve fitting on experimental data of nanofluid dynamic viscosity.

The proposed model in this work has been used for comparing our experimental data with predicted values by a number of existing models in literature. This comparison has been done in order to evaluate the accuracy of the existing model in predicting the thermal conductivity and dynamic viscosity of Ag–MgO/water hybrid nanofluids.

Selected models (correlations) from literature are Hamilton and Crosser model [30], Yu and Choi model [20], and the first and second models of Prasher et al. [31] for thermal conductivity, Brinkman model [25], Lundgren model [26], Batchelor model [27], Wang et al. model [9] and Chen et al. model [34] for dynamic viscosity. Above models can be divided into two sections, theoretical models and empirical correlations. These models are defined as below:

Hamilton and Crosser model [30]:

$$\frac{k_{nf}}{k_f} = \frac{k_p + (n-1)k_f + (n-1)\varphi_p(k_p - k_f)}{k_p + (n-1)k_f - \varphi_p(k_p - k_f)} \qquad (3)$$

n is experimental shape coefficient and can be attained from n = 3/ψ. For spherical particles n is 3 and for cylindrical particles n is 6. Hamilton and Crosser [30] is an extension version of the Maxwell [1] and can introduce the effect of nanoparticle shape by using a shape factor in his proposition.

Yu and Choi model [20]:

$$\frac{k_{nf}}{k_f} = \frac{k_{pe} + 2k_f + 2\varphi_p(k_{pe} - k_f)(1+\beta)^3}{k_{pe} + 2k_f - \varphi_p(k_{pe} - k_f)(1+\beta)^3} \qquad (4)$$

k_{pe} is the thermal conductivity equivalent to nanoparticle and nanolayer obtained from Eq. (5), and is not related to solid nanoparticle thermal conductivity.

$$\frac{k_{pe}}{k_p} = \frac{\left[2(1-\gamma) + (1+2\gamma)(1+\beta)^3\right]\gamma}{-(1-\gamma) + (1+2\gamma)(1+\beta)^3} \qquad (5)$$

β is the ratio of the nanolayer thickness to the original nanoparticle radius and γ is the ratio of nanolayer thermal conductivity to nanoparticle thermal conductivity.

$$\beta = \frac{h}{r_p}, \gamma = \frac{k_{layer}}{k_p} \qquad (6)$$

According to Yu and Choi [20] reports if the ratio of nanolayer thermal conductivity to thermal conductivity of base fluid is more than 10, there is a good correspondence with experimental results and they considered this ratio equal to 100.

It is worth to mention that Yu and Choi [20] model is a modified version of Hamilton–Crosser model that includes the particle–liquid interfacial layer effect for non-spherical particles. The first and second models of Prasher et al. [31] are as follows.

The first model Eq. (1):

$$\frac{k_{nf}}{k_f} = \frac{[k_p(1+2\alpha) + 2k_m] + 2\varphi_p[k_p(1-2\alpha) - k_m]}{[k_p(1+2\alpha) + 2k_m] - \varphi_p[k_p(1-\alpha) - k_m]}\left(1 + \frac{Re.Pr}{4}\right) \qquad (7)$$

The second model Eq. (2):

$$\frac{k_{nf}}{k_f} = \frac{[k_p(1+2\alpha) + 2k_m] + 2\varphi_p[k_p(1-2\alpha) - k_m]}{[k_p(1+2\alpha) + 2k_m] - \varphi_p[k_p(1-\alpha) - k_m]}\left(1 + ARe^m Pr^{0.333}\varphi_p\right) \qquad (8)$$

where matrix conductivity, K_m, is defined in Eq. (9):

$$k_m = k_f\left(1 + \frac{Re.Pr}{4}\right). \qquad (9)$$

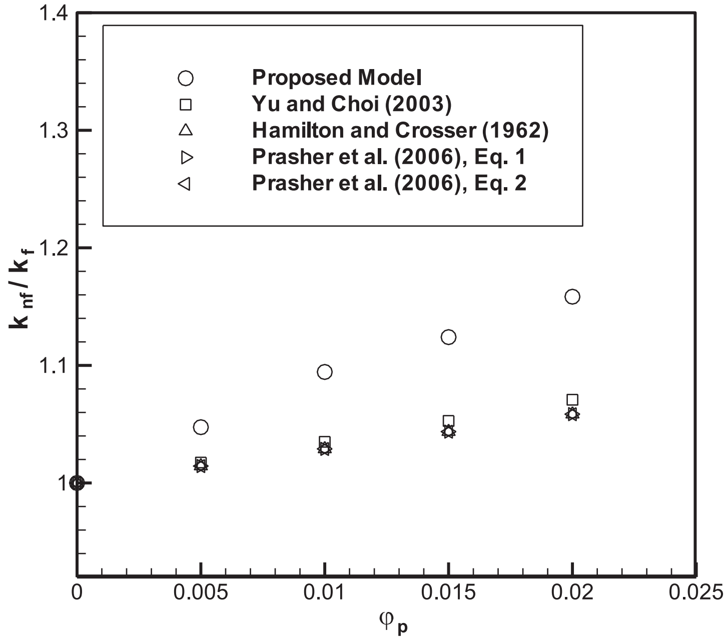

Fig. 4. Comparison between the prediction thermal conductivity from different thermal conductivity models (correlations) with proposed correlation in this work.

In Eq. (9), Re is related to nanoparticle Brownian motion which is obtained from Eq. (10):

$$Re = \frac{v_p d_p}{v} = \frac{1}{v}\sqrt{\frac{18 k_B T}{\pi \rho_p d_p}}, \qquad k_B = 1.3807 \times 10^{-23}\ J/K. \tag{10}$$

In above relation Pr is related to base fluid and α, Bayot number, is defined as below:

$$\alpha = \frac{2 R_b k_m}{d_p} \tag{11}$$

where R_b is the resistance between the fluid and particle layer given in Eq. (12) based on water as a base fluid.

$$R_b = 0.77 \times 10^{-8} \frac{Km^2}{W} \tag{12}$$

Li [41] introduced A as an independent parameter from fluid kind. A and m parameters are presented as below based on water as a base fluid.

$$A = 4 \times 10^4; m = 2.5 \mp (15\%\, of\, 2.5) \tag{13}$$

In these equations the unit of temperature is Kelvin and nanoparticle volume fractions are used in decimal places. Prasher et al. [31] models are based on accounting the convection due to Brownian motion of nanoparticles.

Comparison between the prediction thermal conductivity from different thermal conductivity models (correlations) with proposed correlation is given in Fig. 4. This figure shows that in all nanoparticle volume fractions, the values obtained from proposed correlation are higher than other values predicted by different models, and with increasing nanoparticle volume fraction, the difference between proposed correlation and different models become larger and considerable. This means that all of the used models presented in this comparison lower predicted that experimental data. The first and second models of Prasher et l. [31] at the same nanoparticle volume fraction show the same thermal conductivty, as shown in Table 1. In Table 1 a numerical comparison between measured values of thermal conductivity ratio in this work was done with predicted thermal conductivity ratio by different thermal conductivity models. As can be seen the difference between above two values reaches 10% for nanoparticle volume fraction equal to 0.02.

Researchers in this area attributed the difference between the experimental data and the value predicted by different models to many reasons [42]. One reason maybe was due to the assumption that was used in different models that the nanoparticles are spherical in suspension. In fact the nanoparticles in suspension were as clustering type. The ancient authors used simplified particle dimension such as nominal nanoparticle diameters (for spherical nanoparticles) or nanoparticle diameter and radius (for cylindrical nanoparticles), whereas the nanoparticles may basically exist in cluster form, as reported by many authors, even after using all of dispersing methods such as using CTAB, adjusting pH value or long time of sonication. Based on the data available in literature when the nanoparticles connected together and form clusters have dimensions more than 5 times the nanoparticle dimension. In addition to existence of clusters, their size, shape and orientation of cluster may play an important role in the value of nanofluid thermal conductivity. This discussion emphasizes that the models of thermal conductivity must include the characteristics of clusters other than factors normally

Table 1
Numerical comparison of measured values of thermal conductivity ratio with predicted value by different thermal conductivity ratios models.

Nanoparticle volume fraction	0	0.005	0.01	0.015	0.02
Presented model	1	1.047	1.094	1.124	1.158
Yu and Choi [20] (%diff.)	1	1.017 (2.8%)	1.034 (5.4%)	1.053 (6.3%)	1.071 (7.6%)
Hamilton & Crosser [30] (%diff.)	1	1.014 (3.1%)	1.029 (6%)	1.044 (7.1%)	1.059 (8.6%)
Prasher et al. [31], Eq. (1) (%diff.)	1	1.014 (3.1%)	1.029 (6%)	1.044 (7.1%)	1.059 (8.6%)
Prasher et al. [31], Eq. (2) (%diff.)	1	1.014 (3.1%)	1.029 (6%)	1.044 (7.1%)	1.059 (8.6%)

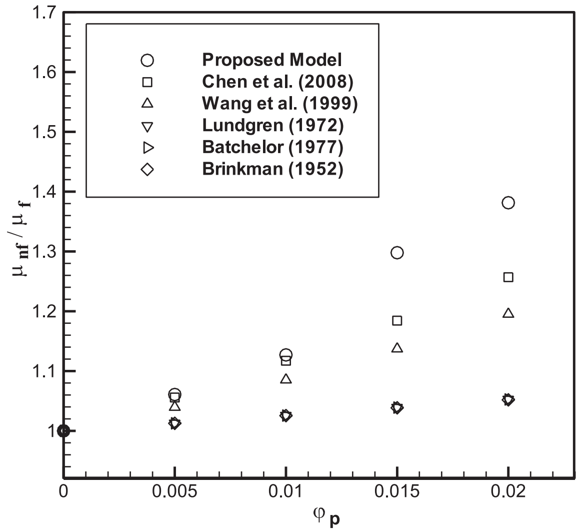

Fig. 5. Comparison between the prediction dynamic viscosity from different dynamic viscosity models with proposed correlation in this work.

used in presenting in this type of thermodynamic properties. Also, it is worth to consider the cluster growth. The last parameter may be important for the time necessary in measuring the thermal conductivity of nanofluids.

Fig. 5 compares the ratio of nanofluid dynamic viscosity to that of base fluid in nanoparticle volume fraction range between 0 and 2% with that predicted by different models. Different models selected from literature are as follows:

Brinkman model [25] predicted dynamic viscosity as:

$$\mu_{nf} = \frac{1}{\left(1-\varphi_p\right)^{2.5}} = \left(1+2.5\varphi_p+4.375\varphi_p^2+\cdots\right)\mu_f. \quad (14)$$

Brinkman [25] model is a generalized model of Einstein correlation for higher concentrations.

Lundgren [26] proposed his model as follows:

$$\mu_{nf} = \frac{1}{1-2.5\varphi_p}\mu_f = \left(1+2.5\varphi_p+6.2\varphi_p^2+O\left(\varphi_p^3\right)\right)\mu_f. \quad (15)$$

Lundgren model [26] is a Taylor series in φ_p.

Batchelor model [27] estimated the dynamic viscosity of nanofluid as:

$$\mu_{nf} = \left(1+2.5\varphi_p+6.2\varphi_p^2\right)\mu_f. \quad (16)$$

Batchelor [27] model is a new model for dynamic viscosity considering the Brownian motion effect of nanoparticles and their interactions.

Wang et al. model [8] is as:

$$\frac{\mu_{nf}}{\mu_f} = \left(1+7.3\varphi_p+123\varphi_p^2\right). \quad (17)$$

Chen et al. model [34] is as follows:

$$\frac{\mu_{nf}}{\mu_f} = \left(1+10.6\varphi_p+(10.6\varphi)^2\right). \quad (18)$$

It is observed that at equal nanoparticle volume fractions, proposed correlation shows higher values with respect to the values predicted by other models (correlations) and with the increasing of nanoparticle volume fraction the difference between the proposed correlation and other models becomes larger. In all nanoparticle volume fractions the values obtained from Batchelor model [27] and Brinkman model [25] are equal. In Table 2 a numerical comparison between measured values of dynamic viscosity ratio in this work was done with predicted dynamic viscosity ratio by different dynamic viscosity models (correlations). As can be seen the difference between above two values reaches 24% for nanoparticle volume fraction equal to 0.02.

Difference between the measured dynamic viscosity and the value predicted by the different models has been attributed to many factors by researchers. These factors are nanoparticle size, shape, concentrations and so on. Above models are based on a correction of one or many above cited factors on dynamic viscosity. A new idea for this difference may be preparation of nanofluids with or without surfactant [43,44]. Basically nanofluids are unstable dynamic fluids. The interaction between the nanoparticles and dispersion medium may play an important role in enhancement of dynamic viscosity. One of the other reasons for above difference may be due to fact that nanoparticles have no spherical shape. If they have an irregular shape, which causes another mechanism in nanofluids, it can influence the dynamic viscosity in flowing flow.

Recently Yang et al. [43] presented a research on relative content of nanoparticles and surfactant in nanofluids. Results of Yang et al. [43] showed that dynamic viscosity is not only related to the relative content of surfactant and nanoparticles, but also strongly dependent on the dispersion type of nanofluid. Furthermore the period of time between the preparing the nanofluid and measuring the dynamic viscosity can produce especial processes that influence the value of viscosity [45].

6. Conclusions

In this work, at first nanofluids with different nanoparticle volume fractions were prepared for investigating the effect of nanoparticle volume fractions on thermal conductivity and dynamic viscosity of Ag–MgO/water hybrid nanofluid and presenting some models to calculate thermal conductivity and dynamic viscosity. With the KD2 system and Brookfield viscometer thermal conductivity and dynamic viscosity were measured experimentally. And then some correlations were presented from curve fitting on experimental data for calculating thermal conductivity and dynamic viscosity of Ag–MgO/water hybrid nanofluid. These correlations are as a function of nanoparticle volume fraction. According to results with increasing the nanoparticle volume fraction, thermal conductivity and dynamic viscosity of nanofluid increase and

Table 2
Numerical comparison of measured values of dynamic viscosity ratio with predicted value by different dynamic viscosity ratio models (correlations).

Nanoparticle volume fraction	0	0.005	0.01	0.015	0.02
Presented model	1	1.061	1.127	1.298	1.381
Chen et al. [34]	1	1.056 (0.5%)	1.117 (0.9%)	1.184 (8.7%)	1.257 (9%)
Wang et al. [8]	1	1.040 (2%)	1.085 (3.7%)	1.132 (13%)	1.195 (13.5%)
Lundgren [26]	1	1.013 (4.5%)	1.026 (9%)	1.039 (20%)	1.053 (24%)
Batchelor [27]	1	1.013 (4.5%)	1.026 (9%)	1.039 (20%)	1.052 (24%)
Brinkman [25]	1	1.013 (4.5%)	1.025 (9%)	1.039 (20%)	1.052 (24%)

presented correlations show higher values in comparison to other existing correlations in literature.

The extension of the present work and other works [46–48] related to the thermophysical properties of nanofluid affords engineers a good option for nanofluid in applications like electronics, automotive, and nuclear applications where improved heat transfer or efficient heat dissipation is required.

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