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ORIGINAL RESEARCH PAPER

Experimental Investigation on the Thermal Conductivity and Viscosity of ZnO Nanofluid and Development of New Correlations

S. Akbarzadeh [1], **M. Farhadi** [1,*], **K. Sedighi** [1], **M. Ebrahimi** [1]
[1]*Mechanical Engineering Department, University of Babol, Babol, I.R. Iran*

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Abstract

In this paper, the measurement of the viscosity of ZnO in ethylene glycol, propylene glycol, mixture of ethylene glycol and water (60:40 by weight), and a mixture of propylene glycol and water (60:40 by weight) and the thermal conductivity in ethylene glycol and propylene glycol as base fluids in the range of temperature from 25 ºC to 60 ºC are investigated. The results indicate that as the temperature increase the viscosity of nanofluid decrease and the thermal conductivity of both base fluid and nanofluid increase. Several existing models for thermal conductivity and viscosity are compared with the experimental data, and they do not demonstrate good comparison agreement. Finally, some new models for predicting the effective viscosity and thermal conductivity are proposed. Furthermore, the viscosity of the base fluid affects the thermal conductivity variation of the nanofluids. The results indicate that the largest enhancements in thermal conductivity are 15% and 9% for EG and PG as base fluids, respectively.

1. Introduction

Nanofluids are suspensions consisting of solid nanoparticles in sizes less than 100 nm. The conventional fluids such as ethylene glycol, oil and water have low thermal conductivity. Using nanoparticles can increase the thermal transport capacities of base fluids. Research conducted in the case of thermal conductivity and viscosity are given. Chandrasekar et al. [1] investigated Al_2O_3/water nanofluid with a nominal diameter of 43 nm at different volume concentrations (0.33–5%) at room temperature.

*Corresponding author
Email address: mfarhadi@nit.ac.ir

A maximum increase in viscosity of Al_2O_3/water nanofluids at 5% volume concentration was 2.36 times that of water. Duangthongsuk and Wongwises [2] used the TiO_2 nanoparticles dispersed in water at volume concentration ranging between 0.2% and 2.0% demonstrated 3–7% more thermal conductivity than water. Schmidt et al. [3] measured the thermal conductivity of 1 vol. % Al_2O_3/decane nanofluids had a thermal conductivity enhancement of 11%. Hrishikesh et al. [4] used Alumina nanoparticles in three ranges of size with surface area-averaged size of 11, 45 and 150 nm. They showed thermal conductivity of alumina (150 nm)/ethylene glycol nanofluid with3% particle volume fraction in a temperature range of 20 ºC to 50 ºC varied from 9.5% to 11%.

	Nomenclature		
		μ	absolute viscosity, Ns/m^2
c_p	specific heat capacity, J/kg K	ρ	density, kg/m^3
d	particle diameter, m	ψ	sphericity, dimensionless
k	thermal conductivity, W/mK		**Subscripts**
k_b	Boltzmann constant, J/K	bf	Base Fluid
n	shape factor, dimensionless	cp	Centi Poise
T	temperature, K	Eff	Effective
	Greek Symbols	nf	Nanofluid
β	ratio of nanolayer thickness to particle radius, dimensionless	P	Particle
Φ	volume concentration, %	r	Relative

Vajjha and Das [5] investigated ZnO nanoparticles in a mixture of ethylene glycol and water of 60:40 (by mass) as a base fluid. They observed thermal conductivity ratio enhancement between 298 and 363 K for a 7% concentration was 18%. Yu et al. [6] measured the thermal conductivity of ZnO in ethylene glycol as a base fluid. The enhanced value of 5.0 vol. % ZnO-EG nanofluid was 26.5%. Palabiyik et al. [7] investigated TiO2 and Al_2O_3 nanoparticles in propylene glycol as a base fluid. The thermal conductivity of the samples showed a nonlinear increase with the particle concentration. The enhancement of thermal conductivity was not temperature dependent and parallels the behavior of pure propylene glycol. Lee et al. [8] investigated the thermal conductivity of nanofluids with Al_2O_3 and CuO nanoparticles that nanofluids with CuO nanoparticles have more enhancement than Al_2O_3. In despite of Al_2O_3 has higher thermal conductivity than CuO.

In this study, the viscosity of ZnO nanoparticles in ethylene glycol, propylene glycol, mixture of ethylene glycol and water (60:40 by weight), and a mixture of propylene glycol and water(60:40 by weight) and the thermal conductivity in ethylene glycol and propylene glycol as base fluids in the range of temperature from 25 ºC to 60 ºC are investigated.

In this work, viscosity and effective thermal conductivity models are reviewed. The results demonstrate that there are significant differences between experimental results and theoretical models. It shows the necessity of experimental workings. At the end, some new models for effective viscosity and thermal conductivity are presented.

2. Theoretical investigations

2.1. Viscosity

Many researchers have studied the effect of parameters such as the size and volume fraction of nanoparticles, the base fluid, and temperature on viscosity. There were some existing theoretical formulas due to estimating the particle suspension viscosities. The Einstein model [9] was the first model to calculate the viscosity of the suspension of spherical solids. Einstein [9] proposed a viscosity correlation for non-interacting particle suspension in a base fluid when the volume concentration was lower than 5%.

$$\mu_{eff} = \mu_l \left(1+2.5\phi\right) \quad (1)$$

Brinkman [10] considered the effect of the addition of one solute-molecule to an existing solution. The correlation was for particle concentrations less than 4%.

$$\mu_{nf} = \mu_{bf} (1-\phi)^{2.5} \quad (2)$$

The correlation was suggested by Wang et al. [5].

$$\mu_{nf} = \mu_{bf} (1+7.3\phi+123\phi^2) \quad (3)$$

Bachelor [11] presented a formula including the effect of Brownian motion.

$$\mu_{nf} = \mu_f \left(1+2.5\phi+6.5\phi^2\right) \quad (4)$$

2.2. Thermal conductivity

Many researchers have studied the thermal conductivity of nanofluids. There were several theoretical models where they could predict thermal conductivity of particle-fluid mixtures in a special range of temperature and volume fractions. Furthermore, many factors such as size, surface area, and shape of nanoparticles can have an effect on the models. The Maxwell model was the first model to determine the effective thermal conductivity of liquid–solid mixtures. Maxwell [12] presented the thermal conductivity model for low solid concentrations. The effective thermal conductivity was:

$$k_{eff}\ / k_b = \left[\frac{k_p + 2k_b - 2(k_p - k_b)\phi}{k_p + 2k_b + \phi(k_p - k_b)}\right] \tag{5}$$

k_p, k_b and Φ were the thermal conductivity of the particle and base fluid and the particle volume fraction in the suspension, respectively.

Hamilton and Crosser modified Maxwell's model to determine the effective thermal conductivity of nonspherical particles by considering a shape factor. The Hamilton and Crosser model [13] was used for determining the effective thermal conductivity of a two-phase mixture:

$$k_{eff}\ / k_b = \left[\frac{k_p + \left(n-1\right)k_b - (n-1)\phi(k_b - k_p)}{k_p + \left(n-1\right)k_b + \phi(k_b - k_p)}\right] \tag{6}$$

n was the empirical shape factor given by n = 3/$\Phi$and Φ was the sphericity. For the spherical shape particle, the sphericity (Φ) is 1.

Bruggeman [14] analyzed the interactions among randomly distributed particles by using the mean field approach. The Bruggeman model [17] was given by

$$k_{eff} = \frac{1}{4}\left[\left(3\phi - 1\right)k_p + (2 - 3\phi)k_b\right] + \frac{k_b}{4}\sqrt{\Delta} \tag{7}$$

$$\Delta = \left[\begin{array}{l}\left(3\phi-1\right)^2 (k_p / k_b)^2 + \left(2-3\phi\right)^2 + \\ 2(2+9\phi-9\phi^2)(k_p / k_b)\end{array}\right] \tag{8}$$

k_{eff} was the effective thermal conductivity of liquid with particle suspension, was the volume fraction of particles, and kb and kp were the thermal conductivities of the base fluid and the particle, respectively.

Jeffrey [15] developed a theoretical model which assumed the conduction of heat through a stationary, random and statistically homogeneous suspension of spherical particles in a matrix of uniform conductivity. He [15] assumed that the volume fraction of particles is small.

$$\frac{k_{eff}}{k_b} = 1 + 3\beta\phi + \left(\begin{array}{l}3\beta^2 + \dfrac{3\beta^2}{4} + \dfrac{9\beta^3}{16} \\ \times\dfrac{\chi+2}{2\chi+3}\end{array}\right)\phi^2 \tag{9}$$

$$\chi = \frac{k_p}{k_{bf}} \qquad \beta = \frac{k_p - k_{bf}}{k_p + 2k_{bf}} = \frac{\chi - 1}{\chi + 2} \tag{10}$$

Timofeeva et al. [16] expressed a mathematical model. It can be written as:

$$k_{nf}\ / k_{bf} = 1 + \frac{3(k_p - k_{bf})\phi}{k_p + 2k_{bf}} \tag{11}$$

Vajjha and Das [17] proposed an empirical model, which involved the dependence of thermal conductivity to temperature and concentration.

$$k_{nf} = A(\phi) + B(\phi)T + C(\phi)T^2 \tag{12}$$

The coefficients A, B, and C were polynomial functions of concentration.

Koo and Kleinstreuer [18] developed a new model for nanofluids. Their model contained the effects of particle size, particle volume fraction, temperature and properties of the base fluid and the particles. Their formula was

$$k_{eff} = \left[\frac{k_p + 2k_{bf} + 2(k_p - k_{bf})\phi}{k_p + 2k_{bf} - (k_p - k_{bf})\phi} \right] k_{bf} + \left[(5 \times 10^4) \beta \phi \rho_{bf} c_{pbf} \sqrt{\frac{k_B T}{\rho_p d_p}} f(T, \phi, etc.) \right] \quad (13)$$

It can be seen that there are not general models to explain the strange behavior of the nanofluids including the viscosity and effective thermal conductivity. Currently there is no reliable theory to acceptably predict the anomalous thermal conductivity of nanofluids. Many parameters influence thermal conductivity and viscosity, including the thermal conductivities of the base fluid and the nanoparticles, the volume fraction of the nanoparticles, the surface area, and the shape of the nanoparticle and the temperature. The significant differences between experimental data and theoretical models demonstrate the necessity of experimental workings.

3. Experimental procedure

3.1. Preparation of nanofluids

There are two techniques for preparing nanofluid, one step and two step methods. The one-step method entails the synthesis of nanoparticles directly in the heat transfer fluid. Two-step method, which is used in the study, first prepares the nanoparticles and then disperses them in the base fluid. The physical properties of nanoparticles are summarized in Table 1. Nanofluid samples are prepared by dispersing ZnO nanoparticles in ethylene glycol/water solution (EG-W solution), pure ethylene glycol, propylene glycol/water solution (PG-W solution) and pure propylene glycol at volume fractions 0-3%.

Table 1
Physical properties of nanoparticle

Purity (%)	size	nanoparticle
+99	30 nm	ZnO

Furthermore, the ZnO nanoparticles have electrostatic stabilization. This occurs by the adsorption of ions on the electrophilic metal surface. The adsorption creates an electrical double/multi-layer, which results in a Columbic repulsion force between the nanoclusters.

For preparing nanofluid, according to the volume fraction, the amount of nanoparticles is calculated, and then measured with a 0.001 precision weighing scale (AND-FX300GD, 0.001-320 gram) and slightly added to the base fluid.

The dispersion can be done with various physical treatment techniques, such as the stirrer, the ultrasonic disruptor, and the high-pressure homogenizer. These techniques deagglomerate the particle clusters in order to obtain homogeneous suspensions. For dispersing ZnO, nanoparticles in the base fluid magnetic stirrer and ultrasonic disruptor technique, high intensity ultrasonic processor (Sonics, 20 kHz and 750 W), are used.

Magnetic stirrer is used for about 45 minutes and then the suspension goes under ultrasonic vibration. The time of vibration differs for each nanofluid. It is 1 hour and 90 minutes respectively for ethylene glycol/ZnO, and propylene glycol/ZnO suspensions. In Figure 1a, the ZnO nanoparticles in propylene glycol as a base fluid before affected by ultrasonic vibration are shown. The homogenous nanofluids after sonication are illustrated in Figure 1b. Because ZnO nanoparticles are stable in ethylene glycol and propylene glycol for more than 72 and 48 hours, respectively. After these times, nanoparticles settle down at the bottom of the container.

Fig.1. a) Propylene glycol mixed with ZnO (b) propylene glycol nanofluid after sonication.

The Viscolite (VL700), which is a vibrational instrument for instant measurement of viscosity, is used in this study. This instrument shows the dynamic viscosity of any fluid is surrounding the sensor in terms of centipoises (cP). The Viscometer is examined in air and water for calibration.

Thermal conductivity measurements are made using the Decagon devices KD2 thermal analyzer. This handheld device uses the transient line heat source technique to evaluate the fluid thermal properties. Insulation measurements are best made with the KS-1 probe with 1.3 mm diameter and 60 mm length. The

KD2 meter was calibrated by using the base liquids before any set of measurements. Minimizing the uncertainty of measurements, three measurements were taken for each concentration of the nanofluids at a given temperature.

4. Results and discussions

In this paper, the effect of temperature and volumetric concentration on viscosity and thermal conductivity of ZnO nanofluids, are investigated. Ethylene glycol, propylene glycol, mixture of ethylene glycol and water (60:40 by weight) and propylene glycol and water (60:40 by weight), were used as the base fluid. The results are presented in two parts namely, the effective viscosity of nanofluids and effective thermal conductivity of nanofluids.

4.1. Effective viscosity of nanofluids

Figures 2 show the viscosity of nanofluid decrease exponentially by increasing temperature. It exhibits that the temperature dependence of nanofluid viscosity is similar to the base fluid. In the propylene glycol as base fluid, nanofluids have the highest viscosity. As it can be seen ZnO nanoparticles in propylene glycol as a base fluid in 3% Vol., 66% reduction in viscosity is observed.

Figure 3 gives the relative viscosity (μr) = (μeff) / (μl), defined as the ratio of the effective viscosity of nanofluid and the base fluid, in terms of volumetric particle concentration. Experimental data are compared with the results of mathematical models. It can be observed that the measured viscosity is much higher than the result of mathematical models. It refers to the interaction between the nanoparticles.

The viscosity increases with an increase in the particle volume fraction. Several viscosity models are investigated and compared with experimental data in this article. In conclusion, correlations are proposed for ZnO nanofluids in a mixture of ethylene glycol and water and a mixture of propylene glycol and water as the base fluid. The effect of volume fraction and temperature take into accounts in these correlations. The temperature and volume concentration ranges 25ºC<T<60ºC and 0-3% volume fraction, respectively.

Figure 4 compares present viscosity data for ZnO/EG nanofluid with similar experimental data presented by Moosavi et al. [19] and Kole et al. [20]. It can be seen that the result of this study is different from other investigators. Many factors such as the size and kind of nanoparticles, nanofabrication methods and measurement methods can effect on results. A temperature dependent correlation between viscosity and volume fraction is presented for ZnO nanoparticles suspended in EG/W as a base fluid.

$$\mu_{nf} = \exp(A \times T + B) \tag{14}$$

μ_{nf} is the ZnO nanofluid viscosity in terms of (c_P), T is the temperature in ºC and A, B, C and D are functions of particle volume percentage (Φ). The coefficients A, B, C and D are functions of volume concentration (Φ) as:

$$A=-0.028+1.82\times\phi-112.92\times\phi^2+1996.52\times\phi^3 \tag{15}$$

$$B=2.16-19.86\times\phi+2029.56\times\phi^2-30245.91\times\phi^3 \tag{16}$$

A temperature dependent correlation between viscosity and volume fraction is presented for ZnO nano particles suspended in PG/W as a base fluid.

$$\mu_{nf} = \exp(A \times T + B) \tag{17}$$

$$A= -0.0337+0.4423\times\phi \tag{18}$$

$$B= 2.836+14.271\times\phi \tag{19}$$

The measured viscosity of ZnO nanofluids compares with proposed correlation in figure 5. It can be seen that there is a good agreement between them.

The experimental data gives an average deviation of 7.5% and 4.7% for EG/W and PG/W as base fluids, respectively.

4.2. Effective thermal conductivity of nanofluids

The thermal conductivity of ZnO (20*nm*) in ethylene glycol and propylene glycol in the range of (0.005-0.03%) as base fluids, are measured. Figures 5 show that the thermal conductivity increases with particle volume fraction. Furthermore, this experimental data have been compared to Hamilton – Crosser [13], Bruggeman [14], Jeffrey [15] and Timofeeva [16] models. As it can be seen in Figure 6 from the comparison of experimental results and these theoretical models, it is observed that these models can't predict the effective thermal conductivity of nanofluids.

This can be due to the fact that these traditional models do not consider particle size, particle Brownian motion, and the effect of nanoparticles clustering, which are important in nanofluids. The effect of temperature on the relative thermal conductivity is shown in figure 7.

The largest enhancements in thermal conductivity are 15% and 9% for EG and PG as base fluids, respectively. It can be observed that by increasing the temperature, thermal conductivity increases. The variation of temperature between 25-60 ºC causes an increase in the Brownian motion and results in the clustering of nanoparticles. Brownian motion result in collisions between nanoparticles and it causes energy transfers by nanoparticles. The results indicate ZnO in ethylene glycol have higher thermal conductivity ratio.

EG and PG are used as base fluids. The viscosity of the base fluid affects the Brownian motion of nano particles and it causes the thermal conductivity variation of the nanofluid [21].

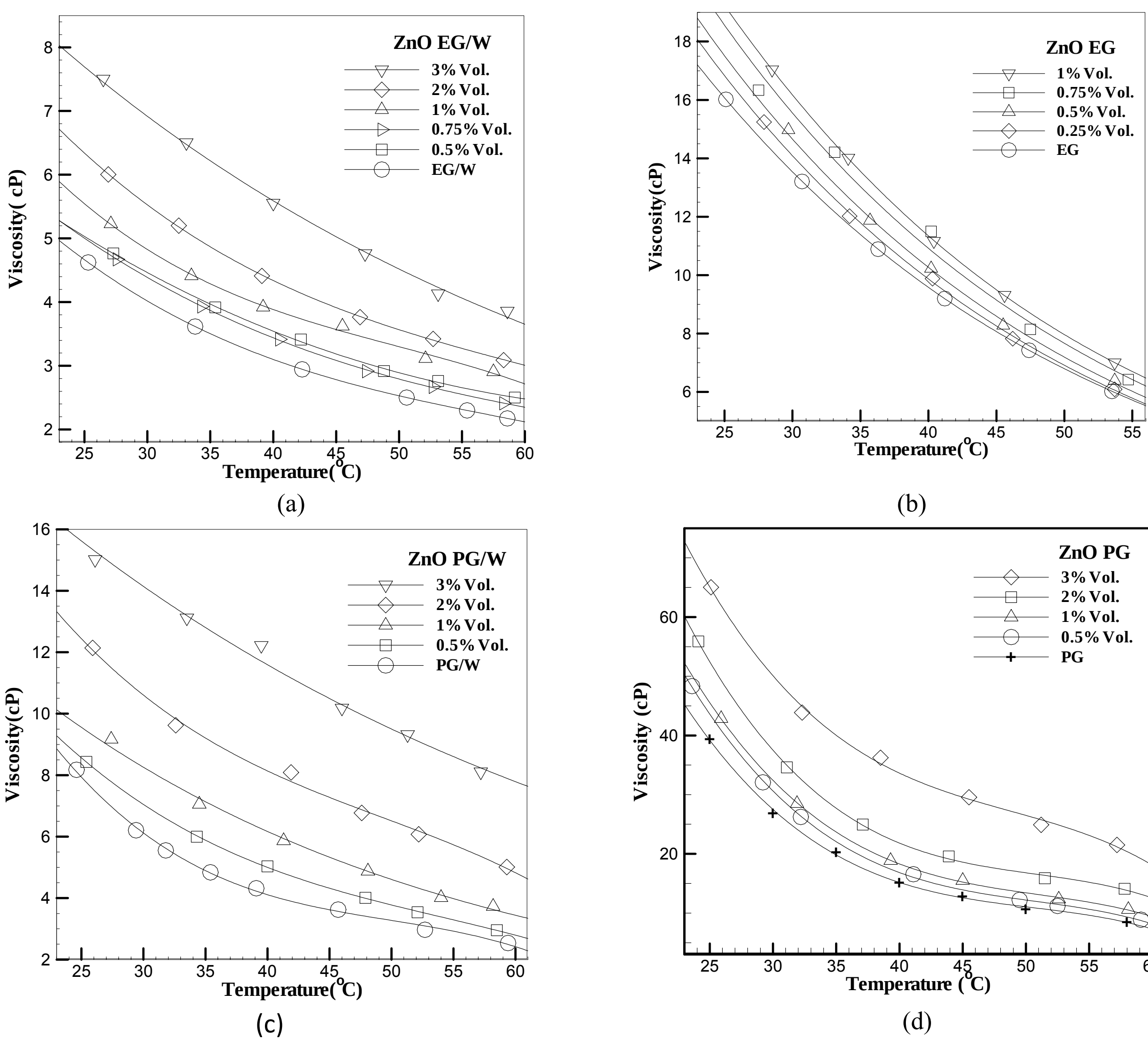


Fig.2. The effect of temperature on the viscosity of ZnO nanofluids (a) EG/water (b) EG (c) PG/water (d) PG.

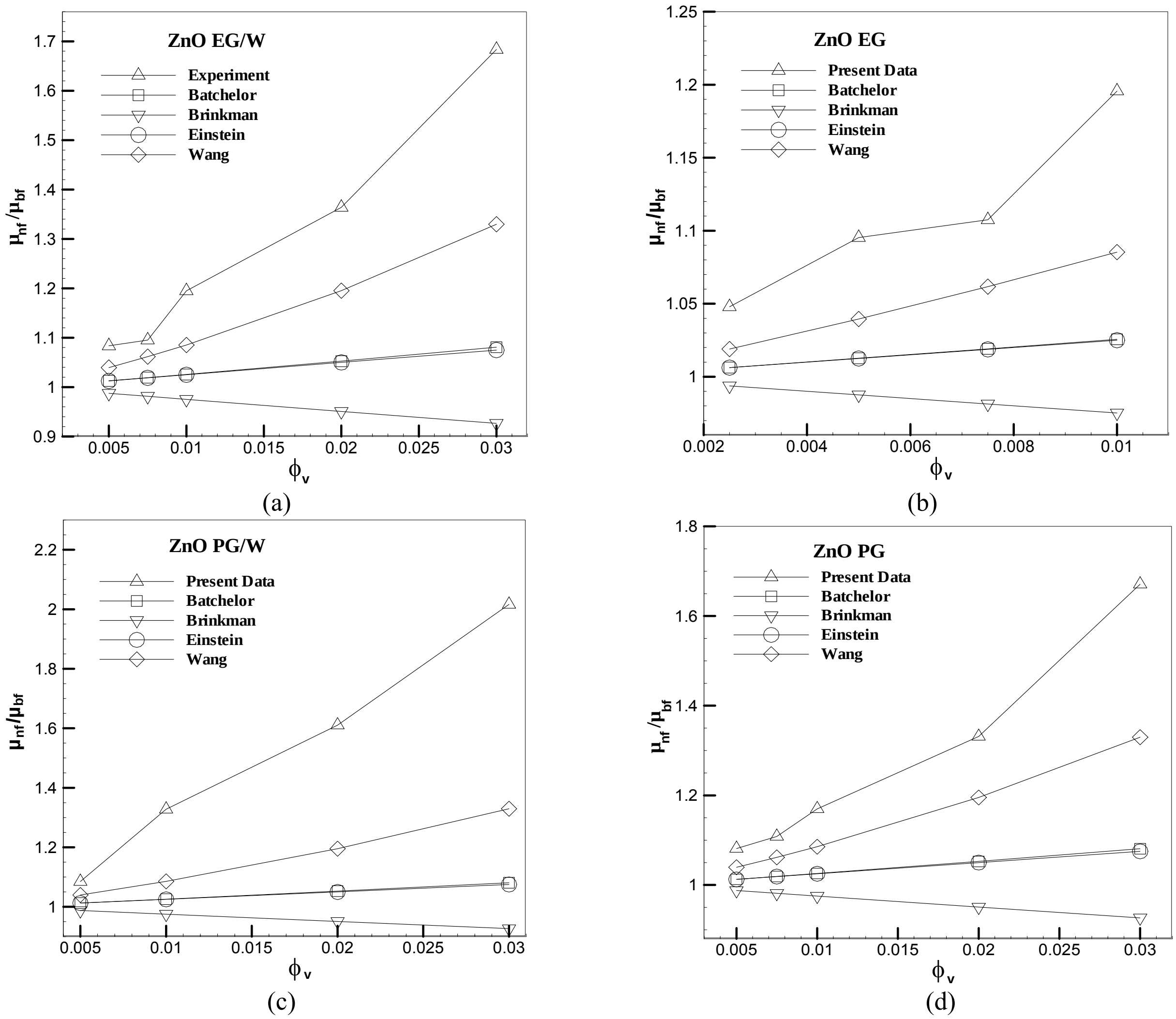


Fig.3. The effect of nanoparticle volume fraction on Relative viscosity of ZnO nanofluids (a) EG/water (b) EG (c) PG/water (d) PG.

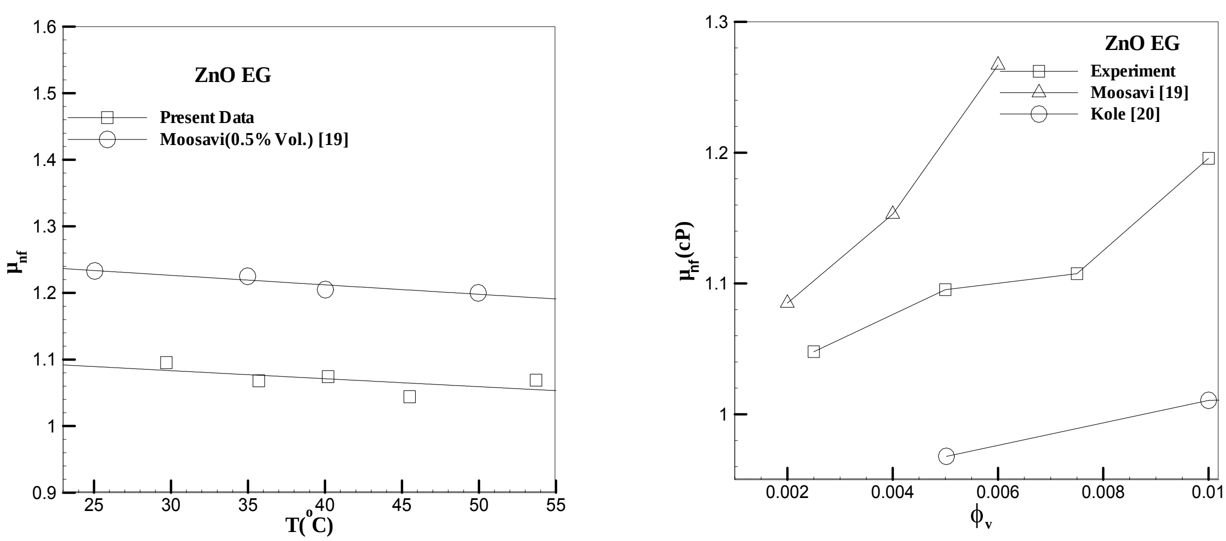


Fig.4. Comparison of the measured viscosity with results from various researchers.

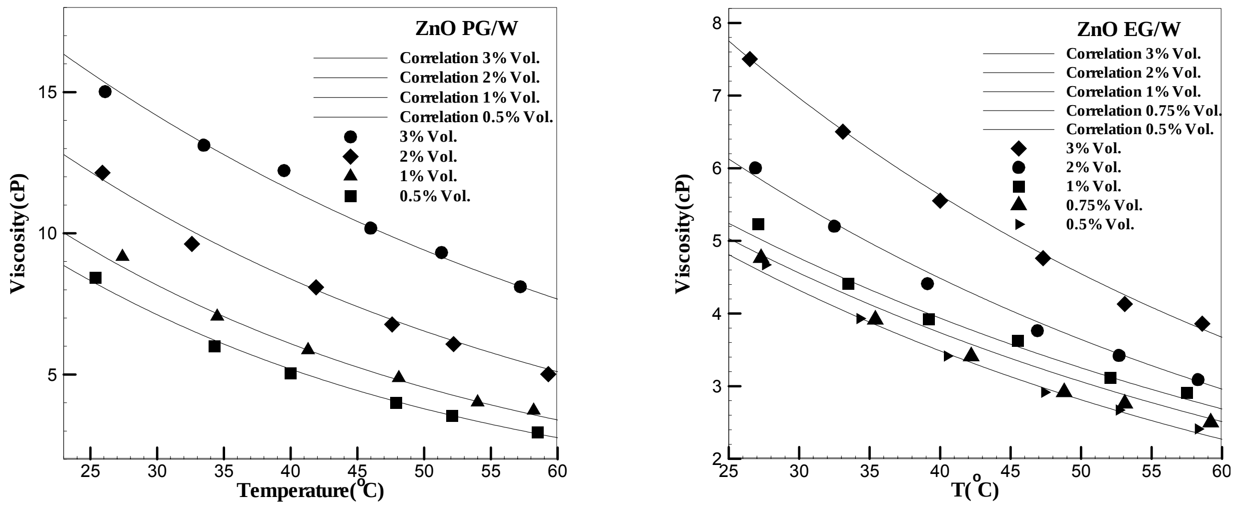


Fig.5. Comparison of measured viscosity with proposed correlation.

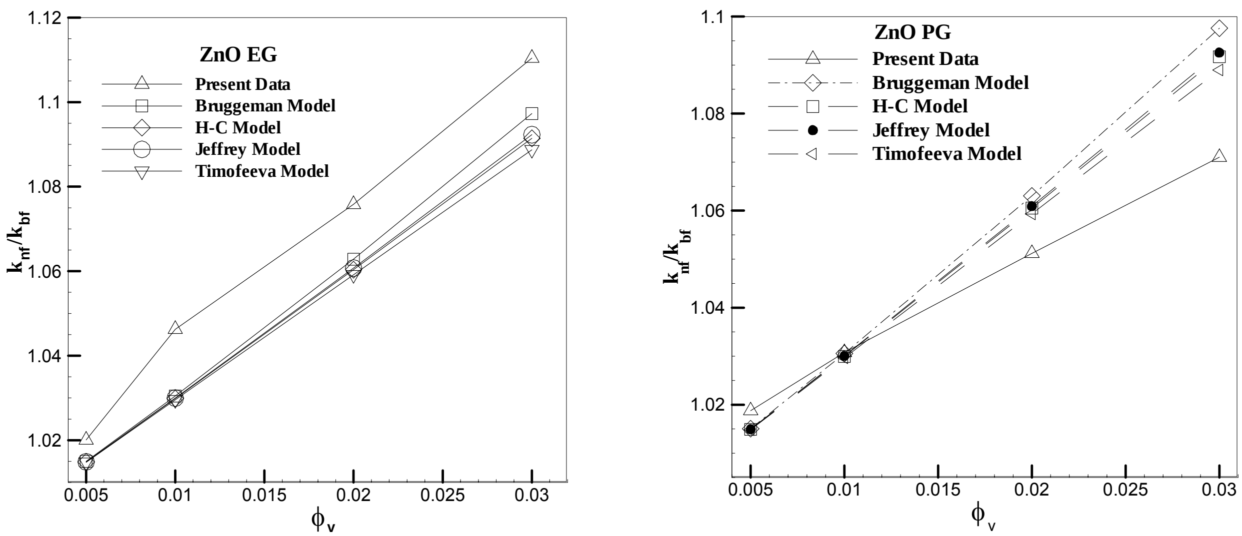


Fig.6. The effect of nanoparticle volume fraction on Enhancement of thermal conductivity of ZnO Nanofluids.

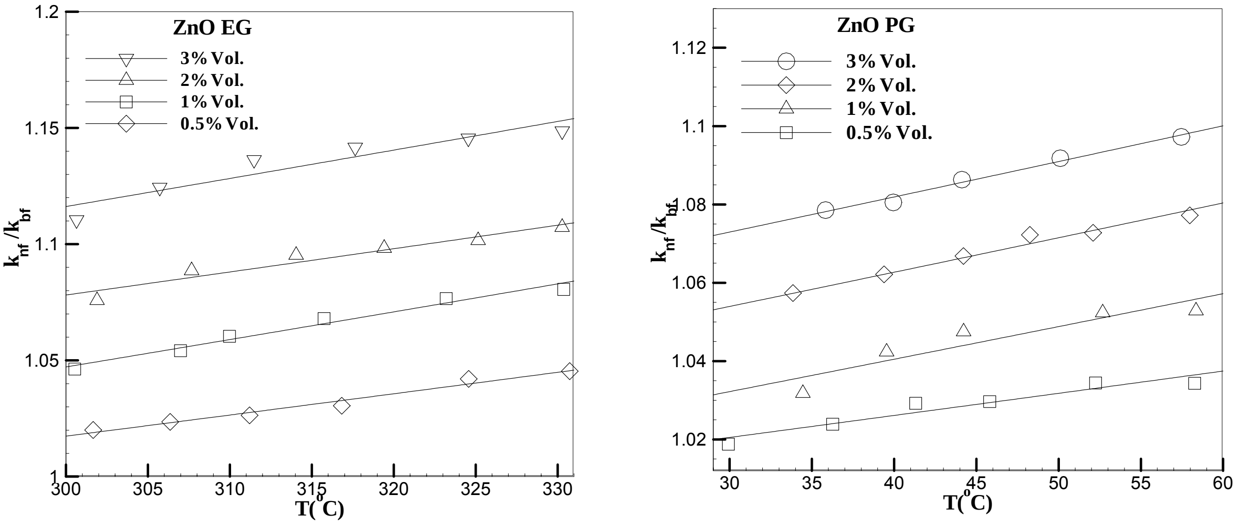
In addition, the effect of electric double layer [22] forming around nanoparticles depends on the base fluid. The thermal conductivity of ZnO nanoparticles in ethylene glycol and propylene glycol as base fluids versus the temperature showed in Figure 8. The prediction of Koo and Kleinstreuer model [18] also demonstrated in this figure. It is clear that the prediction of this model can't predict the experimental results. In figures 9, the results indicated that the measured thermal conductivity ratio of the present study was larger than that of Moosavi et al. (ZnO-67.17 nm) [19] and lower than Kole et al. (ZnO-50 nm) [20].

Furthermore, the present thermal conductivity results compare with experimental presented by Yu et al. [6], Feng et al. [23] and Leong et al. [24].

It is obvious that the result obtained by other researchers is quite different from those of the present data. The main reason for this difference is not clear. Several factors such as differences in the particle size, particle preparation and the measurement technique can affect. Therefore, more experimental studies are necessary. Different thermal conductivity models are compared with experimental results. These models can't predict the variation of thermal conductivity of ZnO nanofluids.

The new correlation is presented for ZnO nanoparticles and have been suspended in EG as a base fluid. The effect of volume fraction and temperature are considered in these correlations.

The temperature and volume concentration ranges 25ºC<T<60ºC and 0-3% vol, respectively.



(a) (b)

Fig.7. The effect of temperature on Relative thermal conductivity of ZnO Nanofluids (a) EG (b) PG.

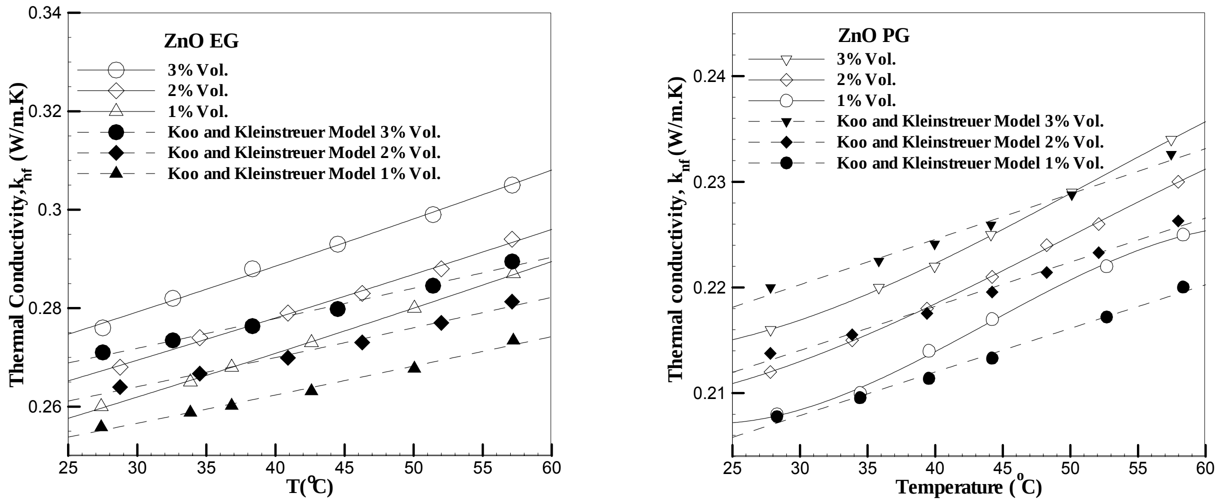


Fig.8. Comparison between experimental results and those of obtained by Koo and Kleinstreuer model in different temperatures.

A temperature dependent correlation between thermal conductivity and volume fraction is proposed for ZnO nanoparticles suspended in EG as a base fluid.

$$\frac{k_{nf}}{k_{bf}} = A + B\times T + C\times T^2 + D\times T^3 + E\times T^4 \quad (20)$$

$$A = -1.8 + 613\times\phi - 38054\times\phi^2 + 691069\times\phi^3 \quad (21)$$

$$B = 0.2785 - 60.12 + 3696.35 - 66660.46 \quad (22)$$

$$\frac{k_{nf}}{k_{bf}} = A + B\times T + C\times T^2 + D\times T^3 + E\times T^4 \quad (23)$$

$$D = 0.0001614 - 0.03384\times\phi + 2.0159\times\phi^2 - 35.792\times\phi^3 \quad (24)$$

$$E = -9.3\times10^{-7} + 1.915\times10^{-4}\times\phi - 0.01123\times\phi^2 + 0.1975\times\phi^3 \quad (25)$$

In figure 10, the thermal conductivity of ZnO in EG from the experiment is compared with correlation.

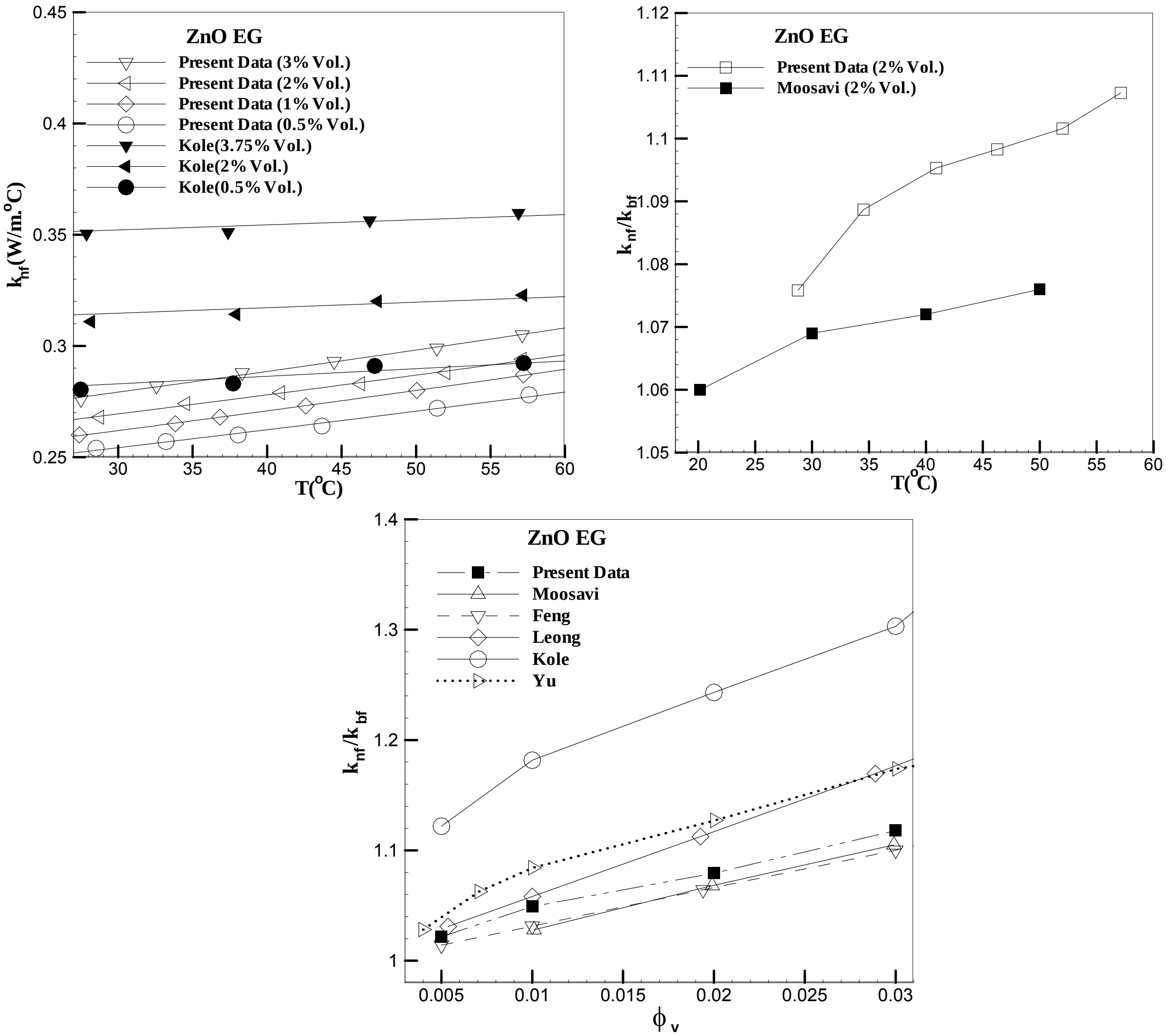


Fig.9. Comparison of the measured thermal conductivity with results from various researchers.

It can be observed that the maximum deviation is 2%. There is an acceptance agreement between the experimental data and the existence correlation. In figure 11, the proposed correlation compared with experimental results presented by Moosavi et al. Yu et al. [6], Feng et al. [23] and Leong et al. [24]. It can be observed that the maximum deviations are 3.7%, 15.24%, 4.5% and 5.8% respectively.

It can be seen that the proposed correlation can predict the experimental results of Moosavi et al. [19], Feng et al. [23] and Leong et al. [24].

5. Conclusions

An experimental study is done to investigate the effect of particle volume fraction and temperature on the viscosity and thermal conductivity of EG, PG, EG/water and PG/water based ZnO nanofluids. Viscosity of nanofluids increases with the increase in particle volume concentration. The Einstein model could not predict it. The thermal conductivity of the samples displayed a nonlinear increase with the particle volume fraction, which the Hamilton and Crosser model and Bruggeman model could not predict. Furthermore, the effect of temperature on thermal conductivity was investigated. The enhancement of thermal conductivity with temperature variation shows that nanofluids have more application in high temperature. The results indicate ZnO in ethylene glycol has the higher thermal conductivity ratio than propylene glycol. The largest enhancements in thermal conductivity are 15% and 9% for EG and PG as base fluids, respectively.

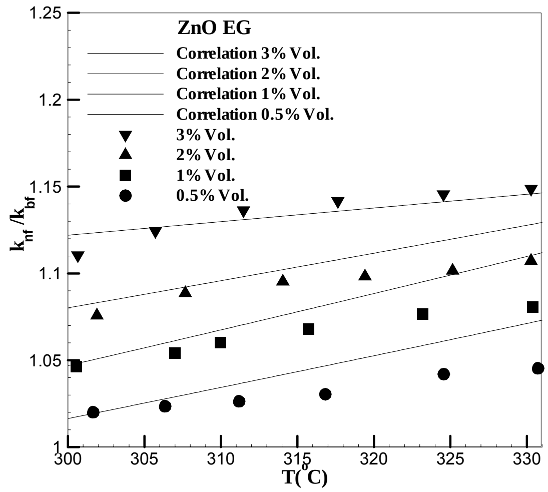


Fig.10. Comparison of measured thermal conductivity with proposed correlation.

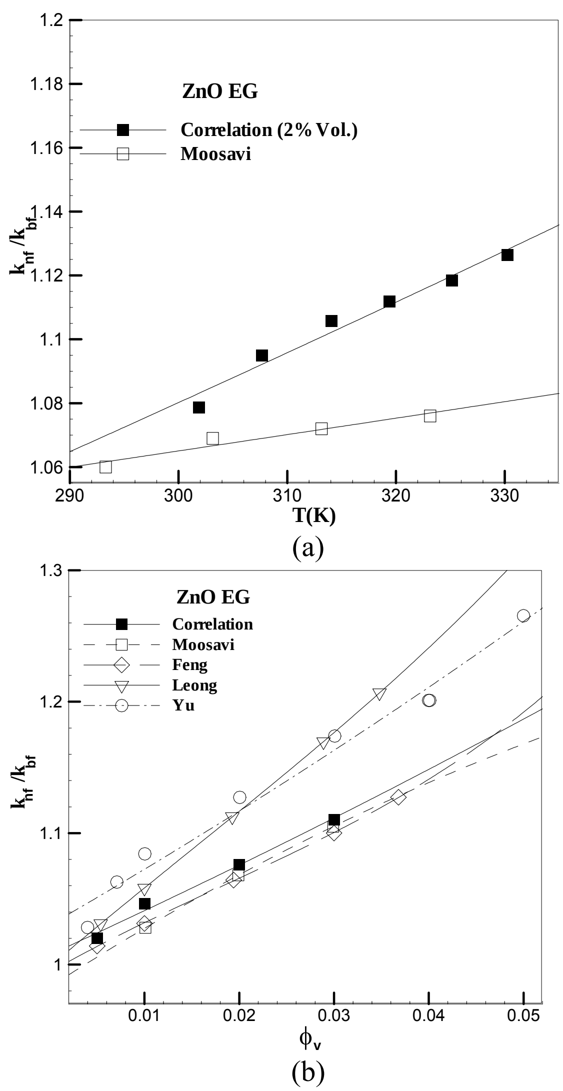


Fig.11. Comparison of proposed correlation with the other researchers' experimental results.

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