Experimental study on thermal conductivity of ethylene glycol based nanofluids containing Al₂O₃ nanoparticles

Mohammad Hemmat Esfe a,*, Arash Karimipour a, Wei-Mon Yan b,*, Mohammad Akbari a, Mohammad Reza Safaei c, Mahidzal Dahari d

a Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Isfahan, Iran
b Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei 10608, Taiwan, ROC
c Young Researchers and Elite Club, Mashhad Branch, Islamic Azad University, Mashhad, Iran
d Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

A R T I C L E   I N F O

Article history:
Received 30 March 2015
Received in revised form 4 May 2015
Accepted 4 May 2015

Keywords:
Nanofluid
Thermal conductivity
Correlation
Al₂O₃ nanoparticles
Temperature

A B S T R A C T

To get more experimental and fundamental understanding of the thermal behavior of nanofluids, the thermal conductivity of Al₂O₃-EG nanofluids have been examined using a KD2-Pro thermal analyzer. The effects of temperature and concentration on thermal conductivity of nanofluid are investigated. The experiments performed at temperature ranging from 24 °C to 50 °C while volume fractions up to 5%. The experimental results exhibited that the thermal conductivity of nanofluids enhances significantly with increase in concentration and temperature. Also, attempts were made to propose new accurate correlations for estimating thermal conductivity at different temperatures and concentrations. For this purpose, two new correlations with very high accuracy were suggested. To estimate thermal conductivity at different temperatures, focusing more on accuracy and usability, several correlations have been proposed. These correlations have been presented separately at different temperatures which can be more accurate.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Conventional fluids such as water, oil and ethylene glycol generally are used for heat transfer. Several techniques have been applied to enhance heat transfer in heating and cooling systems; but the efficiency of these fluids, in the heat transfer applications, is low dispersion of solid particles in various fluids is a new technique to increase heat transfer. Using nanofluid is one of the most important ways to improve the heat transfer which was introduced by Choi [1]. Nanofluids are mixtures of nanometer-sized solid particles suspended in common liquids such as water and EG which recently were used in many fields of thermal engineering [2–7].

The thermo-physical properties of nanofluids are controlled by the physical and chemical specifications of the nanoparticles and the base fluid. Therefore, the using an appropriate type of nanofluid is very important to achieve a high heat transfer rate. In this regard, thermal conductivity of nanofluids is a key property that should be determined. To now, thermal conductivity of nanofluids had been experimentally reported by different researchers around the world [8–11].

A large number of studies devoted to using the oxide nanoparticles such as Al₂O₃, CuO, ZnO, Fe₂O₃, MgO and TiO₂ in base fluids. Das et al. [12] measured the thermal conductivity of Al₂O₃/water and CuO/water nanofluid using temperature oscillation technique at different temperatures and concentrations. Their results showed that with increasing temperature and concentration of nanofluid thermal conductivity can be enhanced about 24.3%. An experimental investigation on the thermal conductivity of Al₂O₃ nanofluid using the transient hot wire method was performed by Chon et al. [13]. In their study, the range of temperature was between 21 and 71 °C and nanoparticle size range was from 11 nm to 150 nm nominal diameters. They indicated with increase in the particle size the thermal conductivity enhancement decreases. Also, their results revealed that for the 47 nm particle size, a temperature of 71 °C, and a 4% concentration, the enhancement amount was about 28%. Murshed et al. [14] determined thermal conductivity of TiO₂/water nanofluid by using a transient hot-wire apparatus. The nanoparticle's shape in the study was rod and spherical. Their results demonstrated that the volume fraction, size and shape of nanoparticles have effects on enhancement of thermal conductivity. For TiO₂ particles in rod-shapes and in

* Corresponding authors.
E-mail addresses: M.hemmatesfe@semnann.ac.ir (M. Hemmat Esfe), wmy@ntut.edu.tw (W.-M. Yan).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.05.010
0017-9310/© 2015 Elsevier Ltd. All rights reserved.
spherical shapes with maximum 5% concentration, the enhancement was respectively observed to be about 33% and 30%, as compared to base fluid.

Li and Peterson [15] evaluated the effect of nanoparticle diameter on the thermal conductivity of Al2O3/water nanofluid by the steady-state method. Experiments were performed over a volume fraction range of 0.5–6.0% for temperature ranging from 27–37 ºC. They found that at 6% volume fraction, when the nanoparticle sizes increase from 36 nm to 47 nm, the thermal conductivity enhancement reduces from 28% to 26%. Zhang et al. [16] measured the effective thermal conductivity of some oxide nanofluid by applying the transient short-hot-wire technique. Their results revealed that the effective thermal conductivities of the nanofluid show no uncommon enhancements and can be predicted accurately by several existing models. Experimental investigations of effective thermal conductivity of Al2O3/water nanofluid with a diameter of 43 nm at different volume fractions (0.33–5%) were presented by Chandrasekar et al. [17]. The nanofluid thermal conductivity was measured by using a KD2 Pro thermal properties analyzer and it was indicated that the thermal conductivity of nanofluid increases with the volume fraction of nanoparticle. They also proposed a new thermal conductivity model could be used for the prediction of thermal conductivity of Al2O3/water nanofluid. Reddy and Vasudeva Raw [18] distinguished the thermal conductivity of TiO2/EG–water as a function of temperature and nanoparticles volume fraction. The measurements were performed in the volume fraction range of 0.2–1.0% for temperature ranging from 30 ºC to 70 ºC. Experimental data showed that in the case of EG–water-based nanofluid with 50%/50% proportions, the thermal conductivity enhancements were respectively 10.6% and 14.2% for 0.2% and 1.0% volume fractions.

Sundar et al. [19] reported the effective thermal conductivity of Fe3O4/water nanofluid by using the transient hot wire method. Tests were performed in the temperature range of 20 ºC to 60 ºC and the volume fraction range of 0.0–2.0%. Also, experimental results demonstrated that for the 2.0% volume fraction at 60 ºC, the thermal conductivity enhancement was 48%. Particle shape effect on the thermal conductivity of ZnO/water nanofluid was experimentally studied under various volume fractions by Jeong et al. [20]. Their experiments showed that at 5.0% volume fraction, the thermal conductivity of the ZnO/water nanofluid enhanced by up to 18% and 12% for the rectangular shape and the spherical nanoparticles, respectively. Hemmat Esfe et al. [21] experimentally presented the thermal conductivity of Mg(OH)2/EG nanofluids with different sizes of MgO nanoparticles including 20, 40, 50, and 60 nm. The experiments were implemented in the temperature ranging from 25 ºC to 55 ºC for volume fractions up to 5%. They proposed an empirical correlation as a function of nanoparticle size, volume fraction and temperature by using the experimental data. Measurements showed that at 5% volume fraction, when the particle size was decreased from 60 nm to 20 nm, the maximum thermal conductivity enhancement was 10%.

Li et al. [22] measured the thermal conductivity of ZnO/EG nanofluid by using the hot wire measuring method. The experimental measurement revealed that ZnO/EG nanofluids with mass fraction of less than 10.5% show Newtonian behaviors. Also they found that thermal conductivity enhances slightly with growing the temperature from 15 ºC to 55 ºC. Yu et al. [23] investigated the thermal conductivity and viscosity of ethylene glycol based ZnO nanofluids and announced that the absolute thermal conductivity increases with increasing the temperature for different temperature ranging from 10 to 60 ºC, while the enhanced ratios are almost constant, and the thermal conductivities of the nanofluids track the thermal conductivities of the base liquid. Hemmat Esfe et al. [24] experimentally investigated the thermal conductivity of the ZnO/EG nanofluid containing nanoparticles with diameters of 18 nm at various temperatures and volume concentrations. Experiments at 5% volume fraction demonstrated that with increasing temperature from 24 ºC to 50 ºC the thermal conductivity ratio increases from 26% to 35%. Hemmat Esfe et al. [25] performed a series of experiments to characterize the thermal conductivity of Mg(OH)2/EG in the temperature range of 25 ºC to 55 ºC for volume concentrations up to 2%. The results clarified that for volume fraction of 2%, the enhancements of thermal conductivity were about 22% and 13% for 55 ºC and 24 ºC, respectively. The thermal conductivity, viscosity and density of homogeneous and stable nanofluids consisting of both synthesized and commercial ZnO nanoparticles dispersed in ethylene glycol (EG) were experimentally measured by Pastoriza-Gallego [26]. The influence of variables such as particle size, temperature and volume fraction on their thermophysical properties were studied at concentrations up to 6.2%. Recently, the nanofluid preparation methods were summarized by Haddada et al. [27] to find a suitable method for preparing stable nanofluids. In Ref. [27], nanofluids are classified according to material type as metallic and nonmetallic nanoparticles since different nanoparticles need their own stability method. Various types of nanoparticles with different base fluids are investigated.

To the best knowledge of the authors, there is little study on thermal conductivity of ethylene glycol based nanofluid containing Al2O3 nanoparticles with proposing new correlations at different temperatures. This motivates the present study.

2. Preparation of nanofluid

To provide Al2O3–EG nanofluid samples, two-step method was utilized without using any surfactant. The chemical and physical data of Merck ethylene glycol are given in Table. 1. Alumina nanoparticles with average grain size of 5 nm with the desired solid volume fraction (0.05 (5%), 0.04 (4%), 0.03 (3%), 0.02 (2%), 0.01 (1%), 0.0075 (0.75%), 0.005 (0.5%) and 0.002 (0.2%) have been poured to the pure EG after weighting. After adding nanoparticles, a magnetic stirrer is used in order to mix the alumina and ethylene glycol for about 1 h. Then the suspensions were inserted in the ultrasonic processor (400 W, 24 kHz) for 8–9 h. This method was used in order to break down the agglomeration between the particles and also prevent the sedimentation and to obtain a uniform dispersion and a stable suspension. The transmission electron microscopy (TEM) image of Al2O3 nanoparticles is shown in Fig. 1.
3. Measurement of thermal conductivity

Different methods are used to measure the thermal conductivity of nanofluid such as transient hot wire [28], steady-state parallel plate [29], cylindrical cell [30], temperature oscillation [31], and 3w method [32]. In the present study, the transient hot wire method is applied due to high speed and accuracy in measurement [33] by using a KD2 Pro instrument. Thermal conductivity of Al₂O₃/EG nanofluids at different solid volume fractions and temperatures was examined.

Based on the catalog of KD2-PRO, KS1 sensor with an accuracy of 5% is the best option to measure thermal conductivity of fluid in the temperature range between 50°C and 150°C. KS1 sensor is able to determine the thermal conductivity when the quantity of thermal conductivity is changed between 0.02 and 2 W/m°C. This sensor is suitable for measuring the thermal conductivity of different type of nanofluid with various base fluid.

4. Results and discussion

In this work, the effects of temperature and nanoparticle volume fraction on thermal conductivity of Al₂O₃/EG nanofluid are studied in details. The experiments were performed at temperature ranges from 24°C to 50°C while volume fractions up to 5%.

The variations of relative thermal conductivity versus volume fractions of nanoparticles at different temperatures are illustrated in Fig. 2. It is clearly found in Fig. 2 that the relative thermal conductivity increases when nanoparticle solid volume fraction increases. This trend reveals that adding nanoparticles improve the thermal conductivity of nanofluids compared to the base fluid (EG). The thermal conductivity ratio of nanofluids was also raised with an increase in temperature. At higher volume fractions, the effect of temperature on the relative thermal conductivity of nanofluid is more tangible. For volume fractions less than 1%, the variation of relative thermal conductivity with temperature is not significant. The main reason of improvement of thermal conductivity with temperature can be described by more collisions between particles and the increase in Brownian motion. On the other hand, the number of dispersed nanoparticles is increased with the volume concentration. The gain in nanoparticles apart from enhance in interactions between the nanoparticles can cause the formation of nanoparticles chains in base fluid and ease the thermal conductivity.

To make a better understanding of the effects of temperature and volume fraction of nanofluid on thermal conductivity, relative thermal conductivity of nanofluids with respect to temperature at different solid volume fractions are plotted in Fig. 3. As can be seen in this figure, the relative thermal conductivity of nanofluids and the
effect of temperature on the thermal conductivity increase when the concentration of nanoparticles increases. The values obtained from experiments indicate that with an increase in the volume fraction of nanoparticles to 5% at ambient temperature, the thermal conductivity enhances to 28.3% compared to the base fluid. The relative thermal conductivity enhancement is less at lower volume fractions. On the other hand, by increasing the temperature from 24 °C to 50 °C and the volume fractions of 1%, 2%, 3%, 4% and 5% the thermal conductivity of nanofluids increases by 4.4%, 8%, 10.8%, 11.6% and 12.7%, respectively, compared to that of the base fluid.

4.1. Proposing new models

Following the study, due to lack of proper and reliable correlation to estimate the thermal conductivity of Al2O3/EG nanofluid, two accurate correlations based on the empirical data points are suggested.

4.1.1. Correlation 1

Correlation 1, as shown in Eq. (1), estimates the thermal conductivity of EG based nanofluid containing Al2O3 as a function of the volume fraction and temperature. This correlation has a very high accuracy which is in excellent agreement with experimental data:

\[
\frac{k_{nf}}{k_{bf}} = 1.04 + 5.91 \times 10^{-5} T + 0.00154 T \varphi + 0.0195 \varphi^2
\]

\[
-0.014 \varphi - 0.00253 \varphi^3 - 0.0001047 \varphi^2 - 0.0357
\]

\[
\times \sin(1.72 + 0.407 \varphi^2 - 1.67 \varphi)
\]

A comparison between experimental data and the results obtained by the correlation 1 is presented in Fig. 4. It can be seen that the most of data are on the bisector or near it which is not a considerable distance. This graph indicates the experimental data points and the values achieved by proposed correlation 1, are in very good compatibility and consistency. Fig. 4 also presents a comparison between the experimental results and outputs of the proposed correlation 1. As can be observed, in most cases, the points

![Fig. 5. The corresponding relations between thermal conductivity predicted by correlation 1 and solid volume fraction and temperature in 3D coordinates.](image)
corresponding to the experimental results and correlation overlap each other or show a slight deviation.

In Fig. 5, the corresponding relations between thermal conductivity predicted by correlation 1 and solid volume fraction and temperature are plotted in 3-dimensional coordinates. In Table 2, the specifications of correlation 1 including the maximum error, MSE and MAE are given. The presented errors in Table 2 reveal that the proposed correlation has a high accuracy.

Table 3

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R² goodness of fit</td>
<td>0.99646517</td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>0.99823505</td>
</tr>
<tr>
<td>Maximum error</td>
<td>4.8108998e-5</td>
</tr>
<tr>
<td>Mean squared error</td>
<td>0.0049782984</td>
</tr>
<tr>
<td>Mean absolute error</td>
<td></td>
</tr>
</tbody>
</table>

To develop predicted models and increasing accuracy of thermal conductivity estimation of Al₂O₃/EG nanofluid, another new correlation based on empirical data is presented.

4.1.2. Correlation 2

The thermal conductivity of Al₂O₃/EG nanofluid is estimated in terms of temperature and volume fraction by correlation 2. This correlation is derived from curve fitting and has acceptable accuracy:

\[
\frac{k_{mf}}{k_{bf}} = 0.999 + 9.58 \times 10^{-5}T + 0.00142T \phi + 0.0519\phi^2 \\
+ 0.00208\phi^2 + 0.00208\phi^4 - 0.00719\phi - 0.0193\phi^3 \\
- 8.21 \times 10^{-5}T \phi^2
\]  

(2)

Regarding the importance of accuracy in the thermal conductivity estimation using the correlation 2, the experimental data and the proposed correlation results are compared in Fig. 6. As shown in Fig. 6, set of points on the bisector or in its neighborhood indicates that there is an excellent match between experimental findings and the results of the correlation 2. The corresponding relations between thermal conductivity predicted by correlation 2 and solid volume fraction and temperature are illustrated in 3-dimensional coordinates in Fig. 7. According to Figs. 3–6, it can be found that both of the correlations have the ability to accurately predict the thermal conductivity of Al₂O₃/EG nanofluids. Table 3 also contains information on the specifications of correlation 2. As shown in Table 3, this equation has very little error and high accuracy.

4.2. Proposing correlations

Because of the essential of proposing the correlations with suitable accuracy, the correlations are presented at various temperatures, separately. This way, these correlations have a higher accuracy which can be used to estimate thermal conductivity in different applications. The proposed correlation at temperature of 24, 30, 35, 40, 45 and 50 °C are presented in Table 4.
knf
5
knf
2

Correlations predict the thermal conductivity of Al2O3 nanofluids. Thus, it can be found that the presented correlations predict the thermal conductivity of Al2O3 nanofluids at different temperatures which can be more accurate.

5. Conclusion

In the present study, the thermal conductivity of Al2O3/EG nanofluids at temperature ranging from 24 °C to 50 °C and volume fractions range of 0.2–5% have been measured. Experimental results show that the thermal conductivity of nanofluid enhances significantly with increase in concentration and temperature. Based on the obtained experimental data, in order to estimate the thermal conductivity of Al2O3/EG nanofluids, two correlations have been proposed. Comparison between experimental data and the values obtained using correlations showed that these correlations have a high accuracy. Therefore, these correlations can predict the thermal conductivity of Al2O3/EG nanofluids in the range of temperature and solid concentration examined in this paper. To estimate thermal conductivity at different temperatures, focusing more on accuracy and usability, several correlations have been proposed. These correlations have been presented separately at different temperatures which can be more accurate.

Conflict of interest

None declared.

Acknowledgments

The authors gratefully acknowledge High Impact Research Grant UMC/HIR/MOHE/ENG/23 and Faculty of Engineering, University of Malaya, Malaysia for their support in conducting this research work. The financial support by the National Science Council, ROC, through the contract MOST 103–2221-E-027-107-MY2 is also highly appreciated.

References


