Modelling Thermal Conductivity Enhancement of Metallic Oxide-based Nanofluids Using Dimensional Analysis

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Abstract

The objective of the present work is to investigate nanofluids thermal conductivity enhancement using available dimensional analysis modeling for thermal conductivity enhancement of metallic oxide-based nanofluids. Nanofluids are engineered by dispersing nanoparticles into ethylene glycol as base fluid with two-step method. Nanofluid samples were prepared with different percentage ratio of nanoparticle mass to 100 mL suspension of 0.2, 0.5, 1.0, 1.5, 2.0, and 2.5 (%w/v). The TEM and XRD characterization are used to verify specification data of the observed nanofluid. From this characterization, it is found that metallic oxide nanoparticles used in the present study consist of spherical particles with nominal diameter of 21 nm and 13 nm for TiO_2 and Al_2O_3, respectively. In this present work, available semi correlation of nanofluid thermal conductivity enhancement derived using the Buckingham-pi theorem in which Brownian motion of nanoparticle is considered. The predicted effective thermal conductivity enhancement of nanofluid in this model is compared with the experimental data. The experimental results show that thermal conductivity increases remarkably with increasing volume fraction of nanoparticles. The results show that the predicted thermal conductivity enhancement using dimensional analysis model demonstrates fairly good agreement for TiO_2/EG and Al_2O_3/EG with nanoparticle concentration of 1.0 to 2.5 % w/v.

Keywords: nanofluids, metallic oxide, thermal conductivity, enhancement, dimensional analysis

Intorduction

In recent years, nanofluids have attracted more attention concerning energy-efficient heat transfer equipment and the problem with energy conservation which is closely related to the prevention of global warming. Nanofluids, first coined by Choi (1995), can be engineered by stably suspending nanosized particles, fibers, sheets, or tube with average sizes below 100 nm in traditional heat transfer fluids (HTFs) such as water, ethylene glycol, or engine oil in low concentrations (≤ 1 vol.%). Nanofluids have been proposed as a promising candidate for advanced HTFs in a variety of important engineering applications ranging from energy storage and electronics cooling to thermal processing of materials. Nanofluids have attracted great interest due to reports of greatly enhanced thermal properties at low volume concentration (dilute suspension). Adding nano-sized solid particle into traditional base fluid exhibits thermophysical properties different from those of base fluid. The thermophysical properties of nanofluids, such as thermal conductivity, viscosity, density, and specific heat are essential parameters to evaluate the thermal performance of heat transfer equipment.

Enhancing thermal conductivity of HTFs and *minimizing pressure drop* in heat exchanger are an innovative way to increase energy-efficient thermal system. The ratio of the pumping power to heat transfer rate is an important parameter to determine performance of heat exchanger equipment. Therefore, rheology properties of nanofluids also constitute a vital effect in determining flow behaviors related directly to pumping power. Both viscosity and thermal conductivity of nanofluids are known to undergo anomalous enhancements, but more thorough investigations should be carried out on these properties because a good deal of controversy and remarkable inconsistencies have been reported in this emerging subject [Keblinski et al. (2008), Pastoriza-Gallego et al. (2011)].

Although the investigation of thermal conductivity has focused most efforts, it is believed that viscosity is also as critical as thermal conductivity in engineering systems [Keblinski et al. (2005), and Murshed et al. (2008)]. Pumping power is proportional to the pressure drop, which in turn is related to fluid viscosity. In laminar flow regime, the pressure drop of fluid is directly proportional to the viscosity. Yanuar et al. (2010) studied experimentally to investigate curve flow characteristics of water-based nanofluids containing metallic oxide nanoparticles (TiO_2 and Al_2O_3) using power law fluid model. It was demonstrated that the higher volume concentration of nanoparticles exhibited shear thinning fluid behavior (pseduoplastics fluid). Since nanofluids tend to have non-Newtonian behavior, the viscosity is not constant at a given temperature and pressure but depends on other factors such as the shear rate of nanofluids at pipe wall.

Research and development activities have been carried out to improve thermal conductivity property of thermofluid since more than a century ago. Adding more thermally solid particles into fluid is an initial idea of Maxwell to enhance thermal conductivity of HTFs. Maxwell as given in Lee et al. (1999) have proposed effective theory medium to predict thermal conductivity of particle suspensions in liquid. Therefore, thermal conductivity of nanoparticle dispersions is called effective thermal conductivity. Since solid materials have much higher thermal conductivities than fluids, it is a straightforward logic to increase the thermal conductivity of fluids by adding solids. Although such suspensions exhibit higher thermal conductivity, they suffer from stability problems. Adding micro- or millimeter-sized solid particles into base fluid will result slurries in which their thermal conductivity enhancement are insignificant at high solid particle loading. In particular, micro- or millimeter-sized solid particles tend to settle down very quickly and thereby causing severe clogging. In addition to this major problems, erosion and high pressure drop will also affect development of this suspension to be used as HTFs.

Unlike milli- and microparticles suspended in conventional base fluid, dispersion of nanoparticles provides an effective technique of enhancing heat transfer characteristics of HTFs. It was demonstrated that nanofluids were extremely stable dispersion and exhibit no significant settling under static conditions (Choi, 1995). Nanoparticles have a greater surface due to ultrafine-sized particles and can yield a stable suspension because of thermoelectric effect. The thermophysical, rheological, and thermoelectric properties of nanofluids are different from their traditional base fluid. A dispersion with low volume concentrations of solid nanoparticles in traditional HTFs is able to dramatically change their properties particularly thermal conductivity enhancement. Thermal conductivity property plays important role in the development of energy efficient heat transfer equipment.

Based upon the published experimental data in the literature, Yu et al. (2008) proposed eight parametric that effect on nanofluid thermal conductivity enhancement i.e., particle volume concentration, particle material, particle size, particle shape, base fluid material, temperature, additive, and acidity. Many experimental and theoretical studies are investigated for thermal conductivity enhancement of nanofluids but the physical mechanism accounting for the thermal conductivity enhancement of nanofluids is not well understood (Yu et al., 2008). Several mechanisms and models have been offered to predict nanofluids thermal conductivity behavior using various assumptions. Nevertheless, the study of nanofluids behavior still remains both theoretically and experimentally challenging.

Keblinksi et al. (2002) presented four possible mechanisms, such as Brownian motion of particles, interfacial liquid layer, ballistic nature of heat transport in nanoparticles, and nanoparticle clustering. Many research groups pointed out that Brownian motion may be one possible reason and have made enormous efforts to model it (Nie et al., 2008). Jang and Choi (2004) suggested that the Brownian motion of nanoparticles at the molecular and nanoscale levels is a key nanoscale mechanism governing their thermal behavior. Their study assumes that the Brownian motion nanoparticles in nanofluid produces convection-like effects on the nanoscale and is able to predict the size-dependent, concentration-dependent and temperature-dependent thermal conductivity. However, none of the existing theories is capable of explaining the anomalous thermal conductivity enhancement of nanofluids.

In this present study, ethylene glycol-based nanofluids containing metallic oxide nanoparticles (TiO_2 and Al_2O_3) are used to as the observed HTFs. Ethylene glycol is chemically more stable, non-toxic and ensure stability to nanofluids when compared to water. A published dimensional analysis model is used to estimate the effective thermal conductivity of nanofluids and compared to data experimental in this experimental investigation. The objective of the present work is to investigate nanofluids thermal conductivity enhancement using available dimensional analysis modeling for thermal conductivity enhancement of metallic oxide-based nanofluids.

Experimental Method and Facility

Sample preparation and characterization

Nanofluids were engineered by dispersing two different metallic oxide nanoparticles (TiO_2 and Al_2O_3) into ethylene glycol as base fluid. Nanofluid samples were prepared with percentage ratio of nanoparticle mass to 100 mL suspension of 0.2, 0.5, 1.0, 1.5, 2.0, and 2.5 (%w/v). The appropriate metallic oxide nanoparticles was carefully weighed using an electronic balance and the volume concentration was calculated. Ethylene glycol were supplied by Dow Chemicals. While, TiO_2 and Al_2O_3 nanoparticles were procured from Sigma-Aldrich USA. The necessary themophysical properties in this experimental study are density, viscosity, specific heat and thermal conductivity. Some of thermophysical properties of nanoparticles and base fluid are listed in Table 1. The appropriate metallic oxide nanoparticles was carefully weighed using an electronic balance and the volume concentration was calculated as listed in Table 2.

Techniques for suspending nanoparticles in base fluid are a crucial step of this present work to make stable and uniformly dispersed nanofluids. A known amount of metallic oxide nanoparticles is mixed with base fluids (ethylene glycol) using magnetic stirrer for 1 hr. To reduce the size of agglomerates, this dispersion is then blended in wet milling process for 15 min and homogenized by using ultrasonic bath for 1 hr. In this experimental work, stable nanofluids are prepare without addition of surfactants or dispersants. The nanofluids prepared as above depicted excellent stability without any visible sedimentation for several weeks.

Table 1. Thermophysical properties of metallic oxide nanoparticles and base fluid.

Property	**Ethylene glycol (EG)**	**TiO_2**	**Al_2O_3**
c_p [J kg^{-1}K^{-1}]	2415	686.2	765
ρ [kg m^{-3}]	1114.4	4250	3970
k [W m^{-1}K^{-1}]	0.252	8.9538	40
μ [m Pa s]	15.7	-	-

Table 2. The volume concenration of the observed nanofluids (% v/v).

Nanoparticle	**Ratio of nanoparticle mass to 100 mL suspension (w/v%)**					
	0.2	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**
TiO_2 (~21 nm)	0.047	0.117	0.235	0.352	0.496	0.587
Al_2O_3 (13 nm)	0.050	0.126	0.252	0.378	0.504	0.630

The X-ray diffraction (XRD) patterns were detected using x-ray diffractometer (Lab X XRD-6000) to identify the crystal phase of the metallic oxide nanoparticle samples. The 2θ values are taken from 3-90^o using Cu X-ray tube (λ=1.54060 Å) with step size of 0.02^o. The voltage and current of diffraction are 40.0 kV and 30 mA, respectively. Acquisition and preliminary analysis of the data were performed by PCPDFWIN v. 2.2. software and the XRD patterns were verified by comparing with the JCPDS-International Centre for Diffraction Data.

In addition to XRD analysis, this metallic oxide nanoparticles used in the present study also were characterized using transmission electron microscopy (TEM) photographs (JEOL JEM-1400) with an an acceleration voltage of 120 kVA. Transmission electron microscopy (TEM) is also a standardized method for imaging and measurements of dimension of nano and micro size structures due to their high imaging speed and high resolution.

Thermal conductivity measurements of nanofluids

In this experimental work, the cylindrical cell steady-state method is used to measure the effective thermal conductivity of nanoparticle dispersions using thermal conductivity of liquids and gases unit (model H111H P.A. Hilton, Ltd.) in temperature range of 30-60 ^{o}C. The principle of effective thermal conductivity measurement is based on creating a temperature difference over a nanofluid sample existing in a radial clearance. The nanofluid sample whose effective thermal conductivity is to be determined fills the small clearance between a heated plug an a water-cooled jacket. The plug is heated using a cartridge heater supplied with power controlled by the standard panel mounted voltmeter and ammeter. The plug is machined from aluminium to reduce thermal inertia and temperature variation and contains a cylindrical heating element whose resistance at the working temperature is accurately measured.

The clearance is small enough to prevent natural convection in the nanofluid sample. Due to considerable small of a radial clearance, the nanofluid sample existing in this space can be presented as a lamina of face area $\pi d_m l$ and thickness Δr to the heat transfer of heat from the heated plug to the jacket. The required measurements for the calculation of the thermal conductivity are the t_1 and t_2 with adjusting the variable transformer. The amount of heat transferred due to the thermal conductivity of the nanofluid sample can be calculated using Fourier law of thermal conduction in cartesian co-ordinates as follows:

$$\dot{Q}_c = kA\frac{\Delta t}{\Delta r} \qquad (1)$$

Where $\dot{Q}_c$ is heat transferred (W), k is effective thermal conductivity of the nanofluid sample (W/m.^{o}C) , Δt is temperature difference of t_1 and t_2 (^{o}C), Δr is radial clearance (m), A is effective area of conducting path through nanofluid sample (m^2).

Before using the unit to determine a thermal conductivity, it is necessary to determine the extent of the incidental heat transfer. It is the heat lost from the electrical element not by conduction but with other mechanism like radiation and convection which can be determined using the following relation:

$$Q_i = Q_e - Q_c \qquad (2)$$

Where Q_e is the electrical heat input calculated using following equation:

$$Q_e = V.I \qquad (3)$$

Where V and I are voltage (V) and current (A), respectively.

Calibration of this equipment is carried out to ensure accuracy of thermal conductivity measurement. The results of the calibration test are illustrated in Fig. 1 and compared with tabular data in the literature for both ethylene glycol and DI water. As shown, this comparison indicates that the thermal conductivity measurement device is capable of achieving a level of accuracy in the measured effective thermal conductivity that is well within $\pm$20%.

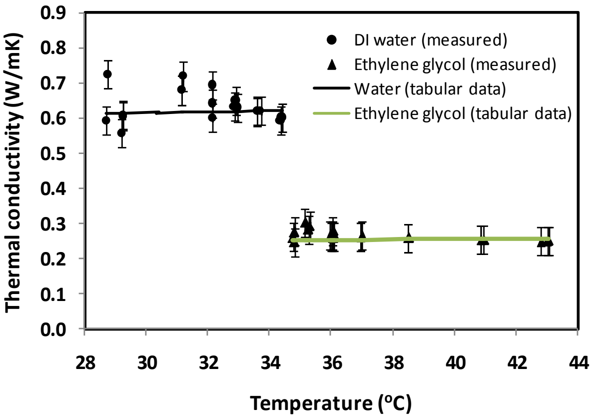


Figure 1. Test facility callibration.

Dimensional analysis and data reduction

Dimensional analysis is used to interpolate the experimental laboratory results to full scale system. A set of dimensionless correlations were established to investigate the thermal conductivity enhancement of metallic oxide-based nanofluids using the Buckingham Pi theorem. The following Buckingham Pi theorem procedure was adopted to determine the dimensionless parameters Π: 1) identify a complete set of independent variables, 2) apply the MLTΘ system, 3) list the dimension of all the independent variables, 4) determine the repeating variables, and 4) evaluate the constant of power product correlation.

By assuming the effective conductivity of nanofluid (k_{eff}) is a function of volume concentration (ϕ_v), particle diameter (d_{np}), thermal conductivity of nanoparticle (k_{np}), thermal conductivity of base fluid (k_{bf}), kinematic viscosity of base fluid (ν_{bf}), density of nanopartcicle (ρ_{np}), temperature of suspension (T_{nf}), and Boltzmann constant (κ_B), it can be written as:

$$k_{eff} = f\left(\phi_v, d_{np}, k_{np}, k_{bf}, \nu_{bf}, \rho_{np}, T_{nf} .\kappa_B\right) \qquad (4)$$

The physical factors need to be identified to apply dimensional analysis to the thermal conductivity of nanofluids. In this present work, the main physical factors chosen are temperature, nanoparticle size, and volume fraction while k_{bf}, T_{nf}, d_{np}, and ν_{bf} are considering as the repeating variables. From the Buckingham Pi theorem, 3 Pi groups can be formed by power products because there are seven independent variables and four dimensions. Since volume concentration ϕ_v is a dimensionless independent variable then Buckingham Pi theorem is not apllied for it. Therefore, the Pi groups can be expressed as:

$$g(\Pi_1, \Pi_2, \Pi_3) = 0 \qquad (5)$$

Dimensionless parameter groups Π_1-Π_3 can be obtained by applying Buckingham Pi theorem procedure. Therefore, the dimensionless correlation of thermal conductivity enhancement of nanofluids can be expressed as:

$$\frac{k_{nf}}{k_{bf}} = f\left(\mathrm{Re}_B, \phi_v, \frac{k_{np}}{k_{bf}}\right) \qquad (6)$$

Or,

$$\frac{k_{nf}}{k_{bf}} = a\,\mathrm{Re}_m^b\,\phi_v^c\left(\frac{k_{np}}{k_{bf}}\right)^d \qquad (7)$$

Where, Re_B is Brownian-Reynolds number and defined as follows:

$$\mathrm{Re}_B = \frac{1}{\nu_{bf}}\sqrt{\frac{18\kappa_B T_{nf}}{\pi\rho_{np} d_{np}}} \qquad (8)$$

The value of constant a and the exponent b-d of Eq. (7) are obtained by substituting the experimental data of thermal conductivity measurement into this correlation using nonlinear regression analysis.

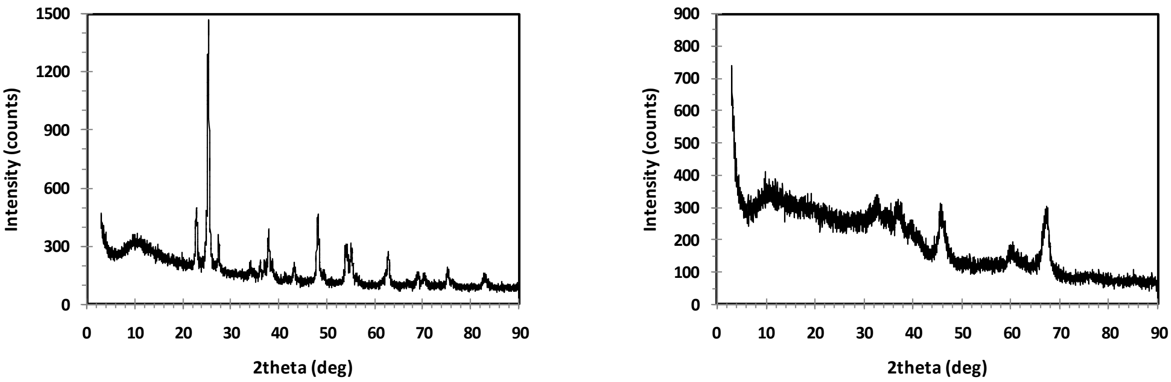
Results and Discussion

TEM and XRD Characterization

The XRD patterns of metallic oxide nanoparticles

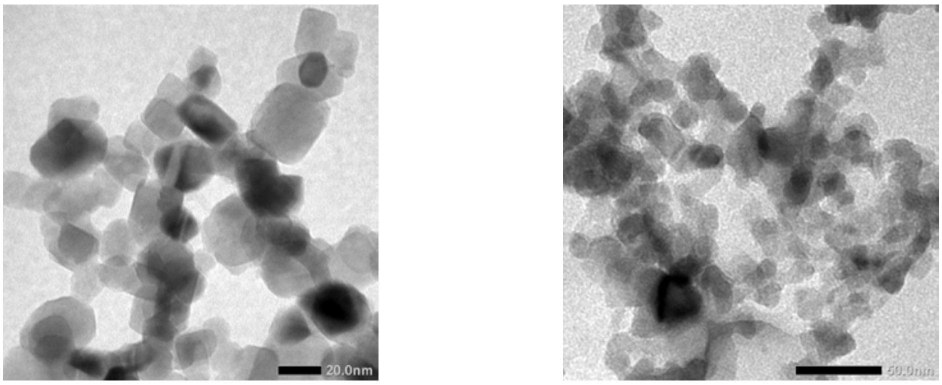
(TiO_2 and Al_2O_3) are shown in Figure 2. These patterns have been found that the metallic oxide nanoparticles used in the experimental study are single-phase nanoparticles with tetragonal structure for TiO_2 (Fig. 2.a). Further verification with the JCPDS file data also confirms the same metallic oxide nanoparticles. According to comparison the JCPDS data, titania indicates a mineral anatase while alumina nanoparticles show γ-Al_2O_3 (Fig. 2.b). The mineral anatase is one of the three mineral forms of titanium dioxide, the other two being brookite and rutile. This verification of the XRD patterns of metallic oxide nanoparticles used in the present study is appropriate with the specification data of Sigma-Aldrich for Titanium (IV) oxide nanopowder and aluminium oxide nanopowder, respectively.

The TEM images of the observed metallic oxide nanoparticles are shown in Fig. 3. These image depict that the samples mainly consist of nanoparticles with nominal diameter of 21 nm and 13 nm for TiO_2 and Al_2O_3, respectively. From the micrograph imaging, it is clear that metallic oxide nanoparticles used in the present study consist of spherical particles.



a. TiO_2 nanoparticles b. Al_2O_3 nanoparticles

Figure 2. The XRD patterns of metallic oxide nanoparticles used in the present work.



a. TiO_2 nanoparticles b. Al_2O_3 nanoparticles

Figure 3. The TEM image of nanoparticles.

Thermal conductivity enhancement

A nonlinear regression analysis is performed to evolve the correlation in Eq. 7. The correlation evolved for determining thermal conductivity enhancement of nanofluids is taken as a function of Brownian-Reynolds number, volume concentration, and ratio of thermal conductivity of nanoparticle to that of base fluid. This following correlation expresses the modeling thermal conductivity enhancement of nanofluids using dimensional analysis.

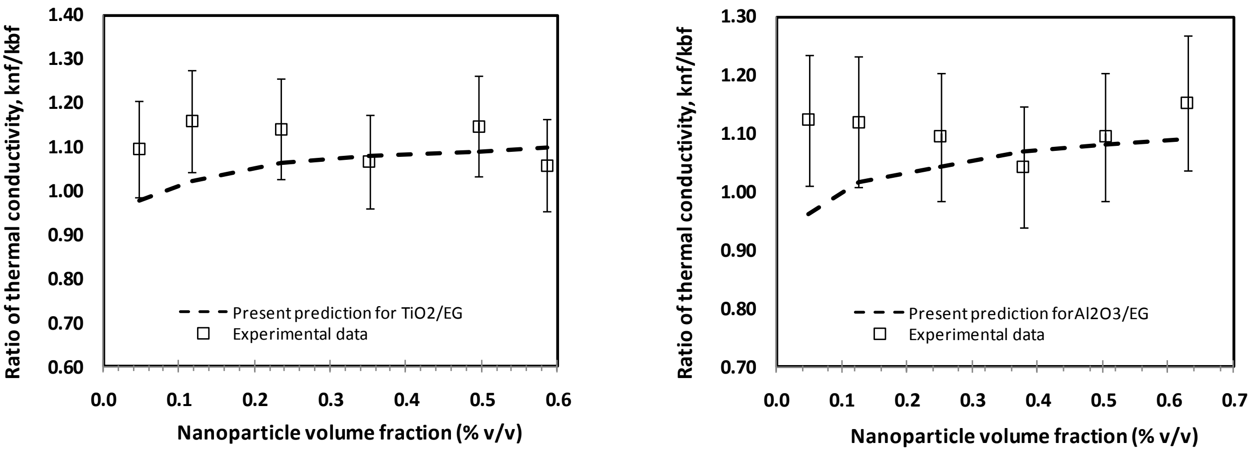
$$\frac{k_{nf}}{k_{bf}} = 1.98\,\mathrm{Re}_m^{0.175}\,\phi_v^{0.05}\left(\frac{k_{np}}{k_{bf}}\right)^{0.2324} \quad \text{for } TiO_2/EG \quad (9)$$

$$\frac{k_{nf}}{k_{bf}} = 1.32\,\mathrm{Re}_m^{0.175}\,\phi_v^{0.05}\left(\frac{k_{np}}{k_{bf}}\right)^{0.2324} \quad \text{for } Al_2O_3/EG \quad (10)$$

The effect of volume concentration on thermal conductivity enhancement is presented with ratio of thermal conductivity. Thermal conductivity ratio, defined as the ratio of the effective thermal conductivity of dispersions to the thermal conductivity of the liquid, is used to ascertain the gain in thermal conductivity of nanofluids.

The influence of nanoparticle concentration on thermal conductivity ratio and prediction by dimensional analysis model discussed above are depicted in Figure 4. The dimensional analysis model is compared with the experimental data in this present work. It is evident from this figure that the ratio thermal conductivity increases with particle concentration in the observed metallic oxide-based nanofluid in ethylene glycol. These figures are demonstrated that the results show fairly good agreement for TiO_2/EG and Al_2O_3/EG with nanoparticle concentration of 1.0 to 2.5 % w/v.

The thermal conductivity enhancement of metallic oxide-based nanofluids especially TiO_2 and Al_2O_3 is also reported by previous researcher using Steady-state method and transient-hot wire as listed in Tabel 1.



a. TiO_2/EG nanofluid b. Al_2O_3 nanofluid

Figure 4. Effect of ratio thermal conductivity of nanofluids with nanoparticle volume fraction.

Table 3. Thermal conductivity data from various studies in metallic oxide-based nanofluids.

Nanofluids	Size (nm)	Measurement technique	Thermal conductivity enhancement (%) with particle concentration	Reference
Al_2O_3/EG	29	Steady-state method	18% for 4 %(v/v)	Wang et al. (2002)
TiO_2/EG	40	Steady-state method	13% for 5 %(v/v)	Wang et al. (2002)
TiO_2/DIW	15	THW method	30% for 5 %(v/v)	Murshed et al. (2005)
Al_2O_3/water	36	Steady-state method	30% for 10 %(v/v)	Li and Peterson (2006)
TiO_2/EG	15	THW method	18% for 5 %(v/v)	Murshed et al. (2008)
γ-Al_2O_3/EO	20	THW method	37.49% for 3 %(w/v)	Vasheghani et al. (2011)

Notation: DIW, EG, and EO stand for deionized water, ethylene glycol, and engine oil, respectively and THW stands for transient hot-wire.

Conclusions

Nanofluids have been prepared by dispersing TiO_2 (~21 nm) and Al_2O_3 (13 nm) nanoparticles in spherical shapes into ethylene glycol with two-step method. A cylindrical cell steady state apparatus, categorized steady-state method, is used to measure the effective thermal conductivity of nanofluids. In this present work, semi correlation of nanofluid thermal conductivity enhancement has been derived using the Buckingham-pi theorem in which Brownian motion of nanoparticle is considered. The predicted effective thermal conductivity enhancement of nanofluid in this model is compared with the experimental data. The experimental results show that thermal conductivity increases remarkably with increasing volume fraction of nanoparticles. It is evident that the ratio thermal conductivity increases with particle concentration in the observed metallic oxide-based nanofluid in ethylene glycol. The results show that the predicted thermal conductivity enhancement using dimensional analysis model demonstrates fairly good agreement for TiO_2/EG and Al_2O_3/EG with nanoparticle concentration of 1.0 to 2.5 % w/v.

Acknowledgements

The authors would like to thank Chemistry Department, Faculty Mathematics and Natural Sciences, Universitas Gadjah Mada for the use of the TEM and XRD facilities, and Universitas

Muhamadiyah Yogyakarta for the use of the thermal conductivity apparatus.

Nomenclature

$\dot{Q}_c$	heat transferred (W),
k	effective thermal conductivity of the nanofluid (W.m^{-1}.^{o}C^{-1})
Δt	temperature difference of t_1 and t_2 (^{o}C)
V	voltage (V)
I	current (A)
d	Diameter (m)
c_p	heat specific (W.kg^{-1}.^{o}C^{-1})
T	Temperature (^{o}C)

Greek letters

ϕ_v	Volume concentration (%v/v)
ϕ	Particle concentration (%w.v)
ν	Kinematic viscosity (mm^2/s)
ρ	Density (kg/m^3)
Re_B	Brownian-Reynolds number

Subsripts

eff	effective
np	nanoparticle
bf	Base fluid
nf	nanofluid

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