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Particle shape effect on the viscosity and thermal conductivity of ZnO nanofluids

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ABSTRACT

The viscosity and thermal conductivity of ZnO nanofluids with nanoparticle shapes of nearly rectangular and of sphere, were experimentally investigated under various volume concentrations of the nanoparticles, ranging from 0.05 to 5.0 vol.%. The viscosity of the nanofluids increased with increases in the volume concentration by up to 69%. In addition, the enhancement of the viscosity of the nearly rectangular shape nanoparticles was found to be greater by 7.7%, than that of the spherical nanoparticles. The thermal conductivity of the ZnO nanofluids increased by up to 12% and 18% at 5.0 vol.% for the spherical and the nearly rectangular shape nanoparticles, respectively, compared to that of the base fluid (water). The shape of the particles is found to have a significant effect on the viscosity and thermal conductivity enhancements.

Effet de forme de particules sur la viscosité et la conductivité thermique de nanofrigorigènes ZnO

Mots clés : Nanofrigorigènes ZnO ; Transfert de chaleur ; Conductivité thermique ; Viscosité ; Effet de forme

1. Introduction

Fluids utilized for heating and cooling are important to many industrial applications, and the thermophysical properties of the fluids play a vital role in the development of energy-efficient heat transfer equipment. Nanofluids are regarded as the next-generation heat transfer fluids, and show great promise in a wide variety of applications, due to their

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Nomenclature

a	radius of primary nanoparticles, nm
C_k	thermal conductivity enhancement factor
C_μ	viscosity enhancement factor
D	fractal index
F	volume of the fractal
k	thermal conductivity, $Wm^{-1} K^{-1}$
n	particle shape factor
q	heat transfer rate, W
R	resistance, Ω
T	temperature, °C
t	time, second

Greek symbols

μ	dynamic viscosity ($N sm^{-2}$)
ε	unit of scalar
φ	volume concentration
ψ	sphericity

Subscript

a	aggregation
eff	effective
m	maximum
p	particle
0	base fluid

enhanced heat transfer performance, compared to that of ordinary fluids. The main advantages of these nanofluids are their higher stability, compared to that of fluids containing micro- or milli-sized particles, and their enhanced thermal conductive capability, compared with that of base fluids (Choi, 1995; Zussman, 2002).

Lee et al. (1999) measured the thermal conductivity of nanofluids with Al_2O_3 and CuO in water and ethylene glycol. They showed that thermal conductivity of the nanofluids significantly depended on the base fluid, particle material, size, and shape. Murshed et al. (2005) investigated nanofluids with dispersed TiO_2 nanoparticles of rod and spherical shape in deionized water. Both the particle size and shape have effects on the enhancement of thermal conductivity. Vajjha and Das (2009) experimentally determined the thermal conductivity of three nanofluids, containing aluminum oxide, copper oxide, and zinc oxide nanoparticles dispersed in an EG (Ethylene Glycol) and water mixture. The volumetric concentration of the particles was up to 10%, and the temperature range of the test was from 298 to 363 K. The results showed that the thermal conductivity of the nanofluids was enhanced with increases in the volumetric concentration of the nanoparticles. In addition, the thermal conductivity increased substantially with increases in temperature. Chen et al. (2009) measured the viscosity of an EG and water mixture with TiO_2 and TNT (titanate nanotubes), and found that the viscosity of nanofluids containing rod-like particles was much higher than for those containing spherical nanoparticles. Timofeeva et al. (2009) investigated the thermal conductivity and viscosity of various shapes of alumina nanoparticles in an EG and water mixture. They suggested that the enhancements of thermal conductivity predicted by the Hamilton–Crosser equation were diminished by the negative contribution of the interfacial thermal resistance between solid and liquid. The viscosity of the nanofluids was dependent on both particle shapes, and the surface properties of nanoparticles. Lee et al. (2011) investigated the viscosity of SiC nanofluids, and found that existing models significantly under-predicted the experimental data. Yu et al. (2009), Lee et al. (2012), and Kole and Dey (2012) investigated the thermal conductivity and the viscosity of nanofluids with ZnO, and detailed specifications of the nanoparticles are shown in Table 1. Yu et al. (2009) found that the thermal conductivity of the nanofluids increased nonlinearly with the volume fraction of the nanoparticles. The enhancement of the thermal conductivity of the nanofluid with a ZnO concentration of 5.0 vol.% was 26.5%, and was well consistent with predictions by the Maxwell and Bruggeman models. Lee et al. (2012) showed that the thermal conductivity of the nanofluid exhibited temperature dependency at a higher concentration, due to the clustering and aggregation of nanoparticles in the fluid. According to Kole and Dey (2012), the large thermal conductivity enhancement and marginal viscosity penalty of the nanofluids were attributed to the superior fragmentation and uniform distribution of ZnO nanoparticle clusters in the base fluid.

Although there are many studies of metallic nanoparticles and oxide nanopartices as additives in nanofluids, including Cu, CuO, Al_2O_3, TiO_2, Fe_3O_4, SiC and CNT (Leonard et al., 2008), researches on the thermophysical properties of thermal conductivity and viscosity with ZnO nanofluid are still considerably limited. In this study, the viscosity and thermal conductivity of ZnO nanofluids containing different shapes of nanoparticles, under various volumetric concentrations and temperature conditions, were investigated.

2. Experiments

2.1. *Synthesis of the nanofluids*

Two types of zinc oxide (ZnO) nanopowder were used in this study. One was a nearly rectangular shaped ZnO powder, whose primary particulate size was 90–210 nm (NanoAmor, 5830CD), and the other was a spherical shaped ZnO powder, whose primary particulate sizes were in the range 20 nm–40 nm (Alfa Aesar, 44899). The dispersant was ammonium polymethacrylate, which is available in the form of an aqueous solution. The volume concentration of the ZnO nanofluids ranged from 0.05 to 5.0 vol.%. For example, the ZnO powder of 5.67 g was dispersed in deionized water of 100 g, containing 0.233 ml of dispersant for the nanofluid of 1.0 vol.%, and then it was magnetically stirred at a temperature of 25 °C.

2.2. *Measurement of the effective viscosity and thermal conductivity of the nanofluids*

The viscosity of the ZnO nanofluids was measured by an Ubbelohde viscometer. The measurement uncertainty of the

Table 1 – Existing studies of the ZnO nanofluids.

References	Base fluid	Particle size	Particle shape	Volume concentration (%)
Yu et al. (1999)	Ethylene glycol	Larger than 200 nm	Sphere	0. 02–5.0
Lee et al. (2012)	Ethylene glycol	Less than 100 nm	Sphere, rectangle	0.5–5.5
Kole and Dey (2012)	Ethylene glycol	Less than 50 nm	Sphere	0.5–3.75

viscometer is lower than 2.0% of the reading value. The measured kinematic viscosity was converted to the dynamic viscosity for comparison with the exiting experimental data by using the particle's density of 5.606 g cm^{-3}. The thermal conductivity of the ZnO nanofluids was measured by the transient hot wire method. Because the test particles are electrically conductive, the transient hot-wire method is the most suitable for these measurements (Nagasaka and Nagashima, 1981). A Teflon coated platinum wire, with a diameter of 76 μm and thickness of Teflon insulation layer of 17 μm, was utilized for the hot wire. Initially the platinum wire immersed in the media was kept in equilibrium with the surroundings. When a uniform voltage was supplied to the circuit, the electric resistance of the platinum wire rises with the temperature of the wire, and the voltage output was measured by an A/D converting system, at a sampling rate of 20 times per second. Details of this method can be found in other literature (ASTM, 1985). The relation between the electric resistance and the temperature of the platinum wire was already known (Bently, 1984). The thermal conductivity was calculated from the slope of the rise in the wire's temperature against logarithmic time interval, as in Eq. (1) (Nagasaka and Nagashima, 1981).

$$k = \frac{q}{4\pi(T_2 - T_1)}\ln\left(\frac{t_2}{t_1}\right) \quad (1)$$

The uncertainties of the measurements for the thermal conductivity of the ZnO nanofluids were evaluated to be less than 1.6%. The details of the uncertainty analyses are shown in Appendix A.

3. Existing theories and models

Brinkman (1952) modified the Einstein model (Einstein, 1906) to a more generalized form, using volume concentration, and viscosity of the nanofluid and base fluid, as shown in Eq. (2).

$$\frac{\mu_{\text{eff}}}{\mu_0} = \frac{1}{(1-\phi)^{2.5}} \quad (2)$$

Batchelor (1997) introduced a correlation to predict the viscosity of nanofluids with spherical nanoparticles, which is defined as Eq. (3). Timofeeva et al. (2009) provided the constants in Eq. (3), whose values were dependent on the particle shapes of platelets, blades, cylinders, and bricks.

$$\frac{\mu_{\text{eff}}}{\mu_0} = \left(1 + 2.5\varphi + 6.2\phi^2\right) \quad (3)$$

The Batchelor equation was validated for particle volume concentrations up to 0.1 vol.%, where the motions of single particles and pair particles' interactions are dominant. Chen et al. (2009) modified the Krieger and Dougherty model to predict the viscosity of nanofluids, which is defined as Eq. (4), where φ_a is the effective particle volume fraction given by Eq. (5). φ_m is the maximum particle packing fraction, which is taken as 0.605 for spherical particles (Goodwin and Hughes, 2000), and 0.30 for stick-like particles (Barnes et al., 1989). D is the fractal index, which has typical values of 1.6–2.5 for aggregates of spherical nanoparticles, and 1.5–2.45 for those of rod-like nanoparticles. Those values depend on the type of aggregation, chemistry environment, particle size and shape, and shear flow conditions. In this study, the nearly rectangular particle's D followed generally accepted value of 1.8, and the spherical particle's D of 1.5 was determined by the minimum estimation deviation with the present experimental data.

$$\mu = \mu_0\left(1 - \frac{\phi_a}{\phi_m}\right)^{-\mu\varphi_m} \quad (4)$$

$$\phi_a = \phi\left(\frac{a_a}{a}\right)^{3-D} \quad (5)$$

Prasher (2006) developed a correlation by modifying the Hamilton-Crosser model to predict the thermal conductivity of the aggregation of nanofluids, as Eq. (6). The nanoparticles are in the form of aggregates. The enhancement of thermal conductivity due to the aggregation is a strong function of the chemical dimension of the aggregates, and the radius of gyration of the aggregates. The effective thermal conductivity of the whole system is calculated using the volume fraction, and the thermal conductivity of the aggregates. The thermal conductivity of aggregates, k_a in Eq. (6), was estimated by using Nan's model, shown in Eq. (7) (Nan et al., 1997).

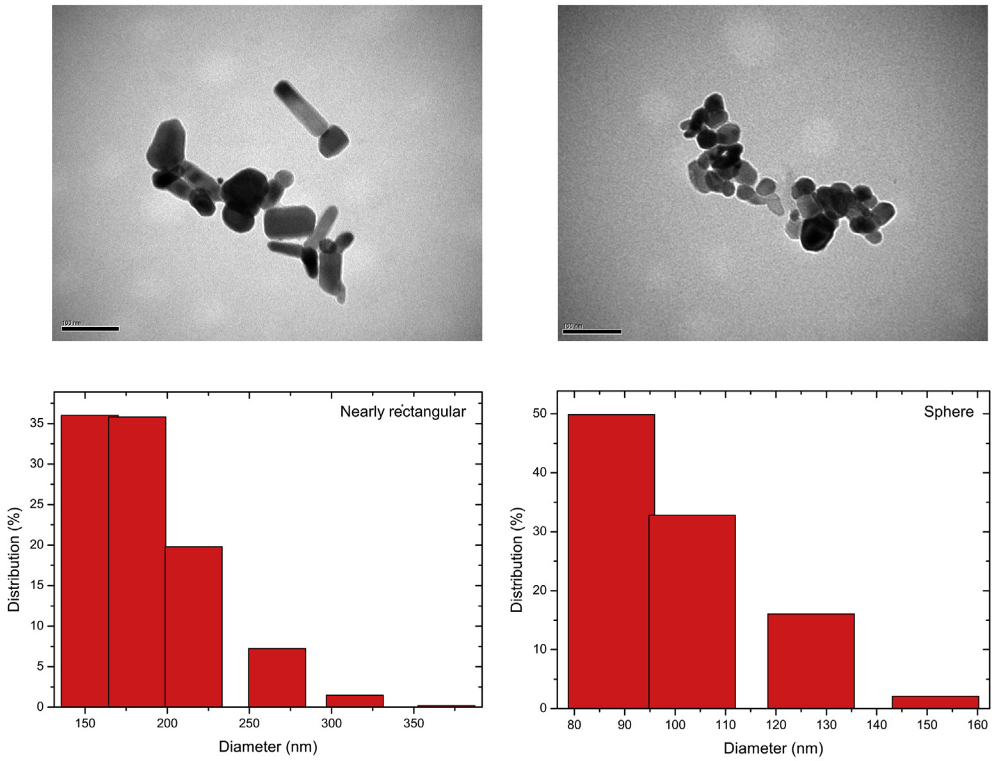
$$\frac{k}{k_0} = \frac{k_a + (n-1)k_0 - (n-1)\phi_a(k_0 - k_p)}{k_a + (n-1)k_0 + \phi_a(k_0 - k_p)} \quad (6)$$

$$\frac{k_a}{k_0} = \frac{1}{4}\left\{(3\phi_a - 1)\frac{k_p}{k_0} + [3(1-\phi_a) - 1] + \left[(3\phi_a - 1)\frac{k_p}{k_0} + (3(1-\phi_a-1)^2 + 8\frac{k_p}{k_0}\right]^{1/2}\right\} \quad (7)$$

4. Results and discussion

4.1. *The particle size and suspension stability of nanofluids*

Fig. 1 shows a TEM image of the ZnO nanofluids, and the particle distribution of the ZnO nanofluids. The shapes of the nanoparticles are nearly rectangular and sphere. The size distribution of the primary particles in the ZnO nanofluids was measured using a dynamic light scattering measurement technique. The average size of aggregated particles was found to be 150–370 nm for the nearly rectangular shape, and



(a) Nearly rectangular shape of ZnO nanoparticles (b) Spherical shape of ZnO nanoparticles

Fig. 1 – TEM image and particle size distribution for the zinc oxide nanofluids. (a) Nearly rectangular shape ZnO nanoparticles (b) Spherical shape ZnO nanoparticles.

87–150 nm for the spherical shape. When the nanofluid is prepared by mixing nanoparticles of powder form with base fluid, agglomeration of individual nanoparticles inevitably occurs due to the strong attraction forces between nanoparticles even after applying sonication method (Das et al. (2008), Gilbert et al. (2009), Kole and Dey (2012b, 2011)). The dispersion stability of the nanofluids can be decided by measuring the zeta potential of the particles. According to the ASTM standard, the dispersion stability is excellent when the absolute value of the Zeta potential is above 40 mV (ASTM Standard D 4187-82, 1985). The present tests using nearly rectangular and spherical shapes show a zeta potential of −47.48 mV and −49.15 mV, respectively. The test nanofluids have acceptable dispersion stability. The particle size and the zeta potential were measured at volume concentration of the nanoparticles of 1.0 vol.%.

4.2. *The viscosity of the nanofluids*

Fig. 2 shows the viscosity of the ZnO nanofluids relative to that of pure water, with particle volume concentration. The viscosity significantly increased with increasing particle concentrations from 5.3% to 68.6% at 0.5 vol.% and 5.0 vol.%, respectively, for the nearly rectangular shape ZnO nanoparticle, and from 5.9% to 59.0% at 0.5 vol.% and 5.0 vol.%, respectively, for the sphere shape ZnO nanoparticle. It should be noted that the viscosity of the nanofluid with a nearly rectangular shape particles is higher by 7.7% than that of the nanofluid with sphere shape particles. The nearly rectangular shape is hard to rotate, compared to the sphere shape, which increases the flow resistance, and also the viscosity.

The experimental data for the viscosity of the ZnO nanofluids was compared with the predictions by the Batchelor model (1997), Brinkman model (1952), Timofeeva et al.'s (2009) model, and the Chen et al. (2009) model. The comparisons using the first two models show that the experimental

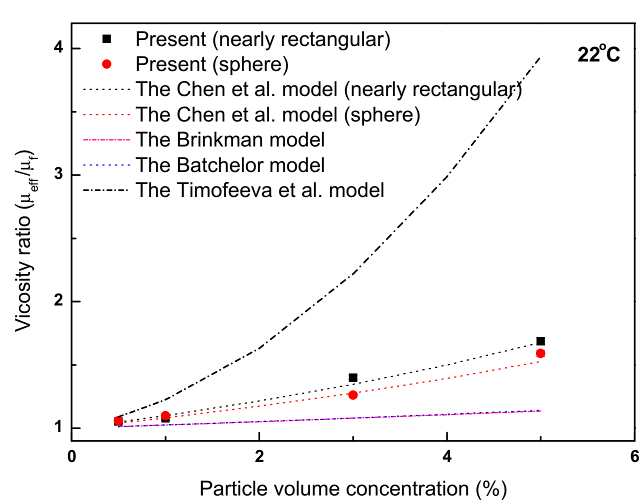


Fig. 2 – Experimental and predicted results for the viscosity of the ZnO nanofluids with nanoparticle concentration.

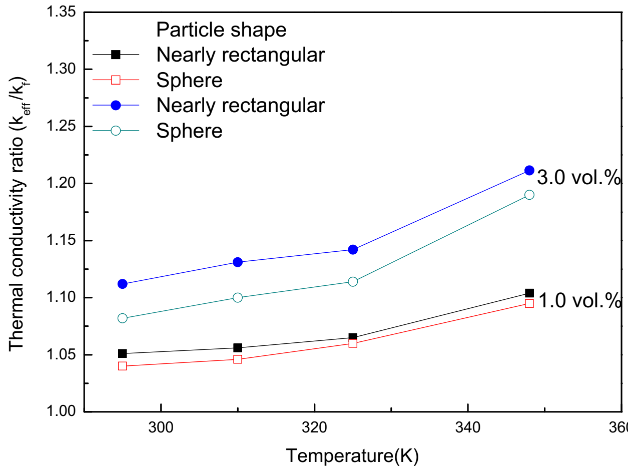


Fig. 3 – Ratio of the thermal conductivity with temperature for the ZnO nanofluids at different nanoparticle concentrations.

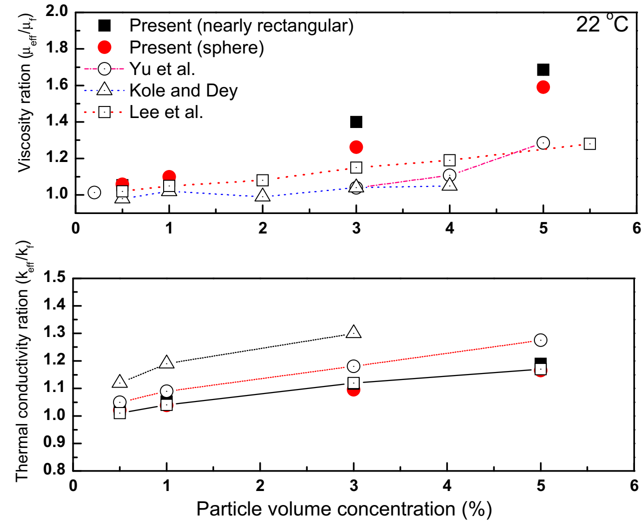


Fig. 5 – Comparison of the viscosity and thermal conductivity between the present and existing data.

data was under-predicted by 14% and 16% for the spherical and nearly rectangular ZnO nanoparticles, respectively. Those large discrepancies might arise from the effect of the shape and size of nanoparticles on the viscosity, which were not considered in the models. The estimated viscosity from the Timofeeva et al. model highly over-predicted the present experimental data. The Chen et al. model, which considered the particle aggregations, shows mean deviations of 2.2% and 1.7% for the nanofluids of the nearly rectangular and sphere particles, respectively. It should be noted that the viscosity of the nanofluids is significantly affected by particle aggregation.

4.3. *Thermal conductivity of the nanofluids*

Fig. 3 shows the ratio of the thermal conductivity of the nanofluid to that of the base fluid at various nanofluid temperatures. It was observed that the ratio of thermal conductivity increases with the increase of temperature, and also with the increase of particle volume concentration. When the particle volume concentration is 3.0 vol.%, the ratio of the thermal conductivity increases by 10.8% with variations of temperature. Fig. 4 shows the ratio of the thermal conductivity of the ZnO nanofluids to that of the base fluid at various particle volume concentrations, and the predicted values by the Prasher model (2006). When the concentration of the ZnO increased from 0.5 vol.% to 5.0 vol.%, the enhancement of the thermal conductivity of the ZnO nanofluid with a nearly rectangular shape increased from 3.0% to 19.8%, and that of the ZnO nanofluid with a sphere shape increased from 2.5% to 16.0%. The experimental data was predicted by the Prasher model with a mean deviation of 0.52% for the sphere particles, and 0.67% for the nearly rectangular particles.

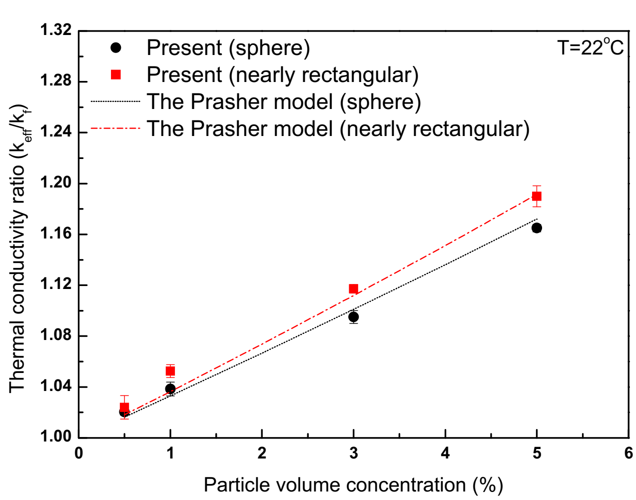


Fig. 4 – Experimental and predicted results for the ratio of thermal conductivity to nanoparticle concentration.

4.4. *Discussions*

Recent studies of the ZnO nanofluid (Yu et al. (2009), Lee et al. (2012), and Kole and Dey (2012)) were compared with the present study, to characterize the thermophysical properties

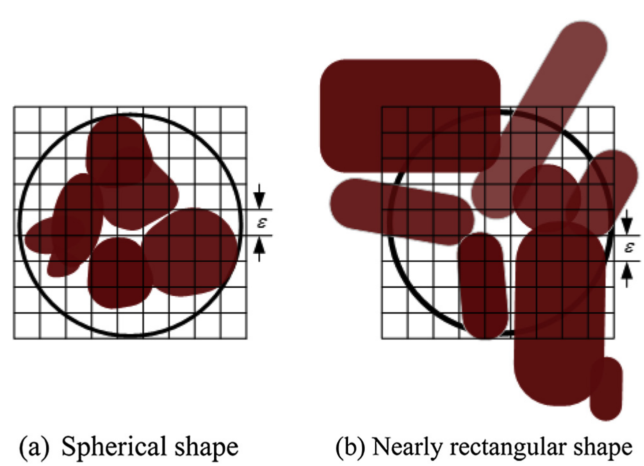


Fig. 6 – Fractal index of section area of agglomerate. (a) Spherical shape (b) Nearly rectangular shape.

Table 2 – Fractal index of agglomerate from the representative agglomeration shape.

Sphere shape				Nearly rectangular shape			
ε	$F(\varepsilon)$	$\ln(F(\varepsilon))$	D	ε	$F(\varepsilon)$	$\ln(F(\varepsilon))$	D
1	0.8	−0.22314		1	0.5	−0.69315	
9	8	2.079442	1.05	9	6	1.791759	1.13
25	20.5	3.020425	0.92	25	19	2.944439	1.13

of the ZnO nanofluids, as shown in Fig. 5. The ratio of the viscosity and thermal conductivity increased with increase of particle volume concentration. However, the results from Kole and Dey showed a different trend in the viscosity, and much higher values in the thermal conductivity, compared to the other studies. As explained by Kole and Dey, the particle size, absence of surfactant, and long duration sonication time might be the reason for the different trends. Considering that the particle size and shape of Lee et al. are most similar to the present, as shown in Table 1, minimum deviation of the present study from them was observed.

The characteristics of thermal conductivity and viscosity for ZnO nanofluid having different shapes have been explained by the increased interface surface area from agglomeration, and the models utilizing the effective aggregate radius, which is dependent on the particle shape, properly estimated the present experimental results. The fractal index (Wang et al., 2003) was calculated from the volume of fractal and the unit of scalar as in Eq. (8), and the nearly rectangular shape showed higher effective agglomerate radius (D) than that of sphere due to its steep change of interface area between particles in agglomerate and base fluid. Fig. 6 showed the fractional index of section area of the agglomerations of sphere and nearly rectangular particles based on the unit of scalar of ε. Table 2 showed the fractal index of agglomerate from the representative agglomeration shape of the ZnO nanoparticles.

$$D = \frac{\Delta \ln F(\varepsilon)}{\Delta \ln \varepsilon} \tag{8}$$

Similar shape effects on the thermal conductivity and the viscosity with the present study were found by Lee et al.'s (1999), Murshed et al.'s (2005), and Ferrouillat et al. (2013). Cui et al. (2011) showed that thermal conductivity of nanofluids having cylinder particle is much higher than that of sphere particle from the enhanced micro-convection for the cylindrical shape by rotational motion through molecular dynamics. Akbulut et al. (2007) attributed the shape effects to the increased steric contribution of the nanostructures to the overall surface interaction. Pilkington and Briscoe (2012) showed that aspect ratio of the nanostructures had an effect on the equilibrium forces mediated by nanofluids that can

Table 3 – Shape effects of nanoparticles on viscosity and thermal conductivity of nanofluids.

Authors	Particle type-Base fluid	Particles shape	Viscosity	Thermal conductivity	Remarks
Timofeeva et al. (2009)	Al_2O_3–EG/H_2O	Platelet, blade, cylinder, and brick	$\mu_{cylinder} \le \mu_{brick} \le \mu_{platelet} \approx \mu_{blade}$	$\mu_{platelet} \le \mu_{cylinder} \le \mu_{brick} \le \mu_{blade}$	Elongated particles and agglomerates resulted in higher viscosity at the same volume fraction due to structural limitation of rotational and transitional Brownian motions
Cui et al. (2011)	Cu–Ar	Sphere and cylinder	N/A	Enhancement of sphere: 14.8% Enhancement of cylinder: 20.31%	Enhanced micro-convection of the cylindrical shape from rotational motion, which increased thermal conductivity
Akbulut et al. (2007)	ZnS	Sphere, rod, and wires	N/A	N/A	Increased steric contribution of the nanostructures to the overall surface interaction
Pilkington and Briscoe (2012)	N/A	N/A	N/A	N/A	Aspect ratio of the nanostructures has an effect on the equilibrium forces mediated by nanofluids that can affect the viscosity of nanofluids
Ghosh and Pabi (2012)	Cu	Cylinder	N/A	$\mu_{low\ aspect\ ratio} \le \mu_{high\ aspect\ ratio}$	Increased contact area with increase of aspect ratio of nanoparticle induced higher rate of heat transfer during the collision
Ferrouillat et al. (2013)	SiO_2-water ZnO-water	Sphere and banana Polygonal and rod	$\mu_{sphere} \approx \mu_{banana}$ $\mu_{rod} \le \mu_{polygonal}$	$k_{sphere} \le k_{banana}$ $k_{rod} \approx k_{polygonal}$	Following the Timofeeva et al.'s analysis (2009). Enhancement is lower than predicted by the H–C model. Banana shape nanoparticles have larger surface area in contact with stabilizing chemicals than that of spherical ones
Ooi and Popov (2013)	Cu-water	Sphere and spheroid	Enhancement: 40–603%	Enhancement: 32–151%	Estimated by the H–C model and the Mueller et al.'s model

Table 4 – Existing studies on size effects of primary particles on thermal conductivity of nanofluids.

References	Particle type	Base fluid	Particle sizes	Thermal conductivity
Chon et al. (2005)	Al_2O_3	Water	11, 47, 150 nm	$\mu_{150\ nm} \leq \mu_{47\ nm} \leq \mu_{11\ nm}$
Li and Peterson (2007)	Al_2O_3	Water	36, 47 nm	$\mu_{47\ nm} \leq \mu_{36\ nm}$
He et al. (2007)	TiO_2	Water	95, 145, 210 nm	$\mu_{210\ nm} \leq \mu_{145\ nm} \leq \mu_{95\ nm}$
Vajjha and Das (2009)	ZnO	EG-water	29, 77 nm	$\mu_{77\ nm} \leq \mu_{29\ nm}$
Anoop et al. (2009)	Al_2O_3	Water	45, 150 nm	$\mu_{150\ nm} \leq \mu_{45\ nm}$
Teng et al. (2010)	Al_2O_3	Water	20, 50, 100 nm	$\mu_{100\ nm} \leq \mu_{50\ nm} \leq \mu_{20\ nm}$
Patel et al. (2010)	Al_2O_3	EG, water, oil	11, 45, 150 nm	$\mu_{150\ nm} \leq \mu_{45\ nm} \leq \mu_{11\ nm}$

affect the viscosity of nanofluids. Ghosh and Pabi (2012) suggested that increased contact area with increase of aspect ratio of nanoparticle induced higher rate of heat transfer during the collision. Microscopically, the interfacial liquid layer between solid and liquid can characterize the thermal conductivity of the nanofluids (Gaganpreet and Srivastava, 2011; Timofeeva et al., 2009; Liang and Tsai, 2011). According to Liang and Tsa, the strength of the solid and liquid interaction was dependent on the nanoparticle's type, size, and agglomerating status of the nanofluid. The strength of the interaction of the solid and liquid might explain the different analysis of the positive or negative effect of the interfacial layer on the thermal conductivity. Besides, it can be utilized to explain the shape effects that are found in the TiO_2, Al_2O_3, and ZnO, but not shown in the CuO (Lee et al., 1999) and alumina (Timofeeva et al., 2009). Above shape effects of nanoparticles on viscosity and thermal conductivity of nanofluids were summarized in Table 3. Chon et al. (2005), Li and Peterson (2007), Anoop et al. (2009), Teng et al. (2010), and Patel et al. (2010) utilized the nanoparticle of Al_2O_3 to investigate the particle size effect on thermal conductivity, and showed that primary particle size can affect the size of aggregates and higher enhancement of thermal conductivity was expected with smaller particle size. He et al. (2007) showed the similar size effect on thermal conductivity by using TiO_2. Table 4 summarized the detail test conditions and results of the existing studies on size effects of primary particles on thermal conductivity of nanofluid. Vajjha and Das (2009) and Kim et al. (2007) investigated the effects of primary particle's size of ZnO on the thermal conductivity of nanofluids. Both of the studies showed that the thermal conductivity increased with decrease of the particle size. Considering that the primary size of the spherical shape was less than that of the nearly rectangular shape and thermal conductivity of nearly rectangular shape is higher than that of spherical shape in the present study, it can be induced that the effects of the particles' shape were much dominant than that of the primary particle's size when the particle was confined to the ZnO. However, further investigation of the solid and liquid interaction, in terms of the nanoparticle type, size, and agglomerating status, is necessary for confirmation.

To utilize the nanofluids in practical applications, both effects of the viscosity and the thermal conductivity need to be simultaneously considered. According to Prasher (2006), the use of nanofluid would be beneficial for laminar flow, in the case of C_μ/C_k being less than 4. The values of the C_μ/C_k of the present study for the spherical and nearly rectangular shape are 3.65 and 4.0, respectively. They are both nearly within the range, but the nanofluid of the spherical shape is slightly more beneficial than that of the nearly rectangular shape, based on Prasher's recommendation.

5. Conclusions

The effects of the shape of nanoparticles in ZnO nanofluids on the viscosity and thermal conductivity were investigated. The viscosity and thermal conductivity of the ZnO nanofluids were higher than those of the base fluid by 5.3–68.6% and 3.0–19.8%, respectively, when the volume concentrations were varied from 0.5 vol.% to 5.0 vol.%. The viscosity and thermal conductivity for the nanofluid with nearly rectangular shape particles were larger than that of the nanofluid with sphere shape particles by 7.7% and 5.9%, respectively, when the volume concentrations were varied from 0.5 vol.% to 5.0 vol.%. The effective aggregate radius of the nanofluid between nearly rectangular shape particles and sphere particles can explain differences in viscosity and thermal conductivity between them.

Appendix A. Uncertainty of thermal conductivity

The uncertainties of thermal conductivity were calculated by the THW method. The thermal conductivity of the nanofluids can be measured by using Eq. (A.1), and the heat transfer rate of q was calculated by Eq. (A.1). In Eq. (A.1), T_1 is the initial temperature of nanofluid, and T_2 is the measured temperature of nanofluid. V_s is the input voltage, R is the resistance, and L is the wire length in Eq. (A.2). The sensitivities of k with T_2 and R_4 are calculated as shown in Eqs. (A.3) and (A.4).

$$k = \frac{q}{4\pi(T_2 - T_1)}\ln(t) \tag{A.1}$$

$$q = \frac{V_s^2 L}{R_T + R_4} \tag{A.2}$$

$$\frac{\partial k}{\partial T_2} = -\frac{V_s^2 L \ln(t) k}{4\pi(T_2 - T_1)^2 (R_T + R_4)} = -\frac{5.6336^2 \times 0.11 \times 0.11 \times 0.606}{4 \times 3.14 \times (9.55 + 2.61)^2 \times 3.25} = -0.00023 \tag{A.3}$$

$$\frac{\partial k}{\partial R_4} = -\frac{V_s^2 L \ln(t) k}{4\pi(T_2 - T_1)^2 (R_T + R_4)^2} = -\frac{5.6336^2 \times 0.11 \times 0.11 \times 0.606}{4 \times 3.14 \times (9.55 + 2.61)^2 \times 3.25^2} = -0.000063 \tag{A.4}$$

The bias error of B_h and the precision error of P_r can be calculated by using Eqs. (A.5) and (A.6), respectively. The values of B_{T_2} and B_{R_4} are measurement errors for the temperature and the resistance. The total uncertainty of the thermal conductivity of the nanofluid under representative conditions is ±1.6%, as shown in Eq. (A.7).

$$B_h = \left(\frac{\partial k}{\partial T_2} B_{T_2}\right)^2 + \left(\frac{\partial k}{\partial R_4} B_{R_4}\right)^2 = (0.00023 \times 0.1)^2 + (0.000063 \times 0.1)^2 = 5.686 \times 10^{-10} \tag{A.5}$$

$$P_r = \frac{2 \times S_r}{\sqrt{M}} = \frac{2 \times 0.02}{\sqrt{6}} = 0.016 \tag{A.6}$$

$$U_r = \sqrt{B_h^2 + P_r^2} = \sqrt{(5.686 \times 10^{-10})^2 + 0.016^2} = 0.016 \times 100 = 1.6\% \tag{A.7}$$

REFERENCES

Akbulut, M., Alig, A.R.G., Min, Y.J., Belman, N., Reynolds, M., Golan, Y., Israelachvili, J., 2007. Forces between surfaces across nanoparticle solutions: role of size, shape, and concentration. Langmuir 23 (7), 3961–3969.

American Society for Testing and Materials, 1985. Zeta Potential of Colloids in Water and Waste Water. ASTM, PA, USA. Standard D 4187-82.

Anoop, K.B., Sundararajan, T., Das, S.K., 2009. Effect of particle size on the convective heat transfer in nanofluid in the developing region. Int. J. Heat Mass Transf. 52, 2189–2195.

Barnes, H.A., Hutton, J.F., Walters, K., 1989. An Introduction to Rheology. Elsevier Science B.V., Netherlands.

Batchelor, G.K., 1997. Effect of Brownian-motion on bulk stress in a suspension of spherical-particles. J. Fluid. Mech. 83, 97–117.

Bently, J.P., 1984. Temperature sensor characteristics and measurement system design. J. Phys. E: Sci. Instrum. 17, 430–439.

Brinkman, H.C., 1952. The viscosity of concentrated suspensions and solutions. J. Chem. Phys. 20, 571–581.

Chen, H., Witharan, S., Jin, Y., Kim, C., Ding, Y., 2009. Predicting thermal conductivity of liquid suspensions of nanoparticles (nanofluids) based on rheology. Particuology 7, 151–157.

Choi, S., 1995. Enhancing Thermal Conductivity of Fluids with Nanoparticles. In: Developments and Applications of Non-newtonian Flows. FED-Vol. 231/MD-Vol. 66. ASME, NewYork, pp. 99–105.

Chon, C.H., Kihm, K.D., Lee, S.P., Choi, S.U.S., 2005. Empirical correlation finding the role of temperature and particle size for nanofluid (Al_2O_3) thermal conductivity enhancement. Appl. Phys. Lett. 87, 153107.

Cui, W., Bai, M., Lv, J., Li, G., Li, X., 2011. On the influencing factors and strengthening mechanism for thermal conductivity of nanofluids by molecular dynamics simulation. Ind. Eng. Chem. Res. 50, 13568–13575.

Das, S.K., Choi, S.U.S., Yu, W., Pradeep, T., 2008. Nanofluids: Science and Technology. John Wiley & Sons, Inc., Hoboken, New Jersey.

Einstein, A., 1906. Eine neue bestimmung der molekul-dimension (A new determination of the molecular dimensions). Annalen der Physik 19, 289–306.

Ferrouillat, S., Bontemps, A., Poncelet, O., Soriano, O., Gruss, J.A., 2013. Influence of nanoparticle shape factor on convective heat transfer and energetic performance of water-based SiO_2 and ZnO nanofluids. Appl. Therm. Eng. 51, 839–851.

Gaganpreet, Srivastava, S., 2011. Effect of particle shape and interfacial layer in thermal conductivity and viscosity of nanofluids. AIP Conf. Proc. 1349, 407–408.

Ghosh, M.M., Pabi, S.K., 2012. Effects of particle shape and fluid temperature on heat-transfer characteristics of nanofluids. J. Mater. Eng. Perform. 22 (6), 1525–1529.

Gilbert, B., Ono, R.K., Ching, K.A., Kim, C.S., 2009. The effects of nanoparticle aggregation processes on aggregate structure and metal uptake. J. Colloid. Interface. Sci. 339, 285–295.

Goodwin, J.W., Hughes, R.W., 2000. Rheology for Chemists – an Introduction. The Royal Society of Chemistry, Baker & Taylor Books, Cambridge.

He, Y., Jin, Y., Chen, H., Ding, Y., Cang, D., Lu, H., 2007. Heat transfer and flow behavior of aqueous suspensions of TiO_2 nanoparticles (nanofluids) flowing upward through a vertical pipe. Int. J. Heat Mass Transf. 50, 2272–2281.

Kim, S.H., Choi, S.R., Kim, D., 2007. Thermal conductivity of metal-oxide nanofluids: particle size dependence and effect of laser irradiation. ASME J. Heat Transf. 129, 298–307.

Kole, M., Dey, T.K., 2011. Effect of aggregation on the viscosity of copper oxideegear oil nanofluids. Int. J. Therm. Sci. 50, 1741–1747.

Kole, M., Dey, T.K., 2012. Thermophysical and pool boiling characteristics of ZnO-ethylene glycol nanofluids. Int. J. Therm. Sci. 62, 61–70.

Kole, M., Dey, T.K., 2012b. Effect of prolonged ultrasonication on the thermal conductivity of ZnO–ethylene glycol nanofluids. Thermochim. Acta 535, 58–65.

Lee, S., Choi, S.U.-S., Li, S., Eastman, J.A., 1999. Measuring thermal conductivity of fluids containing oxide nanoparticles. J. Heat Transfer 121, 280–288.

Lee, S.W., Park, S.D., Kang, S., Bang, I.C., Kim, J.H., 2011. Investigation of viscosity and thermal conductivity of SiC nanofluids for heat transfer applications. Int. J. Heat Mass Trans. 54, 433–438.

Lee, G.J., Kim, C.K., Lee, M.K., Rhee, C.K., Kim, S.W., Kim, C.Y., 2012. Thermal conductivity enhancement of ZnO nanofluid using a one-step physical method. Thermochim. Acta 542, 24–27.

Leonard, J.P., Chung, S.J., Nettleship, I., Soong, Y., Martello, D.V., Chyu, M.K., 2008. Stability of zinc oxide nanofluids prepared with aggregated nanocrystalline powders. J. Nanosci. Nanotechnol. 8, 6361–6366.

Li, C.H., Peterson, G.P., 2007. The effect of particle size on the effective thermal conductivity of Al_2O_3-water nanofluids. J. Appl. Phys. 101, 044312.

Liang, Z., Tsai, H.L., 2011. Thermal conductivity of interfacial layers in nanofluids. Physiol. Rev. E83, 041602.

Murshed, S.M.S., Leong, K.C., Yang, C., 2005. Enhanced thermal conductivity of TiO_2–water based nanofluids. Int. J. Therm. Sci. 44, 367–373.

Nagasaka, Y., Nagashima, A., 1981. Absolute measurement of the thermal conductivity of electrically conducting liquids by the transient hot-wire method. J. Phys. E: Sci. Instrum. 14, 1435–1440.

Nan, C.W., Birringer, R., Clarke, D.R., Gleiter, H., 1997. Effective thermal conductivity of particulate composite with interfacial thermal resistance. J. Appl. Phys. 81, 6692–6699.

Ooi, E.H., Popov, V., 2013. Numerical study of influence of nanoparticle shape on the natural convection in Cu-water nanofluid. Int. J. Therm. Sci. 65, 178–188.

Patel, H.E., Sundararajan, T., Das, S.K., 2010. An experimental investigation into the thermal conductivity enhancement in oxide and metallic nanofluids. J. Nanopart. Res. 12, 1015–1031.

Pilkington, G.A., Briscoe, W.H., 2012. Nanofluids mediating surface forces. Adv. Colloid. Interface. Sci. 179–182, 68–84.

Prasher, R., 2006. Effect of aggregation kinetics on the thermal conductivity of nanoscale colloidal solutions nanofluid. Nano Lett. 6, 1529–1534.

Teng, T.P., Hung, Y.H., Teng, T.C., Moa, H.E., Hsu, H.G., 2010. The effect of alumina/water nanofluid particle size on thermal conductivity. Appl. Therm. Eng. 30, 2213–2218.

Timofeeva, E.V., Routbort, J.L., Dileep, S., 2009. Particle shape effects on thermophysical properties of alumina nanofluids. J. Appl. Phys. 106, 014304.

Vajjha, R.S., Das, D.K., 2009. Experimental determination of thermal conductivity of three nanofluids and development of new correlations. Int. J. Heat Mass Trans. 52, 4675–4682.

Wang, B., Zhou, L., Peng, X., 2003. A fractal model for predicting the effective thermal conductivity of liquid with suspension of nanoparticles. Int. J. Heat Mass Trans. 46, 2665–2672.

Yu, W., Xie, H., Chen, L., Li, Y., 2009. Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid. Thermochim. Acta 491, 92–96.

Zussman, S., 2002. More about Argonne's Stable, Highly Conductive Nanofluids, Technology Transfer at Argonne, Public Communication. Argonne National Laboratory, IL, USA.