
**Journal of Experimental Nanoscience**
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t716100757

# MgO nanofluids: higher thermal conductivity and lower viscosity among ethylene glycol-based nanofluids containing oxide nanoparticles

Huaqing Xie[a]; Wei Yu[a]; Wei Chen[a]
[a] School of Urban Development and Environmental Engineering, Shanghai Second Polytechnic University, Shanghai 201209, P.R. China

Online publication date: 05 November 2010

**To cite this Article** Xie, Huaqing , Yu, Wei and Chen, Wei(2010) 'MgO nanofluids: higher thermal conductivity and lower viscosity among ethylene glycol-based nanofluids containing oxide nanoparticles', Journal of Experimental Nanoscience, 5: 5, 463 — 472

**To link to this Article: DOI:** 10.1080/17458081003628949

**URL:** http://dx.doi.org/10.1080/17458081003628949

*Journal of Experimental Nanoscience*
Vol. 5, No. 5, October 2010, 463–472

Taylor & Francis
Taylor & Francis Group

# MgO nanofluids: higher thermal conductivity and lower viscosity among ethylene glycol-based nanofluids containing oxide nanoparticles

Huaqing Xie*, Wei Yu and Wei Chen

*School of Urban Development and Environmental Engineering, Shanghai Second Polytechnic University, Shanghai 201209, P.R. China*

(*Received 27 June 2009; final version received 16 January 2010*)

Five kinds of oxides, including MgO, $TiO_2$, ZnO, $Al_2O_3$ and $SiO_2$ nanoparticles were selected as additives and ethylene glycol (EG) was used as base fluid to prepare stable nanofluids. Thermal transport property investigation demonstrated substantial increments in the thermal conductivity and viscosity of all these nanofluids with oxide nanoparticle addition in EG. Among all the studied nanofluids, MgO–EG nanofluid was found to have superior features, with the highest thermal conductivity and lowest viscosity. The thermal conductivity enhancement ratio of MgO–EG nanofluid increases nonlinearly with the volume fraction of nanoparticles. In the experimental temperature range of 10–60°C, thermal conductivity enhancement ratio of MgO–EG nanofluids appears to have a weak dependence on the temperature. Viscosity measurements showed that MgO–EG nanofluids demonstrated Newtonian rheological behaviour, and the viscosity significantly decreases with the temperature. The thermal conductivity and viscosity increments of the nanofluids are much higher than the corresponding values predicted by the existing classical models for the solid–liquid mixture.

**Keywords:** nanofluid; heat transfer; MgO nanoparticle; viscosity; thermal conductivity



## 1. Introduction

Thermal conductivity of heat transfer fluids plays a vital role in the development of energy-efficient heat transfer equipments. Over the past decades, great efforts have been made to improve the inherently poor thermal conductivities of traditional heat transfer fluids, such as water, oil and ethylene glycol (EG). Nanofluids, produced by dispersing nanoparticles into conventional heat transfer fluids, are proposed as the next generation of heat transfer fluids due to the fact that their thermal properties are significantly better than those of the base liquids [1–4]. Among all thermal properties, thermal conductivity is the most important and most studied. More than 20 laboratories worldwide have published experimental data on the thermal conductivity of nanofluids. The colloidal fluidic systems show unusually high thermal conductivity even when the concentration of suspended nanoparticles is lower than 5% in volume fraction. At present, the thermal conductivity

*Corresponding author. Email: hqxie@eed.sspu.cn

ISSN 1745–8080 print/ISSN 1745–8099 online

DOI: 10.1080/17458081003628949
http://www.informaworld.com

data measured by different groups are scattered. The dispersion is believed to be due to various factors such as the measuring techniques, the particle size and shape, the particle clustering and sedimentation.

Many kinds of nanomaterials are used as additives for preparing nanofluids. Among these additives, oxide nanoparticles [5–8] consitute one of the important classes. In order to investigate the thermal transport properties of nanofluids containing oxide nanoparticles, five kinds of nanofluids were prepared and the measurement techniques and conditions were the same in order to ensure consistency of the experimental data. Then, the nanofluid with highest thermal conductivity was selected and focused on. The effects of the particle volume fraction, settlement time, measured temperature and viscosity on the thermal transport were investigated in detail.

## 2. Experimental

Five kinds of oxide nanoparticles used in the experiments were purchased from Hangzhou Wanjing New Material Company, China. The mean diameters of all these nanoparticles are about 20 nm. The physicochemical properties of the selected nanofluids are presented in Table 1. The thermal conductivities are for the corresponding bulk oxides [9]. The typical nanofluid preparation procedure is as follows: fixed quality of oxide nanoparticles with different volume concentrations ($\phi = 0.5$–$5\%$) was dispersed in EG. The volume fraction of the powder was calculated from the weight of dry powder using the density provided by supplier and the total volume of suspension. The nanoparticle–fluid mixture was stirred and sonicated continuously for 3 h to ensure the uniform dispersion of nanoparticles in the base fluid.



In the measurement of the thermal conductivity of fluids, transient hot-wire (THW) technique is more appropriate than those steady-state techniques due to numerous advantages, such as the elimination of natural convection effects and faster experimental response. In this study, a self-established transient short hot-wire (SHW) apparatus was applied to measure the thermal conductivities of the base fluid and nanofluids from 10 to 60°C [10]. In addition to the hot-wire system, a temperature-controlled bath was used to maintain different temperatures of samples during the measurement process. The experimental apparatus was calibrated by measuring the thermal conductivity of EG and the accuracy of these measurements was estimated to be within ±1%.

Table 1. Properties of oxides and their nanofluids.

| | Thermal conductivity[a] (W/mK) | Density (g/cm$^3$) | Crystalline | Viscosity (cP) with 5.0 vol.% 30°C | Thermal conductivity enhancement of nanofluids (%) with 5.0 vol.% |
|---|---|---|---|---|---|
| MgO | 48.4 | 2.9 | Cubic | 17.4 | 40.6 |
| $TiO_2$ | 8.4 | 4.1 | Anatase | 31.2 | 27.2 |
| ZnO | 13.0 | 5.6 | Wurtzite | 129.2 | 26.8 |
| $Al_2O_3$ | 36.0 | 3.6 | $\gamma$ | 28.2 | 28.2 |
| $SiO_2$ | 10.4 | 2.6 | Noncrystalline | 31.5 | 25.3 |

[a]Thermal conductivities of the oxides are for the corresponding bulk materials.

The thermal conductivity of the fluid was measured after the nanofluid was settled for more than 30 min to ensure the temperature equilibrium of nanofluids. The rheological property of nanofluids was measured by a viscometer (LV DV-II + Brookfield programmable viscometer, USA) with a temperature-controlled bath. Viscosity measurements were started at 60°C, and temperature was gradually reduced to 10°C in 10°C-intervals. Spindle SC-18 was used in this viscometer and was calibrated by using Brookfield viscosity standard fluids. All the viscosity measurements were recorded at steady-state conditions. The accuracy was estimated to be within ±3%.

## 3. Results and discussion

In order to compare the heat transfer ability of nanofluids containing oxide nanoparticles, the thermal conductivities of different oxide nanofluids were measured using same measuring technique and conditions. It can be seen from Table 1 that the thermal conductivities of MgO–EG nanofluids (EG-based nanofluids containing MgO nanoparticles) are larger than those of nanofluids containing same volume fraction of $TiO_2$, ZnO, $Al_2O_3$ and $SiO_2$. The viscosity of nanofluids is another important transport property for applications of nanofluids as a new class of heat transfer fluids in thermal devices or systems, such as heat exchangers or cooling system. Low viscosity is beneficial to the application of a nanofluid. It is found that the viscosity of MgO–EG nanofluid is the lowest among all the studied oxide nanofluids. Due to their high thermal conductivity and low viscosity, our further work focussed on the thermal conductive property of MgO–EG nanofluids.

Figure 1 shows the dependence of the thermal conductivity enhancement ratios, $(k_{nf} - k_{bf})/k_{bf}$, of the MgO–EG nanofluids at 30°C on the volume fractions. $k_{nf}$ and $k_{bf}$ represent the thermal conductivity of the nanofluid and base fluid, respectively. The experimental results indicate that the thermal conductivity of MgO–EG nanofluids increases nonlinearly with the particle loading. The maximum enhancement is up to 40.6% for a particle volume fraction of 5.0%. At lower volumetric loadings (0.5–1.0%), the slope of the thermal conductivity enhancement to the volume fraction is larger than that at higher volume fraction (2.0–5.0%). This demonstrates that the enhanced rate of thermal conductivity decreases with the volume fraction, mainly due to the particle agglomeration at higher volume fraction. This result is similar to the nanofluids of CuO–EG [11,12].

In addition to MgO–EG nanofluids, the data of some EG-based nanofluids containing oxide nanoparticles are also presented in Figure 1. It is found that the enhancement ratios of EG-based nanofluids with 5.0 vol.% metallic oxide are in the range of 17–29%. Substantial higher increase in thermal conductivity enhancement is seen for the MgO–EG nanofluid. At a MgO particle loading of 5.0 vol.%, the enhancement ratio is up to 40.6%, while that for $Al_2O_3$–EG nanofluid is only 28.2%.

Various mechanisms and classic models have been proposed for explaining the enhanced thermal conductivity of nanofluids using various assumptions, such as Maxwell model [13] and Hamilton and Crosser (H–C) model [14], though these models always underpredict the enhancement ratios of the thermal conductivity of nanofluids. The facts imply that the affecting factors might include the thermal conductivity of bulk materials, particle size, particle Brownian motion, nanolayering, nanoparticle clustering and viscosity.

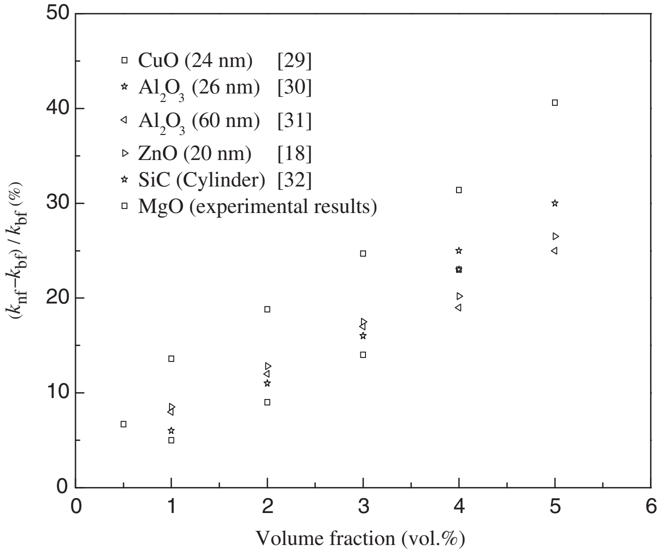


Figure 1. Thermal conductivity enhancement ratios of EG-based nanofluids as a function of loading.



In recent years, some researchers have proposed models based on the influence of agglomeration. For example, Prasher et al. [15] believed that the aggregate could increase thermal conductivity due to percolation effects, as highly conducting particles touch each other in the aggregates. Timofeeva et al. [16] presented a combined experimental and theoretical study of heat conduction and particle agglomeration in nanofluids. The agglomeration might account for the enhancement of thermal conductivity of nanofluids. Chen et al. [17] combined the aggregation mechanism with the Maxwell and Bruggeman models, and gave a good prediction of the effective thermal conductivity of the nanofluids. The rheological behaviour was also explained by the aggregation mechanism [17]. Based on the previous studies, a methodology has been further proposed to predict the effective thermal conductivity of nanofluids considering the effect of the rheological property because it reflects the information of the microstructures of nanoparticles in the suspensions. Our previous thermal conductivity data of ZnO–EG nanofluids [18] fit the aggregation mechanism proposed by Chen et al. [17] quite well.

Figure 2 shows the enhanced ratio of thermal conductivity as a function of the settlement time after nanofluid preparation. It is found that the conductivity decreases with elapsed time in the first 6 h and the decreased value is less than 3.0%. When the settlement time is over 6 h, it will reach a constant value of about 40.0%. The tendency of the settlement time dependence of the thermal conductivity enhancements has also been observed in water-based Cu nanofluids [19] and Fe nanofluids [20]. Previous literature proposed that the decrease was probably due to the appreciable particle agglomeration. When nanoparticles get agglomerated, the ratio of the effective area to the volume decreases. The effective area reduction of the thermal interaction of particles causes a decrease in the thermal conductivity of the fluid. Kim et al. [21] found that the thermal conductivity decreased rapidly for nanofluids without surfactants after preparation.

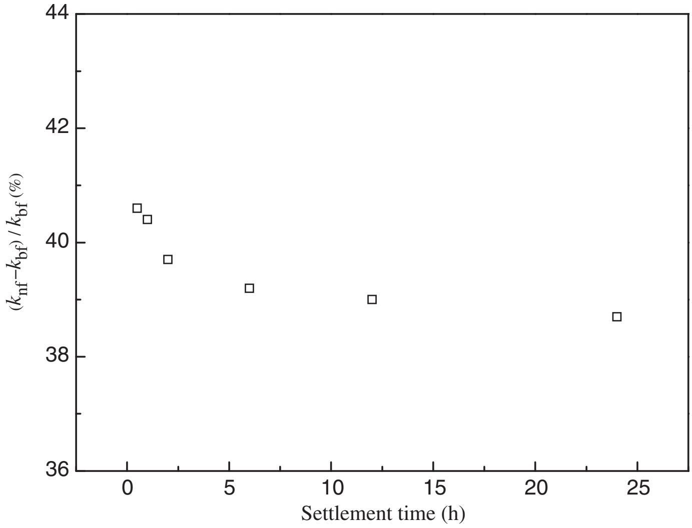


Figure 2. Influence of settlement time on the enhancement ratios of thermal conductivity.



But no obvious changes in the thermal conductivity of the nanofluids with sodium dodecyl sulphate (SDS) as surfactant were observed even after 5 h of settlement. It is clear that the thermal conductivity reflects the stability of the nanofluid to some extent. For the MgO–EG nanofluids, the decrease in the enhancement of thermal conductivity with 24 h is less than 5.0%, indicating the stability of the nanofluids.

Although some groups have reported studies of the thermal conductivity enhancement at elevated temperatures, there are relatively fewer effective data to reach a unanimous conclusion about the influence of temperature on the thermal conductivity. In this article, the effect of temperature on the enhancement of the effective thermal conductivity of nanofluids was investigated by measuring the thermal conductivity of nanofluids for different temperatures with 5.0 vol.% ranging from 10°C to 60°C. The results shown in Figure 3 indicate that the thermal conductivities increase with the increasing temperature, while the enhanced ratios are almost constant. It is clear that the thermal conductivities of the nanofluids track the thermal conductivities of the base liquid, which is similar to the conclusion of Timofeeva et al. [16], while several groups have reported the contrary conclusions [22]. The discrepancy demonstrates that many factors may affect the measured thermal conductivity.

Viscosity is related to molecular momentum transport. It is desirable to determine the viscosity of a nanofluid to evaluate its profit in practical applications. There are some debates about whether nanofluids are Newtonian or non-Newtonian fluids [23]. The analysis of Kabelac and Kuhnke [23] showed that the viscosities of $Al_2O_3$ nanoparticle suspensions decrease with the shear rates. On the contrary, Prasher et al.'s [24] results demonstrated that the viscosities of nanofluids of $Al_2O_3$–propylene glycol are independent of shear rates, indicating that nanofluids are Newtonian fluids in nature. In order to investigate the rheological behaviour, whether MgO–EG nanofluid is Newtonian or

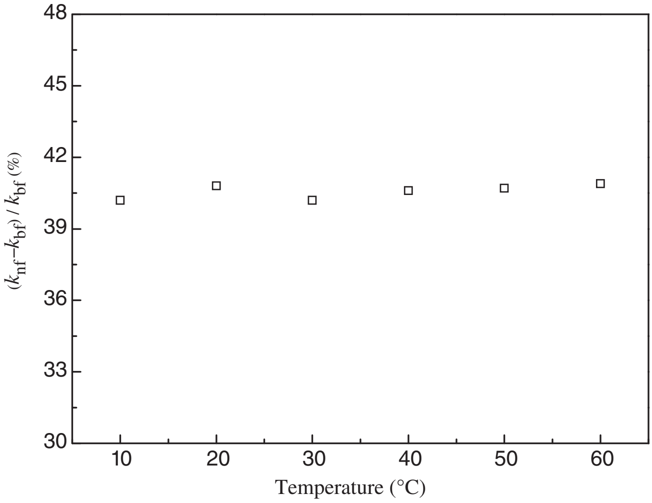


Figure 3. Thermal conductivity enhancement of MgO nanofluids with 5.0 vol.% as a function of temperature.

non-Newtonian fluid should be verified first. The equation governing the Newtonian behaviour of a fluid is given as follows:

$$\tau = \mu\gamma, \tag{1}$$

where $\tau$ is the shear stress, $\mu$ the coefficient of viscosity and $\gamma$ the shear strain rate. The shear stress versus shear rate for 5.0 vol.% MgO nanofluid at 30°C is shown in Figure 4. The linear relation between the shear stress and the shear rate indicates that MgO–EG nanofluids demonstrate Newtonian behaviour.

Figure 5 shows the viscosity of nanofluids with different particle loadings as a function of temperature. With the increase of temperature, the viscosity of nanofluids decreases rapidly. The reason of viscosity decrease with temperature is the weakening effect on the inner-particle/inter-molecular forces [25]. The viscosities of nanofluids considerably increase with particle volume fraction. The effect of the particle fraction is linked to the fact that increasing concentration would have a direct influence on the internal viscous shear stresses [25].

Generally, the viscosities of nanofluids are abnormally increased compared to the corresponding values of the base fluid. Higher concentration leads to higher viscosity of a nanofluid. Figure 6 illustrates the relationship between the relative viscosity enhancement and the volume fraction. When the particle volume fraction of MgO–EG is 0.01, 0.03 and 0.05, the relative viscosity enhancement is 3.5%, 15.1% and 29.2%, respectively. There is a nonlinear relationship between the relative viscosity enhancement and the particle volume fraction. This may be due to the cluster forming of the nanoparticles when the concentration is higher.

There exist several theoretical models that can be used to estimate the viscosity of the particle suspensions. Almost all such models have been derived from the pioneering work

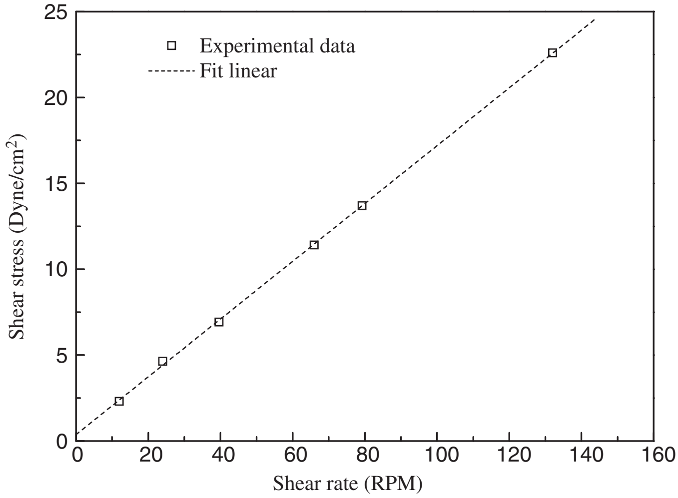


Figure 4. Shear stress versus shear rate for 5.0 vol.% MgO at 30°C.



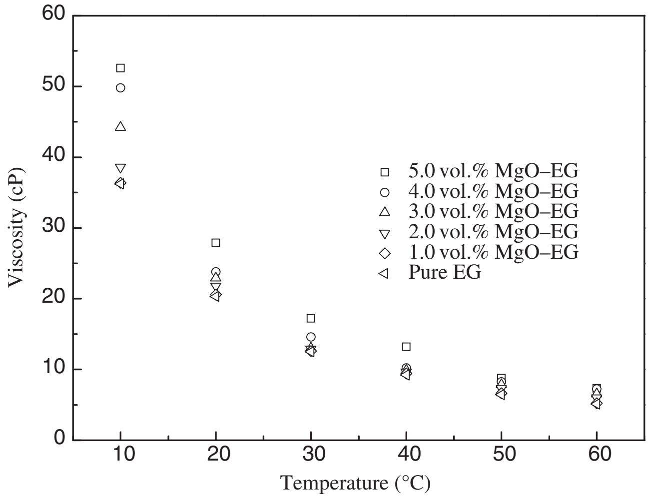


Figure 5. Viscosity of MgO nanofluids as a function of temperature.

of Einstein [26], which is based on the assumption of a linearly viscous fluid containing dilute, suspended and spherical particles. The expression is as follows:

$$\mu_r = \frac{\mu_{\text{nf}}}{\mu_{\text{bf}}} = 1 + 2.5\varphi, \tag{2}$$

where $\varphi$ and $\mu$ are particle volume fraction and fluid dynamic viscosity, respectively. The subscripts bf, nf and $r$ refer, respectively, to the base fluid, the nanofluid and the ratio

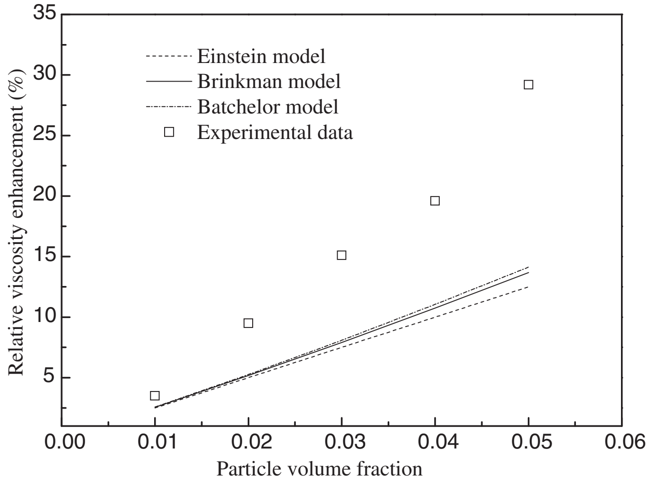


Figure 6. Relative viscosity enhancement of nanofluids with particle volume fraction.



of a nanofluid to the base fluid. Equation (2) was found valid for a very low particle volume fraction ($\varphi < 0.02$). Corrections are needed for those suspensions with higher particle loadings. Brinkman [27] extended Equation (2) to a moderate particle volume concentration ($\varphi < 0.04$) using the following expression:

$$\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} = \frac{1}{(1-\varphi)^{2.5}}. \tag{3}$$

Batchelor [28] further considered the effect due to the Brownian motion of particles for an isotropic suspension of rigid and spherical particles. The following expression was obtained:

$$\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} = 1 + 2.5\varphi + 6.5\varphi^2. \tag{4}$$

The comparison of the experimental data with the predicted values calculated from Equations (2)–(4) is presented in Figure 6. It is observed that the measured viscosities of nanofluids are underpredicted by these expressions. Particle addition is taken into account for the above-mentioned models. However, cluster forming readily takes place when nanoparticles are dispersed in fluids. The characteristic of the particle surface, ionic strength of the base fluid, inter-particle potentials such as repulsive (electric double layer) and attractive (van der Waals) forces may also play a significant role in the viscosity enhancement of the nanofluids [22]. Such enhancement may diminish the benefits of nanofluids. It is imperative to conduct more comprehensive studies on the viscosity of nanofluids.

## 4. Conclusions

Five kinds of EG-based nanofluids containing oxide nanoparticles were prepared, and their transport properties including thermal conductivity and viscosity were investigated.

Among all these studied nanofluids, MgO–EG nanofluid was demonstrated to have superior features with the highest thermal conductivity and lowest viscosity. For MgO–EG nanofluids, their thermal conductivity enhancement increases nonlinearly with the nanoparticle addition. The enhanced value of 40.6% was obtained when the volume fraction of MgO nanoparticles is 0.05. Although the effective thermal conductivity of a nanofluid increases with the temperature, the enhanced ratios are almost kept constant. It is indicated that the thermal conductivities of the nanofluids track the thermal conductivities of the corresponding base fluid. The thermal conductivity and viscosity increments are well beyond the existing classical models for the solid–liquid mixture. This is probably because these models only take particle volume fraction into account and ignore other facts, such as the characteristic of the particle surface, ionic strength of the base fluid and inter-particle potentials.

## Acknowledgements

This work was supported by the Innovation Program of Shanghai Municipal Education Commission (10YZ199), Shanghai Educational Development Foundation and Shanghai Municipal Education Commission (07SG56 and 08CG64) and the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning.



## References

[1] J.A. Eastman, S.U.S. Choi, S. Li, and L.J. Thompson, *Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles*, Appl. Phys. Lett. 78 (2001), pp. 718–720.

[2] N.N.V. Sastry, A. Bhunia, T. Sundararajan, and S.K. Das, *Predicting the effective thermal conductivity of carbon nanotube-based nanofluids*, Nanotechnology 19 (2008), 055704 (8 pp.).

[3] S. Krishnamurthy, P. Bhattacharya, P.E. Phelan, and R.S. Prasher, *Enhanced mass transport in nanofluids*, Nano Lett. 6 (2006), pp. 419–423.

[4] S.P. Jang and S.U.S. Choi, *Role of Brownian motion in the enhanced thermal conductivity of nanofluids*, Appl. Phys. Lett. 84 (2004), pp. 4316–4318.

[5] X.Q. Wang and A.S. Mujumdar, *Heat transfer characteristics of nanofluids: A review*, Int. J. Therm. Sci. 46 (2007), pp. 1–19.

[6] X.Q. Wang and A.S. Mujumdar, *A review on nanofluids. Part II: Experiments and applications*, Braz. J. Chem. Eng. 25 (2008), pp. 631–648.

[7] H.T. Zhu, C.Y. Zhang, Y.M. Tang, and J.X. Wang, *Novel synthesis and thermal conductivity of CuO nanofluid*, J. Phys. Chem. C 111 (2007), pp. 1646–1650.

[8] H.T. Zhu, C.Y. Zhang, S.Q. Liu, and Y.M. Tang, *Effects of nanoparticle clustering and alignment on thermal conductivities of $Fe_3O_4$ aqueous nanofluids*, Appl. Phys. Lett. 89 (2006), 023123 (3 pp.).

[9] Z.S. Chen, X.S. Ge, and Q.Q. Gu, *Calorimetry Technology and Thermophysical Properties Determination*, University of Science and Technology of China Press, Hefei, China, 1990, pp. 156–157.

[10] H.Q. Xie, H. Gu, M. Fujii, and X. Zhang, *Short hot wire technique for measuring thermal conductivity and thermal diffusivity of various materials*, Meas. Sci. Technol. 17 (2006), pp. 208–214.

[11] M.S. Liu, M.C.C. Lin, I.T. Huang, and C.C Wang, *Enhancement of thermal conductivity with (CuO) for nanofluids*, Chem. Eng. Technol. 29 (2006), pp. 72–77.

[12] N.R. Karthikeyan, J. Philip, and B. Raj, *Effect of clustering on the thermal conductivity of nanofluids*, Mater. Chem. Phys. 109 (2008), pp. 50–55.
[13] J.C. Maxwell, *A Treatise on Electricity and Magnetism*, Oxford University Press, Oxford, 1904, pp. 435–441.
[14] R.L. Hamilton and O.K. Crosser, *Thermal conductivity of heterogeneous two-component system*, Ind. Eng. Chem. Fundam. 1 (1962), pp. 187–191.
[15] R. Prasher, P.E. Phelan, and P. Bhattacharya, *Effect of aggregation kinetics on the thermal conductivity of nanoscale colloidal solutions (Nanofluid)*, Nano Lett. 6 (2006), pp. 1529–1534.
[16] E.V. Timofeeva, A.N. Gavrilow, J.M. Mccloskey, Y.V. Tolmachev, S. Sprunt, L.M. Lopatina, and J.V. Selinger, *Thermal conductivity and particle agglomeration in alumina nanofluids: Experiment and theory*, Phys. Rev. E 76 (2007), 061203 (16 pp.).
[17] H.S. Chen, Y.L. Ding, Y.R. He, and C.Q. Tan, *Rheological behaviour of ethylene glycol based titania nanofluids*, Chem. Phys. Lett. 444 (2007), pp. 333–337.
[18] W. Yu, H.Q. Xie, Y. Li, and L.F. Chen, *Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid*, Thermochim. Acta 491 (2009), pp. 92–96.
[19] M.S. Liu, M.C.C. Lin, C.Y. Tsai, and C.C. Wang, *Enhancement of thermal conductivity with (Cu) for nanofluids using chemical reduction method*, Int. J. Heat Mass Transf. 49 (2006), pp. 3028–3033.
[20] K.S. Hong, T.K. Hong, and H.S. Yang, *Thermal conductivity of (Fe) nanofluids depending on the cluster size of nanoparticles*, Appl. Phys. Lett. 88 (2006), 031901 (3 pp.).
[21] S.H. Kim, S.R. Choi, and D.S. Kim, *Thermal conductivity of metal-oxide nanofluids: Particle size dependence and effect of laser irradiation*, ASME, J. Heat Transf. 129 (2007), pp. 298–307.
[22] S.M.S. Murshed, K.C. Leong, and C. Yang, *Investigations of thermal conductivity and viscosity of nanofluids*, Int. J. Therm. Sci. 47 (2008), pp. 560–568.
[23] S. Kabelac and J.F. Kuhnke, *Heat transfer mechanisms in nanofluids – experimental and theory*. Proceedings of the 13th International Heat Transfer Conference, Begell House, 2006, KN-11 (32 pp.).
[24] R. Prasher, P. Bhattacharya, and P.E. Phelan, *Thermal conductivity of nanoscale colloidal solutions (nanofluids)*, Phys. Rev. Lett. 94 (2005), 025901 (4 pp.).
[25] C.T. Nguyen, F. Desgranges, N. Galanis, G. Roy, T. Mare, S. Boucher, and H.A. Mnsta, *Viscosity data for ($Al_2O_3$)-water nanofluid-hysteresis: Is heat transfer enhancement using nanofluids reliable?*, Int. J. Therm. Sci. 47 (2008), pp. 103–111.
[26] A. Einstein, *Eine neue Bestimmug der Molekuldimensionen*, Annalen Der Physik. 19 (1906), pp. 289–306.
[27] H.C. Brinkman, *The viscosity of concentrated suspensions and solution*, J. Chem. Phys. 20 (1952), pp. 571–572.
[28] G.K. Batchelor, *The effect of Brownian motion on the bulk stress in a suspension of spherical particles*, J. Fluid Mech. 83 (1977), pp. 97–111.
[29] S. Lee, S.U.S. Choi, S. Li, and J.A. Eastman, *Measuring thermal conductivity of fluids containing oxide nanoparticles*, J. Heat Transfer 121 (1999), pp. 280–289.
[30] X. Wang, X. Xu, and S.U.S. Choi, *Thermal conductivity of nanoparticle – fluid mixture*, J. Thermophys. Heat Transfer 13 (1999), pp. 474–480.
[31] H.Q. Xie, J. Wang, T. Xi, and F. Ai, *Thermal conductivity enhancement of suspension containing nanosized alumina particles*, J. Appl. Phys. 91 (2002), pp. 4568–4572.
[32] H.Q. Xie, J. Wang, T. Xi, and Y. Liu, *Thermal conductivity of suspension containing nanosized SiC particles*, Int. J. Thermophys. 23 (2002), pp. 571–580.