Viscosity Measurements on Colloidal Dispersions (Nanofluids) for Heat Transfer Applications

David C. Venerus[1*], Jacopo Buongiorno[2], Rebecca Christianson[3], Jessica Townsend[3], In Cheol Bang[4,5], Gang Chen[2], Sung Jae Chung[16], Minking Chyu[16], Haisheng Chen[6], Yulong Ding[6], Frank Dubois[7], Grzegorz Dzido[8], Denis Funfschilling[9], Quentin Galand[7], Jinwei Gao[2], Haiping Hong[10], Mark Horton[10], Linwen Hu[2], Carlo S. Iorio[7], Andrzej B. Jarzebski[8], Yiran Jiang[1], Stephan Kabelac[11], Mark A Kedzierski[12], Chongyoup Kim[13], Ji-Hyun Kim[4], Sukwon Kim[13], Thomas McKrell[2], Rui Ni[9], John Philip[14], Naveen Prabhat[2], Pengxiang Song[15], Stefan Van Vaerenbergh[7], Dongsheng Wen[15], Sanjeeva Witharana[6], Xiao-Zheng Zhao[9], Sheng-Qi Zhou[9]

[1] Illinois Institute of Technology, 10 W. 33rd St., Chicago, IL 60616, USA
[2] Massachusetts Institute of Technology (MIT), 77 Massachusetts Avenue, Cambridge, MA 02139, USA
[3] Olin College of Engineering, Olin Way, Needham, MA 02492, USA
[4] Ulsan National Institute of Science and Technology, School of Energy Engineering, San 194 Banyeon-ri, Eonyang-eup, Ulju-gun, Ulsan Metropolitan City, Republic of Korea
[5] Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
[6] University of Leeds, Clarendon Road, Leeds LS2 9JT, UK
[7] Université Libre de Bruxelles, Chimie-Physique E.P. CP 165/62 Avenue P.Heger, 1050, Bruxelles, Belgium
[8] Silesian University of Technology, Department of Chemical and Processing Engineering, ul. M. Strzody 7, 44-100 Gliwice, Poland
[9] Chinese University of Hong Kong, Department of Physics, G6, North Block, Science Center, Shatin NT, Hong Kong, China
[10] South Dakota School of Mines and Technology, 501 E Saint Joseph Street, Rapid City, SD 57702, USA
[11] Helmut-Schmidt University Hamburg, Institute for Thermodynamics, 22039, Hamburg, Germany
[12] National Institute of Standards and Technology (NIST), MS 863, Gaithersburg, MD 20899, USA
[13] Korea University, Anam-dong, Sungbuk-ku, Seoul 136-713, Republic of Korea
[14] Indira Gandhi Centre for Atomic Research, SMARTS, NDED, Metallurgy and Materials Group, Kalpakkam-603102, India
[15] Queen Mary University of London, School of Engineering and Materials Science, Mile End Road, London, E1 4NS, UK
[16] University of Pittsburgh, Dept. Mechanical Engineering and Materials Science, 648 Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261, USA

* Email: venerus@iit.edu
Fax: x1.312.567.8874

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Abstract:
This article reports viscosity data on a series of colloidal dispersions collected as part of the International Nanofluid Property Benchmark Exercise (INPBE). Data are reported for seven different fluids that include dispersions of metal-oxide nanoparticles in water, and in synthetic oil. These fluids, which are also referred to as 'nanofluids,' are currently being researched for their potential to function as heat transfer fluids. In a recently published paper from the INPBE study, thermal conductivity data from more than 30 laboratories around the world were reported and analyzed. Here, we examine the influence of particle shape and concentration on the viscosity of these same nanofluids and compare data to predictions from classical theories on suspension rheology.

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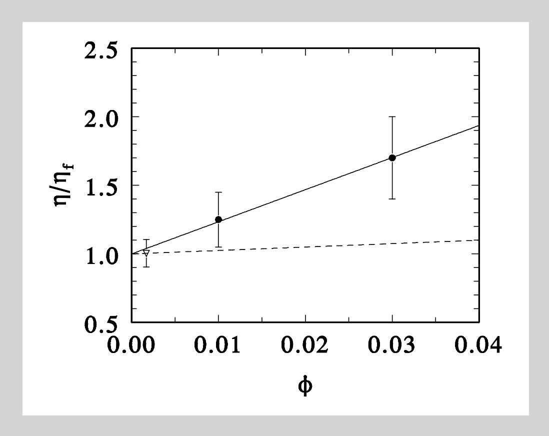

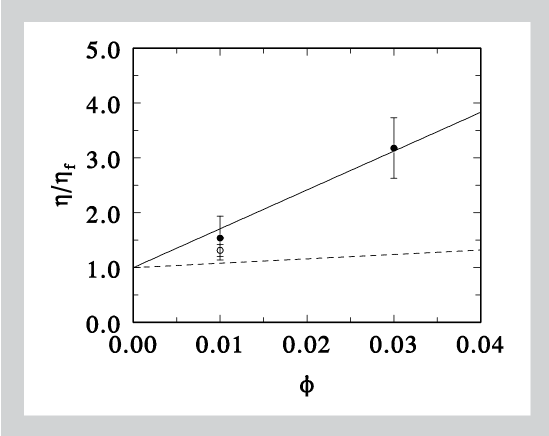

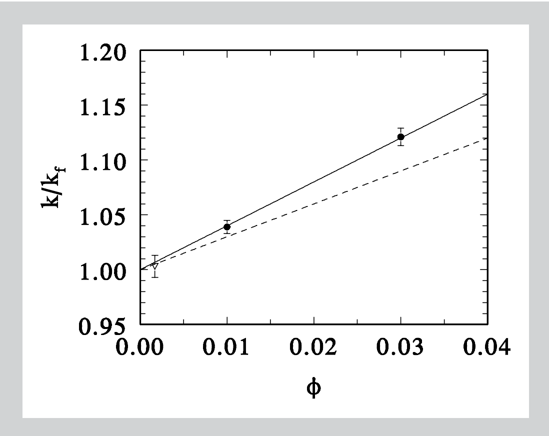

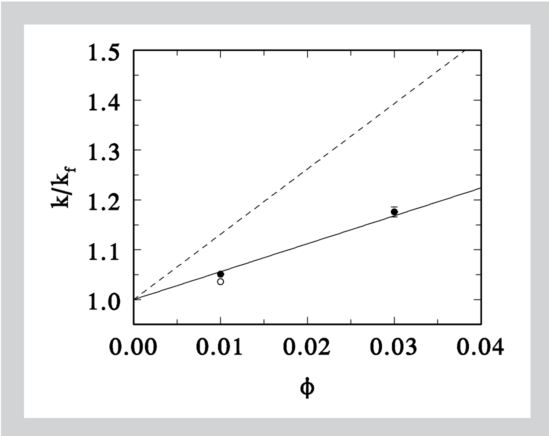

Figure 5 (left above): Relative viscosity η/η_f versus particle concentration ϕ for nanofluids with spherical particles: filled circles for Al_2O_3 particles in oil (S1S3 and S1S4) and open triangle for $Mn_{1/2}Zn_{1/2}Fe_2O_3$ in water (S4S1). Lines indicate $\eta/\eta_f = 1 + [\eta]\phi$ with prediction $[\eta] = 5/2$ (dashed) and fit $[\eta] = 23.4$ (solid).

Figure 6 (right above): Relative viscosity η/η_f versus particle concentration ϕ for nanofluids with rod-shaped particles: filled circles for Al_2O_3 particles in oil (S1S5 and S1S6) and open circle for Al_2O_3 in water (S1S1). Lines indicate $\eta/\eta_f = 1 + [\eta]\phi$ with prediction $[\eta] = 8$ (dashed) and fit $[\eta] = 70.8$ (solid).

Figure 7 (left below): Relative thermal conductivity k/k_f versus particle concentration ϕ for nanofluids with spherical particles: filled circles for Al_2O_3 particles in oil (S1S3 and S1S4) and open triangle for $Mn_{1/2}Zn_{1/2}Fe_2O_3$ in water (S4S1). Data taken from INPBE study [16]. Lines indicate $k/k_f = 1 + [k]\phi$ with prediction $[k] = 3$ (dashed) and fit $[k] = 4.0$ (solid).

Figure 8 (right below): Relative thermal conductivity k/k_f versus particle concentration ϕ for nanofluids with rod-shaped particles: filled circles for Al_2O_3 particles in oil (S1S5 and S1S6) and open circle for Al_2O_3 in water (S1S1). Data taken from INPBE study [16]. Lines indicate $k/kf = 1 + [k]\phi$ with prediction $[k] = 13.1$ (dashed) and fit $[k] = 5.6$ (solid).

$[\eta] = 23.4$ for the spherical particles and $[\eta] = 70.8$ for the rod-shaped particles. The shear thinning behavior observed in alumina nanorod suspensions can also be due to shear induced reorganization of nanorods under confined geometry where the packing can become more efficient. A similar result has been reported in recently published data for nanofluids with spherical particles [8–13], although somewhat lower values of $[\eta]$ = 4–16 were found. A possible explanation for these pronounced differences between theory and experiment is particle agglomeration, which would increase the effective volume fraction of the particles [10–14]. Indeed, light scattering results on these fluids reported elsewhere [16] are consistent with the occurrence of particle agglomeration.

For comparison, we show the relative thermal conductivity versus particle concentration data from the INPBE study [16] in Figures 7 and 8. As with the viscosity data, nanofluids with both spherical and rod-shaped particles show a linear dependence of k/k_f on ϕ. The data for the fluids with spherical particles in Figure 7 show a slightly stronger dependence on particle concentration than predicted: measured $[k] = 4.0$, and predicted $[k] = 3$. This observation is consistent with the presence of particle agglomeration in these systems, and suggests that particle clustering has a larger effect on viscosity than thermal conductivity in nanofluids with spherical particles. The situation is different for the nanofluids with rod-shaped particles as shown in Figure 8. Here, the observed dependence on particle concentration is weaker than predicted: measured $[k] = 5.6$, and predicted $[k] = 13.1$. Apparently, particle agglomeration can significantly reduce the effective thermal conductivity of nanofluids with rod-shaped particles. A second explanation for the reduction in effective thermal conductivity in these nanofluids is interfacial thermal resistance [16].

4 CONCLUSIONS

Viscosity data have been collected as part of an International Nanofluid Property Benchmark Exercise (INPBE). These data are from approximately 10 different laboratories around the world on a series of 10 different nanofluids and their base fluids. In general, the agreement between different laboratories was good with variations of approximately ± 20%, which, in part, could be explained by lab-to-lab temperature variations. Two of seven nanofluids showed shear-thinning behavior; the remaining five showed Newtonian behavior. For nanofluids with both spherical and rod-shaped nanoparticles, the dependence of viscosity (relative to the base fluid viscosity) on particle concentration (volume fraction) was significantly stronger than predicted by dilute suspension theory. This discrepancy was attributed to particle agglomera-

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Map:
Map showing locations of laboratories participating in the International Nanofluid Properties Benchmark Exercise (INPBE).

tion. In contrast, the observed enhancement in thermal conductivity was slightly larger for the spherical particle fluids, and significantly lower for the rod-shaped particle fluids, than predicted by effective medium theory. As noted in the introduction, criteria for the overall effectiveness of nanofluids as heat transfer fluids have been proposed [9, 12], which suggest $[\eta]$ should be 4 - 5 times smaller than $[k]$. Clearly, the nanofluids considered in this study would fail; this suggests that the overall effect of adding nanoparticles to the base fluid is negative in terms of heat transfer performance.

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