International Journal of Heat and Fluid Flow 31 (2010) 246–247

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Letter to the Editor

The international nanofluid property benchmark exercise

Dear Editors,

Since late 2007 we have been leading the International Nanofluid Property Benchmark Exercise, or INPBE, an initiative aimed at eliminating the many inconsistencies in the thermal conductivity database of colloidal suspensions of nanoparticles, also known as 'nanofluids'. Briefly, as dispersions of solid particles in a continuous liquid matrix, nanofluids are expected to have a thermal conductivity that obeys the effective medium theory developed by Maxwell over 100 years ago (Maxwell, 1881). However, data suggesting significant thermal conductivity enhancement beyond Maxwell's prediction have been reported in the literature (Li et al., 2000, 2007; Eastman et al., 2001; Kang and Kim, 2006; Hong, 2005, 2006; Jana et al., 2007; Chopkar, 2006; Shaikh et al., 2007; Xie, 2002a, 2002b; Murshed, 2005; Chon et al., 1531; Kim et al., 2007; Chen, 2008; Shima et al., 2009; Das et al., 2003; Wen et al., 2004; Li and Peterson, 2006), along with proposals of various enhancement mechanisms (micromixing, ordered layering, percolation) to explain such anomalous data (Kumar, 2004; Jang et al., 2004; Prasher, 2005; Patel, 2005; Patel et al., 2008; Keblinski et al., 2002; Wang, 2665; Foygel, 2005; Prasher et al., 2006; Eapen et al., 2007a, 2007b; Philip et al., 2008; Yu and Choi, 2003). Both data and mechanisms have been openly questioned (Shima et al., 2009; Eapen et al., 2007b). In summary, the possibility of very large thermal conductivity enhancement in nanofluids beyond Maxwell's prediction is a hotly debated topic. At the first scientific conference centered on nanofluids (*Nanofluids: Fundamentals and Applications*, September 16–20, 2007, Copper Mountain, Colorado), it was decided to launch INPBE, to resolve the inconsistencies in the database and help advance the debate on nanofluid properties. INPBE was supported by a grant from the National Science Foundation, and involved 34 organizations from the US, Belgium, China, France, Germany, India, Italy, Japan, Poland, Puerto Rico, Singapore, South Korea, Switzerland and the UK participated in the exercise. A complete description of the exercise and its thermal conductivity results have been published in an article recently appeared in the *J Applied Physics* (Vol. 106, 094312, 2009). Viscosity data on the same series of samples collected by 10 INPBE participants will be published in *Applied Rheology*. However, given the general interest in nanofluids and the controversy surrounding their thermal conductivity, we believe the following brief summary may be of interest to the readership of *Int. J. Heat Fluid Flow*, and aid the preparation of future research studies.

The exercise's main objective was to compare thermal conductivity data obtained by different organizations for the same samples. Four sets of test nanofluids were procured (see Table 1). To strengthen the generality of the INPBE results, we selected test nanofluids with a broad diversity of parameters, i.e., aqueous and non-aqueous basefluids, metallic and oxidic particles, near-spherical and elongated particles, and high and low particle loadings. Also, given the large number of participating organizations, the test nanofluids had to be available in large quantities (>2 L) and at reasonably low cost.

To minimize spurious effects due to nanofluid preparation and handling, all participating organizations were given identical samples, and were asked to adhere to the same sample handling protocol. The exercise was 'semi-blind', as only minimal information about the samples was given to the participants at the time of sample shipment. The minimum requirement to participate in the exercise was to measure and report the thermal conductivity of at least one test nanofluid at room temperature. Thermal conductivity was measured by the participating organizations using a variety of experimental approaches, including the transient hot wire method, steady-state methods and optical methods. However, participants could also measure (at their discretion) other nanofluid properties, including (but not necessarily limited to) viscosity, density, specific heat, particle size and concentration. The data were then reported in a standardized form to the exercise coordinator at the Massachusetts Institute of Technology (MIT) and posted, unedited, at the INPBE website (http://mit.edu/nse/nanofluids/benchmark/index.html).

The data analysis revealed that the data from most organizations lied within a relatively narrow band about the ensemble average, with only few outliers. Specifically, for all water-based samples tested, the data from most organizations deviated from the sample average by ±5% or less. For all PAO-based samples tested, the data from most organizations deviated from the sample average by ±10% or less.

The thermal conductivity enhancement afforded by the tested nanofluids increased with increasing particle loading, particle aspect ratio and decreasing basefluid thermal conductivity, as expected from Maxwell's effective medium theory (Maxwell, 1881) and its generalization by Nan et al. (1997). Also, Nan et al.'s theory was found to accurately reproduce the INPBE experimental data (see Fig. 1), thus suggesting that no anomalous enhancement of thermal conductivity was observed in the nanofluids tested in INPBE. As such, resorting to the other theories proposed in the literature (e.g., Brownian motion, liquid layering, aggregation) was not necessary for the interpretation of the INPBE database. It should be noted, however, that the ranges of parameters explored in INPBE, while broad, are not exhaustive. For example, only one nanofluid with metallic nanoparticles was tested, and only at very low concentration.

This study also showed that the choice of measurement technique can affect the measured value of thermal conductivity, but if the enhancement is the parameter of interest, the measurement technique is less important. Therefore, to ensure accurate determinations of nanofluid thermal conductivity enhancement using

doi:10.1016/j.ijheatfluidflow.2010.01.004

Table 1
INPBE nanofluid samples and summary of thermal conductivity data.

Sample #		Sample description[a,b]	Measured thermal conductivity[c] (W/m-K)	Measured thermal conductivity ratio[c] (k/kf)
Set 1	Sample 1	Alumina nanorods (80 × 10 nm), 1% vol. in water	0.627 ± 0.013	1.036 ± 0.004
	Sample 2	De-ionized water	0.609 ± 0.003	N/a[d]
	Sample 3	Alumina nanoparticles (10 nm), 1% vol. in PAO + surfactant	0.162 ± 0.004	1.039 ± 0.003
	Sample 4	Alumina nanoparticles (10 nm), 3% vol. in PAO + surfactant	0.174 ± 0.005	1.121 ± 0.004
	Sample 5	Alumina nanorods (80 × 10 nm), 1% vol. in PAO + surfactant	0.164 ± 0.005	1.051 ± 0.003
	Sample 6	Alumina nanorods (80 × 10 nm), 3% vol. in PAO + surfactant	0.182 ± 0.006	1.176 ± 0.005
	Sample 7	PAO + surfactant	0.156 ± 0.005	N/a
Set 2	Sample 1	Gold nanoparticles (10 nm), 0.001% vol. in water + stabilizer	0.613 ± 0.005	1.007 ± 0.003
	Sample 2	Water + stabilizer	0.604 ± 0.003	N/a
Set 3	Sample 1	Silica nanoparticles (22 nm), 31% vol. in water + stabilizer	0.729 ± 0.007	1.204 ± 0.010
	Sample 2	De-ionized water	0.604 ± 0.002	N/a
Set 4	Sample 1	Mn–Zn ferrite nanoparticles (7 nm), 0.17% vol. in water + stabilizer	0.459 ± 0.005	1.003 ± 0.008
	Sample 2	Water + stabilizer	0.455 ± 0.005	N/a

[a] Nominal values for nanoparticle concentration and size.
[b] PAO = polyalphaolefins lubricant.
[c] Sample average and standard error of the mean.
[d] N/a = not applicable.

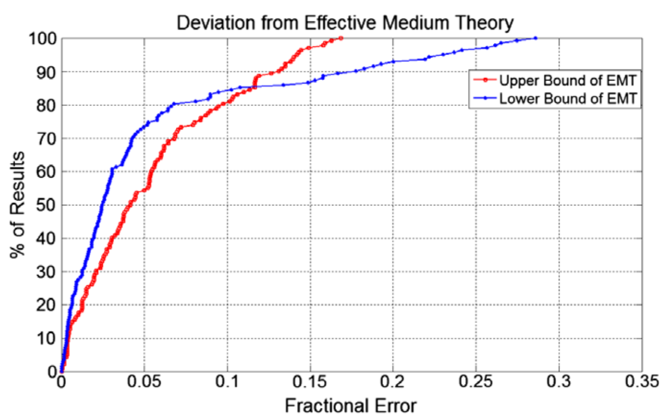

Fig. 1. Percentage of all INPBE experimental data that are predicted by Nan et al.'s theory within the error indicated on the *x*-axis. EMT: effective medium theory. Upper bound: zero interfacial thermal resistance. Lower bound: interfacial resistance equal to 10^{-8} m^2 K/W.

these techniques, it is important to measure both the basefluid and nanofluid thermal conductivity using the same technique and at the same temperature.

References

Chen, G., Yu, W.H., Singh, D., Cookson, D., Routbort, J., 2008. J. Nanoparticle Res. 10 (7), 1109–1114.
Chon, C.H., Kihm, K.D., Lee, S.P., Choi, S.U.S., 2005. Appl. Phys. Lett. 87, 153107.
Chopkar, M., Das, P.K., Manna, I., 2006. Scripta Mater. 55, 549–552.
Das, S.K. et al, 2003. J. Heat Transfer 125, 567–574.
Eapen, J., Li, J., Yip, S., 2007a. Phys. Rev. E 76, 062501.
Eapen, J., Li, J., Yip, S., 2007b. Phys. Rev. Lett. 98, 028302.
Eapen, J., Williams, W.C., Buongiorno, J., Hu, L.W., Yip, S., Rusconi, R., Piazza, R., 2007c. Phys. Rev. Lett. 99, 095901.
Eastman, J.A., Choi, S.U.S., Li, S., Yu, W., Thompson, L.J., 2001. Appl. Phys. Lett. 78 (6), 718–720.
Foygel, M., Morris, R.D., Anez, D., French, S., Sobolev, V.L., 2005. Phys. Rev. B 71, 104201.
Hong, T.-K., Yang, H., Choi, C.J., 2005. J. Appl. Phys. 97, 064311.
Hong, K.S., Hong, T.-K., Yang, H.-S., 2006. Appl. Phys. Lett. 88, 031901.
Jana, S., Salehi-Khojin, A., Zhong, W.H., 2007. Thermochim. Acta 462, 45–55.
Jang, S.P., Choi, S.U.S., 2004. Appl. Phys. Lett. 84, 4316.
Kang, H.U., Kim, S.H., Oh, J.M., 2006. Exp. Heat Transfer 19 (3), 181–191.
Keblinski, P., Phillpot, S.R., Choi, S.U.S., Eastman, J.A., 2002. Int. J. Heat Mass Transfer 45, 855–863.
Kim, S.H., Choi, S.R., Kim, D., 2007. J. Heat Transfer 129, 298–307.
Kumar, H.D., Patel, H.E., Rajeev, K.V.R., Sundararajan, T., Pradeep, T., Das, S.K., 2004. Phys. Rev. Lett. 93 (14), 144301.
Li, C.H., Peterson, G.P., 2006. J. Appl. Phys. 99, 084314.
Li, Q., Xuan, Y.M., 2000. In: Buxan, Wang (Ed.), Heat Transfer Science and Technology. Higher Education Press, pp. 757–762.
Li, C.H., Peterson, G.P., 2007. J. Appl. Phys. 101, 044312.
Maxwell, J.C., 1881. A Treatise on Electricity and Magnetism, second ed. Clarendon, Oxford.
Murshed, S.M.S., Leong, K.C., Yang, C., 2005. Int. J. Therm. Sci. 44, 367–373.
Nan, C.W., Birringer, R., Clarke, David R., Gleiter, H., 1997. J. Appl. Phys. 81 (10) (15 May).
Patel, H.E., Sundararajan, T., Pradeep, T., Dasgupta, A., Dasgupta, N., Das, S.K., 2005. Pramana–J. Phys. 65 (5), 863–869.
Patel, H.E., Sundararajan, T., Das, S.K., 2008. J. Nanoparticle Res. 10 (1), 87–97.
Philip, J., Shima, P.D., Baldev, R., 2008. Nanotechnology 19, 305706 (7pp).
Prasher, R., Bhattacharya, P., Phelan, P.E., 2005. Phys. Rev. Lett. 94, 025901.
Prasher, R., Evans, W., Meakin, P., Fish, J., Phelan, P., Keblinski, P., 2006. App. Phys. Lett. 89, 143119.
Shaikh, S., Lafdi, K., Ponnappan, R., 2007. J. Appl. Phys. 101, 064302.
Shima, P.D., Philip, J., Raj, B., 2009. Appl. Phys. Lett. 94, 1.
Wang, B.X., Zhou, L.P., Peng, X.F., 2003. Int. J. Heat Mass Transfer 46, 2665–2672.
Wen, D., Ding, Y., 2004. J. Thermophys. Heat Transfer 18, 481–485.
Xie, H., Wang, J., Xi, T., Ai, F., 2002a. J. Appl. Phys. 91, 4568–4572.
Xie, H., Wang, J., Xi, T., Liu, Y., 2002b. Int. J. Thermophys. 23, 571–580.
Yu, W., Choi, S.U.S., 2003. J. Nanoparticle Res. 5, 167.

Jacopo Buongiorno
Nuclear Science and Engineering, Massachusetts Institute of Technology, 77 Mass Ave, Cambridge, MA 02139, United States
E-mail address: jacopo@mit.edu

David Venerus
Chemical Engineering, Illinois Institute of Technology, 3300 South Federal Street, Chicago, IL 60616-3793, United States

Available online 7 February 2010