Quarterly Report #7

July 30, 2010

DEVELOPMENT, CHARACTERIZATION, PRODUCTION, AND DEMONSTRATION OF NANOFLUIDS FOR INDUSTRIAL COOLING APPLICATIONS

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Period of Project – 2.5 years

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PUMPING POWER MEASUREMENTS

Pumping power measurements have been made on a series of 40-nm boehmite (AlOOH) alumina "bricks" (2 – 8 vol. percent in water. The alumina nanoparticles were obtained from Sasol and are designated as "Catapal-200". The pH of all compositions was adjusted to 3.2±0.5. A complete characterization of the particles and their nanofluid thermal properties has been published in Journal of Applied Physics **106**, 014304 (2009). While the nanofluid doesn't show large enhancements, it nevertheless serves as good comparisons between the experimental results and calculated results.

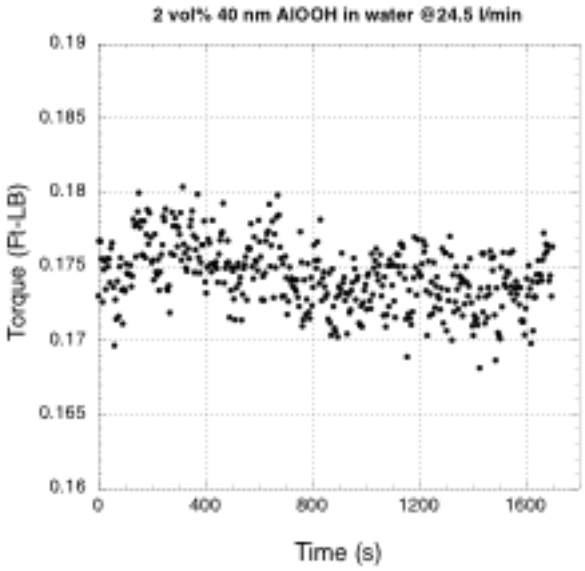

Figure 1. Torque data generated using new computerized system. Each point represents the average of 500 points.

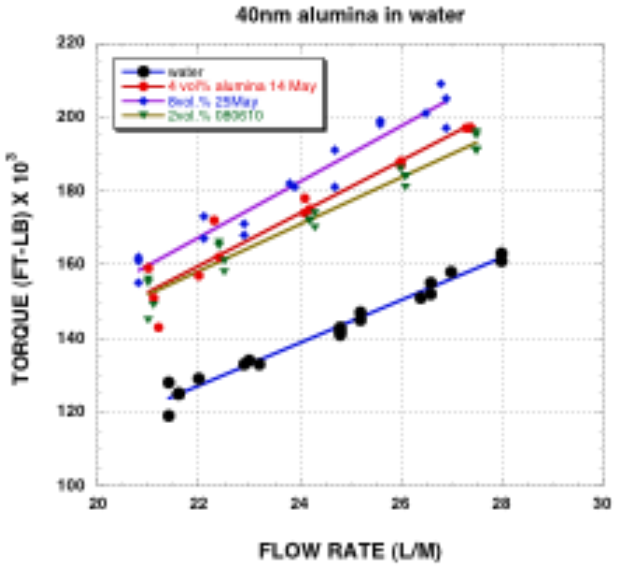

Figure 2. Measured Torque for 2, 4, and 8 volume percent alumina in water as a function of flow rate at 30 ± 2°C.

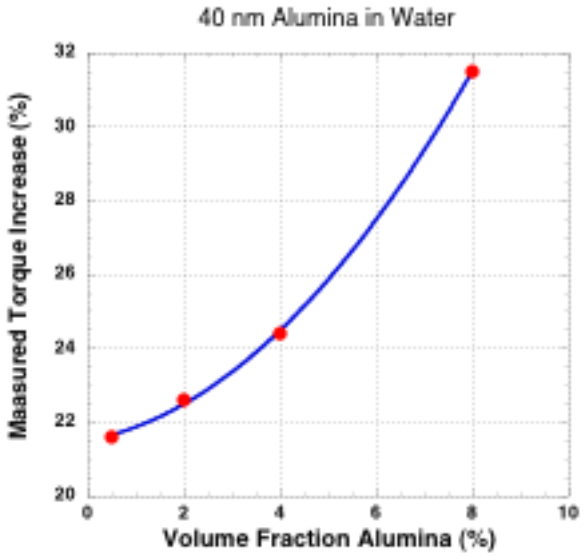

Figure 3. Measured torque vs. volume fraction of nanoparticles at flow rate of 25 l/min.

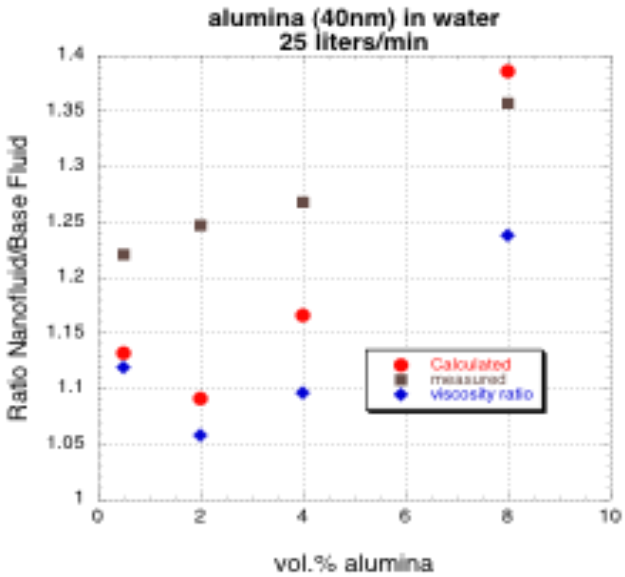

Figure 4. Measured and calculated torque ratios as well as viscosity ratio as a function of volume percent alumina.

The combined data for the 3 compositions compared to water is shown in Fig. 2. The torque is compared at a constant velocity rather than the more conventional comparison to a constant Reynolds number according to a recently published article in Applied Physics Letters **96**, 213109 (2010).

Fig. 3 presents the results of the measured torque increase of the alumina nanofluid compared to water. The line represents a polynominal of 2nd order with R=0.999. Fig. 4 shows that the trend of the torque ratio of the nanofluid to base fluid measured at 25 l/min flow follows the trend of the increasing viscosity. The large discrepancy between the calculated and measured ratios is the result of using a very simplistic model, i.e. flow at a constant velocity in a 1-meter long straight tube having a diameter of 2 cm. The calculated values will increase when we start simulating the actual apparatus.

We have demonstrated that the torque required to pump the nanofluid can be measured and it follows the trend of viscosity increase. The alumina nanofluid was only used to demonstrate the system and analysis. The poor thermal properties of the alumina-based nanofluid and the increased viscosity would preclude using it as a commercial coolant.

HEAT TRANSFER COMPARISON BASES

The criteria for comparing the fluid property-related heat transfer performance of a nanofluid to that of the base fluid under the bases of the constant Reynolds number, constant flow velocity, and constant friction-related pumping power have been developed for turbulent flow and are shown graphically in Figs. 5 and 6.

It is found that the essential factor separating the three comparison bases from each other is the flow velocity ratio mainly depending on the dynamic viscosity ratio. To clearly show the influence of the flow velocity ratio on the heat transfer coefficient ratio, these parameters are plotted in Fig. 5 for the three comparison bases as a function of the dynamic viscosity ratio for a SiC-50/50 ethylene glycol/water nanofluid with a particle volume concentration of 4%. It can be seen from Fig. 5 that, unlike the constant flow velocity comparison (Fig. 5 (b)) and the constant pumping power comparison (Fig. 5 (c)) where the flow velocity ratio is either equal to or close to unity, the flow velocity ratio for the constant Reynolds number comparison (Fig. 5 (a)) is generally greater than unity. In other words, the flow velocity for the nanofluid is generally greater than that for the base fluid with the constant Reynolds number comparison. Therefore, the net result for the constant Reynolds number comparison is a combination of the nanofluid property effect and the flow velocity effect. Since the flow velocity for the nanofluid is higher than that for the base fluid, the constant Reynolds number comparison gives the nanofluid an advantage over the base fluid. If the nanofluid is to be pumped at a higher velocity in order to maintain the same Reynolds number as the base fluid, so could the base fluid be pumped at that velocity to obtain a better heat transfer coefficient. In that case, the base fluid might approach or exceed the performance of the nanofluid, but this condition is not reflected in the constant Reynolds number comparison. As shown in Fig. 6 (a) for the constant Reynolds number comparison, at any value of thermal conductivity ratio, the heat transfer coefficient ratio increases as the dynamic viscosity ratio increases. This result is opposite to those from the constant flow velocity comparison and the constant pumping power comparison of Figs. 6 (b) and (c). It is in contradiction to common sense, and the reason is again rooted in the flow velocity effect. The constant Reynolds number comparison completely ignores the pumping power penalty associated with pumping the higher viscosity nanofluid at a higher flow velocity to reach the same Reynolds number as the base fluid. Therefore, the constant Reynolds number comparison (the most common used in the engineering literature for nanofluids) distorts the physical situation and therefore should not be used.

In contrast to the unrealistic figure of merit associated with the constant Reynolds number comparison, the figure of merit for constant pumping power comparison represents the most unambiguous. With this comparison principle, the heat transfer coefficient of a nanofluid is compared to that of the base fluid under the condition that the nanofluid and the base fluid use the same amount of pumping power. This comparison means that the flow velocity for the nanofluid is slightly lower than that for the base fluid, and gives the most conservative criterion for a beneficial nanofluid. Based on the physical mechanisms

behind these comparisons, the constant pumping power comparison should be used for comparing the heat transfer coefficient of a nanofluid with that of the base fluid.

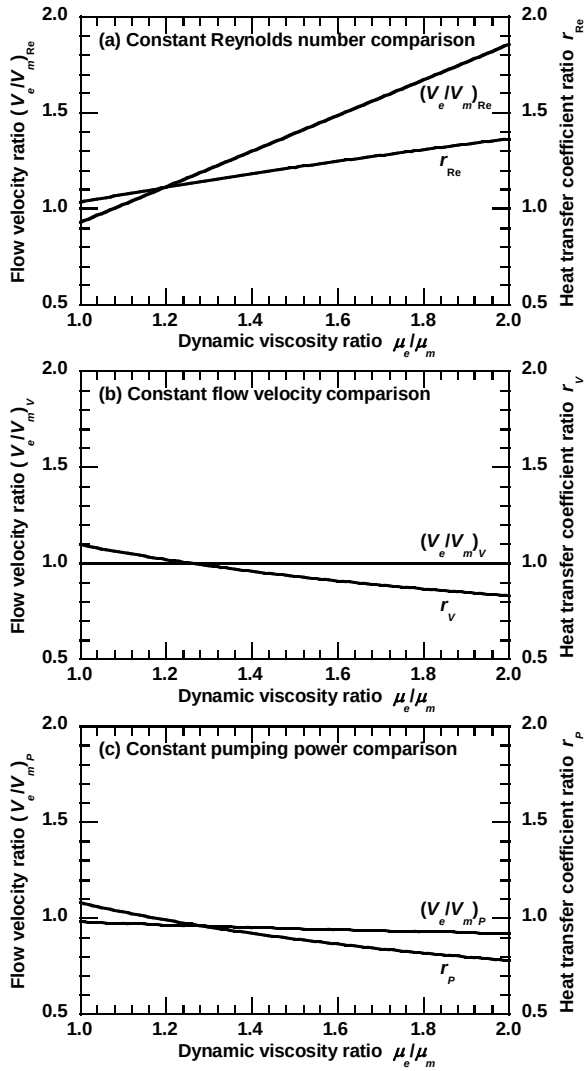

Figure 5. Flow velocity ratio and heat transfer coefficient ratio as a function of dynamic viscosity ratio.

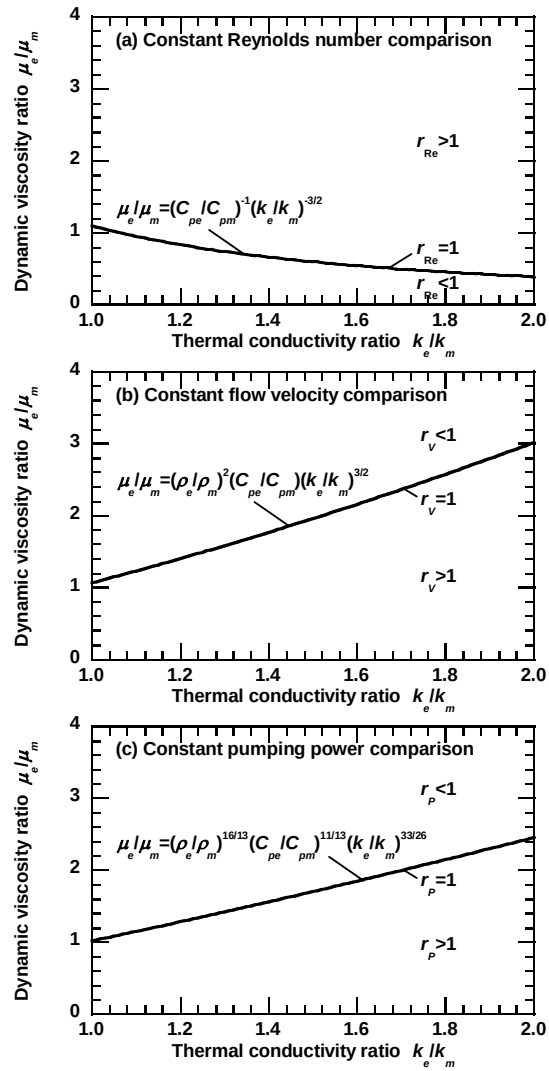

Figure 6. Criteria for a beneficial nanofluid.

The results for the constant flow velocity comparison of Fig. 6 (b) have a similar trend to that for the constant pumping power comparison of Fig. 6 (c), but the constant flow velocity comparison is less restrictive. The pumping power required for a nanofluid will be higher than that for the base fluid under the constant flow velocity comparison due to the increased density and dynamic viscosity of the nanofluid. However, the flow velocity ratio for the constant pumping power comparison is close to unity, and thus the curves of Figs. 6 (b) and (c) are very close in magnitude. Therefore, from a practical viewpoint, when the flow system under consideration is designed for a certain maximum flow rate and when the flow pumping power is only a small portion of the total power consumed, the constant flow velocity comparison provides a quite accurate picture of the effect of the nanofluid properties on the heat transfer performance compared to the base fluid.

HEAT TRANSFER EFFICIENCY OF SIC-EG/H_2O SUSPENSION COMPARED TO SIC-H_2O

Thermal conductivity and viscosity values of SiC-EG/H_2O compared to enhancements of SiC-H_2O nanofluids (measured by KD2Pro, Decagon Devices Inc.) for various particle sizes were presented in the previous report (#6). A series of forced convective heat transfer experiments were carried out for the same set of SiC-EG/H_2O nanofluids presented in the previous report.

We used the suggested merit criteria [5-6] to estimate the cooling efficiency of nanofluids from the experimentally measured properties. It should be noted here that the figures of merit represent a nanofluid as a single phase fluid and doesn't account for possible effects due to the presence of nanoscale particles. The Mouromtseff value (Mo) ratio [5] is used for turbulent flow while the ratio of viscosity and thermal conductivity enhancements (C_η and C_k respectively) is used as a criterion for laminar flow [6]. Since the viscosity is shown to depend on both the temperature and the average particle size, we, by using our dataset, reconstructed a 3D surface reflecting the projected efficiency of SiC-EG/H_2O nanofluids in regard to these two parameters and compared them to the experimental ratio of heat transfer coefficients (Fig. 7).

One can see that the property-based evaluation of the nanofluid efficiency is in an agreement with experimentally measured heat transfer coefficients: suspensions with average particle sizes 66 and 90 nm benefit the heat transfer while performance of suspensions with smaller particles (29 and 16 nm) is less effective than the base fluid. Experimentally measured heat transfer coefficients in most cases follow the same "particle size trend" as the property based merit criteria (Fig. 7). Only the suspensions with 90 nm particles show enhancements above the property based predictions. Both experimental heat transfer data and values calculated from the nanofluid properties show the increase in nanofluid efficiency with increasing temperature, which is most likely related to viscosity decrease in the nanofluids.

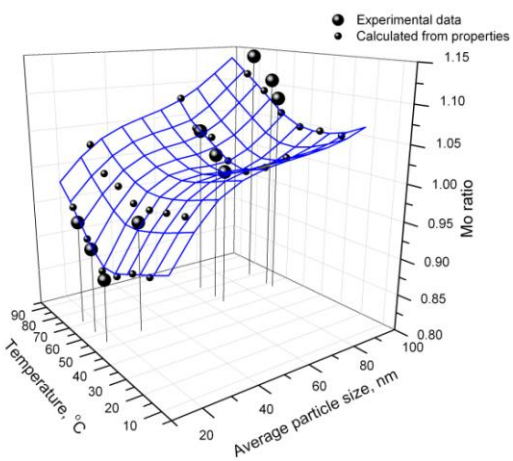

Figure 7. Reconstruction of Mo ratio surface from the experimental property data compared to the ratio of experimentally measured heat transfer coefficients.

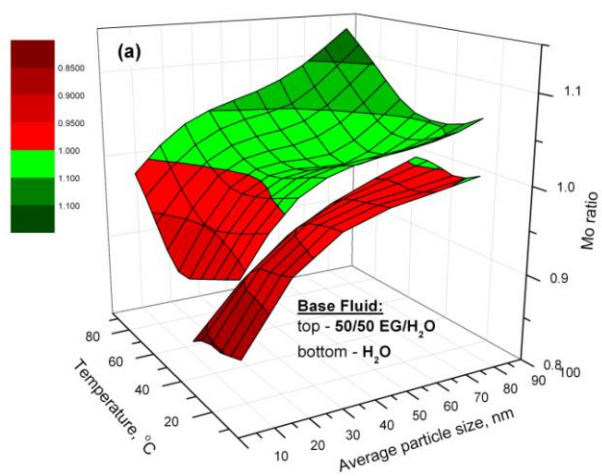

Figure 8a. Property based evaluation of efficiency of 4 vol% SiC fluids in EG/H_2O in comparison to analogous fluids in H_2O for turbulent flow regime at various particle sizes and pH of 9.5±0.3. Red – less efficient than base fluid, green – enhancement in efficiency.

Property-based comparison of SiC suspensions in EG/H_2O and H_2O (Fig.8a) shows similar particle size and temperature dependencies. However the addition of SiC nanoparticles to EG/H_2O significantly improves heat transfer characteristics (14.2% at 72°C), while the best efficiency of the water based suspensions are barely comparable to that of pure water. In laminar flow regime (Fig. 8b) the efficiency of nanofluids also increases with increasing average particle size and temperature and the situation is more forgiving to the increased viscosity of suspensions. The effect of the base fluid on the efficiency of nanoparticle suspensions is another trend observed in the current work.

While most previous studies showed a linear dependence of thermal conductivity and viscosity on the volume concentration [7-8], correlations of Mo ratio to heat transfer coefficient ratio provides insights that absolute values of thermal conductivity (k), viscosity (η), heat capacity (c_p), and density (ρ) may not be as important as their ratio for turbulent heat transfer [5]. The investigations of the particle concentration effects on the heat transfer coefficient are conducted experimentally and theoretically. Mo ratios calculated for suspensions with 90 nm particles at various volume concentrations and temperatures (assuming a linear dependence of nanofluid properties on the particle concentration) are presented on figure 9 together with experimentally measured heat transfer coefficient ratio of 1 and 4 vol% of 90 nm SiC in EG/H_2O. It can be concluded that nanofluids with higher particle concentration are still more efficient in turbulent heat transfer due to the combination of all modified properties (k, c_p, ρ and η). Temperature effects also appear to be stronger in more concentrated suspensions. The suspension with 1 vol% of nanoparticles is experimentally confirmed to have lower heat transfer coefficient than that with 4 vol%.

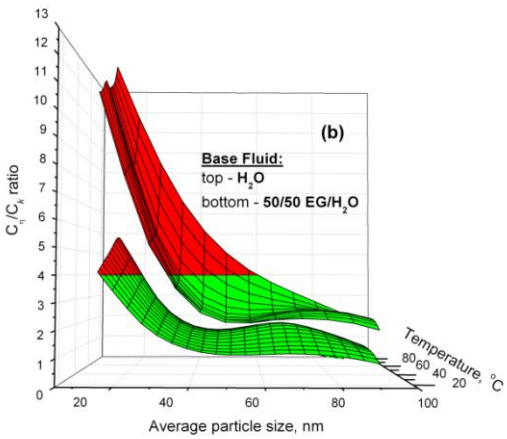

Figure 8b. Property based evaluation of efficiency of 4 vol% SiC fluids in EG/H_2O in comparison to analogous fluids in H_2O for laminar flow regime at various particle sizes and pH of 9.5±0.3. Red – less efficient than base fluid, green – enhancement in efficiency.

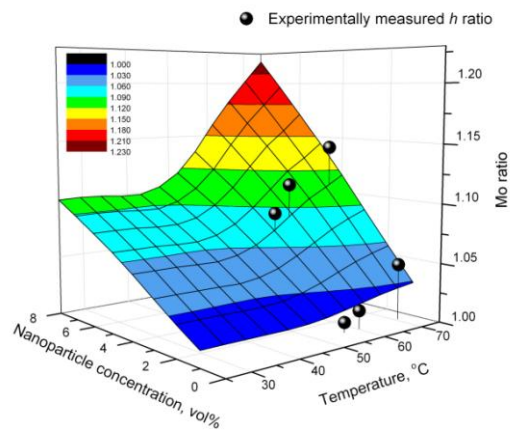

Figure 9. Estimation of heat transfer efficiency for 90 nm SiC suspensions in EG/H_2O at various particle concentrations and temperatures compared to the experimental heat transfer coefficient ratio for 1 and 4 vol% SiC concentrations at different temperatures.

Summarizing this study, the use of larger particles provides better heat transfer properties in both laminar and turbulent flow regimes. The efficiency of nanofluids improves with increasing temperature due to viscosity decreases. Suspensions in EG/H_2O show higher efficiencies as heat transfer fluids than similar H_2O-based nanofluids due to the demonstrated base fluid effect. Suspensions with higher concentration of nanoparticles (within the linear property increase zone) show higher heat transfer efficiency than less concentrated ones.

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Milestones (Could change as a result of funding availability)

FY10 Milestones	Date	Status
Assessment of SiC/water nanofluid as potential for industrial cooling –	10/01/2009	Larger SiC particles with a base fluid of EG/H_2O have shown potential as heat transfer fluids
DECISION TO CONTINUE WITH SiC	10/01/2009	Yes, continue with EG/H_2O based suspensions
Measure heat transfer of nanofluids containing larger SiC particles	04/01/2010	Preliminary results in this report
Modification of viscosity of larger particles of a SiC EG/H_2O nanofluid	05/01/2010	Results in this report
Measure torque required to pump the above nanofluid	06/01/2010	Concentrated on the alumina based nanofluid, results in this report
Measure heat transfer of above nanofluid	05/01/2010	Results in this report
Study erosion of the above candidate nanofluid	08/01/2010	On going
Perform measurements of graphitic nanofluid supplied by Valvoline	07/01/2010	Performed calculations fluid was too viscous to measure, asked Valvoline to remove thickner
Tranfer technology to Saint Gobain and Valvoline to enable manufacturing of sufficient nanofluids for demonstrations	12/01/2010	

Financial Information

Funding at start 8/25/2008 – $180,000

Total Funding to date (July 7, 2010) – $686,736[#]

Available funds as of July 7, 2010 – $176,512

[#]DOE site office is still holding some funding presumably expecting a midyear cut