Base fluid and temperature effects on the heat transfer characteristics of SiC in ethylene glycol/H_2O and H_2O nanofluids

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Experimental data are presented for the thermal conductivity, viscosity, and turbulent flow heat transfer coefficient of nanofluids with SiC particles suspended in ethylene glycol (EG)/water (H_2O) mixture with a 50/50 volume ratio. The results are compared to the analogous suspensions in water for four sizes of SiC particles (16–90 nm). It is demonstrated that the heat transfer efficiency is a function of both the average particle size and the system temperature. The results show that adding SiC nanoparticles to an EG/H_2O mixture can significantly improve the cooling efficiency while water-based nanofluids are typically less efficient than the base fluids. This is one of the few times that substantial nanofluid heat transfer enhancement has been reported in the literature based on a realistic comparison basis of constant velocity or pumping power. The trends important for engineering efficient heat transfer nanofluids are summarized. © *2011 American Institute of Physics*. [doi:10.1063/1.3524274]

I. INTRODUCTION

The interest in nanofluids as potential heat transfer fluids spiked initially due to very promising results on the enhanced thermal conductivity for a nanofluid containing copper in pump oil[1] but was disclaimed later when multiple research groups tested a variety of available combinations of fluids and nanoparticles primarily at room temperature.[2–4] The majority of the studies were conducted for water based fluids, one of the nature's best heat transfer fluids due to a favorable combination of high thermal conductivity and low viscosity. Some disadvantages of water are the limited operating temperature range, high vapor pressure, and high corrosivity.

We previously investigated water-based SiC nanofluids[5,6] and found that the increases in the thermal conductivity were significant but the increase in the viscosity with the introduction of the nanoparticles resulted in the heat transfer coefficient being up to 15% worse than that of the base fluid. Adjusting the *p*H and using larger particle sizes can significantly decrease the viscosity of suspensions but for SiC–H_2O the nanofluid heat transfer coefficient was still just slightly above that of pure water[6,7] at a constant velocity in fully developed turbulent flow.[8] It was shown in several studies[9,10] that the base fluids with the higher viscosity and lower thermal conductivity benefited most from the addition of nanoparticles.

In this paper, we report properties and heat transfer coefficients of SiC nanofluids prepared in a base fluid widely used as a heat transfer fluid for cooling in transportation and power electronics: ethylene glycol (EG) and water (H_2O) mixture with a 50/50 volume ratio. The results are among the few reported in the literature where the heat transfer enhancement for the nanofluid over its base fluid is substantial and based on a realistic criterion. Details of the development of the SiC–EG/H_2O nanofluid are presented, and results are compared to similar water-based nanofluids.

II. MATERIALS AND METHODS

The nanofluids for this study were prepared by mixing EG with a water-based suspension of α-SiC particles (Saint Gobain Inc.) with the average sizes determined from BET (Brunauer-Emmet-Teller surface area determination technique) to be 16, 29, 66, and 90 nm. The *p*H of all nanofluids was maintained at $\sim 9.5 \pm 0.3$ to engage the electrostatic stabilization of the suspensions and to minimize the viscosity increase.

The thermal conductivity of the nanofluids was measured by a KD2Pro thermal property analyzer (Decagon Devices Inc.). An average of at least 100 measurements taken once every 15 min was reported. The viscosity of the nanofluids was measured in the temperature range of 15–85 °C with a Brookfield DV-II rotational type viscometer with a SC4–18 spindle (Brookfield Engineering Inc.).

The forced convective heat transfer experiments for all the studies were carried out at the volume flow rates between 700 and 1200 cc/min to maintain a turbulent flow, which corresponded to Reynolds numbers between 4500 and 7500 at inlet temperatures of ~45, 51, and 62 °C. The heat transfer coefficients measured at the middle of the test section[7] were compared on the basis of constant velocity.

III. RESULTS AND DISCUSSION

The thermal conductivity values of the SiC–EG/H_2O nanofluids increase with increasing particle sizes (Fig. 1),

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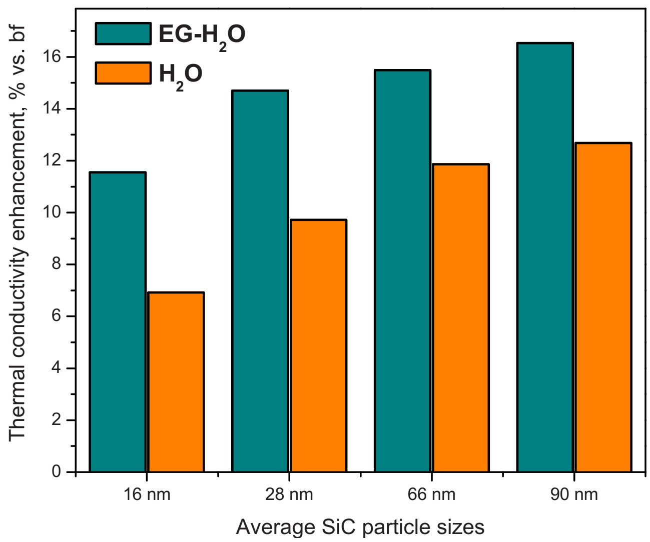

FIG. 1. (Color online) Comparison of the thermal conductivity enhancement in 4 vol % SiC nanofluids with EG/H_2O and H_2O as base fluids at various particle sizes.

which is similar to the behaviors observed in the SiC–H_2O nanofluids.[5,6] When the thermal conductivities of H_2O and EG/H_2O based SiC nanofluids are compared on a common scale (Fig. 1), one can see that the addition of nanoparticles in EG/H_2O results in 4%–5% higher enhancements than in H_2O at the same particle concentrations and sizes. This effect cannot be explained simply by lower thermal conductivity of the EG/H_2O base fluid since the difference in enhancement values expected from the effective medium theory is less than 0.1%.[11] This "base fluid effect" is most likely related to the lower value of the interfacial thermal resistance in the EG/H_2O nanofluids.[6]

The viscosities of the SiC–EG/H_2O (η_{nf}) are presented as relative increases to the base fluid viscosity (η_{bf}) (Fig. 2). At the same temperature, particle concentration, and pH (~4 vol % SiC and pH ~ 9.5), the viscosity decreases with

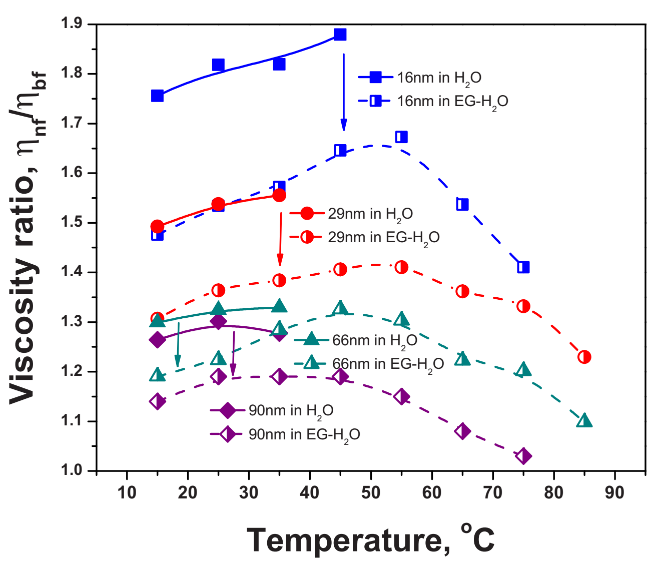

FIG. 2. (Color online) Temperature dependence of nanofluid-to-base fluid viscosity ratio in 4 vol % SiC suspensions in water and 50/50 EG/H_2O at pH ~ 9.5 ± 0.3. Particle sizes are determined by BET.

the increase in the average particle size similar to the H_2O-based suspensions.[6] A lower viscosity is highly desirable for heat transfer applications to minimize the pumping power penalties. Comparing the viscosity increase in analogous water- and EG/H_2O-based suspensions reveals a lesser viscosity increase in the EG/H_2O nanofluids (Fig. 2). The difference in the viscosity increase is more pronounced at smaller particle sizes. According to the classic Einstein–Bachelor equation for hard noninteracting spheres,[12] the percentage viscosity increase should be independent of the viscosity of the base fluid and only proportional to the particle volume concentration. The observed phenomena can be related to the difference in the structure and thickness of the diffuse fluid layers around the nanoparticles in various base fluids, which affects the effective volume concentration and ultimately the viscosity of the suspension.[6]

The temperature dependence of the nanofluid-to-base fluid viscosity ratio shows a slight increase followed by a stronger decrease as the temperature rises above 40–60 °C. This effect is most significant in suspensions of the smallest particles (Fig. 2) and correlates to the highest solid/liquid interface area. The change in viscosities with temperature suggests changes in the hydrodynamic radius of the suspended nanoparticles and/or their agglomeration state. Temperature increase may result in the shift of the isoelectric point[13] altering particle–particle interactions. The higher kinetic energy of the nanoparticles at elevated temperatures may also be a reason for weaker particle-fluid and particle-particle interactions and a lower viscosity increases. The data on the temperature effect in the H_2O-based suspensions are limited to the 15–45 °C range where the slopes are similar to those observed in the EG/H_2O-based nanofluids. Further studies of the temperature dependence are needed for a better understanding of viscosity change in nanofluids.

A series of forced convective heat transfer experiments was carried out for the same set of SiC–EG/H_2O nanofluids discussed above. The experimental results were compared on the basis of the constant velocity[7] and expressed as heat transfer coefficients. The heat transfer coefficient reflects the proportionality between the heat flux and the temperature gradient (the thermodynamic driving force of heat flow) and is a convenient measure when the cooling efficiencies of different fluids are compared. On the other hand, the dimensionless Nusselt number, often used in the literature, represents the ratio of convective to conductive heat transfers within the fluid. This fluid characteristic is useful for evaluation of the heat transfer mechanisms in the fluid but may be misleading for practical evaluation of the cooling efficiency.

The experimental results [Fig. 3(a)] show that when all other nanofluid parameters are the same, the heat transfer coefficients of the SiC–EG/H_2O nanofluids increase with increasing particle sizes. The heat transfer coefficients for the nanofluids with average particle sizes of 66 and 90 nm are higher than those for the EG/H_2O base fluid, while the heat transfer coefficients for the nanofluids with average particle sizes of 16 and 29 nm are lower than those for the EG/H_2O base fluid [Fig. 3(a)]. While the trends in the EG/H_2O-based nanofluids are similar to those in the water-based nanofluids,[6] the effect of adding SiC particles on the heat

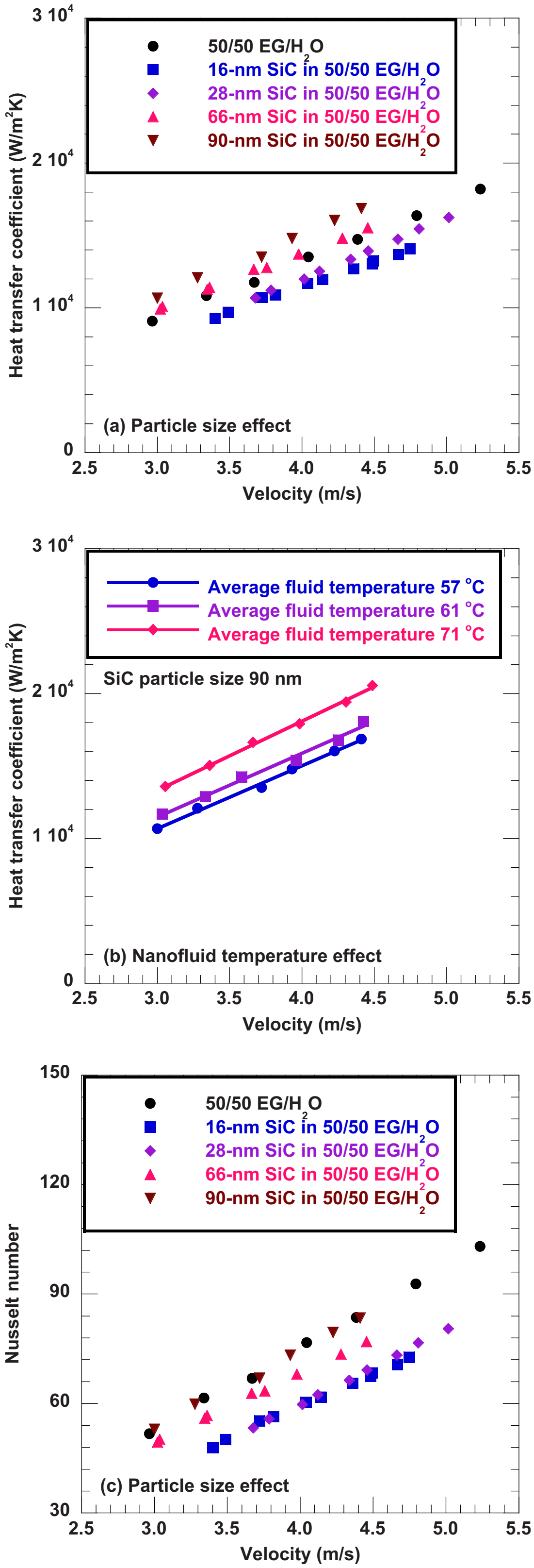

FIG. 3. (Color online) Experiment at heat transfer coefficient of 4 vol % SiC–EG/H_2O nanofluids in fully developed turbulent flow: (a) particle size effect at 55 °C; (b) temperature effect in the nanofluid with 90 nm SiC particles; (c) Nusselt number based comparison of nanofluids (4 vol % SiC–EG/H_2O) to the base fluid.

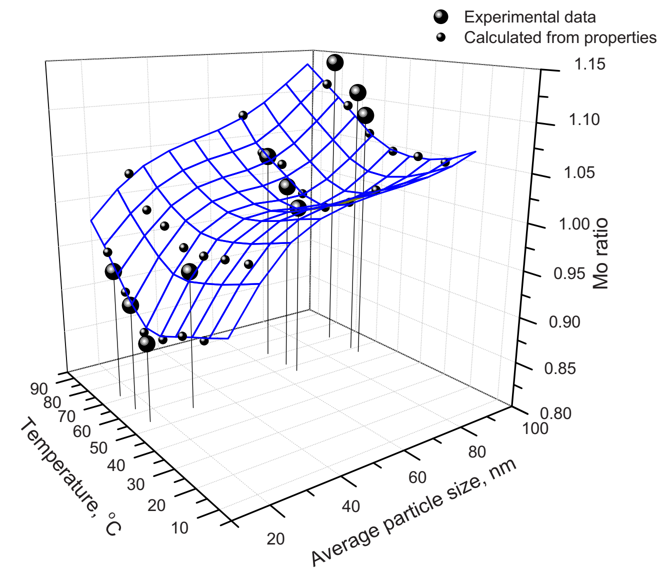

FIG. 4. (Color online) Reconstruction of Mo ratio surface calculated from the experimental property data at various particle sizes and temperatures compared to the ratio of experimentally measured turbulent flow heat transfer coefficients.

transfer coefficient is larger for EG/H_2O than for water. The nanofluid-to-base fluid ratio of experimentally measured heat transfer coefficients improves as the testing temperature goes up, reaching 14.2% increase at 71 °C [Fig. 3(b)]. Such significant heat transfer enhancement for the SiC–EG/H_2O nanofluid over its base fluid has rarely been reported in the literature for any nanofluid when using a realistic basis of comparison, i.e., velocity or pumping power bases which are approximately the same for nanofluids.[8] As shown in Fig. 3(c), the heat transfer enhancements of the 66 and 90 nm SiC-50/50 EG/H_2O nanofluids are not revealed in the Nusselt number comparison. While the Nusselt number is commonly used for comparing experimental data to predicted values where the thermal conductivities are the same, the heat transfer coefficient is a better parameter for comparing the heat transfer performance between two fluids such as a nanofluid and its base fluid in this study where the thermal conductivities are different.

The suggested merit criteria[8,14,15] allow estimating 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 with the properties of the nanofluid and do not account for possible dynamic effects due to the presence of nanoscale particles. The Mouromtseff value (Mo) ratio[15] is used for turbulent flow while the ratios of viscosity and thermal conductivity enhancements (C_η and C_k, respectively) are used together as a criterion for laminar flow.[14] Both criteria are nondimensional and represent a convenient way to estimate the cooling performance of a nanofluid versus its base fluid. The viscosity is shown to depend on both the temperature and the average particle size, while the thermal conductivity enhancement is shown to be dependent on the particle size, but independent on temperature.[5,16] Our nanofluid property data set was used to reconstruct three-dimensional surfaces reflecting the projected efficiencies of the SiC–EG/H_2O nanofluids with regard to these two parameters and to compare them to the experimental ratio of heat transfer coefficients (Figs. 4 and 5).

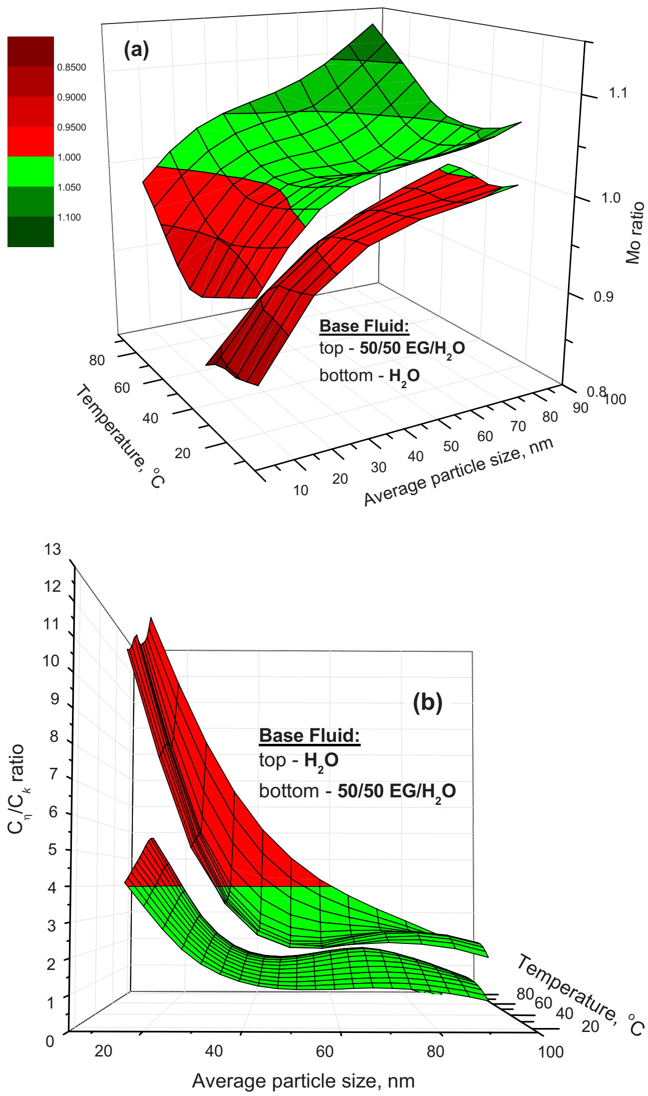

FIG. 5. (Color online) Property-based evaluation of efficiency of 4 vol % SiC fluids in EG/H_2O in comparison to analogous fluids in H_2O for fully developed turbulent (a) and laminar (b) regimes at various particle sizes and pH of 9.5 ± 0.3. At Mo ratio <1 and C_η/C_k ratio >4 nanofluid is less efficient than the base fluid, while Mo ratio >1 and C_η/C_k ratio <4 indicate enhancement in cooling efficiency of nanofluids.

One can see from Fig. 4 that the property-based evaluation of the nanofluid efficiency is in agreement with the experimentally measured heat transfer coefficients. The suspensions with average particle sizes 66 and 90 nm enhance the heat transfer while the performance of the suspensions with smaller particles (29 and 16 nm) is less effective than that of the base fluid. The experimentally measured heat transfer coefficients in most cases follow the same "particle size trend" as the merit criteria calculated from the nanofluids thermophysical properties (Fig. 4). Only the suspensions with 90 nm particles show enhancements above the property-based predictions. Both the experimental heat transfer data and the values calculated from the nanofluid properties show an increase in nanofluid efficiency with increasing temperature, which is most likely related to the dramatic viscosity decrease in the nanofluids.

The comparison of the cooling efficiencies of the SiC suspensions in EG/H_2O and H_2O for the fully developed turbulent flow regime [Fig. 5(a)] is based on the ratio of Mo values determined from the measured viscosity, thermal conductivity, density, and calculated specific heat for the nanofluid and the corresponding base fluid at the same temperature. The surface at Mo ratio >1 and C_η/C_k ratio <4 (green on color graphs) in Figs. 5 indicates the particle sizes and temperatures at which the nanofluid is a more efficient coolant than its base fluid. At the Mo ratio <1 and C_η/C_k ratio >4 (red on color graphs) the nanoparticle suspension is less efficient than the base fluid. One can see that the Mo ratio increases with increasing particle sizes and temperatures similarly in both base fluids. However, the addition of SiC nanoparticles to EG/H_2O significantly improves heat transfer characteristics (14.2% at 71 °C), while the best efficiency of the water-based suspensions are barely comparable to that of pure water.

In the laminar flow regime [Fig. 5(b)], the efficiency of the nanofluids also increases with increasing average particle size and temperature, and the situation is more forgiving to the increased viscosity of the suspensions. The observed base fluid effect on the cooling efficiency of the nanoparticle suspensions requires further studies on the mechanism.

While most previous studies showed a linear dependence of the nanofluid thermal conductivity and viscosity on the particle volume concentration,[3,4] the correlations of the Mo ratio to the heat transfer coefficient ratio imply that absolute values of the thermal conductivity (k), viscosity (η), heat capacity (c_p), and density (ρ) may not be as important as their ratio for turbulent heat transfer.[8] The investigations of the particle concentration effect on the heat transfer coefficient were conducted experimentally by measuring the heat transfer coefficients of nanofluids with 1 and 4 vol % concentrations and theoretically by calculating the Mo ratios for various volume concentrations and temperatures (assuming a linear dependence of nanofluid properties on the particle concentration). The results are presented on Fig. 6 together with the experimentally measured heat transfer coefficient ratio (efficiency ratio) for 1 and 4 vol % of 90 nm SiC in EG/H_2O. The nanofluids with a higher particle concentration are more efficient in turbulent heat transfer due to the combination of all modified properties (k, c_p, ρ, and η). As it seen from the Fig. 6, the increase in the cooling efficiency with rising temperature is 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 %. This results from the ratio of the properties contributing to the turbulent heat transfer:[15] $Mo = \rho^{0.8} c_p^{0.4} k^{0.6} / \eta^{0.4}$, where the fluid density and thermal conductivity have higher powers than the specific heat and viscosity. This indicates that for nanofluids with linear viscosity increase, the cooling potential can be increased by using a higher particle concentration.

IV. CONCLUSIONS

The following trends are important and should be considered for engineering efficient heat transfer nanofluid. The use of larger particles provides better heat transfer properties in both laminar and turbulent flow regimes. The efficiency of

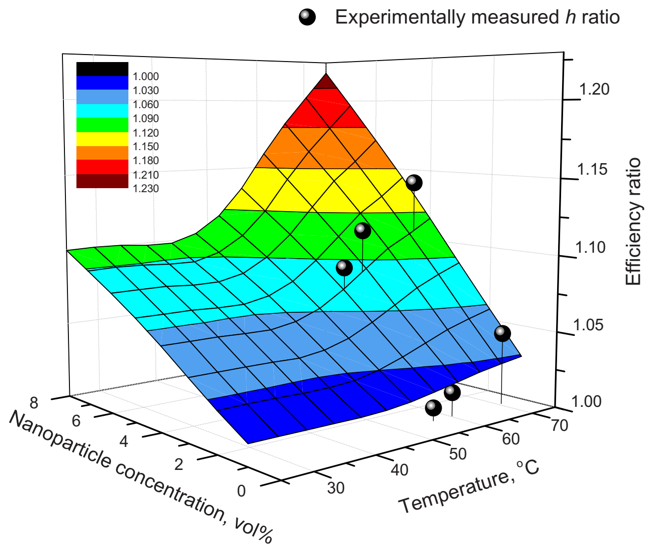

FIG. 6. (Color online) Estimation of heat transfer efficiency for 90 nm SiC suspensions in EG/H_2O at various particle concentrations and temperatures compared to the experimental fully developed turbulent flow heat transfer coefficient ratio (efficiency ratio) for 1 and 4 vol % SiC concentrations at different temperatures. The color scheme denotes every 3% change in cooling efficiency.

nanofluids improves with increasing temperature due to viscosity decreases. The suspensions in EG/H_2O show higher efficiencies as heat transfer fluids than the similar H_2O-based nanofluids due to the demonstrated base fluid effect. (Heat transfer enhancement was measured as high as 14.2% which is a level that has rarely been reported previously and represents a potentially viable commercial fluid.) The suspensions with the higher concentration of nanoparticles (within the linear property increase region) show higher heat transfer efficiency than the lesser concentrations.

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