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MEASUREMENT AND MODEL CORRELATION OF SPECIFIC HEAT CAPACITY OF WATER-BASED NANOFLUIDS WITH SILICA, ALUMINA AND COPPER OXIDE NANOPARTICLES

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ABSTRACT
Nanofluids are being considered for heat transfer applications. However, their thermo-physical properties are poorly known. Here we focus on nanofluid specific heat capacity. Currently, there exist two models to predict a nanofluid's specific heat capacity as a function of nanoparticle concentration and material. Model I is a straight volume-weighted average; Model II is based on the assumption of thermal equilibrium between the particles and the surrounding fluid. These two models give significantly different predictions for a given system. Using differential scanning calorimetry, the specific heat capacities of water based silica, alumina, and copper oxide nanofluids were measured. Nanoparticle concentrations were varied between 5wt% and 50wt%. Test results were found to be in excellent agreement with Model II, while the predictions of Model I deviate very significantly from the data.

INTRODUCTION
Recent research has indicated that dispersions of nanoparticles in a base fluid, known as nanofluids, can increase the boiling critical heat flux and overall performance of thermal systems. Typical nanoparticle concentrations may range from 0.01wt% to 50wt% and common particle materials include silica, alumina, copper oxide, zirconia, carbon nanotubes, etc. Water often serves as the base fluid, though other liquids such as ethylene glycol have been used [1].

As nanofluids are considered for thermal applications, it is necessary to be able to predict their thermo-physical properties. Because nanofluids were initially considered for thermal conductivity enhancement, this property has been extensively studied [2]. However, there have been fewer examinations of nanofluid specific heat capacity [3] [4] [5] [6]. It is the objective of this investigation to complement existing research by (i) measuring the specific heat capacity of water-based silica, alumina and copper oxide nanofluids, and (ii) comparing the predictions of two popular nanofluid specific heat capacity models to data.

NOMENCLATURE

$c_{p,f}$	Specific heat capacity of base fluid (J/g-K)
$c_{p,nf}$	Specific heat capacity of nanofluid (J/g-K)
$c_{p,n}$	Specific heat capacity of nanoparticle (J/g-K)
$c_{p,ref}$	Specific heat capacity of reference (J/g-K)
$c_{p,sample}$	Specific heat capacity of sample (J/g-K)
m_n	Mass of nanoparticles (g)
m_{H20}	Mass of water (g)
m_{ref}	Mass of reference (g)
m_{sample}	Mass of sample (g)
Q_{ref}	Heat flux into reference (Watts)
Q_{sample}	Heat flux into sample (Watts)
Q_0	Heat flux baseline (Watts)
φ	Volume fraction (unitless)
ρ_f	Density of basefluid (g/cm^3)
ρ_n	Density of nanoparticles (g/cm^3)

ρ_{H20}	Density of water (g/cm^3)
V_N	Volume of nanoparticles (cm^3)
V_{H20}	Volume of water (cm^3)

SPECIFIC HEAT MODELS

There are two specific heat models widely used in the nanofluid literature. Model I is similar to mixing theory for ideal gas mixtures [3]. It is a straight average relating nanofluid specific heat, $c_{p,nf}$, to basefluid specific heat, $c_{p,f}$, nanoparticle specific heat, $c_{p,n}$, and volume fraction, φ. Using these parameters, Model I calculates the nanofluid specific heat as,

$$c_{p,nf} = \varphi c_{p,n} + (1-\varphi)c_{p,f} \quad (1)$$

While it is simple and thus widespread in the literature, Model I has little theoretical justification in the context of nanofluids.

Model II [3] [7] is based on the assumption of thermal equilibrium between the particles and the surrounding fluid. It is straightforward to show that also the particle and fluid densities (ρ_n, and ρ_f, respectively) must affect the specific heat of the nanofluid,

$$c_{p,nf} = \frac{\varphi(\rho c_p)_n + (1-\varphi)(\rho c_p)_f}{\varphi\rho_n + (1-\varphi)\rho_f} \quad (2)$$

A rigorous derivation of Equation (2) is presented in [8].

Predictions of nanofluid specific heat capacity were made using both models and compared to experimental measurements. Water was the base fluid of all nanofluids used in this investigation. Therefore, handbook values of temperature-dependent water specific heat and density were used in calculating theoretical nanofluid specific heat [9]. Additionally, the specific heat and density of the nanoparticles were assumed to be equal to the respective thermo-physical properties of particle material in bulk form.

NANOFLUIDS

The specific heat capacities of three nanofluids were analyzed: alumina-water (Nyacol AL20DW), silica-water (Ludox TMA 420859), and copper oxide-water (Alfa Aesar 45407). The nanofluid properties, as cited by the manufacturers, are presented in the table below.

Nanofluid	Particle Size (nm) or Surface Area (m^2/g)	pH	Specific Gravity
NYACOL AL20DW	50 nm	4.0	1.19
Ludox TMA 420859	140 m^2/g	4.0-7.0	1.227-1.244
Alfa Aesar 45407	30 nm		

The stock nanofluids were obtained from commercial vendors, and diluted with de-ionized water to vary their concentrations. Prior to mixing, the nanofluids were manually agitated to ensure uniform dispersion. Dilution was performed by weight percent using a Mettler Toledo XS105 balance. Four unique concentrations were prepared for each nanofluid and are listed in the table below. For each concentration, two identical samples were prepared and tested.

Table 1: Nanofluid sample concentrations

Nanofluid	**Alumina-water**	**Silica-water**	**Copper Oxide-water**
Conc. 1 (stock)	20wt% (6.4vol%)	34wt% (19.0vol%)	50wt% (13.7vol%)
Conc. 2	15wt% (4.6vol%)	25.5wt% (13.5vol%)	37.5wt% (8.7vol%)
Conc. 3	10wt% (2.9vol%)	15wt% (8.5vol%)	25wt% (5.0vol%)
Conc. 4	5wt% (1.4vol%)	8.5wt% (4.1vol%)	12.5wt% (2.2vol%)

While nanofluids were diluted and prepared according to their weight fraction, calculations were performed using volume fraction. Using the nanoparticle volume, V_n, and the water volume, V_{H20}, the volume fraction can be calculated as,

$$\varphi = \frac{V_n}{V_n + V_{H_2O}} \quad (3)$$

Substituting in nanoparticle mass, m_n, and density ρ_n, and water mass, m_{H20}, and density, ρ_{H20}, Equation (3) can be rewritten as,

$$\varphi = \frac{\frac{m_n}{\rho_n}}{\frac{m_n}{\rho_n} + \frac{m_{H20}}{\rho_{H20}}} \quad (4)$$

Equation (4) can be used to determine the nanoparticle volume fraction of nanofluid concentrations created by dilution with de-ionized water.

MEASUREMENT METHOD

A heat-flux type differential scanning calorimeter (TA Instruments Q2000) was used to measure the nanofluid specific heat capacities. The differential scanning calorimeter (DSC) measures the heat flux into a sample as a function of temperature during a user prescribed heating regime. It accomplishes this by comparing the heat flux into a pan containing the sample with the heat flux into an empty pan. Hermetically sealed aluminum pans (TA Instruments) were used.

The classical three-step DSC procedure was followed to measure specific heat capacity [10] [11]. Additionally, testing procedures adhered to protocols set forth in the ASTM Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry (E 1269-05).

The three-step DSC procedure begins with designing a heating regime, which should contain the temperature range of interest. Next, a measurement is taken with two empty sample pans loaded into the DSC. During this measurement, the baseline heat flux, Q_0, is obtained. The results of this measurement indicate the bias in the machine, allowing for it to be accounted for during data reduction.

The second measurement is of a reference sample, with a known specific heat, $c_{p,ref}$. A pan containing the reference sample and an empty pan are loaded into the DSC. The heat flux into the reference sample, Q_{ref}, is recorded throughout the identical heating regime.

The third measurement is made on the actual sample of interest. A pan containing the sample and an empty pan are loaded into the DSC. The heat flux into the sample, Q_{sample}, is recorded during an identical heating regime as the previous two measurements. The heat flux curves from the three measurements are used to comparatively determine the specific heat of the sample, $c_{p,sample}$, where,

$$c_{p,sample} = \frac{Q_{sample}-Q_0}{Q_{ref}-Q_0}\frac{m_{ref}}{m_{sample}}c_{p,ref} \quad (5)$$

and m_{ref} and m_{sample} represent the masses of the reference and sample, respectively. Sample masses were measured using a Perkin Elmer AD6 autobalance.

In these tests, de-ionized water was used as the reference sample, with specific heat values obtained from a handbook [9]. The DSC heating procedure consisted of three segments:

1. Equilibrate and remain isothermal at 25°C for one minute
2. Ramp to 75°C at 10°C/min
3. Remain isothermal at 75°C for one minute

Heat flux measurement was continuous from 25°C to 75°C. However, for analysis, specific heat capacities were calculated at 35°C, 45°C and 55°C. An uncertainty analysis was performed via the propagation of error. Uncertainty in the measurement of specific heat capacity was found to be on the order of 10^{-4} (J/g-K). For each sample of nanofluid concentration, three measurements were taken. These values were then averaged to yield the data points and related standard deviations presented below.

Prior to nanofluid measurement, this DSC methodology was validated by analyzing two pure fluids, ethylene glycol and glycerin. The results obtained from these measurements were compared against handbook values of specific heat for these liquids [12]. Next, three measurements were performed on each nanofluid sample. The averages of these measurements were used to calculate the specific heat capacity and error bars indicate standard deviation.

RESULTS AND DISCUSSION

DSC measurements of pure ethylene glycol and glycerin were in good agreement with literature values of specific heat capacity. The results of these tests, presented in Tables 2 and 3 below, validate the DSC methodology and machine calibration.

Table 2: Propylene Glycol

Temperature (°C)	Theoretical c_p (J/g-K)	Measured c_p (J/g-K)
35	2.56	2.54 ± 0.191
45	2.62	2.64 ± 0.185
55	2.65	2.65 ± 0.185

Table 3: Glycerin

Temperature (°C)	Theoretical c_p (J/g-K)	Measured c_p (J/g-K)
35	2.39	2.41 ± 0.008
45	2.41	2.42 ± 0.002
55	2.42	2.44 ± 0.001

Figures 1-9 show the nanofluids data and the curves predicted by Models I and II. As expected, as nanoparticle concentration increases, the specific heat capacity decreases. However, Model I largely underestimates the decrease, while Model II offers a much more accurate prediction of nanofluid specific heat capacity. These conclusions are consistent with the alumina nanofluid results reported in [3], and expand the validity of Model II to silica and copper oxide nanofluids.

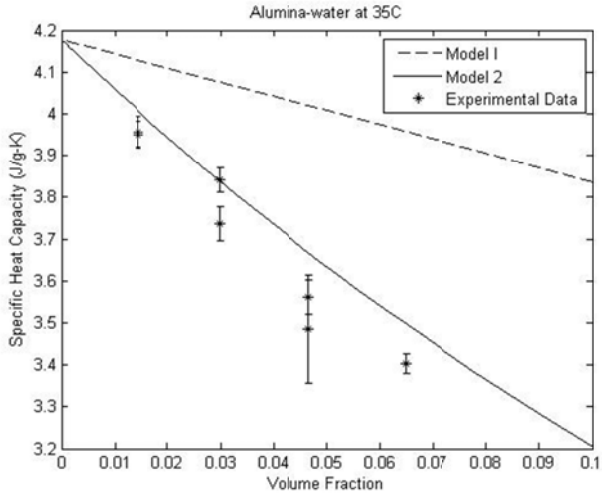

Figure 1: Alumina-water at 35°C

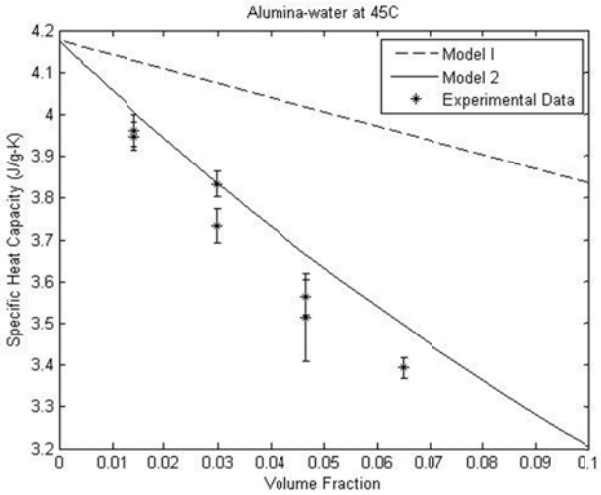

Figure 2: Alumina-water at 45°C

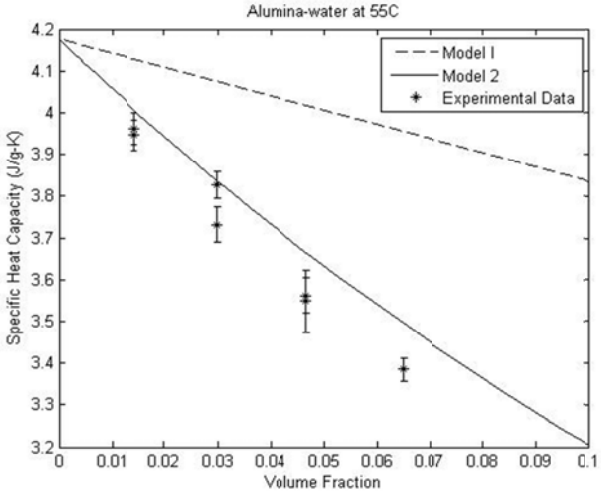

Figure 3: Alumina-water at 55°C

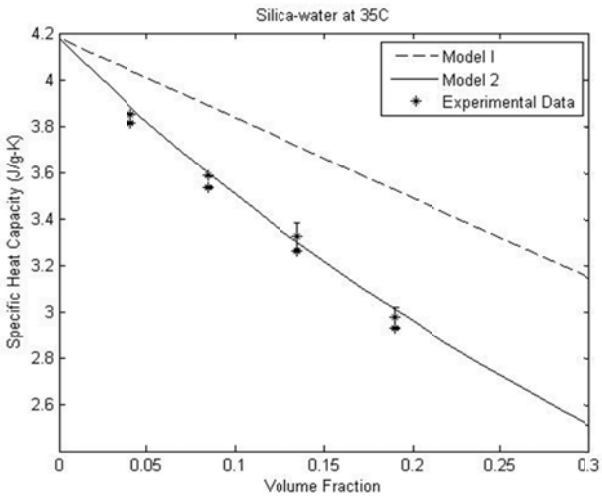

Figure 4: Silica-water at 35°C

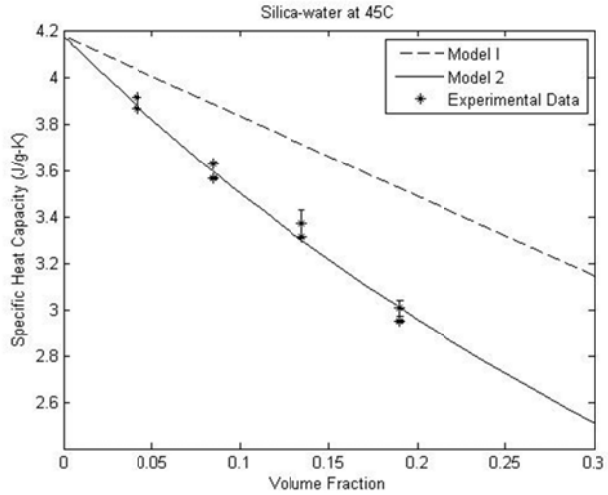

Figure 5: Silica-water at 45°C

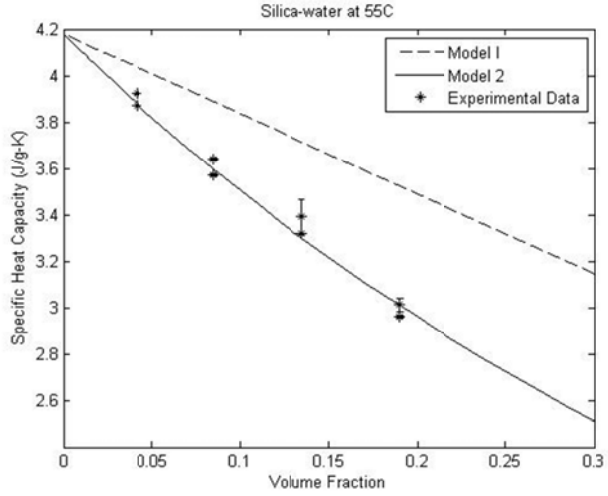

Figure 6: Silica-water at 55°C

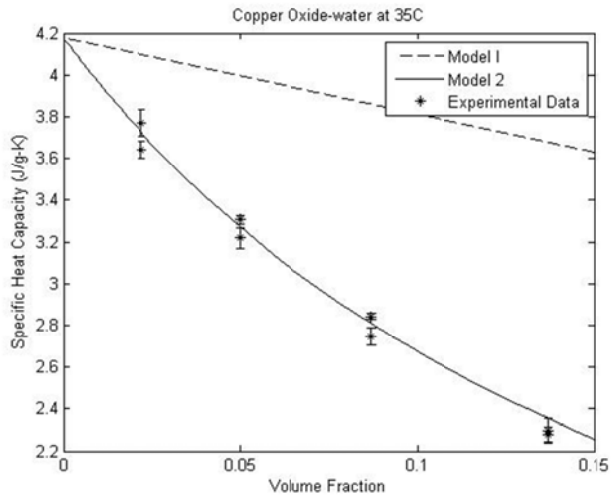

Figure 7: Copper Oxide-water at 35°C

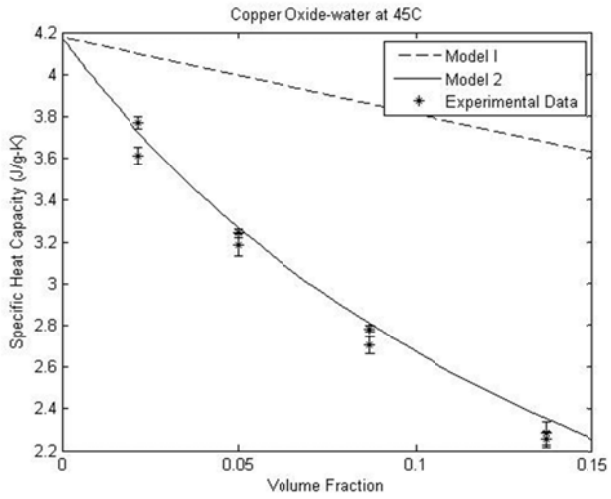

Figure 8: Copper Oxide-water at 45°C

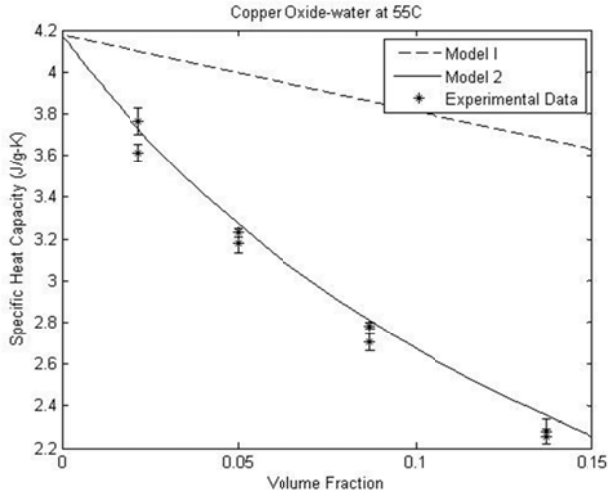

Figure 9: Copper Oxide-water at 55°C

Even for Model II, there appear to be small discrepancies between the data and predictions. These could come from errors in the listed stock nanofluid concentrations, experimental uncertainties in dilution or inconsistencies in using the bulk material properties in the model, instead of the actual nanoparticle properties. Recent research suggests that these properties may differ if the material is in nanoparticle form versus bulk form [8]. Agglomeration/sedimentation of the nanoparticles could also affect the results [8]. Investigation of these effects is left for future work.

CONCLUSIONS

Using a heat flux differential scanning calorimeter (DSC), the specific heat capacities of water-based silica, alumina and copper oxide nanofluids at various nanoparticle concentrations were measured. The DSC procedure was validated by measuring the specific heat capacities of pure ethylene glycol and glycerin, which were confirmed against handbook values. The nanofluid data were used to test the predictions of two popular mixture models for specific heat. The results clearly suggest that the model based on particle/fluid thermal equilibrium (Model II) yields more accurate predictions than the model based on a straight volume-weighted average of the particle and fluid specific heats (Model I). Given its sound theoretical basis, we believe Model II is generally applicable, while Model I should be abandoned. To further improve the accuracy of Model II, future investigations could focus on measuring the actual density and specific heat of the nanoparticles in dispersion and compare them to those of the bulk materials.

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