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New specific heat data for Al_2O_3 and CuO nanoparticles in suspension in water and Ethylene Glycol

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ABSTRACT

In this paper, specific heat measurements are performed for two water-based nanofluids, water-Al_2O_3-10 nm and water-CuO-29nm, and an Ethylene Glycol-Al_2O_3-10 nm nanofluid, with different concentrations: 0,24%, 1,03% and 4,05% for water-CuO nanofluid; 2% and 5% for water-Al_2O_3 nanofluid, and 1%, 2,5% and 5% for EG-Al_2O_3 nanofluid. Under controlled temperature and humidity conditions and following a rigorous three-step measuring procedure, some new specific heat data are obtained during the pseudo-steady heating phase (i.e. with a very low heating rate of 0.2 K/min) for 283K–358K temperature range with water-based nanofluid, and for 283K–423K range with EG-based nanofluids.

A performance comparison for four theoretical and empirical models has been performed with respect to the present experimental data. A new correlation, obtained from a recalibrating coefficients of an existing empirical model, has been proposed.

1. Introduction

The nanofluid, a mixture often composed of extremely fine metal particles suspended in a saturated liquid (for example water, engine oil, Ethylene Glycol), possesses improved thermal properties that can produce a significant increase of heat transfer compared to conventional heat transfer fluids. Since the pioneer works by Masuda et al. [1], Choi [2], Pak and Cho [3] and Xuan and Roetzel [4], the nanofluids have received a rather special attention from the researchers around the world. They appear to constitute an interesting alternative for various thermal applications, especially those requiring high surface heat fluxes, see for examples [5,6] and [7,8]. A review of some relevant works showing the nanofluids capability of heat transfer enhancement can be found in Kakaç and Pramuanjaroenkij [9] and Godson et al. [10].

Almost all of the first research works concerning with the nanofluids were devoted to the characterization of their thermophysical properties, in particular the thermal conductivity; only in recent years that researchers have been interested in the determination of the nanofluids dynamic viscosity, see in particular Khanafer and Vafai [11] for a review of relevant works in this area. In spite of the efforts deployed by researchers, the actual database of nanofluid thermal properties still remain relatively limited. One should mention that the nanofluids exhibit some unique yet still not very well understood behavior such as the stability/unstability of the suspensions when subject to the heating effects, see for example Hachey et al. [12] and Nguyen et al. [13]. From the practical point of view, such an issue of the nanofluids stability appears rather crucial because it directly influences a possible use or no-use of nanofluids in real thermal applications.

Regarding the thermal properties characterization for nanofluids, one can surprisingly notice a significant lack of the specific heat data, an important property that must be known or appropriately estimated prior to designing any thermal system. Only few experimental studies have been identified in the literature. In the following, some relevant experimental works related to nanofluids similar to those under study are presented and commented. Pak and Cho [3] were likely the first who measured the specific heat of several water-based nanofluids. They proposed the following formulas to calculate the density and the specific heat of nanofluids (Eq. (2) is hereafter referred as the M1 model):

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Nomenclature

A, B, C	constants used in various correlations
C_p	specific heat, J/kg K
C_{pr}	nanofluid-to-base fluid specific heat ratio (Eq. (5))
C_{ps}	specific heat of solid particle, J/kg K
Q	heat flux, W
T	temperature, K
T_i	fluid sample temperature at a given time, K
d_p	particle diameter, nm
m	mass of the fluid sample, kg
t	time, s

Greek letters

Φ	particle volume fraction
ρ	fluid density, kg/m^3

Subscripts

bf	base fluid
blank	without fluid in the measuring cell
i	particular data point at a given time
nf	nanofluid
p or s	solid particle
sample	fluid sample

$$\rho_{nf} = (1-\phi)\cdot\rho_{bf} + \phi\cdot\rho_p \tag{1}$$

$$(C_p)_{nf} = (1-\phi)\cdot(C_p)_{bf} + \phi\cdot(C_p)_p \tag{2}$$

In an interesting and likely the first paper on the conception and modeling of nanofluids, Xuan and Roetzel [4], based on the thermal equilibrium assumption, proposed the following formula to estimate the nanofluid specific heat (Eq. (3) is hereafter referred as the M2 model):

$$\left(\rho C_p\right)_{nf} = (1-\phi)\cdot\left(\rho C_p\right)_{bf} + \phi\cdot\left(\rho C_p\right)_p \tag{3}$$

Namburu et al. [14] considered SiO_2 nanoparticles of 20, 50 and 100 nm in size suspended in a 60:40 (by weight) Ethylene Glycol and water mixture, with particle volume fractions ranging from 0 to 10%. Their specific heat data appear to be close to the estimation by the M2 model.

Zhou and Ni [15] performed measurements with 45 nm Al_2O_3-water nanofluid for particle fraction up to 21.7% and 298–313K temperature range, have also shown that the M2 model appears to be better than M1 model for estimating nanofluid specific heat.

Vajjha and Das [16] have performed specific heat and density measurements on 53 nm-Al_2O_3-nanofluids mixtures of 60:40 water-Ethylene Glycol - water mass fraction of 60% and 40% of EG - with particle fraction varying from 0 to 10% and temperature from 315 to 360K. They observed, when using Eqs. (2) and (3)) again their data, that both models have produced significant errors in the estimation of C_p; and stipulated that both models seem not suitable for estimating this property. In 2009, Vajjha and Das [17] presented their complete specific heat data, obtained for three individual types of nanoparticles - 44 nm Al_2O_3, 20 nm SiO_2 and 77 nm ZnO - in suspension in a 60:40 EG/water solution, for the 315–363K temperature range and particle volume fractions up to 10%. Again, they have found similar results regarding the performance of the above models. They then proposed the following correlation (Eq. (4) will be hereafter named the M3 model):

$$\frac{C_{pnf}}{C_{pbf}} = \frac{\left(AT + B\frac{C_{ps}}{C_{pbf}}\right)}{(C+\phi)} \tag{4}$$

Eq. (4) is applicable over the 315–363K temperature range, particle fraction from 0 to 10% for Al_2O_3 and SiO_2, and from 0 to 7% for ZnO; the empirical coefficients A, B and C for Al_2O_3 nanoparticles are, respectively 0.0008911, 0.5179 and 0.4250 [17].

The good performance of the M2 model was also observed in the work by O'Hanley et al. [18] who have studied water-based nanofluids using three types of nanoparticles (SiO_2, Al_2O_3, and CuO) with the mass concentration of the particles ranges from 5% to 50%.

In 2013, Mondragón et al. [19] have conducted an experimental characterization of the properties of nanofluids destined for use under high temperature conditions. They considered water based-nanofluids with particles of SiO_2, Al_2O_3 and also Carbon Nanotubes with particle volume fraction up to 5% and temperature up to 353K. Their data show that the M2 model seems to be appropriate for estimating the nanofluids specific heat.

Barbés et al. [20] recently measured thermal conductivities and specific heat capacities of (40–50 nm) nanoparticles of Al_2O_3 dispersed in water and Ethylene Glycol with particle volume fraction up to 9.3% for Al_2O_3-water and up to 8.1% for Al_2O_3-EG, and for temperature varying from 298 to 338K. The M2 model provides an excellent agreement against their experimental specific heat data for the studied nanofluids. In 2014, this group performed similar measurements for nanofluids composed of (23–37 nm) CuO particles suspended in water and Ethylene Glycol for the same temperature range, see Barbés and Páramo [21]. The particle volume fraction was up to 2% for CuO-water and up to 3% for CuO-EG. Again, the same finding regarding the M2 model good performance in estimating C_p has been observed.

Sekhar and Sharma [22] experimentally measured the specific heat and viscosity properties of 47 nm alumina-water nanofluids for low particle concentration (from 0.01 to 1%) and temperature interval of 298–318K. Using their own data and others from various researchers for Al_2O_3, CuO, SiO_2 and TiO_2 water-based nanofluids, the following correlation (Eq. (5), hereafter named the M4 model) has been proposed:

$$C_{pr} = \frac{C_{nf}}{C_{bf}} = 0.8429\left(1+\frac{T_{nf}}{50}\right)^{-0.3037}\left(1+\frac{d_p}{50}\right)^{0.4167}\left(1+\frac{\phi}{100}\right)^{2.272} \tag{5}$$

Eq. (5) is applicable for the 293–323K temperature range, particle diameter d_p from 15 to 50 nm and particle volume fraction ranging from 0.01 to 4%. It has an acceptable accuracy according to the authors; the relative error of Eq. (5) varies from −8% to +10% with respect to the experimental database considered.

Teng and Hung [23] measured the density and specific heat of 20 nm-Al_2O_3- water nanofluids, with particle concentration of 0.5, 1 and 1.5% (by weight), for temperature ranging from 298 to 338K. Their specific heat data are found to be appropriately represented by both the models M1 and M2, although the latter gives slightly a better performance than M1 model.

Mostafizur et al. [24] considered cylindrical-shaped Al_2O_3 particles in suspension in methanol with very low volume fractions (0.05, 0.10, 0.15, 0.20 and 0.25%). Nanofluids thermo-physical properties - conductivity, viscosity, density and specific heat – have been measured for temperature ranging from 278 to 298K.