



A critical investigation of the anomalous behavior of molten salt-based nanofluids☆



Khalil Khanafer^a, Fatemeh Tavakkoli^b, Kambiz Vafai^{b,*}, Abdalla AlAmiri^c

^a Mechanical Engineering Department, Australian College of Kuwait, Safat 13015, Kuwait

^b Mechanical Engineering Department, University of California, Riverside, CA 92521, USA

^c Mechanical Engineering Department, United Arab Emirates University, P.O. Box 17555, Al Ain, United Arab Emirates

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ABSTRACT

A critical investigation is presented in this work to study the effect of nanoparticle addition, temperature, and nanoparticle size-dependence on the specific heat capacity of both conventional and molten salt-based nanofluids. The effects of temperature and nanoparticle volume fraction on the specific heat capacity of conventional nanofluids are in agreement in all studies cited in this review. Different correlations based on the available data were developed as a function of temperature and volume concentration only. However, the effect of nanoparticle size-dependence was ignored in these correlations. A general correlation for Al₂O₃–water nanofluids, one of the most commonly studied nanofluids, that takes into account the effect of temperature, volume fraction, and nanoparticle size-dependence was developed and verified in this review. Disagreement was reported for the results of the specific heat capacity of molten salt-based nanofluids. A number of studies showed an enhancement in the specific heat capacity of nanofluids using 1% concentration of nanoparticles by weight only. However, other studies have shown deterioration in the specific heat capacity of nanofluids compared with the base mixture using various volume concentrations of nanoparticles. Moreover, very few studies have demonstrated the effect of nanoparticle size-dependence on the specific heat capacity of molten salt nanofluids and disagreement in the results was reported in these studies. Few models based on the conventional specific heat model were developed to determine the specific heat capacity of molten salt nanofluids. These models suffer from the lack of knowledge of many terms in these equations which make them impractical. Different mechanisms were assumed in the literature to explain the abnormal behavior of molten salt nanofluids. Additional theoretical and experimental research studies are required to clarify the mechanisms responsible for specific heat capacity enhancement or deterioration in nanofluids.

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1. Introduction

Recent advances in nanotechnology have led to the development of an innovative class of heat transfer fluids (nanofluids) created by dispersing nanoparticles (10–50 nm) in traditional heat transfer fluids. Nanofluids show the potential to significantly increase heat transfer rates in a variety of areas. A significant number of studies associated with heat transfer enhancement using nanofluids has been conducted by many researchers [1–14]. The thermal properties of nanofluids such as thermal conductivity, specific heat capacity, viscosity, nucleate pool boiling heat transfer coefficient, and critical heat flux have been studied. Khanafer and Vafai [3] presented a critical synthesis of the variants within the thermophysical properties of nanofluids. They demonstrated that the experimental results for the effective thermal conductivity and viscosity reported by several

authors are in disagreement. Correlations for the effective thermal conductivity and viscosity were synthesized and developed in their study in terms of pertinent physical parameters based on the reported experimental data.

While many studies in literature have reported enhanced effective thermal conductivity of nanofluids, specific heat capacity measurements have shown controversial results [3,15–27]. Zhou and Ni [18] presented an experimental study of the specific heat of water-based Al₂O₃ nanofluid. Their results indicated that the specific heat of nanofluids decreased gradually as the nanoparticle volume fraction increased. Das and co-workers [15–17] found reduced specific heats of nanofluids consisting of silicon dioxide, zinc oxide, and alumina nanoparticles, respectively, dispersed in a mixture of water and ethylene glycol as compared to that of the base fluid. Moreover, they experimentally illustrated that the specific heat value of the nanofluid increases moderately with an increase in temperature [17]. Zhou et al. [19] indicated that the specific heat capacity of CuO nanofluid decreased gradually with increasing volume concentration of nanoparticles. Khanafer and Vafai [3] have demonstrated analytically and verified experimentally

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* Corresponding author.

E-mail address: vafai@engr.ucr.edu (K. Vafai).

[19] that the addition of nanoparticles decreases the specific heat capacity of nanofluid at room temperature. Sundar et al. [20] estimated experimentally specific heat capacity values of Al₂O₃ nanofluid at different concentrations and at different temperatures. They have shown that the specific heat of the Al₂O₃ nanofluid decreases with an increase in the nanoparticle volume fraction.

Furthermore, several studies in the literature have demonstrated disagreement in the specific heat capacity results of molten salt doped with nanoparticles [21–27]. Nelson et al. [21] reported that the specific heat of nanofluids (exfoliated graphite nanoparticle fibers suspended in polyalphaolefin at mass concentrations of 0.6 and 0.3%) was found to be 50% higher compared with pure polyalphaolefin. Shin and Banerjee [22] conducted an experimental study showing the effect of dispersing silica nanoparticles (1% by weight) for enhancing the specific heat capacity of the eutectic of lithium carbonate and potassium carbonate (62:38 ratio). A differential scanning calorimeter instrument was used to measure the specific heat of the molten salt eutectic after addition of nanoparticles. They found that the specific heat of the nanofluid was enhanced by 19–24%. Chieruzzi et al. [26] experimentally studied the effect of nanoparticles on heat capacity of nanofluids based on molten salts as PCM for thermal energy storage. The base salt mixture was a NaNO₃–KNO₃ (60:40 ratio) binary salt and the nanoparticles used were silica (SiO₂), alumina (Al₂O₃), titania (TiO₂), and a mix of silica–alumina (SiO₂–Al₂O₃). Thermophysical property measurements were performed by differential scanning calorimetry analysis and the dispersion of the nanoparticles was analyzed by scanning electron microscopy (SEM). Their obtained results showed that the addition of 1.0 wt.% of nanoparticles to the base salt increased the specific heat by 15% to 57% in the solid phase and by 1% to 22% in the liquid phase. The authors referred this enhancement to the high specific surface energies associated with the high surface area of the nanoparticles per unit volume. Surprisingly, concentrations lower and higher than 1.0 wt.% of nanoparticles showed specific heat capacity deterioration compared with base salt mixture of NaNO₃–KNO₃ (60:40). Lu and Huang [27] showed that the specific heat of the molten salt-based alumina nanofluids decreased with increasing particle concentration.

Various correlations were developed in the literature to estimate the specific heat capacity of water-based nanofluids as a function of

temperature and volume fraction of nanoparticles. The size-dependence of Al₂O₃ nanoparticles was ignored. The aim of this investigation is to develop a robust correlation based on the available experimental data for the specific heat of water-based nanofluids as a function of various pertinent parameters and propose possible physical reasons for the deviations between the experimental data and the analytical model-based thermal equilibrium of the specific heat capacity.

One can notice from the cited literature that there are controversial results reported for the specific heat of molten salt nanofluids. Further theoretical and experimental research is needed in order to explain this disagreement in the results. Various possible mechanisms were proposed in the literature without any theoretical or experimental validation. However, there is no robust description of the anomalous behavior of molten salt-based nanofluids including enhancement or deterioration of the specific heat capacity. The specific heat capacity of molten salt-based nanofluids data is still contradictory in various research publications. Another objective of this study is to discuss the variants within different mechanisms that describe the anomalous behavior of the specific heat capacity of nanofluids and propose possible physical reasons for the deviations between experimental and analytical studies.

2. Specific heat capacity of conventional nanofluids

The vast majority of studies on conventional nanofluids have used an analytical model for the specific heat by assuming thermal equilibrium between nanoparticles and the base fluid phase as follows:

$$\begin{aligned}
 (\rho c)_{eff} &= \rho_{eff} \left(\frac{Q}{m \Delta T} \right)_{eff} = \rho_{eff} \frac{Q_f + Q_p}{(m_f + m_p) \Delta T} = \rho_{eff} \frac{(mc)_f \Delta T + (mc)_p \Delta T}{(m_f + m_p) \Delta T} \\
 \rightarrow (\rho c)_{eff} &= \rho_{eff} \frac{(\rho c)_f V_f + (\rho c)_p V_p}{\rho_f V_f + \rho_p V_p} \\
 \Rightarrow c_{eff} &= \frac{(1 - \phi_p) \rho_f c_f + \phi_p \rho_p c_p}{\rho_{eff}}
 \end{aligned}
 \tag{1}$$

where ρ_p is the density of the nanoparticle, ρ_f the density of the base fluid, c_p and c_f are the heat capacities of the nanoparticle and the base

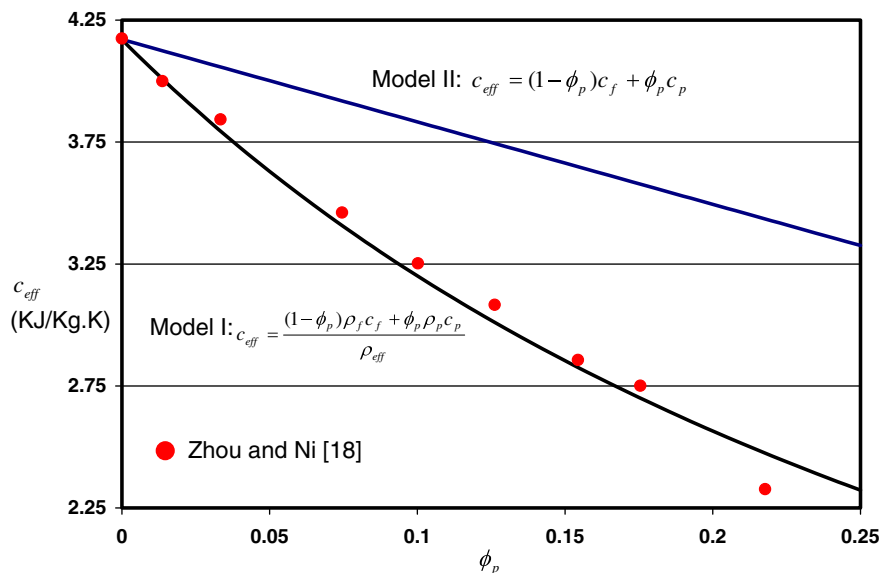


Fig. 1. Comparison of the heat capacity of Al₂O₃–water nanofluid obtained by models I and II given in Eqs. (1) and (2) and the experimental data of Zhou and Ni [18] (Reprinted from Khanafer and Vafai [3] with permission from Elsevier).

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