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Specific heat measurements of five different propylene glycol based nanofluids and development of a new correlation

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ABSTRACT

This paper presents the specific heat measurements of five different nanofluids containing aluminum oxide (Al_2O_3), zinc oxide (ZnO), copper oxide (CuO), titanium oxide (TiO_2) and silicon dioxide (SiO_2) nanoparticles dispersed in a base fluid of 60% propylene glycol and 40% water by mass (60:40 PG/W). The measurements were carried out over a temperature range of −30 to 90 °C, for nanoparticle volumetric concentrations of 0.5% to 6% and for average particle sizes ranging from 15 to 76 nm to evaluate their effects on the specific heat. From comparison, it was found that the existing specific heat correlations were not able to predict the measured experimental values. Therefore, a new correlation was developed to predict the specific heat of measured nanofluids. This new correlation is in good agreement with 610 experimental data points of the five nanofluids with a maximum deviation of −5% exhibited by the Al_2O_3 nanofluid and an average deviation of −0.094%, considering all five nanofluids.

1. Introduction

Nanofluids have become a topic of interest for improving heat transfer performance related to energy savings. Therefore, researchers have been investigating the various thermophysical properties of nanofluids. Most of the researchers gave attention to the thermal conductivity and viscosity properties. However, specific heat (*Cp*) is also a vital characteristic of nanofluids, but currently very limited literature is available on the specific heat of nanofluids. Even less is available for propylene glycol based nanofluids, which prompted our study. Mixtures of glycol and water are commonly used in cold regions for heating and cooling applications. The addition of ethylene or propylene glycol to water depresses the freezing point of the mixture but also decreases its thermal conductivity. Due to ethylene glycol's toxicity, it is not used in residential facilities, where there is a chance of the mixing of this fluid with potable water. Therefore, the non-toxic, propylene glycol is preferred. A mixture of 60% propylene glycol and 40% water (60:40 PG/W) by mass is most commonly used in sub-arctic climate, which has the lowest freezing temperature (−51.1 °C) [1] among glycol and water mixtures. One of the drawbacks with using PG/W is its low thermal conductivity when compared to pure water. This can be overcome by dispersing high thermal conductivity nanoparticles in PG/W to increase the thermal conductivity of the fluid. The addition of particles changes the specific heat, so we have conducted specific heat measurements of 60:40 PG/W based nanofluids with various nanoparticles, e.g., Al_2O_3, ZnO, CuO, SiO_2 and TiO_2. The particle volumetric concentrations were varied from 0.5% to 6% and the temperature ranged from 243 K (−30 °C) to 363 K (90 °C). The objective of this study was to measure the specific heats of PG/W based nanofluids and analyze the data for dependence on various parameters. Next, then compare the measured data with available theory. If the agreement was not good, then develop a correlation to calculate specific heat of PG/W based nanofluids, as a function of temperature, volumetric concentration, particle size, density and specific heat and the base fluid density and specific heat.

1.1. Importance of accurate specific heat measurement

Basic heat transfer equations presented by Bejan [2] show that an accurate value of the specific heat is essential for determining total heat transfer rate $\dot{q}$, heat exchanger effectiveness ε, Nusselt number *Nu* and the thermal diffusivity α. These equations (Eqs. (1)–(4)) summarized below show that they all depend on the specific heat.

$$\dot{q} = \dot{m} \cdot Cp \cdot \Delta T = \varepsilon \cdot C_{min} \cdot (T_{hot\ inlet} - T_{cold\ inlet}) \quad (1)$$

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Nomenclature

Cp	specific heat (J kg^{-1} K^{-1})
Cv	volumetric specific heat (J m^{-3} K^{-1})
d	diameter of particle (nm)
e	effusivity ($Ws^{0.5}$ m^{-2} K^{-1})
K	thermal conductivity (W m^{-1} K^{-1})
Nu	Nusselt number
PG/W	propylene glycol and water
Pr	Prandtl number
T_0	reference temperature (273 K)
Re	Reynolds number
T	temperature (K)

Greek symbols

ρ	density (kg m^{-3})
ϕ	particle volumetric concentration %

Subscripts

bf	base fluid
nf	nanofluid
o	at reference temperature T_0
np	nanoparticle

$$\varepsilon = \frac{1-\exp(-NTU\cdot(1-C^*))}{1-C^*\exp(N-TU(1-C^*))}$$
$$\text{where, } C^* = \frac{C_{min}}{C_{max}},\quad C = \dot{m}c_p,\ C_{min} \text{ is the smaller of C,} \tag{2}$$
$$\text{and NTU} = UA/C_{min}$$

$$Nu = 0.023 * Re^{0.8} * Pr^{0.4}\ (turbulent\ flow) \tag{3}$$

$$\text{where } Pr = \frac{Cp\,\mu}{k}$$

$$\text{Diffusivity } \alpha = \frac{k}{\rho\,Cp} \tag{4}$$

An analysis was performed examining the influence of specific heat on the thermal and fluid dynamic performance of the fluid in a counter flow concentric tube heat exchanger. Using the ε-NTU method outlined by Kays and London [3] and the Eqs. (1)–(3), an analysis was performed with varying specific heat of the cooler fluid to can examine how it affects the Prandtl number, Nusselt number, heat transfer coefficient, overall heat transfer coefficient, heat transfer rate, NTU, effectiveness, and temperature difference. The parameters used in this analysis are outlined in Table 1. The values of the parameters taken where mirrored after a small heat exchanger manufactured by Hilton [4].

The enhancement of the various parameters is calculated using Eq. (5).

$$Parameter\ \% = \frac{Enhanced - Normal}{Normal} \tag{5}$$

The 'Normal' variable refers to the parameter calculated with water, while the 'Enhanced' variable refers to the calculated parameter with some increase in specific heat. The effects of specific heat on various parameters are shown in Fig. 1. First, note the Prandtl number, Nusselt number, heat transfer coefficient and heat transfer rate parameters uses the left axis, while the NTU, effectiveness, and temperature difference of cooler fluid parameters uses the right axis. From the figure, we can see most of the parameters show a fairly linear relationship. The Prandtl number shows a one to one relationship with specific heat. Nusselt number and heat transfer coefficient show a less dependent relationship with specific heat. This is due to the Prandtl number being raised to 0.4. As shown in the figure we can see if specific heat could be increased by 29%, then Nusselt number and heat transfer coefficient would both increase by 10.7%. Overall heat transfer coefficient showed least dependence of specific heat than any of the other parameters as seen when specific heat increases by 29% the overall heat transfer coefficient only increases by 7.5%. This could be due to overall heat transfer coefficient enhancement is also dependent on the heat transfer area and heat transfer coefficients on both sides of the heat exchanger. The NTU parameter shows to decrease with increasing specific heat this is due to the C_{min} (which is usually the cooler fluid) increases equally to increasing specific heat. The decrease of NTU effects effectiveness and temperature difference of the cooler fluid. Even though the temperature difference of the cooler fluid decreases the heat transfer rate increases as seen when specific heat increases by 29% the heat transfer rate increases by 8.4%.

However, there is a void in the knowledge regarding the specific heat of PG/W based nanofluids in the present literature discussion about the previous theoretical and experimental research was provided in the following sections.

Table 1
Parameters for study of specific heat effects on thermal and fluid dynamic performance.

Parameters	Value
Hot inlet (K)	363
Cold inlet (K)	310
Hot fluid velocity (m/s)	0.25
Cold fluid velocity (m/s)	0.25
Fluid	Water
Heat exchanger [4]	Concentric Tube in counter flow
Outer diameter (m)	0.022
Inner diameter (m)	0.012

1.2. Previous work

1.2.1. Theoretical studies

Pak and Cho [5] were one of the first to propose a correlation, Eq. (6), for the specific heat of nanofluid in 1998, based on a mixture of liquid and particle.

$$Cp_{nf} = (1-\phi)Cp_{bf} + \phi Cp_{np} \tag{6}$$

where Cp is the specific heat, ϕ is the volumetric concentration of nanoparticles, the subscripts bf represents base fluid, np the nanoparticles, and nf the nanofluid. This equation does not satisfy the conservation of energy principle. Therefore, Xuan and Roetzel [6] modified Eq. (6) based on conservation of energy of both particles and fluid, assuming thermal equilibrium between two phases.

$$m_{nf}\,Cp_{nf}(\Delta T) = m_{bf}\,Cp_{bf}(\Delta T) + m_{np}\,Cp_{np}(\Delta T) \tag{7a}$$

which can be simplified to

$$\rho_{nf}\,Cp_{nf} = (1-\phi)\rho_{bf}\,Cp_{bf} + \phi\rho_{np}\,Cp_{np} \tag{7b}$$

where the nanofluid density is obtained from the mixture theory.

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_{np} \tag{8}$$