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Investigation of the thermal conductivity of propylene glycol nanofluids and comparison with correlations

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ABSTRACT

Experimental study has been carried out to determine the thermal conductivity of five different nanofluids containing aluminum oxide, copper oxide, zinc oxide, silicon dioxide and titanium dioxide nanoparticles dispersed in a base fluid of 60:40 (by mass) propylene glycol and water mixture. The effect of particle volumetric concentration up to 6% was studied with temperatures ranging from −30° to 90 °C. Experiments showed an increase in thermal conductivity of nanofluids with increasing concentration and temperature. The thermal conductivity of nanofluids showed a strong dependence on particle volumetric concentration, particle size, properties of particles and the base fluid and temperature. Several existing theoretical models for thermal conductivity of nanofluids were compared with the experimental data, but they all showed disagreement. From comparisons, the most agreeable model was selected and a curve-fit constant was derived to match the data of propylene glycol nanofluids. This model expresses the thermal conductivity of nanofluids as a function of Brownian motion, Biot number, fluid temperature, particle volumetric concentration, and the properties of the nanoparticles and the base fluid. This model provided good agreement with 600 experimental data points obtained from five different nanofluids with an average absolute deviation of 1.79 percent. Because of the enhanced thermal conductivity with increasing temperature, nanofluids should be more beneficial at higher temperature applications.

1. Introduction

Heat exchangers are used in a wide range of applications from food processing to residential heating to cooling automobile engines. While heat exchangers have been steadily improved through better materials and increased surface area, the heat transfer fluid remains unchanged. In cold regions of the world the heat transfer fluid is a glycol-water mixture to avoid freezing. Liquids have inherently low thermal conductivity compared to that of a solid and glycols have lower thermal conductivity than water. The thermal conductivity of a liquid can be increased by dispersing solid particles in that liquid. This concept of dispersing solid particles in fluid has existed for years. Researchers first tried to use micro- and millimeter particles suspended in fluids, but encountered problems such as sedimentation, clogging, erosion and high pumping power. With nanoparticles, several of the problems were resolved. Thus, a new class of heat transfer fluids evolved called nanofluids. Nanofluids are defined as suspensions of solid nanoparticles (less than 100 nm) in fluid. Nanofluids can consist of a variety of nanoparticles, such as metals (Al, Cu, Ag, Au), metal oxides (Al_2O_3, ZnO, CuO, TiO_2) and carbon-based materials (nanotubes, graphite, nanodiamonds). The nanoparticles are traditionally dispersed in base fluids such as water (W), ethylene glycol (EG), propylene glycol (PG) and oils. As recommended in ASHRAE [1], in cold regions, it is a common practice to use a mixture of glycol and water for heating and cooling of buildings. The addition of ethylene or propylene glycol to water depresses the freezing point of mixture, but also decreases its thermal conductivity. Due to ethylene glycol's toxicity, it is substituted by propylene glycol in residential buildings, even though propylene glycol has lower thermal conductivity than ethylene glycol. This weakness can be overcome by suspending nanoparticles in PG/W mixture to increase the thermal conductivity of the fluid. More than 50% of the fossil fuel consumed in cold regions like Alaska goes to building heating due to the long duration of the winter season. Therefore, PG/W nanofluids are attractive candidates to reduce fossil fuel burning in the cold regions including the sub-arctic and arctic regions. In spite of this promising application, there has been a lack of studies conducted on the thermal conductivity of PG/W based nanofluids. To fulfill this need, we have conducted measurements of the thermal conductivity of various nanoparticles (Al_2O_3, ZnO, CuO, SiO_2

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Nomenclature

d_p	nanoparticle diameter (m)
c_p	specific heat (J kg^{-1} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
m	empirical constant for different nanofluids
Pr	Prandtl number
R_b	thermal boundary resistance (m^{-2} KW^{-1})
Re	Brownian Reynolds number
T	temperature (K)
T_0	reference temperature (273 K)
PG/W	propylene glycol and water mixture
K	Boltzmann constant 1.381×10^{-23} (J K^{-1})

Greek symbols

α	reciprocal of particle Biot number
μ	viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
ϕ	particle volumetric concentration%

Subscripts

bf	base fluid
nf	nanofluid
p	nanoparticle
w	water

and TiO_2) suspended in 60:40 PG/W (by mass) with concentrations and temperatures ranging from 1% to 6% and −30° to 90 °C, respectively. The 60:40 PG/W mass ratio is chosen because it guarantees freeze protection down to the low temperature of −51.1 °C, per ASHRAE [1].

The objectives of this research were to generate thermal conductivity data of propylene glycol/water based nanofluids and develop a correlation, which are quite limited in the literature. The temperature range of −30° to 90 °C, was selected to be applicable for cold regions such as Alaska. Five different nanofluids based on CuO, Al_2O_3, ZnO, SiO_2 and TiO_2 nanoparticles of particle sizes of 15–76 nm were selected. Nanofluids with particle volumetric concentrations of 0–6%, which is the practical range for good performance were prepared and measured. The goal was to generate a large volume of data with all these variations. And then compare the large dataset to existing correlations for proper prediction of the thermal conductivity of nanofluids. If no correlations match, then develop a new correlation from the experimental data for this class of nanofluids.

A brief discussion about the past research and different models is provided in the following sections. Different theoretical models for predicting thermal conductivity of nanofluids are summarized. Subsequently, comparisons are performed between experimental data of the present study and previous models. These comparisons show that the model of Prasher et al. [2] performs better than other models by coming close to our experimental data collected from six different PG/W based nanofluids, but is not an excellent match, as it was not derived from PG/W base fluid. In order to make it applicable for the PG/W base fluid, a correlation exponent of the Brownian Reynolds number in the Prasher et al. model is modified by rigorous statistical analysis of our 600 experimental data points. This new constant improves the accuracy of the model and makes it applicable for PG/W based nanofluids.

1.1. Previous work

1.1.1. Experimental

In the 19th century, Maxwell [3] developed a theoretical model to predict thermal conductivity of solid particles in liquids. Maxwell's model worked for micro- and millimeter particles, but under-predicted the thermal conductivity of nanofluids. Thermal conductivity measurements of nanofluids started with Masuda et al. [4] in the year 1993. By dispersing nanoparticles in water, they observed changes in its thermal conductivity. They dispersed Al_2O_3, TiO_2 and SiO_2 nanoparticles in water and observed thermal conductivity increased with increasing particle concentration for Al_2O_3 and TiO_2. They did not observe any change in thermal conductivity with SiO_2 nanoparticles, possibly due to low particle volumetric concentration and low thermal conductivity of SiO_2.

Lee et al. [5] measured thermal conductivity of Al_2O_3 and CuO nanoparticles suspended in ethylene glycol and water (EG/W) using a transient hot wire method. They found that a 4% volume concentration of CuO nanoparticles increased the thermal conductivity by 20%. They determined that thermal conductivity increased linearly with volume concentration. Eastman et al. [6] reported higher thermal conductivity with Cu/EG nanofluids compared to that of pure EG and CuO/EG mixtures. A volumetric concentration of 0.3% Cu in EG improved the thermal conductivity by 40% compared to the base fluid. Choi et al. [7] dispersed multiwall carbon nanotubes (MWCNT) in oil and reported 160% enhancement of the thermal conductivity for a particle volume concentration of 1%. They observed a nonlinear relationship between the thermal conductivity enhancements and the nanotube concentration. This phenomenon was also found with oxide and metallic nanoparticles.

The thermal conductivity of SiC particles dispersed in EG/W measured by Xie et al. [8] showed a 22.9% enhancement at a 4% volumetric concentration. Das et al. [9] studied the effects of temperature (21 °C–51 °C) on thermal conductivity of nanofluids with volumetric concentrations varying from 1% to 4%. Their choice of nanofluids consisted of Al_2O_3 and CuO dispersed in water. They found that for a 1% concentration of CuO, the thermal conductivity of the nanofluid (k_{nf}) was enhanced from 6.5% at 21 °C to 29% at 51 °C. Wang et al. [10] described a model considering the surface adsorption between nanoparticles and fluid. They compared their model with experimental data of 50 nm CuO/Water with a volume concentration less than 0.5%. Murshed et al. [11] measured thermal conductivity of TiO_2/Water nanofluids. They found that their experimental data did not match with existing theoretical models. Putnam et al. [12] measured the thermal conductivity of C-60 and C-70 suspended in toluene with volume concentration less than 1%. Similarly, they measured Au particles suspended in ethanol. They found no significant increase in k_{nf} with concentrations less than 1%. They said that effective medium theory couldn't predict the thermal conductivity of nanofluids with volume concentrations less than 1%. Liu et al. [13] presented a chemical reaction method to produce CuO nanoparticles. Utilizing their nanoparticles, they found that k_{nf} was enhanced by 23.8% for 0.1% volume concentration for CuO/Water nanofluid. Li et al. [14] performed experiments on an Al_2O_3/Water nanofluid with volume concentration up to 6% using transient and steady state methods. They did not notice any difference in measured values between the two methods. So, they concluded that their thermal conductivity values of nanofluids are independent of measurement technique.