



A new model for density of nanofluids including nanolayer[☆]



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ABSTRACT

Nanofluids, which are suspension of nanoparticles in conventional heat transfer fluids, attracted researchers while they show higher thermal conductivity and specific heat capacity. The important parameters that have influence on thermal fluid properties of nanofluids include the volume fraction of the nanoparticles, temperature, density of fluid base and nanoparticles, nanoparticles size, nanolayer, thermal conductivity of base fluid and particles, and pH. Nanolayer is an approved interfacial layer between particles and base fluid involved in some of modeling for effective thermal conductivity and effective viscosity of nanofluids. Therefore, this layer must effect on other properties of nanofluids such as density. In this study, investigation into the density of nanofluids has done experimentally. The nanofluids investigated for density measurements consist of SiO₂–water, MgO–glycerol, CuO–glycerol, and SiO_x–ethylene glycol/water for a range of 1%–6% volume fraction as well as a temperature range of 10 °C to 40 °C. The results show that mixture model for density of nanofluids (density of nanofluid = density of base fluid multiply by volume fraction of base fluid + density of nanoparticles multiply by volume fraction of nanoparticles), which is generally cited in literature, has higher value than experimental data. For higher volume fraction of nanoparticles, the gap between the experimental results and the mixture model gets more. This is due to the nanolayer that also shows nanolayer density can be between void and the base fluid density. Therefore, based on the experimental data, a new model for density of nanofluids developed, which includes nanolayer. It was also found that the amount of the void in the nanolayer is more sensitive to nanoparticle size and not to base fluids or nanoparticles material.

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1. Introduction

Thermal and physical properties of fluids play a vital role in developing heat transfer equipment with high efficiency. Conventional heat transfer fluids like water, engine oil, glycerol, and ethylene glycol (EG) have limitations on heat transport. On the other hand, rapid development of technology and generating enormous amount of heat in new heat transfer systems such as microelectromechanical machines and high efficiency heat exchangers require enhanced heat transfer fluids. The main factor in the efficiency of thermal transport of a heat transfer fluid is the thermal conductivity. However, conventional heat transfer fluids have poor thermal properties comparing with solids. A way to improve thermal conductivity of the conventional heat transfer fluids is to disperse solid particles into them. The idea of dispersing micrometer- or millimeter-sized solid particles in fluids can be traced back to Maxwell theoretical work in 1873 [1]. Numerous theoretical and experimental studies have been done to increase thermal conductivity properties of

fluids by dispersing millimeter- or micrometer-sized particles in fluids. Although adding these solid particles may improve thermal conductivity of conventional heat transfer fluids, they could cause clogging, wearing, and significant pressure drop as well as stability and sedimentation problems. By using nanometer-sized particles (nanoparticles), Choi [2] proposed employing nanofluids, which are solid–liquid composite materials, including nanoparticles suspended in different heat transfer fluids (base fluids). Numerous studies have been done to evaluate nanofluids properties to introduce them into industrial design and applications. Volume fraction of the nanoparticles, temperature, nanoparticle size, nanolayer, thermal conductivity of the base fluid, pH of the nanofluid, and the thermal conductivity of the nanoparticles have been pointed out by several authors as important parameters effecting on properties of nanofluids [1,3,4]. The density of a nanofluid is one of the most important physical properties of the nanofluid (as a fluid), which has not been investigated deeply to date. Classical mixture density model (linear approach for densities and volume fractions) for conventional solid–liquid mixture has been used by almost all of the researchers [5–45] when calculating nanofluids' density, which has not considered nanolayer. However, nanolayer as a fact is an approved layer existing between a nanoparticle and the base fluid [1] in a nanofluid.

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Nomenclature

EG	ethylene glycol
m	mass, g
n	approximate number of nanoparticles
r	radius, nm
t	equivalent thickness, nm
V	volume, cm^3

Greek symbols

ρ	density, kg/m^3
φ	volume fraction

Subscript

p	nanoparticle
f	based fluids
nf	nanofluids
v	void

In this paper, it is investigated that the density of four different nanofluids consist of SiO_2 -water, MgO -glycerol, SiOx -EG 60%-water 40%, and CuO -glycerol experimentally as well as the influences of nanolayer on nanofluid density to develop a new model. Experimental works have been done to measure density of the nanofluids accurately. The result of the experimental density measurements shows a gap between the experimental data and the mixture model approach. The gap increases by increasing the volume fraction of the nanoparticles, which shows nanolayer plays a role. Therefore, a new model has been developed for calculation of nanofluid density including nanolayer.

2. Solid-liquid interfacial layer

Some theoretical analyses and molecular simulations have been done to investigate properties of liquids at solid-liquid interfaces. The probing structure of these interfaces was difficult, and the theoretical analyses were not verified experimentally. Henderson and van Swol [46] analyzed the properties of a fluid in presence of a hard wall. In their research, theoretical analysis has been done and the results of molecular dynamic simulation of hard sphere fluid bounded by a pair of planar wall were used. They predicted density oscillation of molecules close to the solid-liquid interface from the simulation results. They also discussed the presence of layering of fluid molecules in the interface of planar wall and fluid. Thompson and Robbins [47] worked on epitaxial order of fluid near solids. They showed the degree of slip on solid is directly related to wall-fluid interaction. They indicated that at large interactions, substantial epitaxial ordering happens, and the first or two fluid layers become locked to the wall. Huisman et al. [48] investigated structure of solid-liquid interface with a synchrotron X-ray diffraction method. The method can be effective because of deep penetration of X-rays in matter. The specular reflectivity was measured in Ga/diamond (111)- 2×1 interface. They reported exponentially decaying density oscillation in the Ga/diamond interface. In their experiment, liquid gallium was super-cooled so the layering could be consequence of local freezing.

In 1998, Huisman and van der Veen [49] introduced a model for the density profile in the solid-liquid interface by measuring specular X-ray reflectivity of liquid gallium around solid diamond. They offered a model for interface structure of gallium atoms closed to surface of diamond, forming as solid like layer with high electron density.

Doerr et al. [50] studied thin liquid hexane films on silicon with specular and off-specular X-ray scattering. Their experimental results show

one solid-liquid interfacial layer extended to 4 nm from the interface. They concluded that the ordering of an interfacial layer in solid-liquid interface is independent of liquid film thickness. Yu et al. [51] studied interfacial properties of thin liquid film of TEHOS (tetrakis(2-ethylhexoxy)silane) on silicon (111) substrate by X-ray reflectivity. They showed that three electron density oscillations near the interface with a period of about 1 nm, which is consistent with molecular density. In 2000, Yu et al. [52] studied interface layering of TEHOS as a normal liquid at room temperature, which was higher than the freezing point. Samples of various thicknesses had been tested and density oscillations of a period of 1 nm independent of the film thicknesses reported. Yu et al. [53] used synchrotron X-rays to study solid-liquid interface of three different liquids on silicon substrates. They studied ultrathin (45–90 Å) and thick (5000 Å) liquid films and found that the liquid molecules form 3–6 layers at the interface with plane close to molecular dimensions.

According to the above-mentioned studies, there is no doubt in presence of liquid ordering in the solid-liquid interfaces. However, there are no certain models for predicting the interfacial layer properties.

3. Experimental procedure and material

The Rudolph DDM 2911 laboratory density meter, which is one of the most capable measuring instruments with the accuracy of $0.00005 \text{ g}/\text{cm}^3$, has been used to measure nanofluid density in the temperature range.

In these experiments, SiO_2 , SiOx , CuO , and MgO nanoparticles from nanostructured and amorphous material companies with particle size and density of 80 nm– $2.40 \text{ g}/\text{cm}^3$, 20 nm– $2.40 \text{ g}/\text{cm}^3$, 40 nm– $6.40 \text{ g}/\text{cm}^3$, and 40 nm– $3.58 \text{ g}/\text{cm}^3$, respectively, have been used. Deionized water, glycerol, and a 60:40 (in weight) EG-water mixture were used as base fluids to produce SiO_2 -water, MgO -glycerol, SiOx -EG 60%-water %, and CuO -glycerol nanofluids. The deionized water, EG, and glycerol were obtained from Merck South Africa Company, with density of 0.99704, 1.115, and $1.261 \text{ g}/\text{cm}^3$ at 25 °C, respectively.

Sample preparation were carried out using a very sensitive mass balance with 0.1 mg readability and accuracy of 0.2 mg and a dispenser with 0.01 ml readability and accuracy of 0.005 ml. Nanoparticles were dispersed with different volume concentrations (1%, 2%, 4%, and 6%) in the base fluids. The mixtures were stirred and agitated thoroughly and by using ultrasonicator to find homogenous nanofluids. The nanofluids of 60 ml were stirred and sonicated (40 kHz, 150 W) continuously for 1 to 2 h depending on the base fluid and volume fractions. During the sonifications, the temperature of the samples increases, which may cause the evaporation of the base fluid; therefore, the samples were placed in a thermostatic constant temperature bath during sonication. All samples prepared before the density measurements and then each sample was measured by DDM 2911 Digital Density Meter. The density meter was calibrated with air and deionized water according to the user manual before starting nanofluids' density measurements. The density meter set to measure the samples for 10 °C, 20 °C, 30 °C, and 40 °C. The tube inside the density meter was washed by deionized water and acetone after completion of each sample measurement and dried by an air pump which was assembled inside the density meter.

4. Model development, results, and discussion

Four different kinds of nanofluids were used for density measurement: SiO_2 -water, SiOx -EG/water, CuO -glycerol, and MgO -glycerol. These nanofluids were chosen while they show more stability (without using surfactant) concerning the previous achievements in this laboratory [58–61]. However, the density measurements have

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