Effect of nanomaterial properties on thermal conductivity of heat transfer fluids and nanomaterial suspension

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Abstract Energy has been rated as the single most important issue facing humanity in the current as well as next 50 years. Securing clean energy has become the top priority of most developed countries. Considering the rapid increase in energy demand worldwide, intensifying the heat transfer process and reducing energy loss due to ineffective use have become an increasingly important task. Fundamentally, energy conversion and transportation occur at atomic or molecular levels, Nanoscience and nanotechnology are expected to play a significant role in revitalizing the traditional energy industries and stimulating the emerging renewable energy industries.

Nanofluid is a modern engineering heat transfer fluid with superior potential for enhancing the heat transfer performance of conventional fluids such as water, ethylene glycol and oils. It is consisting of solid nanoparticles with sizes typically of 1–100 nm suspended in base fluids. Many attempts have been made to investigate its important thermal properties, i.e. thermal conductivity; however, no definitive agreements and idea have emerged about this property. This article reports the effect of different nanomaterial on the thermal conductivity enhancement of nanofluids experimentally. TiO_2, Fe_3O_4 and Al_2O_3 nanoparticles dispersed in water and ethylene glycol with volume concentration of 1 – 7.5 vol. % is used in the present study. A transient hot-wire apparatus (KD2 pro) is used for measuring the thermal conductivity of nanofluids. The results show that all the heat transfer fluids show an increase in thermal conductivity with the addition of nanoparticles in it. The measured thermal conductivity of nanofluids increased as the particle concentrations increased and are higher than the values of the base liquids. This confirms the effect of volume concentration of nanoparticles on the thermal conductivity enhancement.

Keywords: Thermal conductivity, Enhancement, Nanofluids, Sonication, Maxwell and H – C model,

1. Introduction

Nanofluids are liquid suspensions of particles with at least one of their dimensions smaller than 100 nm. After the pioneering work of Choi (1995), nanofluids become a new class of heat transfer fluids. Their potential benefits and applications in many industries from electronics to transportation have attracted great interest from many researchers both experimentally and theoretically. Efforts in research in the nanofluids area have increased annually since 1995; more than 450 nanofluid-related research papers were published in *Science Citation Index* journals. Very recent papers Yu (2008) and Murshed (2008) provide a detailed literature review of nanofluids including synthesis, potential applications, and experimental and analytical analysis of effective thermal conductivity, effective thermal diffusivity, and convective heat transfer. Published results show an enhancement in the thermal conductivity of nanofluids, in a wide range even for the same host fluid and same nominal size or composition of the additives. Since this enhancement cannot be explained with the existing classical effective thermal-conductivity models, such as the Maxwell (1881) or Hamilton–Crosser (1962) models, this also motivates a wide range of theoretical approaches for modeling these thermal phenomena. Reported results show that the particle volume concentration, particle material, particle size, particle shape, base fluid material, temperature, additive, and acidity play an important role in enhancement of the thermal conductivity of nanofluids. The effect of the fluid temperature on the effective thermal conductivity of nanoparticle suspensions was first presented by Masuda et al (1993). They reported that for water-based nanofluids, consisting of SiO_2 and TiO_2 nanoparticles, the thermal conductivity was not much more temperature dependent than that of the base fluid. Contrary to this result, Das et al. (2003) observed a two-to-four fold increase in the thermal conductivity of nanofluids, containing Al_2O_3 and CuO nanoparticles in water, over a temperature range of 21˚C to 51˚C. Several groups Patel (2003), Wen (2004), Chon (2005), Li (2006), Wang (2007), Murshed (2008), Mintsa (2008) reported studies with different nanofluids, which support the result of Das et al. (2003). Recently, Khedkar et.al (2012) shows effect of Sonication time and elapsed time on the thermal conductivity of CuO nanoparticles with water and ethylene glycol based composition. For the temperature dependence of the relative thermal conductivity (ratio of effective thermal conductivity of nanofluids to thermal conductivity of base fluid), although a major group of publications showed an increase with respect to temperature, some of the other groups observed a moderate enhancement or temperature independence (Masuda 1993, Venerus 2006, Zhang 2006, Yang 2006, Timofeeva 2007].

2. Experimental

Different types of nanofluids composition were prepared by dispersing measured amount of Al_2O_3 Fe_3O_4 and TiO_2 nanoparticles in a measured amount of de-ionized water and ethylene glycol. The nanoparticles were weighed using Simazdu ADU220D model having high precision, whose accuracy is 1×10^{-3} g. The suspensions were mixed with magnetic stirrer for 4 hours, followed by ultrasonic vibration with the help of the sonicator (Chromtech ultrasonicator, 1500 watts) for about 1 hour to obtain a uniform suspension. In order to investigate the effect of nanoparticle concentration, nanofluids with 0.5, 1, 2, 3, 4, 5, and 7.5 % by volume were prepared. Measurements were carried out at room temperature. The thermal conductivity of nanofluids was measured using a KD2 thermal conductivity analyzer (Decagon Device Inc. USA), which is worked on principle of the transient hot wire method. The KD2 meter is equipped with a probe of dimension 60 mm long and 0.9 mm in diameter, in which a heating element and a thermo-resistor are set in. The probe is connected to a microprocessor for controlling the heat addition and recording the measurements necessary for the calculation of the thermal conductivity.

3. Results and discussion

Figure 1 shows the effective thermal conductivity and percent enhancement of Al_2O_3 nanofluids as a function of nanoparticle volume concentration at room temperatures. As expected, it is observed that the thermal conductivity of nanofluids increases with an increase in the particle volume concentration. The results show that the thermal conductivity of nanofluids is nearly linear increases as the volume fraction increases.

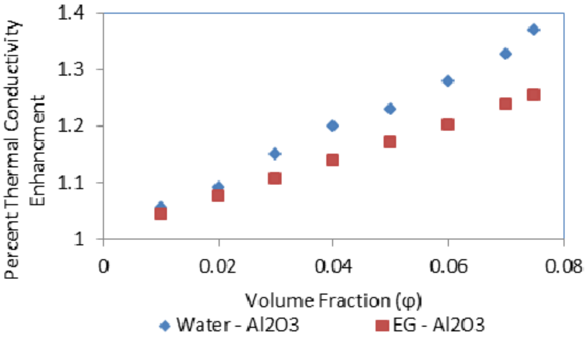

Figure 1 Effective Thermal conductivity and percent enhancement of Al_2O_3 – water /EG nanofluids versus nanoparticle volume concentration at room temperatures

The percent enhancement in effective thermal conductivity of TiO_2 and Fe_3O_4 nanofluids as a function of particle volume concentration at room temperatures is shown in Figure 2 and 3 Similar to Al_2O_3, it is observed that the thermal conductivity of nanofluids is linearly increases as the volume concentration of nanoparticles in to base fluids.

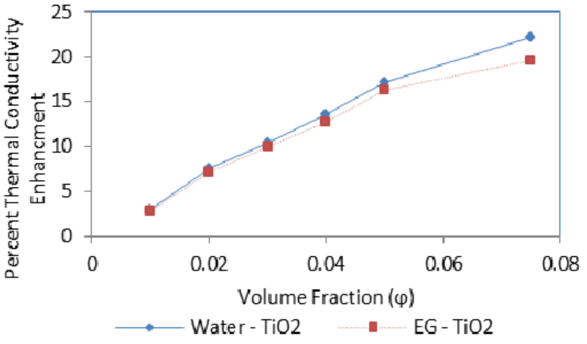

Figure 2 Percent enhancement in Effective Thermal conductivity of TiO_2 – water /EG nanofluids versus nanoparticle volume concentration at room temperatures

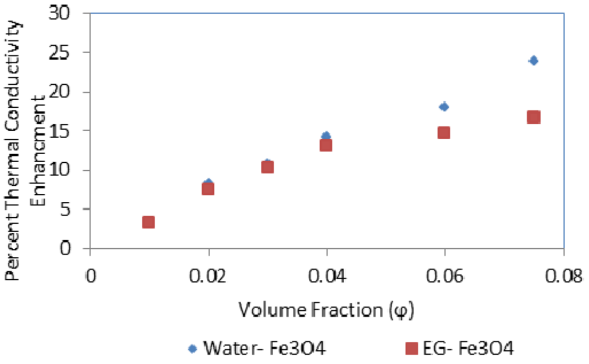

Figure 3 Percent enhancement in Effective Thermal conductivity of Fe_3O_4 – water/EG nanofluids versus nanoparticle volume concentration at room temperatures

Figure 4 shows on the same plot the thermal conductivity of Al_2O_3 Fe_3O_4 and TiO_2 nanofluids at room temperature to better compare the influence of the type of nanoparticles. The results clearly show that the increase in thermal conductivity is significantly larger for Al_2O_3 nanofluids, and the increase is more definite as the particle concentration increases. For example, an increase in thermal conductivity of 3% by volume concentration is about 10% for TiO_2 nanofluid while it is about 33% for Al_2O_3 nanofluid. The particle size of both TiO_2 and Al_2O_3 nanoparticles are 6 nm and 35 nm respectively, but thermal conductivity difference is probably due to higher thermal conductivity of Al_2O_3 nanoparticles and not influenced by the size of nanoparticles in our case. The thermal conductivity of Al_2O_3 nanoparticles is 40 W/m K and that of TiO_2 is 8.4 W/m K.

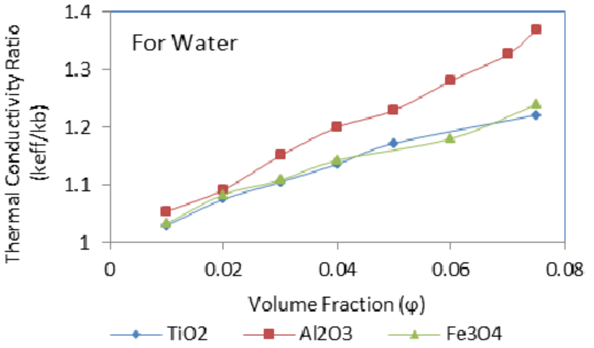

Figure 4. Thermal conductivity ratio (k_{eff}/k_b) of the TiO_2, Fe_3O_4 and Al_2O_3 nanofluids as a function of particle concentration.

Various models by different research group have been developed to predict the thermal conductivity of base fluids containing nanoparticles. Maxwell model (1881) is one of the first models, which predicts the thermal conductivity of suspension of fluids and particles. In general, models are developed with the assumption of continuous matter. At the nanometer level, assumption breaks down because the size of liquid molecules is on the same order as the size of particles suspended within it. After this also Maxwell, model is famous for predicting the thermal conductivity of nanofluids. This model accurately measures the thermal conductivity of dilute suspensions of large and spherical particles. Moreover, it predicts the thermal conductivity of nanofluids, Keff mathematically as follows,

$$k_{eff,Maxwell} = \frac{k_p + 2k_l + 2(k_p - k_l)\emptyset}{k_p + 2k_l - (k_p - k_l)\emptyset} k_l \qquad (1)$$

where k_l is the thermal conductivity of the base fluid, k_p is the thermal conductivity of the particle, and $\emptyset$ denotes the volume fraction or concentration of the dispersed particles. A related model is that of Hamilton and Crosser (1962). The H-C model, a modification of Maxwell's original model, can be used to predict the thermal conductivities of suspensions containing large, nonspherical particles. The HC model mathematically expressed by

$$k_{eff,H-C} = \frac{k_p+(n-1)k_l+(n-1)(k_p-k_l)\emptyset}{k_p+(n-1)k_l-(k_p-k_l)\emptyset}k_l \qquad (2)$$

where n is the shape factor of the particles (n) 3 for a spherical particle. Recently, models have been developed to account for the enhanced thermal conductivities shown by nanofluids. One such model was developed by Bruggeman [20].

$$k_{eff,Bruggaman} = \frac{1}{4}[(3\emptyset-1)k_p + (2-3\emptyset)k_l + k_l\sqrt{\Delta}/4$$

$$\Delta = [(3\emptyset-1)^2(\frac{k_p}{k_l})^2 + (2-3\emptyset)^2 + 2(2+9\emptyset-9\emptyset^2)(\frac{k_p}{k_l})$$

(3)

where, k_{eff} is the effective thermal conductivity of liquid with particle suspension, φ is the volume fraction of particles, and k_l and k_p are the thermal conductivities of the base fluid and the particle, respectively.

Figs. 5 and 6 clearly illustrates that none of the models accurately predict the experimentally determined values of thermal conductivity. The increments in thermal conductivities predicted by the Maxwell models are linear with the increments in volume fractions of nanoparticles, and its values are lower than the experimentally determined values.

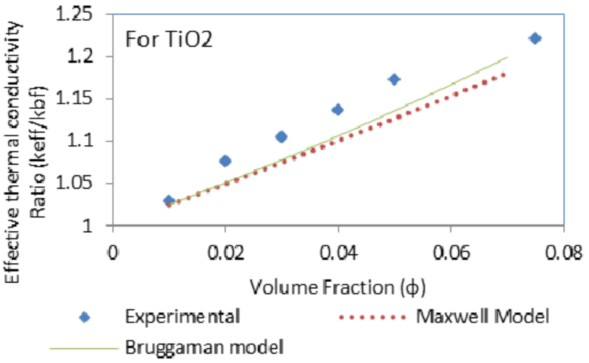

Figure 5 Experimental data for the relative thermal conductivity enhancement of TiO_2 nanofluids from this study, compared to models.

These models neglect effects associated with the nanoparticle–fluid interface and the size of the nanoparticles (i.e. They consider only the thermal conductivities of the base fluid and particles). Experimental thermal conductivity is around 10% higher for TiO_2 water 4 % composition than that of the theoretical predictions of the Bruggeman models, whereas for Al_2O_3 water nanofluids it can be seen from Fig. 5 that the experimental thermal conductivity is about 15% higher than that of the theoretical predictions of the Bruggeman models for a sample of 0.4 volume fraction nanoparticles in deionized water. By considering interactions between randomly distributed particles the Bruggeman model shows a better prediction than that of Maxwell models.

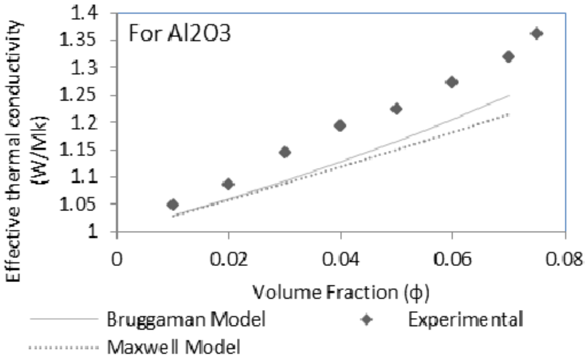

Figure 6 Experimental data for the relative thermal conductivity enhancement of Al_2O_3 nanofluids from this study, compared to models.

4. Conclusion

The work concentered on thermal conductivity of deionised water based TiO_2 and Al_2O_3 nanoparticles and its various compositions. A KD2 thermal conductivity analyzer was used to measure the thermal conductivity of TiO_2 Fe_3O_4 and Al_2O_3 nanofluids in the range of 1 – 7.5 % volume concentration of nanoparticles at room temperature. Basic observation confirms that the addition of nanoparticles into base fluids increases overall thermal conductivity of composition. For example, at volume concentration of 2 % composed of both TiO_2 and Al_2O_3 nanofluids 7.5 % and 8.9 % enhancement found, whereas 13.6 % and 20 % for 4 % respectively. It is also observed that Al_2O_3 nanoparticles – water composition showing higher enhancement than TiO_2 nanoparticle – water composition. TiO_2

nanoparticles have lower nanoparticles size, then also it shows lower enhancement since property of material affects the thermal conductivity of nanofluids composition. From comparison of thermal conductivity enhancement it is observed that theoretically measured values are different from experimentally calculated.

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