An Experimental Determination of Temperature-Dependent Thermal Conductivity of Cyclohexane-Based Nanofluids

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ABSTRACT

This paper presents an experimental determination of temperature-dependent thermal conductivity of cyclohexane-based nanofluids. Nanofluid samples were prepared with sodium-oleate-stabilized copper oxide nanoparticles for various particle loadings. The thermal conductivity of nanofluids was measured by utilizing the transient plane source technique. The measurement temperature was varied from 10 to 50°C with an increment of 10°C. It was shown that thermal conductivity of cyclohexane-based nanofluids is inversely proportional to temperature and is increased almost linearly as more nanoparticles are introduced. The enhancement becomes more pronounced with raising temperature, probably due to the more intensive diffusion of nanoparticles at higher temperatures.*

Keywords: nanofluids, cyclohexane, CuO nanoparticles, thermal conductivity, transient plane source technique

1 INTRODUCTION

In a recent review, comprehensive data on thermal conductivity of nanofluids were gathered by Yu et al. 0 for a great number of combinations of base liquids and nano-structured additives. It was shown that water and ethylene glycol have been the dominant base liquids as both are commonly used as heat transfer fluids. The enhanced thermal conductivity of nanofluids justifies their utilization as promising high-performance heat transfer fluids. Prior research on nanofluids have therefore been focused on single-phase heat transfer phenomena.

However, as recently proposed by Khodadadi and Hosseinizadeh [2], further utilization of nanofluids as superior phase change materials (PCM), referred to as nanoparticle-enhanced PCM (NePCM), to store thermal energy has attracted growing attention. Depending on the various temperature ranges of thermal energy storage applications, this emerging utilization demands research on nanofluids with base liquids other than water and ethylene glycol. For example, for service temperature between 0 and 100°C, hydrocarbons with high latent heat of fusion have long been considered the favorable candidate [3]. Although the calorimetric properties, e.g., latent heat of fusion and specific heat capacity, of nanofluids become rather important when it comes to solid-liquid phase change applications, the enhancement of thermal conductivity due to the presence of nanoparticles (or other nano-structured materials) is still of primary interest.

As an example, a cyclic alkane, cyclohexane (C_6H_{12}), that could be used for cold storage was chosen as the base liquid in the present study. Copper oxide (CuO) nanoparticles were utilized as the nano-structured additives. Temperature-dependent thermal conductivity of the cyclohexane-based nanofluids was measured experimentally for various particle loadings.

2 EXPERIMENTAL DETAILS

2.1 Preparation of Nanofluids

The CuO nanoparticles, which are stabilized by sodium oleate, were synthesized and provided by Clary and Mills [4]. A transimission electron microscopy (TEM) image, as shown in Figure 1, displays that the CuO nanoparticles were nearly spherical with an average diameter of approxiately 10 nm.

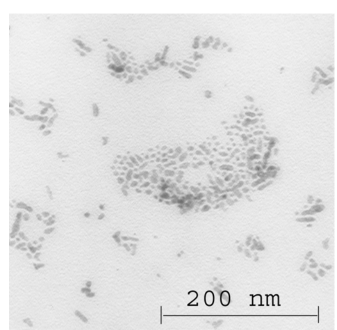

Figure 1: TEM image of the synthesized sodium-oleate-stabilized CuO nanoparticles [4].

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The nanofluids were prepared by dispering desired amounts of the synthesized sodium-oleate-stabilized CuO nanoparticles into a 99.96% cyclohexane (Pharmco-Aaper, Brookfield, CT) at room temperature, then stirring rigorously on a hot-plate magnetic stirrer (SP131325Q, Thermo Fisher, Dubuque, IA) at 60°C for 30 minutes. As illustrated in Figure 2, six opaque ink-like nanofluid samples were prepared with various volume fractions, i.e., 0.063, 0.125, 0.25, 0.5, 1.0, and 2.0 vol%. It is noted that the samples were prepared in mass fractions and a conversion to volume fractions was performed based on the known densities of cyclohexane (779 kg/m^3) [5] and bulk CuO (6,310 kg/m^3) [6]. In the calculations, the effect of the presence of the surfactant was neglected. Furthermore, as observed in Figure 2, the samples gradually become less stable as the particle loading is increased. Desirable long-term stability of hydrocarbon-based colloids with these sodium-oleate-stabilized CuO nanoparticles was proven by Clary and Mills [4], although in this study a thin layer of precipitated nanoparticles was found in the bottom of the container for the most concentrated sample (2.0 vol%). However, for particle loading below 1.0 vol%, no significant precipitation was visually observed.

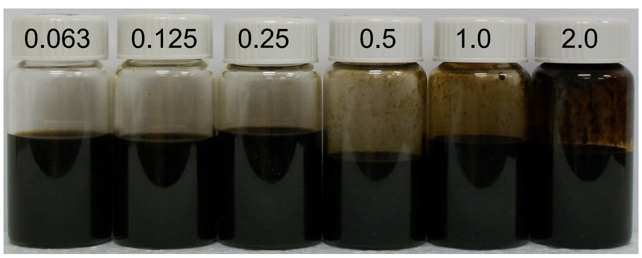

Figure 2: Photos of cyclohexane-based nanofluid samples with various volume fractions (vol%) of CuO nanoparticles.

2.2 Experimental Set-up and Procedure

The measurements of thermal conductivity of the nanofluid samples were performed by employing a Hot Disk Thermal Constants Analyser (TPS 500, Hot Disk AB, Gothenburg, SWEDEN). The principle of operation of this instrument is the transient plane source (TPS) technique [7], which enables a rapid measurement within several seconds. Obviously, transient methods are appropriate for measuring thermal conductivity of liquids. Since natural convection will incur as heating is applied, measurements must be completed within a short time period in order to avoid the onset of natural convection. The specified accuracy and reproducibitiy of this instrument are 5 and 2%, respectiviely. These features were assured by testing the instrument with deionized water at room temperature (~21°C). Two individual tests, each of which had ten runs, were conducted and the average values were determined to be 0.5971 W/mk ± 0.36% and 0.6012 W/mk ± 0.50%, which were both in excellent agreement with the well-documented value of 0.6 W/mK.

A programmable circulator (TC-502P, Brookfield Engineering, Middleboro, MA) with a stability of only 0.01°C was used to precisely control the measurement temperature. By directly connecting its input and output ports, the circulator served as a constant temperature bath. A distilled water/ethylene glycol 1:1 mixture was used as the bath fluid. In order to place the nanofluid samples in the reservior of the bath, a cylindrical aluminum (Al) block was fabricated to serve as a sample holder. The low thermal resistance of this pure Al block allows a rapid response to the variation of the bath temperature. Four cylindrical holes, each of which accommodates a glass container with a typical volume of 6 mL, were drilled on the top end of the block. The thin gap between the Al sample holder and the glass container was filled with the bath fluid to reduce the contact resistance. A nanofluid sample was poured into the glass container and the TPS sensor was suspended vertically and submerged into the sample, as demonstrated in Figure 3.

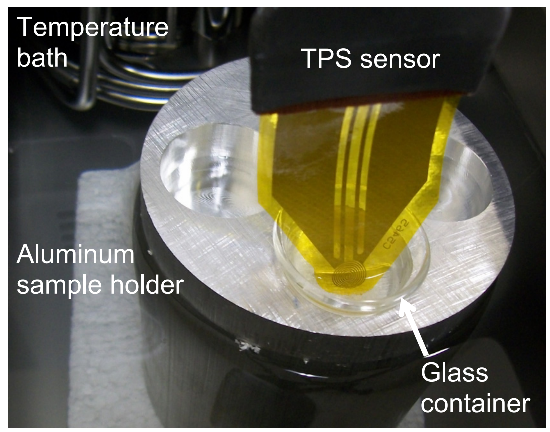

Figure 3: Experimental arrangement for the TPS measurement system.

A lid, which is not shown in Figure 3, was used to cover the opening of the glass container during the measurements. This further suppressed convective and radiative heat losses and gains from the environment. At each of the measurement temperatures of interest, the measurements were started 30 minutes after the bath temperature had reached the set point. In addition, the wait time period between two consecutive measurements was at least 2 minutes, which was considered to be long enough to have thermal equilirium rebuilt in the samples. For each of these samples, 10 measurements were carried out at each temperature and the average thermal conductivity was obtained with a standard deviation less than 0.1%.

3 RESULTS AND DISCUSSION

In view of the freezing and boiling points of cyclohexane, which are 6.5 and 80.5°C, respectively, the measurement temperature was varied from 10 to 50°C with an increment of 10°C. The measured thermal conductivity as a function of temperature is presented in Figure 4.

It is observed that thermal conductivity of cyclohexane-based nanofluids is inversely proportional to temperature, which also agrees with previous data for cyclohexane [8]. This decreasing trend is almost linear for the most dilute sample (0.063 vol%). Actually, since the particle loading is extremely low, this sample may be considered as a baseline case of particle-free cyclohexane. However, as the particle loading is further increased, nonlinear dependence on temperature becomes more pronounced.

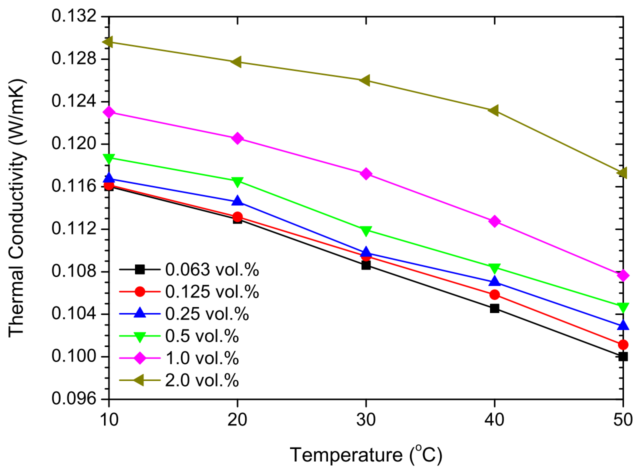

Figure 4: Measured thermal conductivity of cyclohexane-based nanofluids as a function of temperature.

On the other hand, at constant temperatures, thermal conductivity enhancement is proportional to the particle loading. Since the particle loading of these samples is increased by a factor of 2, the observe enhancement of thermal conductivity also grows nonlinearly. It is noted that the enhancement becomes more significant at higher temperatures. For example, at 40 and 50°C, thermal conductivity of the 2.0 vol% sample is greater than that of the 0.063 vol% sample by approximately 15%, whereas the enhancement is only 12% at 10°C. In addition to the static enhancement that could be predicted by the effective medium theory, e.g., the Maxwell's equation, the enhanced dynamic contribution due to the more intensive diffusion of nanoparticles, e.g., Brownian and thermophoretic motions, is likely responsible for the more pronounced enhancement of thermal conductivity at higher temperatures.

4 CONCLUSIONS

Cyclohexane-based nanofluids with sodium-oleate-stabilized CuO nanoparticles were prepared for various particle loadings and their thermal conductivity was measured by utilizing the transient plance source technique. The measurement temperature was varied from 10 to 50°C at every 10°C. It was shown that thermal conductivity of cyclohexane-based nanofluids decreases with increasing temperature. The trend is almost linear at low particle loadings and becomes apparently nonlinear when the concentration of nanoparticles is above 0.5 vol%. At constant temperatures, thermal conductivity enhancement became more pronounced as the particle loading was increased. In addition, the enhancement was observed to be more marked at higher temperatures.

ACKNOWLEDGEMENTS

This material is based upon work supported by the US Department of Energy under Award Number DE-SC0002470. The first author acknowledges financial support provided by the Alabama EPSCoR under the Graduate Research Scholars Program (Rounds 5 and 6). Thanks are also due to Mr. D. Clary and Dr. G. Mills of the Department of Chemistry and Biochemistry at Auburn University for providing the synthesized nanoparticles and guiding the preparation of nanofluids.

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