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ScienceDirect

Diamond & Related Materials 15 (2006) 2078 – 2081

DIAMOND AND RELATED MATERIALS

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Thermal transport properties of diamond-based nanofluids and nanocomposites

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Abstract

The focus of this work is to examine the effects nanoparticles, in particular nanodiamond, have on the heat transfer of fluids and polymer solids. Sample preparation techniques that provide suitable nanoparticle dispersion in both liquid and solid samples are discussed. Liquid suspensions are characterized by measuring particle size distributions and liquid viscosities; heat transfer properties are qualitatively compared via an ad-hoc thermal transport test setup. Polymer samples are visually characterized to ensure nanoparticle dispersion and thermal conductivity is measured using a flash lamp technique.

Keywords: Nanofluid; Nanodiamond; Thermal conductivity

1. Introduction

In this work we report on the thermal transport properties of nanodiamond-based nanofluids and polymer nanocomposites. Nanofluids, consisting of nanoscale particles dispersed in a liquid matrix, have been gaining interest lately due to their potential to greatly outperform traditional thermal transport liquids [1]. Suggested applications range from computer processor liquid cooling to thermal management of power transformers [2]. The mechanism(s) responsible for the thermal properties of nanofluids are not completely understood, though several have been suggested, including the effects of Brownian motion and convection, the particle/fluid interface, and particle size and agglomeration. In this work the thermal transport properties were investigated as a function of particle size distribution and particle concentration. Samples were prepared with the aid of ultrasonic dispersion, and particle size distribution was measured using photon correlation spectroscopy. Particle sizes ranged from <50 nm to >1 μm. Nanofluids with up to 16 wt.% of nanodiamond were investigated. In addition to thermal properties, the role of sedimentation stability in the thermal behavior of various nanofluids was investigated. Means to improve nanoparticle dispersion via surface modification were also suggested.

Nanodiamond-based polymer nanocomposites were also studied; thermal conductivity of polymer nanocomposites was measured using a Netzsch Nanoflash thermal conductivity measurement system (based on a transient technique measuring attenuation of a thermal spike produced with a flash lamp). Similarly, particle size distribution and dispersion effects, as well as effects of nanoparticle concentration, were investigated and will be discussed.

2. Experimental details and results

The use of ultrasound in preparing Midel–nanodiamond (ND) and –alumina nanofluids was investigated. It was observed that untreated, or under-treated, nanofluid samples suffered from sedimentation that was shown to affect the heat transport characteristics of the fluid–nanoparticle composite. The ultrasonic processor used in these studies was a Cole Parmer High Intensity 750 W Ultrasonic Processor, which is a *horn* type ultrasonic source that allows for submersion of the ultrasonic horn into the sample, providing more efficient transfer of energy to the sample. In order to quantify the effectiveness of ultrasonic dispersion, a Beckman Coulter N5 Submicron Particle Size Analyzer was used, which is capable of sizing particles in suspension from <10 nm to >3 μm in diameter by utilizing a technique known as photon correlation spectroscopy (PCS). Initial characterization of various types of nanodiamond was

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doi:10.1016/j.diamond.2006.08.007

performed in order to determine the best candidate for nanofluid preparation. Unimodal size distributions for several types of nanodiamond are shown in Fig. 1. It is worth noting that the *unimodal* size distribution obtained from PCS is an average particle size, and is used for comparison purposes, whereas the actual particle size distribution can possess several peak sizes; PCS is capable of displaying the individual peaks in weight (or equivalent volume) percent, which is used for detailed particle size analysis. In general, it was observed that higher ultrasonic power density and longer sonication time result in drastically reduced particle sizes; and furthermore, that reducing the average particle size decreases the rate of sedimentation observed. It will be shown that sedimentation of suspended nanoparticles inhibits the ability of the nanofluid to effectively conduct heat.

In addition to particle size characterization of nanofluids, viscosity was also investigated. If nanofluids are to be used in systems where fluid flow is controlled by pumps, viscosity plays an important role. As such, preliminary viscosity results were obtained for Midel–nanodiamond nanofluids for various concentrations. The results are summarized in Fig. 2; clearly, nanodiamond content greatly affects viscosity, with an increase of nearly 80% for 3 wt.% ND and an increase of 140% for 3 wt.% ND that has been allowed to sediment. More detailed studies, including temperature-dependant viscosity measurements, are underway.

Preliminary heat transport experiments were conducted to determine the effectiveness of various nanofluid processing techniques by comparing the processed nanofluid with a control sample. Initially, thermal conductivity of the nanofluids was measured using the Nanoflash system described above; however, the low thermal conductivity of the oil used in this study prohibited accurate results (due to instrument limitations). In response, an ad-hoc experiment was designed to compare the temperature rise at one end of a cylinder of nanofluid, with the opposing end submerged in a heat bath of constant temperature (usually 90 °C); the temperature rise was compared to that of a pure fluid (containing no nanoparticles). To verify the test setup, two liquids with different thermal conductivities were compared: water ($\kappa = 0.59$ W/m K) and Midel oil ($\kappa = 0.16$ W/m K); the water consistently rose to a higher temperature than the Midel oil, thus verifying at least the validity of this setup to qualitatively compare fluids. When testing nanofluids, various test configurations (i.e. different angles of vials shown in Fig. 3) were tried in an effort to identify the possible effects of convective heat flow; however, no definitive conclusions were made when comparing the various configurations, and thus these results will not be discussed in this paper. For each test run discussed here, data was acquired at one second intervals until the temperature rise was observed to stabilize. Quantitative comparisons using this technique are not possible, as both thermal conduction and convection play a role in the heat flow; as such, this technique is used only as a qualitative comparison of the overall effectiveness of one fluid to conduct heat as compared to another. Each experiment, therefore, used one control fluid (pure, with no nanoparticles) and one fluid under test; due to possible subtle changes in experimental conditions, *global* comparisons were not made, and only the two liquids under test at a given time were compared.

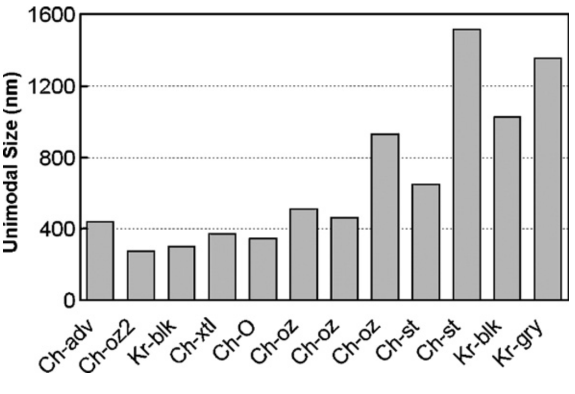

Fig. 1. Unimodal size distributions (via PCS analysis) for several types of nanodiamond suspended in Midel oil.

Viscosity (cP @ 25°C)	
Midel Oil	42
Midel Oil + 1% ND	45
Midel Oil + 3% ND	74
Midel Oil + 3% ND (sedimented)	101

Fig. 2. Viscosities of Midel–nanodiamond nanofluids with varying weight percentages of nanodiamond.

The initial nanofluids tested were Midel–0.5 wt.% ND (purified from soot using oxidation by ozone). The heat flow of the nanofluid was observed to be initially better than that of pure oil (see Fig. 4A). However, sedimentation that was visually observed to occur within 5 min of $t = 0$ is believed to have hindered the heat flow in the nanofluid; therefore, pure oil surpassed the nanofluid. These results prompted the use of lower concentrations of solids in the nanofluids and more rigorous (higher power densities and longer time) ultrasonic processing.

In order to ensure that sedimentation would not occur during testing, a Midel–ND nanofluid was prepared with only 0.1 wt.% of nanodiamond particles; the sample was then sonicated and larger particles were allowed to sediment; after which the stable fluid was separated from the sediment, resulting in a nanodiamond concentration of <0.1 wt.%; the suspension was stable

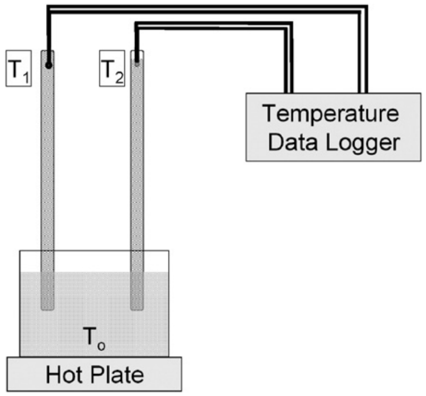

Fig. 3. Schematic of comparative *vertical* heat flow experiment; temperatures T_1 and T_2 are monitored at one end of the cylinders, with the opposing ends submerged in a heat bath of temperature T_o. Qualitative comparisons are made between various nanofluids and their *pure* counterparts.