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Enhanced thermal conductivity of alumina nanoparticle suspensions by femtosecond laser irradiation

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ABSTRACT

This work reports significant enhancements over the Hashin-Shtrikman upper bound, by means of femtosecond laser irradiation, of thermal conductivity of alumina nanoparticle suspensions dispersed in water. By adjusting laser parameters, the applied femtosecond laser irradiation could enhance the colloidal stability of the suspension and reduce the size of nanoparticles. The thermal conductivity and zeta potential of the suspensions were measured before and after the laser-induced stabilization and fragmentation processes. When the laser stabilization and laser fragmentation processes were combined, the thermal conductivity of the suspension increased up to about 40% compared to the thermal conductivity of the base fluid at 1 wt%. This laser technique demonstrates a strong potential to produce nanofluids with high thermal conductivity and colloidal stability.

1. Introduction

The stability and thermal conductivity of colloidal suspensions of solid nanoparticles, so called “nanofluids”, are key factors that provide useful advantages for industrial applications involving heat transfer and magnetic fluids [1–5]. For use as working fluids in thermal systems, such as heat pipes, a colloidal suspension should have high thermal conductivity with high colloidal stability [6,7]. Experimental and theoretical studies have shown that the effective thermal conductivity of a colloidal suspension depends on experimental parameters, including particle material, base fluid material, particle size, particle shape, volume fraction, temperature, and clustering of nanoparticles [8–15].

Aggregation is one of the important factors in determining the thermal performance of a heat transport system. For example, even though nanoparticles initially may be well dispersed in liquid, they have the tendency to aggregate, thus quickly settling down. This leads to degraded thermal-transport properties [16]. In contrast, aggregation can also enhance thermal transport by leading to local percolation behavior under different conditions [13–15]. Aggregation, which increases the mass of the aggregates, will decrease the Brownian motion of the nanoparticles, whereas it can increase thermal conductivity arising from the percolation effects in the aggregates [13]. Prasher et al. showed that aggregation can lead to anomalistic enhancements in thermal conductivity, which is about 20% higher than the predicted value [14].

It has been reported that exposure of nanoparticles suspensions to electromagnetic fields affects the dispersion/coagulation state of the colloids and modify the size and the shape of the nanoparticles. Attempts have been made to increase the stability by using a mercury lamp, continuous-wave Ar-ion laser, and pulsed KrF excimer laser [17–19]. An Nd:YAG laser (wavelength of 355 nm, full width at half maximum (FWHM) of 6 ns) was employed to increase the thermal conductivity of a ZnO nanoparticle suspension (60 nm ZnO/water). They demonstrated that high-power laser irradiation $\sim$O (10^8 W/cm^2) can increase the effective thermal conductivity by a small fraction of the particles generated by the laser fragmentation process.

Femtosecond laser irradiation has been considered as an effective way to change the shape and size of nanoparticle aggregates [20–22]. In addition, it has been shown that femtosecond laser irradiation (wavelength of 800 nm, FWHM of 56 fs) of colloidal Au nanoparticles (diameter $\sim$ 25 nm) at relatively high laser fluences ($F = 1.3$–5.3 J/cm^2) can fragment Au nanoparticles, generating small (2.5 nm) colloidal particles, with long-term stability over a period longer than 3 months [23]. It has been reported that femtosecond laser irradiation of gold nanoparticles in liquid can fragment the agglomerate, increase colloidal stability, and enhance the thermal conductivity of gold nanoparticles suspension [24–26]. The nanofluids were produced by pulsed laser ablation in liquid and laser irradiation controlled the size of nanoparticle agglomerates. The laser-produced nanofluids exhibit enhanced stability and

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increased thermal conductivity by up to 4% [25]. Seo et al. reported substantial enhancement of colloidal stability of aqueous nanoparticle suspensions by means of ultrashort laser-pulse irradiation (wavelength of 800 nm, FWHM of 50 fs). They proposed two possible mechanisms for the laser stabilization process: (1) electrostatic discharge of electrons from particles; and (2) dehydration of aluminum hydroxide on the surface [27]. However, it has not been reported yet that femtosecond laser irradiation can also enhance the thermal conductivity of alumina nanoparticle suspensions.

This work demonstrates that femtosecond laser irradiation at ~100 GW/cm^2 can enhance substantially the thermal conductivity of alumina nanoparticle suspensions in deionized (DI) water. At low fluences ($F \sim 10$ mJ/cm^2), thermal conductivity k, by means of the laser stabilization effect, was enhanced up to 23% compared to the thermal conductivity of the base fluid. At high fluences ($F \sim 5$ J/cm^2), high-power laser irradiation fragmented the nanoparticles into smaller ones. The value of k was enhanced up to 12% with relatively low stability as compared to the thermal conductivity of the laser-stabilized samples. When the laser stabilization and fragmentation processes were combined, k was enhanced up to 38% at 1 wt%.

The main concept presented here contains into two parts, as shown in Fig. 1. First, laser irradiation at a low fluence ($F = 10$ mJ/cm^2) can enhance the thermal conductivity of the suspension by stabilizing the colloidal suspension, which is called the laser stabilization process. Second, laser irradiation at a high fluence ($F = 5.1$ J/cm^2) can enhance the thermal conductivity of the suspension by fragmenting the nanoparticles and reducing their size, which is called the laser fragmentation process. Finally, high-k nanofluids with high stability was achieved by combining these two processes.

2. Materials and methods

2.1. Sample preparation and laser process

Alumina nanoparticles having a nominal size of 50 nm (Alfa Aesar) were used in the experiment. Alumina nanoparticles (50 mg) were mixed with DI water (4.95 g) to produce 1 wt% nanoparticle suspensions. The particles were then dispersed in an ultrasonic bath operating for 1 h at a frequency of 40 kHz and an output power of 70 W. A femtosecond laser (wavelength: 800 nm; pulse duration: 50 fs at FWHM; repetition rate: 1 kHz) having a fit-to-Gaussian spatial distribution of intensity and a spot size of 6 mm was employed. The peak laser irradiance and irradiation time varied up to ~10^{14} W/cm^2 and 2 h, respectively. To ensure uniform laser irradiation of the particles, the samples were agitated using a magnetic stirrer during laser irradiation.

2.2. Measurement methods

The ζ potential and the mean size of the clustered particles based on dynamic light scattering (DLS) were measured using a commercialized system (Malvern Instrument, Zetasizer Nano Z). In the ζ potential and DLS measurements, the original sample of 1 wt% was diluted to 0.1 wt% before the analysis. The morphology of the nanoparticles was examined by transmission electron microscopy (TEM, JEOL, JEM-2200FS). To prepare the TEM samples, a droplet of the colloidal suspension was dispersed onto a carbon-coated copper-based TEM grid. The liquid was then removed from the grid using an absorbent paper to minimize agglomeration during the drying process. The thermal conductivity of the suspensions was measured using the 3ω method [28,29]. A 3ω sensor was fabricated by depositing a 300-nm-thick Au film over a 30-nm-thick Cr adhesion layer onto a glass substrate. The sensor used in the present study was tested with several reference liquids: methanol, ethanol, and DI water [30]. The bias and random errors yielded test results with a measurement uncertainty of 2% at 25 °C (Fig. 2). In macroscopic observation of the nanofluid samples using digital photographs, no sedimentation or agglomeration of nanoparticles was observed before and after laser irradiation.

3. Results and discussions

3.1. Zeta potential, hydrodynamic diameter, and thermal conductivity by the laser-stabilization process

The ζ potential, hydrodynamic diameter, and k ratios (the ratios of thermal conductivities of the nanofluid to the base fluid: k_f/k_b) of

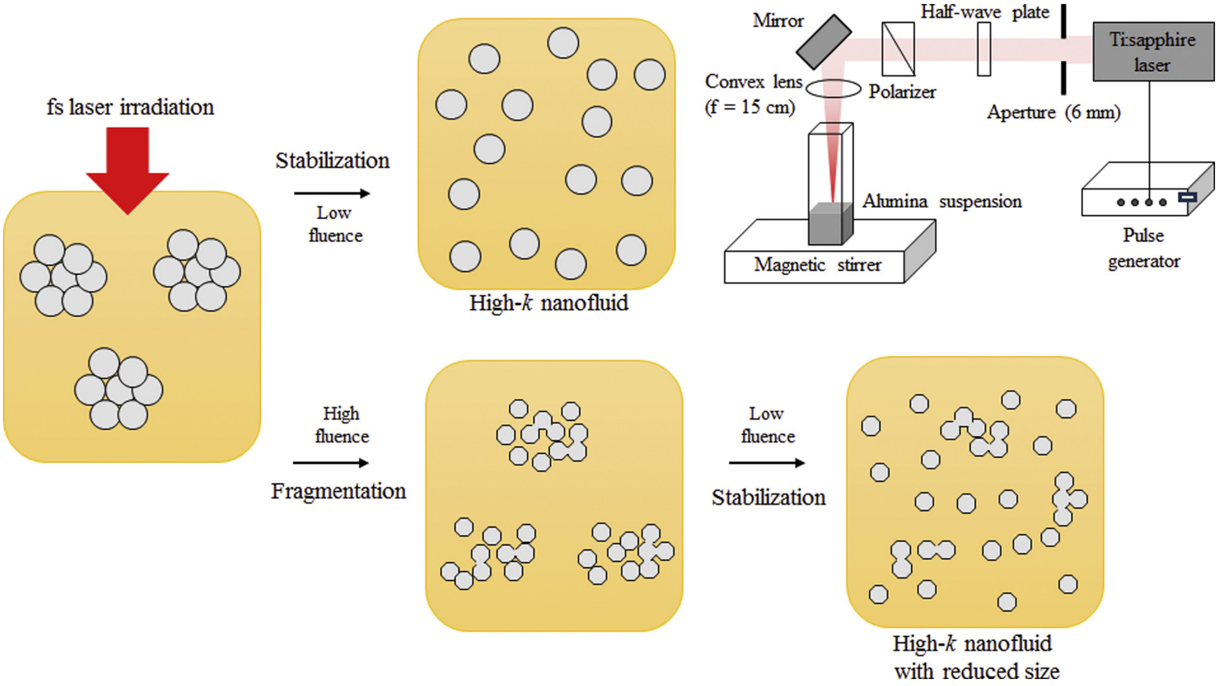

Fig. 1. Schematic concept and experimental setup of the proposed laser process to enhance thermal conductivity of an alumina nanoparticle suspension.