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Effect of particle shape on suspension stability and thermal conductivities of water-based bohemite alumina nanofluids

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The suspension stability and thermal conductivity of water-based bohemite alumina nanofluids created using nanoparticles of various shapes (brick, platelet, and blade) at concentrations from 0.3 vol% to 7.0 vol% were theoretically and experimentally investigated. To quantitatively examine the effect of nanoparticle shape on suspension stability, this study uses the laser-scattering method rather than the zeta-potential measurement or the sedimentation test because both the zeta-potential and sedimentation tests cannot systematically represent the suspension stability of nanofluids. Using the DLVO (Derjaguin and Landau, Verwey and Overbeek) theory, we explain why the suspension stability varies with nanoparticle shape despite similar volume fraction of nanoparticles, pH, and temperature. The thermal conductivities are also measured by the transient hot wire method, which was developed in house. Experimental data are compared with theoretical results predicted by the Hamilton–Crosser model, which considers the effect of nanoparticle shape. It is shown that the model cannot predict nanofluids thermal conductivity relative to nanoparticle shape. Finally it is clearly shown that the thermal conductivity of nanofluids strongly depends on the suspension stability of bohemite alumina with various shapes.

1. Introduction

One of the well-known thermal characteristics of nanofluids is the enhancement of thermal conductivity at low concentration [1–3]. In order to choose nanofluids with excellent cooling performance, the thermal conductivities of the nanofluids have been experimentally and theoretically investigated by worldwide research groups [1–19]. Water-based nanofluids, Al_2O_3 in particular, have been the subject of multitudinous studies due to their superior thermal characteristics, suspension stability, and the high productivity of nanoparticles. As shown in Fig. 1, many research groups reported that Al_2O_3 nanofluids increase thermal conductivity linearly up to 30%, depending on the concentration of Al_2O_3 nanoparticles. However, the most of previous studies are focused on the relationship between the enhancement of thermal conductivity and volume fraction or temperature. Recently Timofeeva et al. [19] examined how the shape of the alumina nanoparticle (e.g., cylinder, brick, blade, platelet) affects the thermal conductivity of Al_2O_3 nanofluids suspended in a 5:5 mixture of DI (deionized) water and EG (ethylene glycol). For each nanoparticle type, they used the two-step method to manufacture nanofluids, which they decanted to create the suspension and then used the supernatant as a stabilizer. They used the KD2 Pro to show that particle shape does have an effect on the enhancement of thermal conductivity. Their work also shows that 32% is the maximum enhancement of thermal conductivity of water/EG-based Al_2O_3 nanofluids with cylinder-shaped nanoparticles. However, they did not examine the effect of the particle shape on the suspension stability of nanofluids, which is an important factor in the enhancement of thermal conductivity [3,20–22].

We manufactured water-based bohemite alumina nanofluids with brick, platelet, and blade, using the two-step method. Then we used a laser-scattering method to observe nanofluid suspension stability to quantitatively understand how the suspension stability was affected by nanoparticle shape. We explain the effect of particle shape on suspension stability, using the DLVO (Derjaguin and Landau, Verwey and Overbeek) theory. Also, the thermal conductivities are measured using the transient hot wire method, which has 1% uncertainty [23]. We compare our experimental results with results from the Hamilton–Crosser model. Based on the results, the

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Nomenclature

a	equivalent radius of nanoparticles
A	Hamaker constant
d	Distance between the particles
k	Thermal conductivity [W/mK]
I	Intensity of transmitted laser
n	Shape factor
q	Heat [W]
t	time [sec]
T	Temperature [°C]

Greek symbols

ε	Degradation factor
ε_0	Permittivity of vacuum [F/m]
ε_r	Dielectric constant of the medium
ϕ	Volume faction [%]
Φ	Energy [J]
κ	Inverse of the Deybe length [1/m]
ξ	Sphericity
ψ	Sphericity
ψ_0	Surface Potential [V]

Subscripts

A	Attractive
BF	Basefluid
eff	Effective
NF	Nanofluids
NP	Nanoparticle
R	Repulsive

model cannot predict nanofluid thermal conductivity relative to nanoparticle shape. We clearly show that suspension stability depends on nanoparticle shape and strongly affects thermal conductivity enhancement of water-based bohemite alumina nanofluids.

2. Materials

For this study, we used alumina nanoparticles with various shapes: brick, platelet, and blade. The nanoparticles were supplied by Sasol Inc. Using XRD (X-ray diffraction), the nanoparticles were confirmed to be bohemite alumina. To manufacture water-based Al_2O_3 nanofluids with a nanoparticle concentration of 0.3–7.0 vol %, we used the two-step method [24] without any surfactant or additives. We measured the pH values of the nanofluids by PHH 244 (Omega Engineering Inc.) with 0.02 pH accuracy. The measured pH values of the nanofluids are between 5.6 and 5.7 regardless of the shape and the volume fraction. Thus the effect of the pH on both suspension stability and enhancement of the thermal conductivity is eliminated. The morphologies of the alumina suspended in the nanofluids were examined by TEM (transmission electron microscope). TEM images show that suspended Al_2O_3 nanoparticles in the DI water are similar to the geometry provided by Sasol, Inc., as shown in Fig. 2. However, the primary size presented by the provider is different from the hydraulic nanoparticle size. So we measured the particle size distribution using the Zetasizer Nano ZS particle size analyzer (PSA; Malvern Instrument Ltd.).

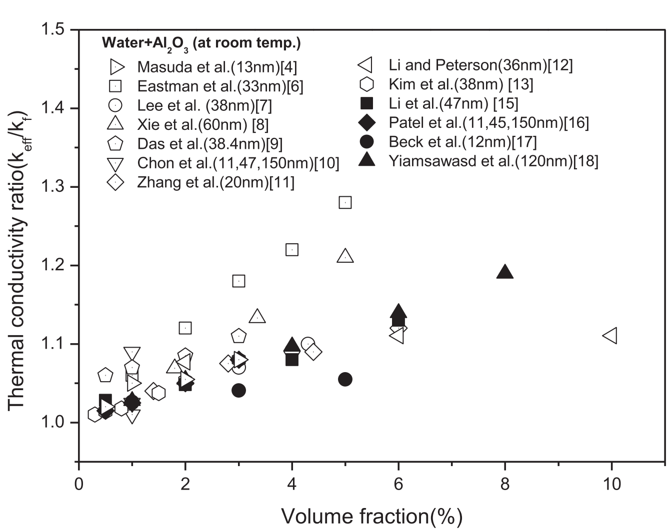

Fig. 1. Thermal conductivities of water-based Al_2O_3 nanofluids.

3. Measurement and theory

3.1. Suspension stability and DLVO theory

To quantify the suspension stability of nanofluids, previous researchers have measured their zeta-potential value [25,26]. However, several researchers have posited that, due to the inherent weakness of nanofluid suspension stability, the zeta-potential value is an inadequate representation, despite the fact that the absolute value of the zeta potential is larger than 30 mV [27,28]. In fact, in the current study, we show that zeta-potential value cannot represent the suspension stability of nanofluids by comparing the results of the sedimentation test and the zeta-potential value measured by this study, as shown in Fig. 3.

We quantitatively evaluate the suspension stability of Al_2O_3 nanofluids using a laser-scattering method (Fig. 4) rather than by using zeta potential and the sedimentation test. The laser-scattering method measures the intensity of light transmitted by each nanofluid solution: nanoparticles suspended in nanofluids both scatter and absorb electromagnetic waves such as lasers. As a result, we can quantitatively observe the suspension stability of nanofluids by detecting the intensity of light transmission as a function of time. As shown in Fig. 4, the measurement system consists of a He–Ne laser (λ = 632.8 nm, 200 mW), a sample medium (i.e., nanofluids), and detecting units (photodiode and power meter). Using the data, the suspension stability of nanofluids can be more precisely evaluated using the suspension degradation factor, which is defined as

$$\varepsilon = \frac{I_{initial}}{I(t)} \tag{1}$$

where I and ε are the intensity of transmitted laser and the degradation factor of suspension stability, respectively.

Moreover, using the DLVO theory [29], we will explain why the suspension stability of nanofluids varies according to nanoparticle shape under fixed conditions (volume fraction of nanoparticles, pH, and temperature). Colloidal scientists generally use DLVO to evaluate suspension stability by using the total interaction energy among nanoparticles. The total interaction energy is given by