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Thermal Conductivities and Viscosities of Al_2O_3-water Nanofluids with Low Volume Concentrations

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ABSTRACT

Al_2O_3-water nanofluids containing low volume concentrations (0.1-0.5 vol. %) of Al_2O_3 nanoparticles with 40nm and 65nm average particle size were produced using a two-step method with ultrasonication and without any surfactant. The thermal conductivities and viscosities were evaluated by KD2-pro thermal property meter and rotational viscometer respectively at different temperature. Thermal conductivities measurements show that the thermal conductivities of Al_2O_3-water nanofluids are higher than water. The thermal conductivities with average particle size of 40nm and 65nm are respectively enhanced by 17.9% and 11.2% when approximately 0.5vol.% of Al_2O_3 nanoparticles are added. Furthermore, the experimental results show the thermal conductivities increased nearly linearly with the nanoparticle volume concentration increasing, and significantly increased with the temperature increasing. Comparison between the experiments and the theoretical models shows that the measured thermal conductivities are much higher than the values calculated from theoretical models, indicating new heat transport mechanisms included in nanofluids. In the contrast to thermal conductivities, the viscosities measurements show that the viscosities of the Al_2O_3-water nanofluids significantly decrease with increasing temperature, and increased nonlinearly with the nanoparticle volume concentration. As the volume concentration of nanoparticles is increased up to 0.5%, the viscosities of Al_2O_3-water nanofluids with average particle size of 40nm and 65nm are respectively increased nonlinearly up to 28.3% and 17.5%, which exceed the Einstein model predictions.

Keywords: Al_2O_3-water nanofluid, Thermal Conductivity, Viscosity

1. INTRODUCTION

Heat transfer fluid plays a vital role in the development of high performance heat-exchange devices. But compared with most solids, conventional heat transfer fluids have poor heat transfer properties. Despite considerable previous research and development focusing on industrial heat transfer requirements, major improvements in heat transfer capabilities have been lacking. As a result, development of advanced heat transfer fluids is clearly essential to improve the effective heat transfer behavior of conventional heat transfer fluids.

A new class of heat transfer fluids called nanofluids has been proposed by Choi[1] in 1995, which has opened a new dimension in heat transfer processes. Nanofluids refer to a new kind of heat transport fluids by suspending nanoscaled metallic or nonmetallic particles in base fluids. The advantages of these nanofluids are (1) better stability compared to those fluids containing micrometer or millimeter sized particles and (2) higher thermal conductive capability than the base fluids themselves.

In the past, thermal conductivities of Al_2O_3-water nanofluids were investigated by several researchers including Shou et al.[2], Das et al.[3], Xie et al.[4], Li et al.[5], Wang et al.[6], and Lee et al.[7] who reported 2% to 30% enhancement of containing barely 1.0vol.% to 5.0vol.% nanoparticles. Their experimental data for Al_2O_3-water were shown in Fig.1. Compared with the experimental studies on thermal conductivity of nanofluids, there are limited viscosity studies reported in the literature. Masuda et al.[8] were likely the first to measure the viscosity of several water based nanofluids for temperature ranging from room condition to 67°C. Putra et al.[9] have also provided results showing the temperature effect on Al_2O_3-water nanofluid viscosity for two particle concentrations, namely 1% and 4%. Most recently, Mare et al.[10] obtained some new temperature dependent viscosity data for Al_2O_3-water at relatively high particle concentrations using a Brookfield viscometer with rotating cylinder.

From this previous research, the thermal conductivities and viscosities of Al_2O_3-water nanofluids were measured at Al_2O_3 nanoparticle concentrations greater than or equal to 1% by volume. However, little experimental data exist on the thermal conductivities and viscosities of nanofluids with low volume concentrations (<1.0%) of Al_2O_3 nanoparticles. In order to see how Al_2O_3-water nanofluids would behave in the very low volume concentration range from 0.1% to 0.5%, especially their thermal conductivities and viscosities, an experimental investigation was performed. It is the intention to be concern of a more intensive use of nanofluids.

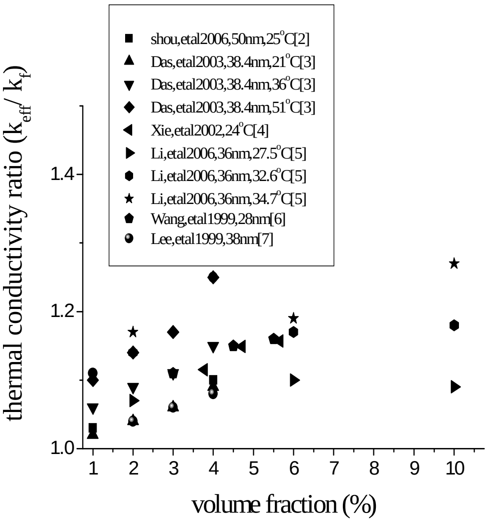
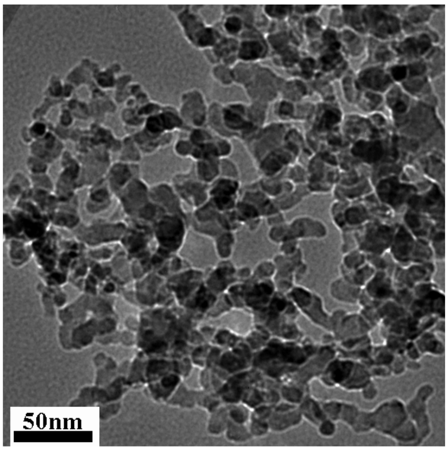


Fig.1 Thermal conductivities ratio of Al_2O_3-water nanofluids as a function volume fraction

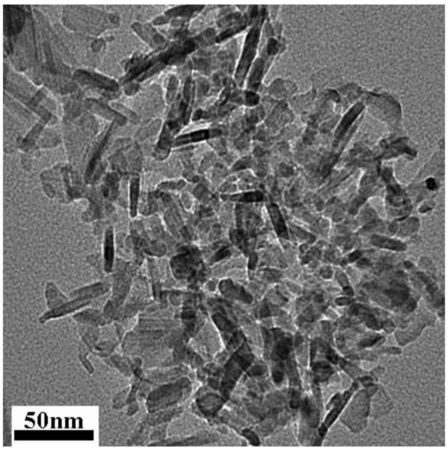
2. MATERIALS AND NANOFLUIDS PREPARATION

2.1 Materials

The Al_2O_3 powder (produced by Nachen, Beijing, China) with alumina content >99.9% was used in this study. The thermal conductivities and densities of Al_2O_3 nanoparticles are 40 W/m K and 3965 kg/m^3 respectively. Fig.2 (a) and (b) show the TEM photographs of the Al_2O_3 particles whose average diameters are 40nm and 65nm respectively. Morphologies of these particles are basically spherical or near spherical.



(a)



(b)

Fig.2 TEM photographs of Al_2O_3 particles.

2.2 Production and Dispersion Characteristics of Al_2O_3-water Nanofluids

Al_2O_3-water nanofluids with low volume concentrations of Al_2O_3 nanoparticles from 0.1% to 0.5% were produced by a two-step method without any surfactant. Sonication with an ultrasound generator (20 kHz, 100W) was used to disperse Al_2O_3 nanoparticles in DI water. To determine the optimum sonication time, as a example of 40nm average size with 0.1% volume concentrations, the sonication time was varied from 1 to 15 hours, and the corresponding average size, zeta-potential and absorbancy of Al_2O_3 nanoparticles dispersed in DI water were measured using LS13320 (Backman Counlter Inc, USA), PALS (BIC, USA) and JH722 (Jinghua, Shanghai, China). The measured results were shown in Fig.3, Fig.4 and Fig.5 respectively.

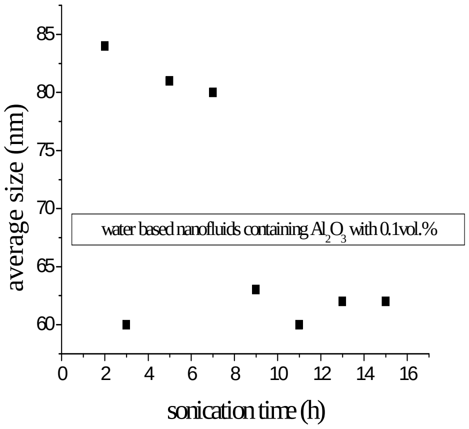


Fig.3 Influence of sonication time on average size of Al_2O_3 particles dispersed in water

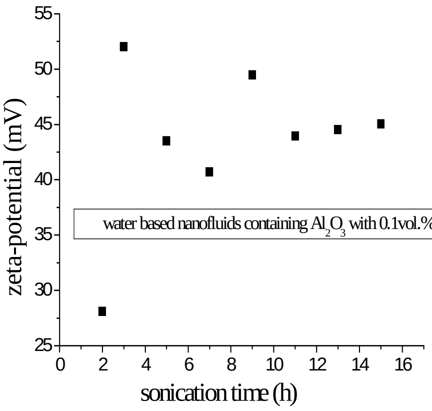


Fig.4 Influence of sonication time on zeta-potential of Al_2O_3 particles dispersed in water

From Fig.3, it is observed that the average size reaches a minimum value of approximately 60 nm after 3h of sonication time and then increase with the extension of sonication time, which shows that 3h is the optimum sonication time.

In Fig.4 and Fig.5, when the sonication time is 3h, the values of zeta-potential and absorbancy are the highest of 54mV and 1.552 respectively, indicating that the nanoparticles are well dispersed. From the above independent studies, it can be seen that Al_2O_3 (40nm)-water nanofluid sonicated for 3 hours is the best dispersed and most stable. Using the same method, it can be demonstrated that 3h is also the optimum sonication time for Al_2O_3 (65nm) nanoparticles dispersed in DI water.

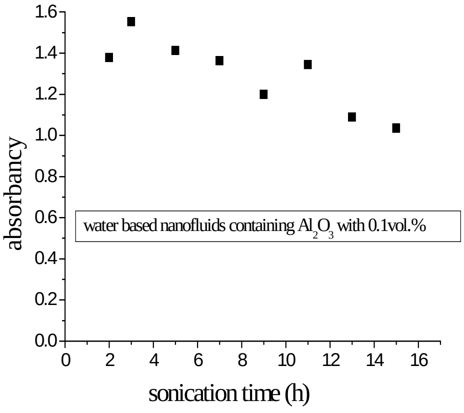


Fig.5 Influence of sonication time on absorbancy of Al_2O_3 particles dispersed in water

3. MEASUREMENT OF THERMAL CONDUCTIVITY

The thermal conductivities of nanofluids were measured using a KD2-pro thermal property meter (Analyx Technology Corporation, USA). This apparatus has 5% accuracy, which is based on the transient-hot-wire method to determine the thermal properties of fluids. The thermal conductivities of the fluids are computed using the temperature difference vs. time data. It basically comprises a hand-held readout unit and a single-needle sensor that is inserted into the fluids specimen. The probe integrates in its interior a heating element and a thermoresistor which is connected to a microprocessor for controlling and conducting the measurements.

Fig.6 shows thermal conductivities of Al_2O_3-water nanofluids against particles concentration at room temperature. Addition of Al_2O_3 to water significantly enhances the thermal conductivities, which increase with increasing Al_2O_3 volume concentration and decreasing Al_2O_3 average size. At 0.5% volume concentration of Al_2O_3 nanoparticles with 65nm average particle size, 11.2% enhancement has been achieved, and at the same volume concentration with 40nm average particle size, the enhancement increases to 17.9%. Fig.6 also shows that the measured thermal conductivities of Al_2O_3-water nanofluids are enhanced approximately linearly with the volume concentrations of Al_2O_3 nanoparticles, which agree well with the predicted values by the Jang and Choi[11,12] over a very wide volume concentrations range from 0.01% to 5%.

Various theoretical models have been developed to compute the thermal conductivity of two-phase materials based on the thermal conductivities of the solid/liquid and their relative volume fractions. The theoretical models are shown in table. 1, and the corresponding theoretical results are also shown in Fig.6. It can be seen that the measured thermal conductivities are greater than the values calculated using the theoretical models. So these theoretical models can not explain the thermal conductivities enhancement of those naofluids, and further investigation on the heat conductivity mechanism of nanofluids is needed.

In nanofluid, the main mechanism of thermal conductivity enhancement can be thought as the stochastic motion of the nanoparticles which will be dependent on fluid temperature. So this amount of enhancement with temperature is quite explicable [17].

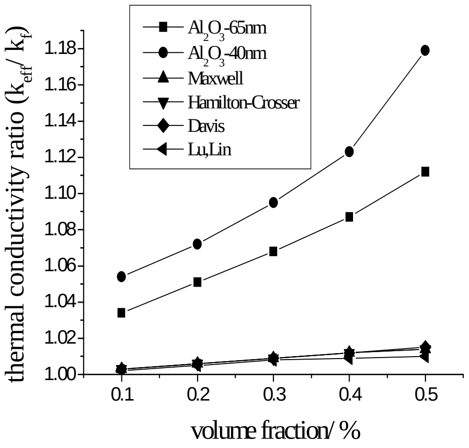


Fig.6 Thermal conductivities ratio of Al_2O_3-water nanofluids and comparison with theoretical models

Table.1 Conventional theoretical models of thermal conductivity of solid/liquid suspensions

Models	Expressions
Maxwell[13]	$\frac{\mathrm{k}_{eff}}{\mathrm{k}_{\mathrm{f}}}=\frac{\mathrm{k}_{\mathrm{p}}+2\mathrm{k}_{\mathrm{f}}-2\varphi\left(\mathrm{k}_{\mathrm{f}}-\mathrm{k}_{\mathrm{p}}\right)}{\mathrm{k}_{\mathrm{p}}+2\mathrm{k}_{\mathrm{f}}+\varphi\left(\mathrm{k}_{\mathrm{f}}-\mathrm{k}_{\mathrm{p}}\right)}$
Hamilton-Crosser[14]	$\frac{\mathrm{k}_{eff}}{\mathrm{k}_{\mathrm{f}}}=\frac{\mathrm{k}_{\mathrm{p}}+\left(n-1\right)\mathrm{k}_{\mathrm{f}}-\left(\mathrm{n}-1\right)\varphi\left(\mathrm{k}_{\mathrm{f}}-\mathrm{k}_{\mathrm{p}}\right)}{\mathrm{k}_{\mathrm{p}}+\left(n-1\right)\mathrm{k}_{\mathrm{f}}+\varphi\left(\mathrm{k}_{\mathrm{f}}-\mathrm{k}_{\mathrm{p}}\right)}$
Davis[15]	$\frac{k_{eff}}{k_f}=1+\frac{3(\alpha-1)}{\alpha+2-(\alpha-1)\varphi}[\varphi+f(\alpha)\varphi^2+o(\varphi^3)]$
Lu，Lin[16]	$\frac{k_{eff}}{k_f}=1+a\varphi+b\varphi^2$

Fig.7 shows the enhancement of thermal conductivities of Al_2O_3-water nanofluids with temperature increasing. It is interesting to see there is a considerable nonlinear increase in the temperature range from 17°C to 57°C for the two kinds of Al_2O_3 (40nm, 65nm respectively) -water nanofluids. At temperature 17°C, the enhancement is only about 7.23% and 4.89% with 0.2vol.% particles, but at 57°C this value increases to about 23% and 19.18%. It is more interesting that with temperature rising from 17°C to 57°C the thermal conductivities enhancement with 0.5vol.% particles is much higher than Al_2O_3-water nanofluids with 0.2vol.% particles. So it can be said that the enhancement of thermal conductivities shows a dramatic increase with temperature increasing, and the increasing rate depends on the concentrations of nanoparticle.

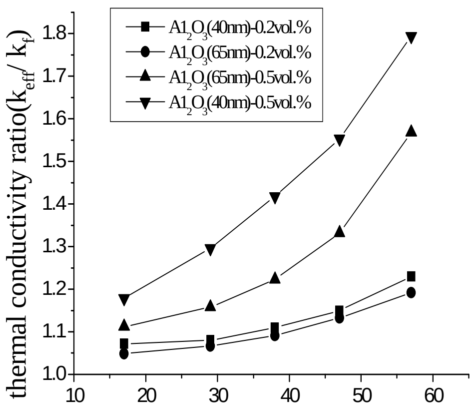


Fig.7 Temperature dependence of thermal conductivity enhancement for Al_2O_3 -water nanofluids

4. MEASUREMENT OF VISCOSITY

The viscosities of Al_2O_3-water nanofluids with low volume concentrations from 0.1% to 0.5% were measured with rotary viscometer at the temperature range from room temperature to 42 °C.

Fig.8 gives the relative viscosities of Al_2O_3-water nanofluids at room temperature. As shown in Fig. 8, the viscosities of Al_2O_3-water nanofluids are higher than water. At 0.5vol.% concentration, their viscosities with 40 and 65 nm average particle size increase 28.3% and 17.5% respectively. Fig.8 also shows that the measured viscosities of the Al_2O_3-water nanofluids increase with decreasing nanoparticles size, and increase nonlinearly with the Al_2O_3 nanoparticle volume concentrations increasing.

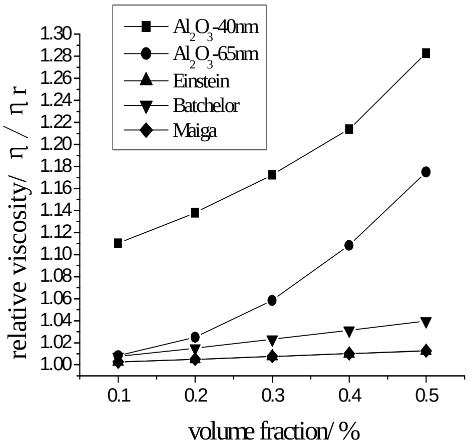


Fig.8 Relative viscosity of Al_2O_3-water nanofluids as a function of nanoparticle volume fraction

Table. 2 Conventional models of viscosity of solid/liquid suspensions

Models	Expressions
Einstein[18]	$\eta=\eta_r\left(1+2.5\varphi\right)$
Batchelor[19]	$\eta=\eta_r\left(1+2.5\varphi+6.25\varphi^2\right)$
Maiga et al.[20]	$\eta=\eta_r\left(1+7.3\varphi+123\varphi^2\right)$

The comparison between the measured viscosities and the theoretical models (as shown in table. 2) is shown in Fig.8. From Fig.8, the measured viscosities of the Al_2O_3-water nanofluids are greater than predicted by the Einstein[18], Batchelor[19] and Maiga et al.[20] theoretical models. The theoretical models show that there is a linear relationship between the viscosities of Al_2O_3-water nanofluids and the volume fraction of Al_2O_3 nanoparticles while the measured data shows a nonlinear relationship.

As the same to thermal conductivity, the temperature also greatly effects viscosity of Al_2O_3-water nanofluid as shown in Fig.9. The experimental results show that viscosities of the Al_2O_3water nanofluids decrease with the temperature increasing, with nearly the same tendency as that of pure water. For 0.1vol.% particles at temperature 22°C, the viscosities of Al_2O_3 (40nm, 65nm)-water nanofluids are about 1.105mp·s and 1.007 mp·s, but at 42°C these values decrease to about 0.636 mp·s and 0.569 mp·s respectively. The Brownian motion and the diffusion of the nanoparticles would increase with increasing temperature which would reduce the wall effect in the capillary tubes and reduce the effect of viscometer size on the viscosity [21].

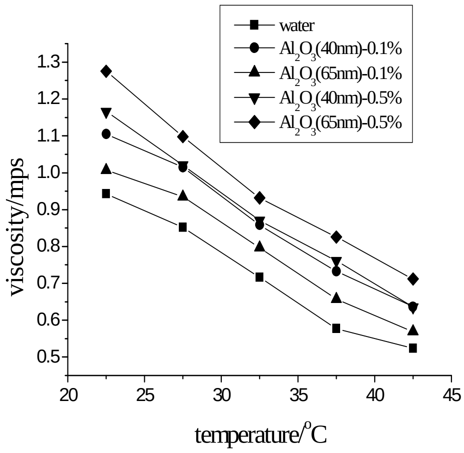


Fig.9 Temperature dependence of viscosity for Al_2O_3 –water Nanofluids

5. CONCLUSIONS

Experimental work has been carried out on the thermal conductivities and viscosities of Al_2O_3-water nanofluids, which were produced using a two step method with ultrasonication and without any surfactant. The effects of Al_2O_3 volume concentration, temperature and average paticle size on the thermal conductivities and viscosities have been examined. Thermal conductivities measurements show that the thermal conductivities increase with temperature increasing and average particle size decreasing, and there is a linear relationship between the volume concentrations and the thermal conductivities. The enhancement of the thermal conductivities could not be adequately predicted by the theoretical models. The viscosities measurements show that the viscosities of the Al_2O_3-water nanofluids decrease with increasing temperature, and increases with the average particle size decreasing. It is also observed that the Al_2O_3-water nanofluids have a nonlinear relation between their viscosity and volume concentration even at very low volume (0.1-0.5%) concentrations.

NOMENCLATURE

k_{eff}	thermal conductivity of nanofluid
k_f	thermal conductivity of base fluid
k_p	thermal conductivity of particle
α	k_p / k_f, thermal conductivity ratio
n	particle shape factor, n =3 for spheres, n =6 for cylinders
φ	particle volume fraction
a	For spherical particles, a =2.25 for α=10, a=3.00 for $\alpha= \infty$
b	For spherical particles, b =2.27 for α=10, b=4.51 for $\alpha=\infty$
η	viscosity of nanofluid
η_r	viscosity of base fluid

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