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Experimental Study on the Effective Thermal Conductivity and Thermal Diffusivity of Nanofluids

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This paper reports measurements of the effective thermal conductivity and thermal diffusivity of various nanofluids using the transient short-hot-wire technique. To remove the influences of the static charge and electrical conductance of the nanoparticles on measurement accuracy, the short-hot-wire probes are carefully coated with a pure Al_2O_3 thin film. Using distilled water and toluene as standard liquids of known thermal conductivity and thermal diffusivity, the length and radius of the hot wire and the thickness of the Al_2O_3 film are calibrated before and after application of the coating. The electrical leakage of the short-hot-wire probes is frequently checked, and only those probes that are coated well are used for measurements. In the present study, the effective thermal conductivities and thermal diffusivities of Al_2O_3/water, ZrO_2/water, TiO_2/water, and CuO/water nanofluids are measured and the effects of the volume fractions and thermal conductivities of nanoparticles and temperature are clarified. The average diameters of Al_2O_3, ZrO_2, TiO_2, and CuO particles are 20, 20, 40, and 33 nm, respectively. The uncertainty of the present measurements is estimated to be within 1% for the thermal conductivity and 5% for the thermal diffusivity. The measured results demonstrate that the effective thermal conductivities of the nanofluids show no anomalous enhancement and can be predicted accurately by the model equation of Hamilton and Crosser, when the spherical nanoparticles are dispersed into fluids.

KEY WORDS: nanofluids; short-hot-wire method; thermal conductivity; thermal diffusivity.

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1. INTRODUCTION

The thermophysical properties of fluids containing spherical or cylindrical solid particles have been investigated for several decades [1–5]. Since a large enhanced thermal conductivity for a dispersion of metallic or non-metallic nanoparticles or nanotubes in conventional fluids was reported and the term of nanofluids was coined by Choi [6] in 1995, many researchers [7–10] have reported their theoretical, numerical, and experimental results on the thermophysical properties of nanofluids. Recently, Kumar et al. [11] reported an enhanced thermal conductivity of about 20% for a nanofluid of only 0.00013% Au in water. Since such an anomalous enhancement is expected to have wide applications in thermal engineering, nanofluids have received considerable attention in thermal science and engineering. However, it is very difficult to explain why nanofluids would have such a high thermal conductivity. Meanwhile, there are large differences among the thermal conductivities reported by different researchers. Therefore, it is necessary to reconsider the reliability of the measurements reported so far.

This paper reports on accurate measurements of the effective thermal conductivity and thermal diffusivity of various nanofluids by using a transient short-hot-wire (SHW) technique. To remove the influences of the static charge and electrical conductance of the nanoparticles on measurement accuracy, the SHW probes are coated by a pure Al_2O_3 thin film with a sputtering apparatus. The electrical leakage of the coated SHW probes is carefully checked, and only those probes that are coated well are used for measurements. The tested nanofluids are Al_2O_3/water, ZrO_2/water, TiO_2/water, and CuO/water, and measurements are carried out for various volume fractions and temperatures. The nanoparticles are all spherical and the average diameters of Al_2O_3, ZrO_2, TiO_2, and CuO particles are 20, 20, 40, and 33 nm, respectively. The measured results show that the effective thermal conductivity and thermal diffusivity increase generally as the volume fraction of the particles increases. However, the effective thermal conductivities of the nanofluids do not show an anomalous enhancement for the case of a dilute dispersion of these spherical nanoparticles, and can be accurately predicted by the model equation of Hamilton and Crosser [1].

2. EXPERIMENTS

The effective thermal conductivity and thermal diffusivity of nanofluids are simultaneously measured by the transient SHW technique. Since the principle and procedures of the SHW technique have been described in detail previously [12–14], only a brief description is given here. The SHW technique was developed from the conventional transient hot-wire (THW) technique and was based on the numerical solution of two-dimensional transient heat conduction for a short wire with the same length-to-diameter ratio and boundary conditions as those used in the actual measurements. The numerical results for the dimensionless volume-averaged hot wire temperature rise $\theta_V[=(T_V - T_0)/(q_V r^2/\lambda)]$ are approximated by a linear equation in terms of the logarithm of the Fourier number $Fo[=(\alpha t)/r^2]$, where T_0 and T_V are the initial liquid temperature and volume-averaged hot wire temperature, respectively, q_V is the heating rate generated per unit volume, r is the radius of the SHW, t is the time, and λ and α are the thermal conductivity and thermal diffusivity of liquid, respectively. The coefficients A and B, the slope and intercept, are determined by the least-squares method for a relevant range of Fourier number corresponding to the measuring periods. The measured temperature rise $\Delta T_V[=T_V - T_0]$ of the wire is also approximated by a linear equation with coefficients a and b, which are also determined by the least-squares method for the time range before the onset of natural convection. A comparison of the above two equations allows us to evaluate the thermal conductivity (λ) and thermal diffusivity (α) of nanofluids from

$$\lambda = \frac{VI}{\pi l}\frac{A}{a} \tag{1}$$

and

$$\alpha = r^2 \exp\left(\frac{b}{a} - \frac{B}{A}\right) \tag{2}$$

where r and l are the radius and length of the hot wire, and V and I are the voltage and current supplied to the wire.

A SHW probe and a Teflon cell with a volume of about 30 cm^3 were designed and fabricated. Figure 1a shows the dimensions of the SHW probe used in the present measurements. The SHW probe is mounted on the Teflon cap of the cell. A short platinum (Pt) wire with a length of 14.5 mm and a diameter of 20 μm is welded at both ends to Pt lead wires of 1.5 mm in diameter. Using distilled water and toluene as standard liquids of known thermophysical properties, the length and radius of the hot wire and the thickness of the Al_2O_3 film are calibrated before and after application of the insulating film coating. Figure 1b shows the dimensions of the Teflon cell used for nanofluid measurements. It has an inner diameter of 30 mm and a height of 47 mm so that the total inner volume is 33.2 cm^3. Two thermocouples are located at the same height to the upper and lower welding spots of the hot wire and lead

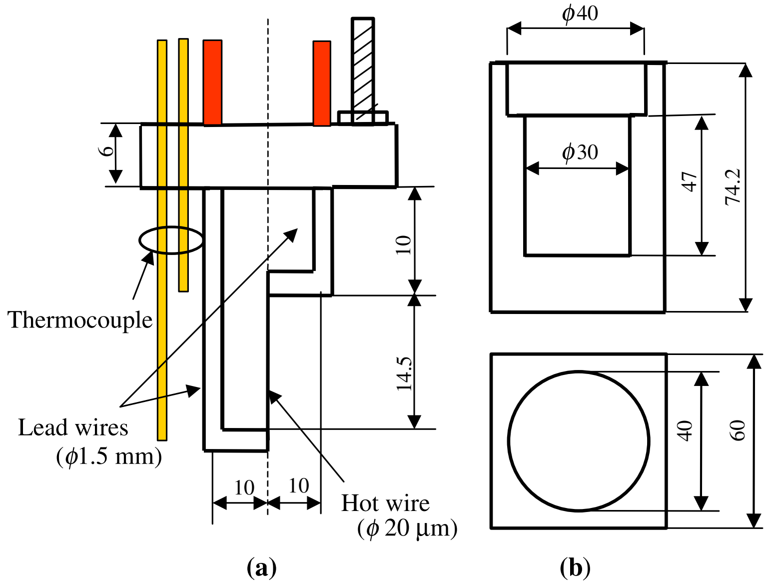

Fig. 1. Schematic of the short-hot-wire probe and experimental cell (dimensions in mm).

wires, respectively, to monitor the temperature homogeneity. In order to minimize temperature fluctuations, the hot-wire cell was placed in a thermostatic bath at the control temperature for which the thermal conductivity measurements were performed. Based on the uncertainty analysis given by Zhang and Fujii [14], the uncertainties of thermal conductivity and thermal diffusivity measurements in the present study are estimated to be within 1.0% and 5.0%, respectively.

3. RESULTS AND DISCUSSION

The samples of Al_2O_3/water, ZrO_2/water, and TiO_2/water nanofluids were made by Sigma-Aldrich Co., where the powders were directly dispersed into the deionized water with a sonic method. The CuO/water nanofluid was directly made by the present authors with the same method. All the samples used in the present study have no surfactants. Generally, the particles themselves have an inherent static charge. The absolute value is very small, but due to the extremely small size of the particles, the charge is large enough to keep them in suspension without settling and aggregation. For the cases of lower volume fractions, our measurements have shown that the values of the effective thermal conductivity and thermal diffusivity did not change over a period of 48 hours.

Figure 2 shows the transmission electron microscope (TEM) photographs of Al_2O_3, ZrO_2, TiO_2, and CuO particles used for the present measurements. It is noted that, because the TEM must work in a vacuum, these photographs were taken only after drying the nanofluids. Therefore, we can clearly know the shape and size of the nanoparticles by TEM photographs, but not the intrinsic dispersion of nanoparticles in the water.

Figures 3a and 3b show the measured effective thermal conductivity and thermal diffusivity of Al_2O_3/water nanofluids for mass fractions of particles $\phi_w = 0, 10, 20$, and 40%. For distilled water ($\phi_w = 0$) the present results in the temperature range of 5–50°C agree well with the standard values recommended in Refs. 15 and 16. As shown in Fig. 3, the effective thermal conductivity and thermal diffusivity of the nanofluids increase with an increase in the particle concentration and in the temperature. Furthermore, as for the temperature dependence, the slopes are the same as

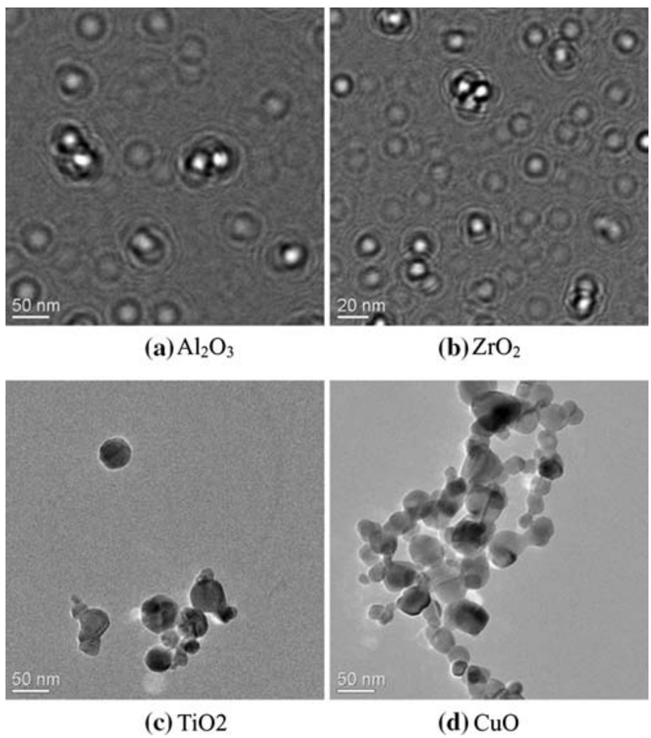

Fig. 2. TEM photographs of Al_2O_3, ZrO_2, TiO_2, and CuO particles.

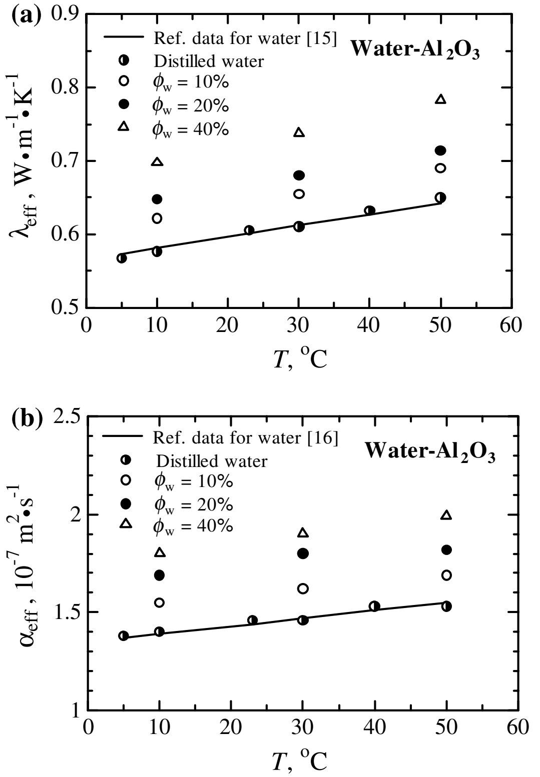

Fig. 3. Effective (a) thermal conductivity and (b) thermal diffusivity of water-Al_2O_3 nanofluids.

those for pure water. This means that the temperature-dependent thermal conductivity and thermal diffusivity of nanoparticles do not affect the temperature dependence of the effective thermal conductivity and thermal diffusivity of nanofluids in the range of the present concentrations.

Figures 4a and 4b show the effective thermal conductivity and thermal diffusivity of Al_2O_3/water nanofluids for different particle concentrations and temperatures. In these figures, the thermal conductivity and thermal diffusivity are normalized by using the values of pure water. The present thermal conductivities are close to those measured by Lee et al. [8] and Xie et al. [9], but lower than ones obtained by Masuda et al. [5]. The solid line further represents the values predicted by the Hamilton and Crosser model equation (H-C model) [1], where the effective thermal conductivity, λ_{eff}, is expressed as

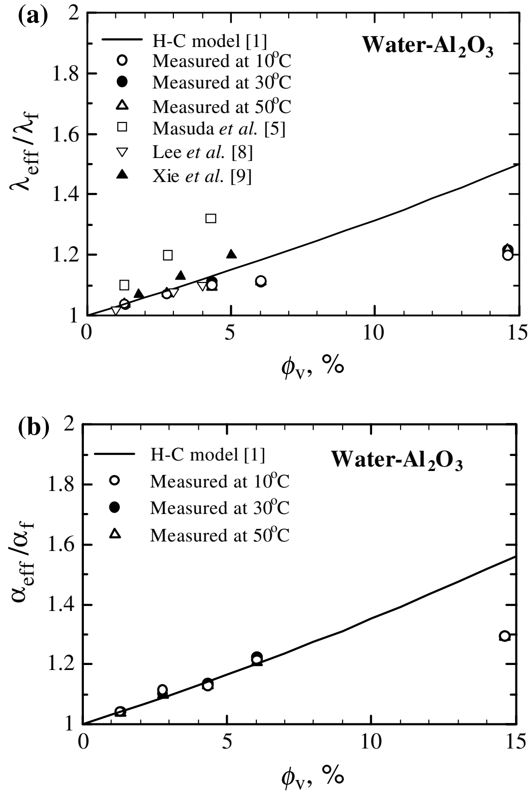

Fig. 4. Normalized (a) thermal conductivity and (b) thermal diffusivity of water-Al_2O_3 nanofluids.

$$\lambda_{eff} = \lambda_1 \frac{[\lambda_2 + (n-1)\lambda_1 - (n-1)\phi_v(\lambda_1 - \lambda_2)]}{[\lambda_2 + (n-1)\lambda_1 + \phi_v(\lambda_1 - \lambda_2)]} \tag{3}$$

Here, λ_1 and λ_2 are the thermal conductivity of the fluid and particles, respectively. And n is a constant that depends on the shape of the dispersed particles and on the ratio of the conductivities of the two phases. When the particles are spherical, the theoretical result shows that n is equal to 3 and independent of both the particle size and the ratio of the conductivities. Therefore, in the present paper, n is taken to be 3. ϕ_v is the volume fraction of the particles and is calculated by

$$\phi_v = \frac{\phi_w \rho_w}{\rho_p + \phi_w \rho_w - \phi_w \rho_p} \tag{4}$$

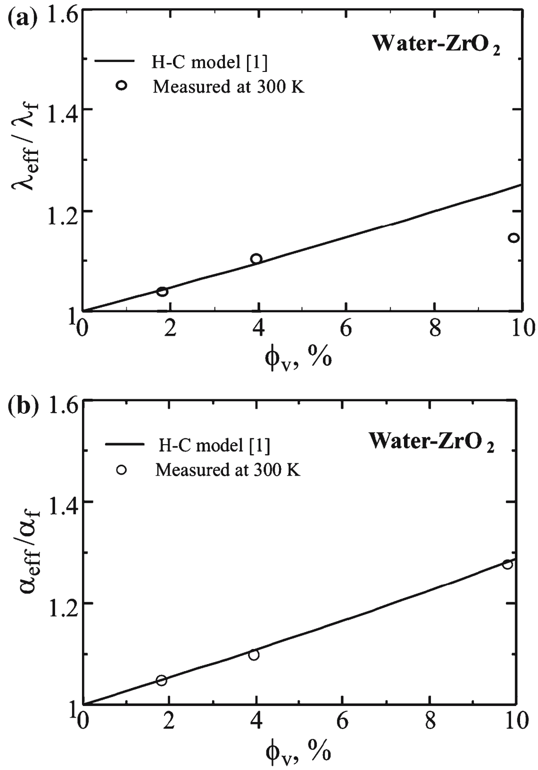

Fig. 5. Normalized (a) thermal conductivity and (b) thermal diffusivity of water-ZrO_2 nanofluids.

where ρ_w and ρ_p are the density of the fluid and particles, respectively. ϕ_w is the mass fraction of the particles dispersed in the nanofluids. Based on the definition of the thermal diffusivity, the effective thermal diffusivity of nanofluids can be calculated by

$$\alpha_{eff} = \frac{\lambda_{eff}}{\rho_{eff} C_{eff}} \tag{5}$$

where ρ_{eff} and C_{eff} can be calculated by

$$\rho_{eff} = \rho_p \phi_v + \rho_w (1 - \phi_v) \tag{6}$$

and

$$C_{eff} = C_p \phi_w + C_w (1 - \phi_w) \tag{7}$$

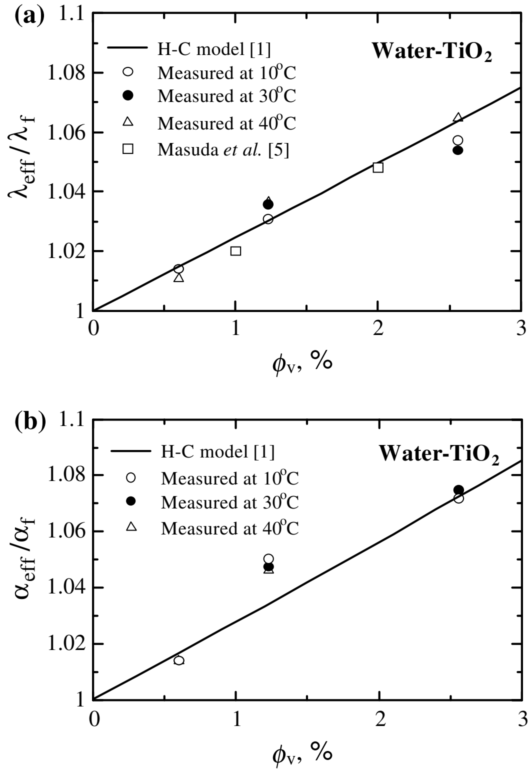

Fig. 6. Normalized (a) thermal conductivity and (b) thermal diffusivity of water-TiO_2 nanofluids.

and C_w and C_p are the specific heat capacities of the fluid and particles, respectively.

As shown in Fig. 4, the present effective thermal conductivity and thermal diffusivity in a lower volume fraction range agree well with the values predicted by the H-C model. On the other hand, in the higher volume fraction range, the measured results are lower than the predicted values. This is due to the settling of some fraction of particles that occurred at the higher volume fraction. Furthermore, the normalized thermal conductivity and thermal diffusivity are almost independent of the temperature. This confirms that the temperature dependence of these properties of nanofluids is not dominated by the solid phase but by the fluid phase.

Figures 5 to 7 show the normalized effective thermal conductivity and thermal diffusivity of ZrO_2/water, TiO_2/water, and CuO/water nanofluids. The present thermal conductivities agree well with those obtained

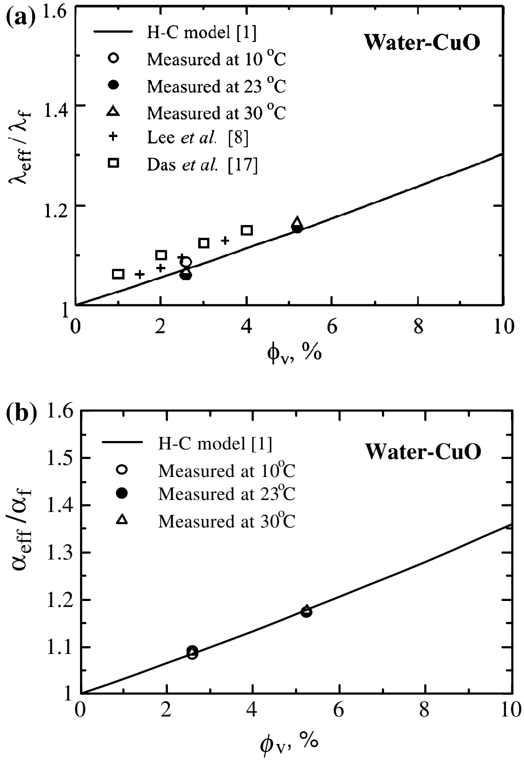

Fig. 7. Normalized (a) thermal conductivity and (b) thermal diffusivity of water-CuO nanofluids.

by Masuda et al. [5] for TiO_2/water nanofluids shown in Fig. 6a, but are lower than ones obtained by Lee et al. [8] and Das et al. [17] for CuO/water nanofluids shown in Fig. 7a. All of the present values in a range of lower volume fractions agree well with those predicted by the H-C model, although the absolute values are dependent on the thermal properties of nanoparticles.

The results mentioned above, together with consideration of the present measurement uncertainty, clearly indicate that the dispersion of nanoparticles does not cause any anomalous enhancements for the thermal conductivity and thermal diffusivity as those reported by some other authors [6, 11]. Furthermore, the magnitude of the enhancement can be predicted using the existing model. Although it is very difficult to point out clearly the problems encountered in the previous experiments [6, 11], it is found that the electrical insulation of the hot-wire probe is very important when the hot-wire method is applied to measurements of nanofluids. Even in our measurements, an insufficient insulation of the wire has resulted in clustering of nanoparticles on the wire surface, and then in much different values of the thermal conductivity and thermal diffusivity of nanofluids. Furthermore, proper mixing and stabilization of the particles are also very important. To check the stabilization of the particles, we have measured the volume fraction of the particles after the experiments as well as observed the time variation of the thermal conductivity and thermal diffusivity.

4. CONCLUSIONS

The effective thermal conductivity and thermal diffusivity of Al_2O_3/water, ZrO_2/water, TiO_2/water, and CuO/water nanofluids have been measured accurately for various volume fractions and temperatures. The present results show that the effective thermal conductivity and thermal diffusivity increase with an increase in the particle concentration and in the thermal conductivity of nanoparticles. The effective thermal conductivities of nanofluids have not shown any anomalous enhancements. All of the measured values agree well with those predicted by the H-C model at lower volume fractions.

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