Journal of Alloys and Compounds 434–435 (2007) 569–571
Journal of ALLOYS AND COMPOUNDS
www.elsevier.com/locate/jallcom

A simple model to estimate thermal conductivity of fluid with acicular nanoparticles

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Available online 28 September 2006

Abstract

In this work, the effects of particle rotation on thermal conductivity are discussed. The effective conduction volume of a particle in rotation is larger than that of the particle itself. Taking the rotation of acicular particles into consideration, this study develops the predictive equation for thermal conductivity of fluid containing acicular CuO nanoparticles. Good agreement between the actual and estimated values proves that the proposed equation can provide precise prediction of thermal conductivity of fluid containing acicular CuO nanoparticles.

Keywords: Nanostructures; X-ray diffraction; Heat conduction

1. Introduction

Enhancing heat transfer for operation and maintenance of equipment has been the focus of researches in many fields. In some cases, particles have been added to fluids in order to improve thermal conductivity. Many predictive equations have been proposed to estimate the increase in thermal conductivity due to the addition of particles. Nevertheless, previous models were developed on the basis of the solid/liquid suspension concept [1]. Great discrepancies between values estimated by equation and those obtained from experiments arise when the added particles are of nanoscale, thus undermining the predictive accuracy of the equation. According to Xuan and Li [2], as well as Eastman et al. [3], the thermal conductivity of nanofluids depends strongly on the volume fraction and properties of the added nanoparticles.

To understand why such discrepancy occurs, so that the equation can be modified to ensure better prediction accuracy, factors such as size, surface area and shape of the added particles [4–9] as well as interfacial shell [10] have been studied. Besides, some researchers used the concept of the n-point probability function $S_n(r^n)$ to discuss macroscopic properties of two-phase random heterogeneous media, and to extend the sphere system into the spheroid system by utilizing the arbitrary aspect ratio [11]. Garboczi and Douglas proposed the concept of intrinsic conductivity to solve the problem of effects of shapes and sizes of particles on thermal conductivity [12].

Nanoparticles in fluids are engaged in Brownian motion, causing random collision between solid particles and liquid molecules. As a result, these particles remain steadily suspended in the fluid and deposition rarely occurs. The effect of particle motion on thermal conductivity should be taken into consideration when modifying conventional prediction equations. In this literature, the conventional prediction equations for thermal conductivity are modified into the simple prediction equations for thermal conductivity of nanofluids containing CuO acicular nanoparticles by considering the factors of perturbation motion and shape of added particles. The results calculated by these simple prediction equations are compared with those of the corresponding experiments in order to verify the accuracy of theoretical estimation of the proposed prediction equations.

2. Maxwell equation

Among conventional models of effective thermal conductivity of solid/liquid suspensions, Maxwell theory predicts that spherical particles can enhance heat-transfer performance [1]. The equation proposed by Maxwell for estimating thermal

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doi:10.1016/j.jallcom.2006.08.229

conductivity is as follows:

$$k_{\text{maxwell}} = \frac{k_p + 2k_l + 2(k_p - k_l)\phi}{k_p + 2k_l - (k_p - k_l)\phi} k_l \quad (1)$$

where k_p represents the thermal conductivity of the solid particles added, k_l the thermal conductivity of the bulk liquid, and ϕ is the volume fraction, vol%. Since the Maxwell equation considers only spherical particles of even distribution, the shape factor can thus be neglected. Consequently, the increase in thermal conductivity is dependent on the volume concentration of the solid particles. Nevertheless, comparing with the experimental data, the values predicted by the equation are underestimated. Consequently, the equations can be modified to ensure greater prediction accuracy if one understands the possible factors of occurrence of such discrepancy, such as diameter, surface area and shape of the added particles. However, little has been done on examining the effect of particle rotation on thermal conductivity.

3. Effect of nanoparticle rotation

Brownian motion causes the particles to be engaged in random motion, both translational and rotational. In Maxwell equations, the particles are assumed to be spherical and hence their rotation will have no influence on the volume covered. However, the situation will be different when the particles added to the nanofluid are acicular in shape (Fig. 1). The sample nanofluids used in this study were prepared by the submerged arc nanoparticle synthesis system (SANSS) [13]. When the applied electrical energy produces a heating source for generating an adequate arc of high temperature, which ranges from 6000 to 12000 °C [14], copper, the bulk metal used in this study, is melted and vaporized. In addition, deionized water, which is the dielectric liquid in this investigation, is also heated and vaporized rapidly by part of the submerged arc. The increase in volume as a result promotes a quick removal of the vaporized aerosol from the surface of the metal electrodes. The vaporized metal present in the base solvent within the vacuum chamber changes its current phase state through the nucleation, growth and solidification stages, and eventually becomes metal nanoparticles dispersed in the base solvent, forming nanofluids. When these particles rotate, the corresponding volume covered will not be the same as the volume of these particles.

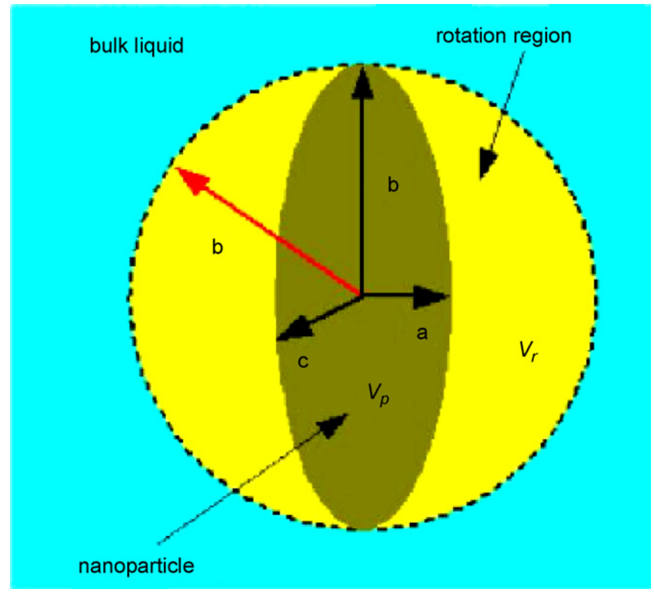

Fig. 2. Effect of nanoparticle rotation.

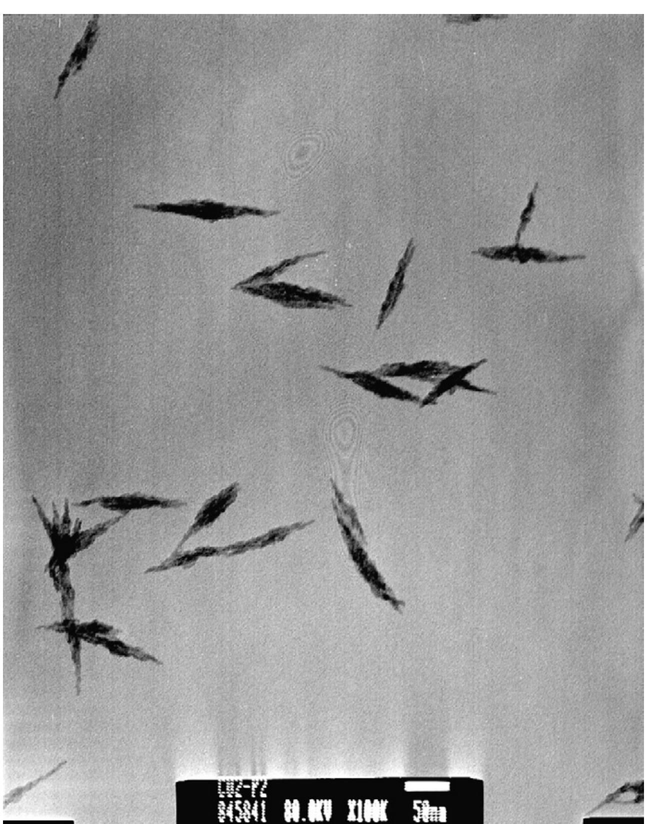

Fig. 1. TEM image of deionized water-based nanofluid containing copper oxide particles.

With the ellipsoid particle simulating the acicular particle (Fig. 2), the increasing ratio of the volume when it rotates in a radius of the long axis is described in the following.

$$\psi = \frac{V_r}{V_p} = \frac{(4/3)\pi b^3}{(4/3)\pi abc} \quad (2)$$

As shown in Fig. 1, the ratio of the principle axes is 8:3:3 (a:b:c ≒ 8:3:3) and b is more or less equal to c, so Eq. (2) can be further simplified as

$$\psi^* = \frac{V_r}{V_p} = \frac{(4/3)\pi b^3}{(4/3)\pi a^2 b} \quad (3)$$

In Eq. (3), the difference between the volume of field influenced by rotation of the particle (V_r) and that of the particle itself (V_p) is $\Delta V (\Delta V = V_r - V_p)$. The thermal conductivity of the increased volume is defined as $k_{\Delta V}$, and it should be between that of the liquid and the solid. When the speed of rotation approaches infinity, the thermal conductivity of the increased volume will be close to that of the solid particles. On the other hand, when

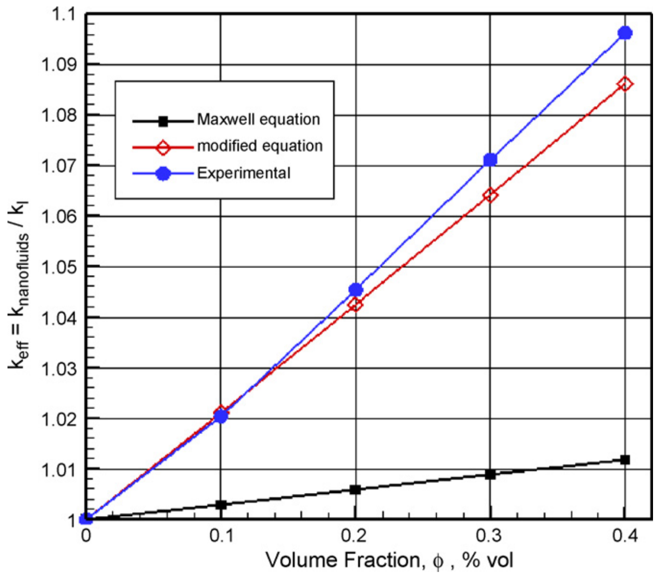

Fig. 3. The increasing ratio of the thermal conductivity.

the speed of rotation is close to zero, the thermal conductivity of the increased volume will approach that of the liquid. Hence, the increase in volume due to rotation will change the volume fraction. For the extreme case of $k_{\Delta V} = k_p$, Maxwell equation can be renovated to Eq. (4).

$$k_{eff} = \frac{k_p + 2k_l + 2(k_p - k_l)\psi^* \phi}{k_p + 2k_l - (k_p - k_l)\psi^* \phi} k_l \quad (4)$$

where k_p and k are detailed in the reference [9], and k_p/k_l is about 250. The diameter of the nanoparticles is obtained by the dynamic light scattering particle size distribution analyzer (HORIBA, LB-500), the secondary diameter is 85 nm. X-ray diffraction analysis confirms that the ingredient of nanoparticles is CuO. The concentration of the nanofluids is measured by UV–visible spectrophotometers and compared with samples of standard volume fraction. The CuO nanofluids used in this experiment are of 0.1, 0.2, 0.3, and 0.4 vol%. The thermal conductivity of the nanofluids is obtained by the transient hot-wire method [15,16].

4. Results and discussion

Fig. 3 shows the increasing ratio of the thermal conductivity ($k_{eff} = k_{nanofluids}/k_l$) of the fluids containing CuO nanoparticles in experiment compared to, predictions of Maxwell's equations, and those of the modified equations. For the fluids of the highest concentration 0.4 vol%, the experimental thermal conductivity increases about 9.6%. In this figure, it can be found that thermal conductivities predicted by Maxwell's equations are obviously underestimated. With the standard based on the practical values of the experiments, the largest error of the thermal conductivities predicted by Maxwell's equations is within 8% for all the samples. As to those predicted by modified equations, the errors are reduced to below 1% if the $k_{\Delta V}$ is assumed to be equal to k_p.

5. Conclusions

The Maxwell equation has been in use for many years and considers only spherical particles added to solid/liquid suspensions. Subsequent researches have made modifications to the equation taking into account other factors such as shape and layer adsorption. This study explores the effect of rotation of acicular particles on the changes in volume concentration. Experimental results and analyses reveal that rotation has significant influence on the volume concentration and the shape of the particle in rotation also contributes to the effect. The Maxwell equation is modified with the rotation of particles considered. With the $k_{\Delta V} = k_p$, the discrepancy between the estimated and actual values is greatly reduced, thus enhancing the accuracy of the Maxwell equation in predicting thermal conductivity.

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