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Experiment and calculation of the thermal conductivity of nanofluid under electric field

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ABSTRACT

Nanofluid has attracted the attention of many scholars for the excellent heat transfer enhancement capacity. In addition, electric field can further strengthen the nanofluid's ability of heat transfer. The thermal conductivity enhancement rate of nanofluid under electric field was studied using transient hot wire method under different electric field intensities, temperatures and particle concentrations. The influences of those parameters have been discussed. Besides, based on the static thermal conductivity and the dynamic heat conduction coefficient, a novel prediction model was established, which had a good agreement with experiment data. The mechanism of thermal conductivity enhancement under electric field was analyzed according to the prediction model.

1. Introduction

In 1995, Choi [1] first proposed the concept of nanofluid, namely to add some nanometer metal or nonmetallic oxide particles into base fluid by certain method to form a new heat transfer medium. Choi used the traditional heat transfer coefficient formula of liquid and solid two-phase mixture to calculate the thermal conductivities of nanofluids. The results showed that adding nanoparticles in base fluid could increase the thermal conductivity. After that, the thermal conductivity enhancement of nanofluid attracted the attention of many scholars.

The establishment of calculation model for thermal conductivity of nanofluid is of great significance. Early in the nineteenth century, Maxwell [2] proposed a thermal conductivity model of suspensions with micron or millimeter solid particles. The relationship between effective thermal conductivity and thermal conductivity of pure fluid is as follows.

$$\lambda_{eff}/\lambda_f = \frac{\lambda_p + 2\lambda_f + 2\phi(\lambda_p - \lambda_f)}{\lambda_p + 2\lambda_f - \phi(\lambda_p - \lambda_f)} \tag{1}$$

Maxwell only considered the thermal conductivity of particle, base fluid thermal conductivity, particle volume fraction. It is valid for two-phase mixture with suspended micron or millimeter scale solid particles, but it can't explain the abnormal increase of thermal conductivity in nanofluid. In recent years, researchers have developed and improved the Maxwell model. Taking different influence factors into consideration, many new models were established to explain the abnormal increase in thermal conductivity of nanofluid.

Hamilton and Crosser [3] considered the particle's spherical degree, and proposed the following model (2).

$$\lambda_{eff}/\lambda_f = \frac{\lambda_p + (n-1)\lambda_f + (n-1)\phi(\lambda_p - \lambda_f)}{\lambda_p + (n-1)\lambda_f + \phi(\lambda_p - \lambda_f)} \tag{2}$$

The formula can be applied to non-spherical particles, yet not so effective with respect to nanofluids.

Based on effective medium approximation and fractal theory, Wang [4] considered the size effect and surface adsorption and obtained the calculation model (3).

$$\frac{\lambda_{eff}}{\lambda_f} = \frac{(1-\phi) + 3\phi\int_0^\infty \frac{\lambda_{cl}(r)n(r)}{\lambda_{cl}+2\lambda_f}dr}{(1-\phi) + 3\phi\int_0^\infty \frac{\lambda_f n(r)}{\lambda_{cl}+2\lambda_f}dr} \tag{3}$$

The formula was tested by the experimental results of CuO-water nanofluids. Results showed that considering the effect of surface adsorption improved the accuracy of the model, but the spatial distribution and agglomeration effects of nanoparticles were not taken into consideration.

Combining the Maxwell theory and the theory of the average polarization of the interface shell effect, Xue [5] obtained an implicit formula (4).

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Nomenclature

c	specific heat capacity [J/(kg·k)]
E	electric field intensity [MV/m]
F_e	volume force of electric field [N]
I	current [A]
k_B	Boltzmann constant [1.3806505e-23 J/K]
l	movement distance per unit time [m]
L	length of the hot wire [mm]
m	quality [kg]
n	spherical degree [–]
q_e	charge density [C/m^3]
Q	energy delivered per unit time [J/s]
u	velocity [m/s]
U	zeta potential [mV]
r	radius [m]
R_0	electric resistance [Ω]
t	time [s]
T	temperature [°C]

Greeks

μ	viscosity coefficient [kg/(m·s)]
ε	dielectric constant [–]
ρ	density [kg/m^3]
ϕ	volume concentration [–]
λ	thermal conductivity [W/(m·k)]
θ	mass concentration [–]
Φ	temperature rise of the hot wire [°C]

Subscripts

p	particle
$f\,(bf)$	pure fluid, namely base fluid
eff	effective
nf	nanofluid
s	static
d	dynamic

$$9\left(1-\frac{\upsilon}{\lambda}\right)\frac{\lambda_{eff}-\lambda_f}{2\lambda_{eff}+\lambda_f} + \frac{\upsilon}{\lambda}\left[\frac{\lambda_{eff}-\lambda_{c,x}}{\lambda_{eff}+B_{2,x}(\lambda_{c,x}-\lambda_{eff})}+4\frac{\lambda_{eff}-\lambda_{c,y}}{2\lambda_{eff}+(1-B_{2,x})(\lambda_{c,y}-\lambda_{eff})}\right]=0 \tag{4}$$

The calculated values were in good agreement with the experimental results of carbon nanotube-oil and γ-Al_2O_3-water nanofluids. Moreover, the model provided an explanation for the anomalous increase in thermal conductivity of nanofluid.

The micro convection around the particles and the thermal resistance of the interface were analyzed by Prasher [6].

$$\begin{aligned}&\lambda_{eff}/\lambda_f=(1+A\phi\mathrm{Re}^m\mathrm{Pr}^{0.333})\,\frac{1+2\alpha+2\phi(1-\alpha)}{1+2\alpha-\phi(1-\alpha)}\\&\alpha_f=2R_b\lambda_f/d_p\end{aligned} \tag{5}$$

By quantitative analysis, Prasher demonstrated that the particle Brown motion caused by micro convection is the main reason for the abnormal increase of the thermal conductivity of the nanofluid.

In experimental field, there are also many studies carried out by different researchers to measure thermal conductivities of various nanofluids. Masuda et al. [7] added 13 nm Al_2O_3 nanoparticles and 27 nm TiO_2 nanoparticles into water to get nanofluids with different concentrations. The thermal conductivities of nanofluids were measured using transient hot wire method. Experimental results showed that adding nanoparticles in the base fluid greatly enhanced the thermal conductivity. For example, when adding 4.3% volume concentration of γ-Al_2O_3 and TiO_2 particles in water, the thermal conductivity rose by 32% and 11% respectively, while the viscosity of the fluid did not increase significantly. Using the steady plate method, Wang et al. [8] measured the thermal conductivities and viscosities of nanofluids with 28 nm γ-Al_2O_3 particles in water, ethylene glycol and oil. Experimental results indicated that adding 3% volume concentration of γ-Al_2O_3 nanoparticle, the thermal conductivity was increased by 12%. Das [9,10] studied 1.0% volume concentration 38.4 nm CuO-water nanofluid and found that when the temperature elevated from 21 °C to 50 °C, the thermal conductivity enhancement rate rose from 1.06 to 1.30. Wang [11] summarized the experimental data of the existing literature and concluded that the thermal conductivity enhancement of nanofluid was associated with the concentration of the nanoparticle, the kind of the base fluid, temperature as well as the type and size of the nanoparticle. Liao et al. [12] studied the forced convective heat and flow transfer of CuO-water nanofluid in a horizontal stainless steel tube with 1 mm diameter and pointed out that the increase of the thermal conductivity of nanofluid is the main reason for heat transfer enhancement. Putra [13] studied the natural convection heat transfer of nanofluids in a horizontal cylindrical cavity experimentally, in which temperature on both sides of the horizontal cylinder was kept constant and the side face of the cylinder was adiabatic. It was found that unlike heat conductive and forced convective heat transfer, natural convective heat transfer of nanofluids exhibited a deterioration tendency. Deterioration was affected by nanoparticle concentration and cylindrical cavity shape.

In active heat transfer strengthening field, the electric field heat transfer enhancement method (EHD) got much attention among researchers for its evident effect, simple generation, easy control, available for micro-gravity or some other special occasions, and low energy consumption. The electric field can be used to further improve the heat transfer performance of nanofluids. Nanoparticles in the electric field are under control of electrophoretic force, dielectric electrophoretic force and electric induced contraction force. The calculation formula is as follows.

$$F_e=q_eE-\frac{1}{2}E^2\nabla\varepsilon+\frac{1}{2}\nabla\left[E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\rho\right] \tag{6}$$

These additional forces can enhance the movement of nanoparticles, increase the chance of collisions between particles, help destroy the boundary layer, and thus strengthen the heat transfer among nanoparticles. Jung et al. [14] studied the dynamic characteristics of Al_2O_3 nanoparticles under alternating current electric field. The static electricity force and the dielectric electrophoretic force were considered, as well as the nanoparticles' viscous forces and Brownian force. The influences of the particle size, zeta electric potential and electric field frequency on the movement of nanoparticles were studied. Results showed that the average speed of nanoparticles increased with the decrease of particle diameter and the increase of zeta potential. Besides, with increasing frequency, nanoparticles' moving range would reduce. Jung's studies presented that the electric field had a positive effect on manipulating the movement of nanoparticles. Unfortunately, their work did not include heat transfer.

In the existing research, there are few calculation models or direct measurement of the thermal conductivity of nanofluid under the electric field. In the present study, the theoretical model of the thermal conductivity of nanofluid under the electric field is developed and direct measurement is carried out. Based on the static