Materials Chemistry and Physics 148 (2014) 195–200

Contents lists available at ScienceDirect

Materials Chemistry and Physics

journal homepage: www.elsevier.com/locate/matchemphys

Effective thermal conductivity of nanofluids considering interfacial nano-shells

Haifeng Jiang, Hui Li, Qianghui Xu, Lin Shi*

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- A model with interfacial nano-shell for thermal conductivity is developed.
- Effect of thermal conductivity and thickness of nano-shell has been investigated.
- Thermal conductivity predicted by this model fits well with experimental data.

ARTICLE INFO

Article history:
Received 21 December 2013
Received in revised form
11 June 2014
Accepted 21 July 2014
Available online 7 August 2014

Keywords:
Nanostructures
Thermal conductivity
Transport properties
Composite materials

ABSTRACT

Nanofluids that are produced by dispersing nanoparticles into traditional heat transfer fluids, show greater thermal conductivities than regular fluids. An interfacial nano-shell between the nanoparticle and the base fluid was used to derive an expression for the effective thermal conductivity of nanofluids. Unlike with traditional models, the effective thermal conductivity predicted by the present model is not only affected by the ratio of the thermal conductivities of the particle and the media and their relative volume fractions, but is also affected by the nanoparticle radius and the thermal conductivity and thickness of the interfacial nano-shell. The calculated results predicted by this model agree quite well with available experimental data.

1. Introduction

Heating or cooling fluids are important for many industries. With ever-increasing thermal loadings due to smaller microelectronic devices and greater power outputs for engines, cooling of such systems is a crucial problem in high-tech industrial sectors. Thermophysical properties, particularly the thermal conductivity, are vital properties that have to be taken into account in the development of energy-efficient heat transfer devices [1]. Thermal conductivity enhancement by the dispersion of solid particles in liquids was verified by Maxwell [2] more than a century ago. However, most previous studies of the thermal conductivity of solid/liquid mixtures had been confined to those containing millimeter or micrometer-sized particles.

Nanofluids, prepared by dispersing nanometer-sized particles into conventional heat transfer fluids such as water (H_2O), ethylene glycol (EG), or thermic oil are expected to be effective heat transfer media. The term nanofluid was coined by Choi and his colleagues [3,4] in 1995 at Argonne National Laboratory. The improved thermal conductivity of nanofluids compared to that of the base fluid in which they are dispersed has potential for many applications as heat transfer fluids [5–7]. Many studies have sought to achieve more stable nanofluids and to improve the effective thermal conductivity of suspensions. The thermal conductivity of nanofluids as a function of nanoparticle volume fraction has been widely investigated [1,4,6,8–14]. A maximum increase in the thermal conductivity of approximately 30% was observed for 5 vol% Al_2O_3 with average diameters of 60 nm dispersed in EG Ref. [12]. The effective thermal conductivity for 4 vol% CuO with a mean radius of about 12 nm mixed with EG was increased by up to 20% [4]. An unusual result for a nanofluid containing EG and only 0.3 vol% Cu nanoparticles with an average diameter of 6 nm showed the effective thermal conductivity increased by up to 40% [1].

All these experimental results are much larger than the theoretical results predicted by existing models, e.g. Maxwell's model [2], the Hamilton and Crosser model [15], and Davis' model [16]. These models were based on the particle volume fraction and the

* Corresponding author. Tel.: +86 10 6278 7613.
E-mail addresses: rnxsl@mail.tsinghua.edu.cn, jhf11@mails.tsinghua.edu.cn (L. Shi).

http://dx.doi.org/10.1016/j.matchemphys.2014.07.031
0254-0584/

Nomenclature

T	temperature
k	thermal conductivity
r	radial distance from the center of the nanoparticle
t	interfacial nano-shell thickness
Q	heat flow
A	surface area at distance r from the center of the nanoparticle
n	degree of sphericity of nanoparticle
R_{Bd}	interfacial thermal resistance

Subscripts

nf	nanofluid
bf	base fluid
p	nanoparticle
pe	equivalent nanoparticle
l	interfacial nano-shell

Greek symbols

α	ratio of the thermal conductivities of the base fluid and the nanoparticle (k_{bf}/k_p)
φ	nanoparticle volume fraction

thermal conductivities of the particle and the base media. Hamilton and Crosser also considered the influence of particle shape on the effective thermal conductivity of two-phase mixtures [15]. The inconsistence between the experimental data and theoretical predictions demonstrates that these models developed for millimeter or micrometer-sized particles as the discontinuous phase do not accurately reflect the effect of particle size, Brownian motion of the particle, particle clustering, liquid layering (nano-shell), ballistic transport and nonlocal effects, nanoparticle thermophoresis, thermal boundary, and near-field radiation, which have been proposed as potential mechanisms affecting the effective thermal conductivity of nanofluids [4,17–25].

In solid-fluid mixtures, the liquid molecules around a nanoparticle surface have a similar structure to the solid and behave much like a solid [26]. Since this layer is in an ordered solid-like state, it would have an intermediate thermal conductivity between the particle and the bulk media [27]. This liquid layer assumption has been used in many theoretical studies to predict the increased thermal conductivity of nanofluids [28–31]. This nano-shell provides as a thermal connection between the nanoparticles and the base fluid which lowers the contact thermal resistance. However, the exact thermal conductivity and the thickness of such an interfacial nano-shell are not yet known. The concept of nanoshell was proposed by investigators to be a region where the thermophysical properties of the base fluid was influenced by the presence of nanoparticle, so the structure and properties of such interfacial nanoshell are complicated and unknown and previous models of thermal conductivity profiles within nanoshell were all based on assumptions [30–34].

This paper presents a mathematical model for the interfacial nano-shell with a nonlinear thermal conductivity distribution, which the interfacial thermal conductivity profile and the slope are contiguous at the interface with the nanoparticle and the base fluid. An expression is given for the effective thermal conductivity of the nanofluid which includes the effect of the nano-shell. The results obtained with this model compare well with available experimental data as well as with other models. The model is then used to evaluate the impact of the nanoparticle radius, nano-shell thickness, nanoparticle volume fraction, and thermal conductivity ratio of the nanoparticle to the base media.

2. Model formulation

2.1. Earlier models

Many models have been developed to predict the effective thermal conductivity of solid/liquid suspensions. However, none of those models satisfactorily predict the observed experimental data for nanofluids. The expressions for the conventional mathematical models summarized by Choi et al. [35] are:

Maxwell [2]:

$$\frac{k_{nf}}{k_{bf}} = 1 + \frac{3(1-\alpha)\varphi}{(1+2\alpha)-(1-\alpha)\varphi} \tag{1}$$

Hamilton and Crosser [15]:

$$\frac{k_{nf}}{k_{bf}} = 1 + \frac{n(1-\alpha)\varphi}{1+\alpha(n-1)-(1-\alpha)\varphi} \tag{2}$$

Jeffery [36]:

$$\frac{k_{nf}}{k_{bf}} = 1 + 3b\varphi + \left(3b^2 + \frac{3b^2}{4} + \frac{9b^3}{16}\,\frac{1+2\alpha}{2+3\alpha} + \frac{3b^4}{2^6} + \ldots\right)\varphi^2 \tag{3}$$

Davis [16]:

$$\frac{k_{nf}}{k_{bf}} = 1 + \frac{3(1-\alpha)\varphi}{(1+2\alpha)-(1-\alpha)\varphi}\left[\varphi + f(\alpha)\varphi^2 + O(\varphi^3)\right] \tag{4}$$

Yamada and Ota [22]:

$$\frac{k_{nf}}{k_{bf}} = \frac{1+2\alpha\varphi^{-0.2}+2(1-\alpha)\varphi^{0.8}}{1+2\alpha\varphi^{-0.2}-(1-\alpha)\varphi} \tag{5}$$

Lu and Lin [37]:

$$\frac{k_{nf}}{k_{bf}} = 1 + A_1\varphi + B_1\varphi^2 \tag{6}$$

Nan [23]

$$\frac{k_{nf}}{k_{bf}} = \frac{1+2(\alpha+M)+2(1-\alpha-M)\varphi}{1+2(\alpha+M)-(1-\alpha-M)\varphi} \tag{7}$$

where k_{nf} is the effective thermal conductivity of the solid/liquid mixture and k_{bf} is the thermal conductivity of the base media, n is the degree of sphericity, φ is the volume fraction, α is the ratio of thermal conductivity of the base fluid to the nanoparticle (k_{bf}/k_p), M is defined by $R_{Bd}\cdot k_{bf}/r_p$, r_p is the radius of particle, $b = (1-\alpha)/(1+2\alpha)$, and A_1 and B_1 are constants related to α. The parameter R_{Bd} represents the impact of interfacial resistance. R_{Bd} is assumed to be 0.77×10^{-8} K m^2 W^{-1} for H_2O-based nanofluids and 1.2×10^{-8} K m^2 W^{-1} for EG-based nanofluids [38–40].

2.2. Interfacial nano-shell thermal conductivity models

The analysis of the ordered liquid layer in the nano-shell assumes a nanoparticle/liquid suspension with spherical particle of radius r_p and an outer interfacial nanolayer with thickness t as shown in Fig. 1. The thickness, t, and the thermal conductivity, k_l, of this nano-shell strongly depend on the nanoparticle and base media properties and the interactions between them. This model assumes that the thermal conductivity distribution inside the interfacial nano-shell is nonlinear across the nanolayer thickness.