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Research Paper

A new thermal conductivity model for nanorod-based nanofluids

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HIGHLIGHTS

- A new thermal conductivity model for nanorod-based nanofluids is proposed.
- A physical model of a nanorod with layer is split apart in axial and radial direction.
- Analytic solutions of control equations of the splitted physical models are combined.
- Allocation in different directions is depended on the aspect ratio of the nanorod.
- The present model shows better precision for nanorod-based nanofluids.

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ABSTRACT

As a new kind of solid/liquid suspension, nanofluid needs to be further explored since its measured thermal conductivity is significantly greater than the classic prediction when containing specially shaped particles, for instance nanorods. Various thermal conductivity models for spherical or tubular nanoparticles based nanofluid have been proposed, but none is specifically responsible for nanorod-based nanofluids. In this paper, a physical model of a nanorod with an interfacial layer in a fluid medium is split apart in axial and radial direction respectively to build various differential equations. And a new thermal conductivity model for nanorod based nanofluids is developed based on the combination of the analytic solutions of those differential equations. The allocation proportion of heat conduction in axial and radial directions in the present model is depended upon the ratio of the flanking and ends (top and bottom) surface area of the nanorod. Finally, the present model and some classic models are compared with the available experimental data retrieved for thermal conductivity of nanorod based nanofluids. And the comparison results show the present model achieves better precision.

1. Introduction

As a product of the application of nanotechnology in conventional thermal fluid field, nanofluid is a new type solid/liquid suspension with even and stable dispersion as well as outstanding thermal transfer performance. Use of nanofluid can solve the problems such as sedimentation, cohesion and corrosion which happen conventionally in heterogeneous solid/liquid mixture with millimeter or micrometer particles, and increase the thermal performance of base fluids more remarkably [1].

The thermal conductivity of nanofluids seems to be one of the hottest issues and it has been widely studied since the birth of nanofluids. A large number of theoretical investigations and calculation models on the thermal conductivity of nanofluids have been proposed by considering some specific influence factors. Koo and Kleinstreuer [2] proposed a thermal conductivity model by considering the impact of Brownian motion in nanofluids, and they found that the thermal conductivity depends on particle volume fraction, particle size, particle material and temperature. Xue [3] considered the interface effect between the solid particles and the base fluid and proposed a novel model based on Maxwell theory and average polarization theory, they found that the theoretical results were in good agreement with the experimental data for nanotube/oil and Al_2O_3/water nanofluids. Yu and Choi [4,5] proposed two thermal conductivity models by renovating Maxwell model and Hamilton-Crosser model to including the interfacial layer effect. Xiao et al. [6,7] proposed a novel form of thermal conductivity of nanofluids by considering the effect of Brownian motion based on the fractal geometry theory.

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Nomenclature

A, B, C	customization parameters in the present model
E_0	average field intensity
H	height of nanorod, nm
k	thermal conductivity, W (m K)$^{-1}$
M, N	customization parameters in the present model
n	empirical shape factor
q	heat flux
r	radial distance from the center of the nanoparticle (nanorod), nm
R	radius of nanorod, nm
t	thickness of the interfacial layer, nm
T	temperature, K
x, z	x-axis, z-axis

Greek letters

α, β	customization parameters in the present model
β_1	parameter in Murshed model
β_2	parameter in Murshed model
ϕ	volume fraction of nanoparticles, %
θ	azimuthal angle
σ	parameter which characterizes the diffuseness of the interfacial boundary

Subscripts

eff	effective
f	basefluid
lr	interfacial layer
$lr1$	flanking interfacial layer in the radial direction
$lr2$	end interfacial layer in the radial direction
$lr3$	flanking interfacial layer in the axial direction
p	particle (rod)

Although tons of thermal conductivity models for nanofluids have been proposed, there are still some scientific issues that need to be solved. Firstly, most existing thermal conductivity models are proposed for spherical particle based nanofluid [3,4,6,8–12], while a minority of models aimed at CNTs based nanofluids [13–17]. With the development of nano-powders synthesis technology, some special shaped nanoparticles for instance nano-rods, nano-sheets have also been applied in the field of nanofluids [18–23]. However, there is a lack of theoretical research on the particle shape effect in the thermal conductivity of nanofluid. And the mechanical use of conventional models will exceed their application scope and lead to larger deviations since those models have not involved particle shape effect [3–6,8–17]. Therefore, there is a critical need for proposing thermal conductivity model that includes particle shape effect.

On the other hand, considering the effect of the interfacial layer is regarded as an effective approach and quite a few models have been proposed by analyzing the heat conduction of a spherical particle or a CNT with interfacial layers [3–5,15–17]. However, the heat conduction process for nano-rods is different to both spherical particles and CNTs since the heat conduction of a spherical particle is orientation independent, while only radial direction was considered for a CNT due to the colossal aspect ratio [5,15–17]. For nanorod based nanofluid, the end effect can't be ignored because of the limited aspect ratio. Therefore, how to build a thermal conductivity model for nanorod based nanofluids based on the heat conductions in both radial and axial directions is a new scientific issue need to solve.

Considering above problems, the special aim of this paper is to build a model to involve the particle shape effect by analyzing the heat conduction in both radial and axial directions of a nanorod. It is expected that this study can improve the integrity of current thermal conductivity model of nanofluids, especially for those contain specially shaped nanoparticles.

2. Mathematical model for nanorod based nanofluids

2.1. Overview of classic models

It is generally and internationally agreed among the field of academy that the earliest thermal conductivity model for spherical particle based suspension is developed in 1891 by Maxwell [8]. And then Maxwell model is inherited to calculate the thermal conductivity of nanofluids. In recent decades, many thermal conductivity models for spherical particle based nanofluids have been proposed, and some of them are established by upgrading Maxwell model. A concise list of those models is as follows:

(a) Maxwell model [8]:

$$k_{eff} = k_f \frac{k_p + 2k_f + 2\phi(k_p - k_f)}{k_p + 2k_f - \phi(k_p - k_f)} \tag{1}$$

(b) Bruggeman model [9]:

$$k_{eff} = \frac{1}{4}\left[(3\phi - 1)k_p + (2 - 3\phi)k_f\right] + \frac{k_f}{4}\sqrt{\Delta} \tag{2}$$

$$\Delta = (3\phi - 1)^2(k_p/k_f)^2 + (2 - 3\phi)^2 + 2(2 + 9\phi - 9\phi^2)(k_p/k_f) \tag{3}$$

(c) Bhattacharya model [10]:

$$k_{eff} = \phi k_p + (1 - \phi)k_f \tag{4}$$

(d) Timofeeva model [11]:

$$k_{eff} = k_f(1 + 3\phi) \tag{5}$$

Besides above thermal conductivity models for spherical particles based nanofluids, there are also some models for nanofluids containing nanotubes. Some expressions of those models are as follows:

(e) Hamilton and Crosser model [24]:

$$k_{eff} = k_f \frac{k_p + (n-1)k_f + (n-1)\phi(k_p - k_f)}{k_p + (n-1)k_f - \phi(k_p - k_f)} \tag{6}$$

where n is the empirical shape factor, which defined as the ratio of the surface area of a sphere (with the same volume as the given particle) to the surface area of the particle. The empirical shape factor is given by $n = 3/\psi$ and ψ is the sphericity. The sphericity is commonly defined as 1 and 0.5 for the spherical and cylindrical shapes, respectively. For regularly spherical nanoparticles, $n = 3$, which reduces this formula to Maxwell's.

(f) Xue model [13]:

$$k_{eff} = k_f \frac{1 - \phi + 2\phi \frac{k_p}{k_p - k_f} \ln \frac{k_p + k_f}{2k_f}}{1 - \phi + 2\phi \frac{k_f}{k_p - k_f} \ln \frac{k_p + k_f}{2k_f}} \tag{7}$$