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Thermal circuits based model for predicting the thermal conductivity of nanofluids

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ABSTRACT

A cell model based on thermal circuits is presented in this paper. The effective nanofluid thermal conductivity is rooted in heat transfer principles and scaling analysis. A combined series-parallel thermal circuits model has been presented for the static component of effective thermal conductivity and the heat transfer by micromixing due to Brownian motion of the particles have been taken in parallel to the static circuit. The effect of stationary, well-dispersed solids suspension as well as that of the convection due to Brownian motion has been considered. While the entire model is phenomenological, the coefficient for the Brownian motion component was empirical. The model was validated using data from nine studies that included oxide-water, oxide-ethylene glycol (EG), metal-water and metal-EG systems. Amongst the oxides, Al_2O_3, TiO_2, CuO, and ZnO were considered. The coefficient was found to be of the order of one which validated the expectation that $\frac{hd_p}{k_L} \sim \frac{PrRe^{1/2}}{\pi^{1/2}}$. The model was further refined by empirically determining the form of the coefficient for the convective term due to Brownian motion. It was found that the convective term is a function of temperature, solids volume fraction and particle size. A key aspect of the model is that it identifies a critical diameter at which the thermal conductivity is the maximum.

1. Introduction

Nanofluids connote a colloidal suspension with dispersed nanosize particles in a base fluid. As a result, changes in the physical properties when compared with the base fluid is observed. One of the more important properties is the thermal conductivity. Changes in the observed thermal conductivity has been quite complex for a thorough understanding of the phenomenon. Experiments over the past two decades [1–24] have revealed that the thermal conductivity of such a suspension can be significantly higher than that of the base medium. For example, Masuda [1] showed that different nanofluids (i.e., Al_2O_3- water, SiO_2-water, and TiO_2-water combinations) generated an effective nanofluid thermal conductivity increase of up to 30% at volume fractions of less than 4.3%. Such an enhancement phenomenon was also reported by Eastman and Choi [25] for CuO-water, Al_2O_3-water and Cu-Oil nanofluids. Early attempts to explain this behavior have made use of the classical Equivalent Medium Theory (EMT) by Maxwell for statically homogenous, isotropic composite materials with randomly dispersed spherical particles of uniform size [26]. It has been observed that the Maxwell model and its derivatives that consider only the solid volume fraction significantly underpredicts the experimental values. Nan et al. [27] proposed a model that considers two bounds of the EMT model within which a large percentage of the observed conductivities were observed to lie [28]. Nonetheless, significant deviations were observed which were attributed to factors external to the volume fraction of the solids [28]. Keblinski et al. [29] explored the four possible explanations for anomalous increase of thermal conductivity: Brownian motion of particles, molecular level layering of the fluid at the liquid-fluid/particle interface, the nature of heat transport in nanoparticles and the effects of nanoparticle clustering. Jacob Eapen [30] found that most of the models are phenomenological in nature and believed that effectiveness of nanofluids depends not only on the thermal conductivity but also on other properties such as viscosity and specific heat. Several models were developed to quantify the observed enhancements [25,29,31–38]. The more recent focus has been the role of Brownian motion [35,39–41]. Yu and Choi [33] proposed a modified Maxwell's model by considering the effect of nano-layer for spherical particles and extended it for non spherical particles [42]. Xue [43] combined Maxwell's theory and average polarization theory to predict effective thermal conductivity of nanofluids. Xue and Xu [44] derived an equation based on Bruggeman model where they considered the effect of interfacial shells between the nanoparticles and the base fluids.

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Nomenclature

R	resistance
Q	heat flow
V	volume
a	length of the unit cell
d	diameter
T	temperature
R′	radius of the particle
r	radius
k	conductivity
h	heat transfer coefficient
Re	Reynolds number
Pr	Prandtl number
u	velocity
Nu	Nusselt number
k_B	Boltzmann constant
δ	boundary layer thickness
φ	volume fraction
ν	kinematic viscosity
μ	dynamic viscosity
ρ	density
α	thermal diffusivity

Subscripts

BC	convection due to Brownian Motion
bf	base fluid
cyl	cylinder with a diameter of the particle and length of the unit cell
eff	effective
L	liquid
nf	nanofluid
p	particle
remain	remainder of the cylinder after removing the cylinder with diameter and length equal to the particle diameter
s	solid
T	thermal
z	cylinder with diameter and length equal to the particle diameter containing the particle

Xie et al. [45] proposed an effective thermal conductivity of nanofluids by considering the effect of different factors such as nano-layer thickness, particle size, and volume fraction Xuan et al. [46] applied the theory of Brownian motion and diffusion-limited aggregation model to simulate random motion and the aggregation process of the nanoparticles. Shukla and Dhir [47] developed a model for thermal conductivity of nanofluids based on the theory of Brownian motion of particles in a homogeneous liquid combined with the macroscopic Hamilton- Crosser model and predicted that the thermal conductivity will depend on the temperature and particle size. Prasher et al. [48] showed that enhancement in the thermal conductivity of nanofluids is mainly due to the localized convection caused by the Brownian movement of particles. The model captured the effects of particle size, choice of base liquid, thermal interfacial resistance between the particles and liquid, temperature. Prasher et al. [38] used aggregation kinetics of nanoscale colloidal solutions combined with physics of thermal transport to capture the effects of aggregation on the thermal conductivity of nanofluids. The study developed a unified model which combines the micro convective effects due to Brownian motion with the change in conduction due to aggregation. Feng et al. [49] proposed a new model for effective thermal conductivity of nanofluids based on nanolayer and nanoparticles aggregation. The study derived a model based on the fact that a nanolayer exists between nanoparticles and fluid and some particles in nanofluids may contact each other to form clusters. Jie et al. [50] proposed a new model for thermal conductivity of nanofluids, which is derived from the fact that nanoparticles and clusters coexist in the fluids of nanofluids. Wang et al. [31] proposed a model based on the effective medium approximation and the fractal theory to predict thermal conductivity of nanofluids. Jang and Choi [51] considered four modes of energy transport in the nanofluids such as (i) collision between base fluid molecules, (ii) thermal diffusion of nanoparticles in fluids, (iii) collision between nanoparticles due to Brownian motion, and (iv) thermal interaction of dynamic nanoparticles with the base fluid molecules to calculate a new theoretical model to predict thermal conductivity of nanofluids. Koo and Kleinstreuer [39] proposed a model by considering Brownian motion of the particles. Patel et al. [52] proposed that specific surface area and Brownian motion are supposed to be the most significant reasons for the anomalous enhancement in thermal conductivity of nanofluids and they presented a semi-empirical approach for the same by emphasizing the above two effects through micro-convection. Kumar et al. [35] developed a cell model that predicted the dependence of the thermal conductivity enhancement on the particle fraction and particle size along with the use of kinetic theory to relate the particle conductivity to the particle velocity. Patel et al. [53] presented a cell model for predicting the thermal conductivity of nanofluids. In this model they proposed that since the thermal conductivity is a direct function of the particle conductivity, the heat transfer coefficient be written as a function of the thermal conductivity of the solid particle rather than that of the fluid. This change would affect the coefficient in their model by over two orders in magnitude. In addition, instead of considering the Brownian motion to be in parallel to that of the overall conduction pathways, it considered that the conduction through the particle and that due to Brownian Motion were in series while that through the base fluid was in parallel to these two mechanisms. Murugesan and Sivan [54] developed upper and lower limit for thermal conductivity of nanofluids. The upper limit was estimated by coupling heat transfer mechanisms like particle shape, Brownian motion and nanolayer while the lower limit was the Maxwell equation. Mehta et al. [55] used a similar cell model as presented by Patel et al. [53] but with two major differences. The Brownian motion component was considered to be parallel to the nanofluid conductivity. In addition, they used the Maxwell's model to account for the static nanofluid conductivity.

In this paper, we present a model for the effective nanofluid thermal conductivity rooted in heat transfer principles and scaling analysis. There are a few significant differences in the model developed in this paper as compared to those reported in literature. First, past cell based models have considered that the bulk fluid and the particle resistances are in parallel. A few of the models that considered Brownian motion, kept the resistance of the liquid film around the particle to be to be in series (Patel et al., [53]) but not the entire fluid consisting of the projection of the particle along the axis of the heat flow. 1-D heat transfer in a stationary fluid, would result in a part of the fluid to be in series with the particle. This aspect has been included in the present model. Thus we present a unique series-parallel circuit. Secondly, some of the authors of the cell models have considered the Brownian motion of the particles resulting in an increase in the heat transfer coefficient of the stationary fluid around the particle. These authors have not considered the effect of micromixing due to Brownian motion