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A new effective thermal conductivity model for a bio-nanofluid (blood with nanoparticle Al_2O_3)☆

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ABSTRACT

Recently application of nano-technology in medicine and cancer therapy has generated a lot of interest in thermal properties of bio-nanofluid such as blood with nanoparticles suspension. In this study effective thermal conductivity of blood with suspension of Al_2O_3 nanoparticles as a bio-nanofluid was studied. A two-step model based on parallel mixture rule, thermal resistance concept and Maxwell-type equations was developed. First a model based on the parallel mixture rule and thermal resistance concept was used to predict the blood cells thermal conductivity. Then a model for the effective thermal conductivity of the bio-nanofluid was developed. It was shown that the results of the proposed model for the blood thermal conductivity agree well with the available data in the literature.

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1. Introduction

Fluids with suspended nanoparticles are called nanofluids, a term first proposed by Choi in 1995 of the Argonne National Laboratory, U.S.A. [1]. Nanofluid is considered to be the next-generation heat transfer fluids as they offer exciting new possibilities to enhance heat transfer performance compared to pure liquids. Recently, researchers have demonstrated that nanofluids (such as water or ethylene glycol) with CuO or Al_2O_3 nanoparticles exhibit enhanced thermal conductivity [1]. Thus, the use of nanofluids, for example in heat exchangers, may result in energy and cost savings and should facilitate the trend of device miniaturization. More exotic applications of nanofluids can be envisioned in biomedical engineering and medicine in terms of optimal nano-drug targeting and implantable nano-therapeutic devices [2]. Therefore the knowledge of bio-nanofluid thermo-physical properties (such as blood with nanoparticles) becomes essential when flow and heat transfer study of blood in drug delivery and new cancer therapy is considered.

The enhancement of thermal conductivity achieved in nanofluids is much greater than what has been predicted by conventional theories such as Maxwell [3] or Hamilton and Crosser [4]. Several experimental studies have explained the reason behind the enhancement of effective thermal conductivity such as the effect of the solid/liquid interfacial layer and the Brownian motion [2,5–9]. For example, Xuan and Li [10] summarized all existing experimental observations. They concluded that k_{eff} is a function of both thermal conductivities of the nano-material as well as carrier fluid, particle volume fraction, distribution, surface area, and shape.

Keblinski et al. [11] listed four possible explanations for the cause of an anomalous increase of thermal conductivity: Brownian motion of the nanoparticles, molecular-level layering of the liquid at the liquid/particle interface, the nature of heat transport in the nanoparticles, and the effects of nanoparticle clustering. They ruled out the possibility of the Brownian motion effect by comparing the time scales of Brownian motion and the thermal response, a point revisited in the Results and discussion section. Xue [5] proposed a thermal conductivity model based on Maxwell's theory and average polarization theory to take care of the interfacial effect (i.e., liquid nano-layer). Bhattacharya et al. [12] investigated the effect of particle Brownian motion by using a molecular dynamics type approach which does not consider the motion of fluid molecules and requires two experimentally determined parameters. Keblinski et al. [13] made an interesting simple review to discuss the properties of nanofluids and future challenges.

Most recent studies are about properties of nanofluid with water or ethylene glycol base fluid. The researchers have attempted to find thermo-physical properties of nanofluid especially the effective thermal conductivity in order to analyze thermal behavior of it in different applications.

Currently, there is no reliable theory to predict the anomalous thermal conductivity of nanofluids. It is known that the thermal conductivity of nanofluids depends on parameters such as base fluid thermal conductivity, nanoparticles thermal conductivity, the volume

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Nomenclature

k_f	base fluid thermal conductivity
k_p	nanoparticle thermal conductivity
k_{layer}	nano-layer thermal conductivity
k_{eff}	effective thermal conductivity
ϕ (phi)	volume fraction
r	nanoparticle radius
h	nano-layer thickness

fraction, the surface area, the shape of the nanoparticles and the temperature [1]. To the authors' knowledge, to date there is no detailed studies on the thermo-physical properties of the blood with suspended nanoparticles. The intention of this study is to develop a new model for effective thermal conductivity of bio-nanofluid (blood + Al_2O_3). First a model based on the parallel mixture rule [14] and thermal resistance concept [15] was used to predict the blood cells thermal conductivity. Then a model for the effective thermal conductivity of the bio-nanofluid (blood with suspended nanoparticles) was developed. The developed model was based on the Maxwell equation. In addition, the equation developed earlier by Leong et al. [16] was used in the model development. Finally, the new model was used to evaluate the effect of volume fraction of nanoparticles on the blood thermal conductivity.

2. Theory

Almost all available theoretical models regarding thermal conductivity are classified into three categories: a) particles are covered with a nano-layer and the thermal conductivity is evaluated for the combined particles and the nano-layer; b) the effective medium theory and the polarization theory are used; and c) the effect of Brownian motion and the other intermolecular forces between particles are considered.

The model proposed in this paper is based on the Maxwell equation, parallel mixture rule, and the thermal resistance concept. In addition, the model uses the Leong et al. [16] earlier study which was based on nano-layer coverage assumption. First the model predicts the blood cells thermal conductivity using parallel mixture rule and the thermal resistance concept. Then the model uses the Maxwell and Leong, equations in two different ways to predict the thermal conductivity of bio-nanofluid (blood + Al_2O_3). Table 1 shows the effective conductivities as suggested by various models.

Two approaches were used in the following sections. In the first approach the model equation suggested by Leong et al. [16] is used to calculate the thermal conductivity of bio-nanofluid. Here blood is the base fluid and Al_2O_3 is the nanoparticle. This is similar to the approach that Leong et al. used to calculate the thermal conductivity of water and Al_2O_3. In their case water was base fluid and Al_2O_3 was the particles. In the second approach the results of [16] is used with plasma as base fluid and Al_2O_3 as nanoparticles. The second approach does not account for the blood cells. Therefore, Maxwell equation is then used to calculate the thermal conductivity of bio-nanofluid (plasma and nanoparticles and blood cells). In this case, for application of Maxwell's equation, the blood cells are considered as particles, while a mixture of plasma and Al_2O_3 is the base fluid. (It is known from the literature that Maxwell equation provides good estimate when applied to the fluid with suspended microparticles.)

Table 1
Nanofluid effective thermal conductivity models.

Nanofluid thermal conductivity formula	Reference
$k_{eff} = \frac{k_p + 2k_f + 2(k_p - k_f)\phi}{k_p + 2k_f - (k_p - k_f)\phi} k_f$	Maxwell [4]
$k_{eff} = \frac{(k_p - k_{layer})\phi k_{layer}(2\beta_1^3 - \beta_2^3 + 1)}{\beta_1^3(k_p + 2k_{layer}) - (k_p - k_{layer})\phi(\beta_1^3 + \beta_2^3 - 1)} + \frac{(k_p + 2k_{layer})\beta_1^3(\phi\beta_2^3(k_{layer} - k_f) + k_f)}{\beta_1^3(k_p + 2k_{layer}) - (k_p - k_{layer})\phi(\beta_1^3 + \beta_2^3 - 1)}$	Leong et al. [16]

$\beta = {}^h/_r$; $\beta_1 = 1 + {}^\beta/_2$; $\beta_2 = 1 + \beta$; $k_{layer} = 10k_f$(Assumed) [16].
r: nanoparticle radius h: nano-layer thickness.

3. Proposed thermal conductivity model

The proposed model is based on two steps. First we calculate the blood cells thermal conductivity using parallel mixture rule and the thermal resistance concept as described in subsequent Section 3.1. Then the Maxwell and Leong et al. equations are used in two different ways to predict the thermal conductivity of bio-nanofluid (blood + Al_2O_3), as described in Section 3.2 below.

3.1. Calculation of blood cells thermal conductivity

As known blood is a combination of plasma and blood cells including red blood cells (RBC), white blood cells (WBC) and plackets. Table 2 shows the number of concentration and size of blood cells [17].

There are experimental data for thermal conductivity of plasma and red blood cells as well as blood itself. However, the thermal conductivity of the white blood cells and plackets is not known. Therefore, following equations are used to calculate the thermal conductivity of blood cells.

3.1.1. First model

According to the parallel mixture rule [14], thermal conductivity of blood is given as:

$$k_{blood} = \varphi_{plasma} k_{plasma} + \varphi_{blood\ cells} k_{blood\ cells}. \tag{1}$$

All parameters in Eq. (1), with the exception of blood cells thermal conductivity, are known as are listed in Table 3 [18]. Using Eq. (1), the effective thermal conductivity of blood cells is found to be 0.4 W/m K.

3.1.2. Second model

This model is based on thermal resistance concept [15]. The model assumes a cubic vessel full of blood with particles completely mixed and considers the heat transfer in the x-direction as illustrated in Fig. 1.

As noted before, blood consists of a mixture of plasma and blood cells with the volume fractions of different components are listed in Table 3. The model assumes a one-dimensional steady state heat transfer. The thermal resistance between blood cells ($R_{blood\ cells}$) and plasma (R_{plasma}) is given as:

$$R_{blood} = R_{cells} + R_{plasma} \tag{2}$$

$$\frac{1}{k_{blood}A} = \frac{\varphi_{bloodcells} l}{k_{bloodcells}A} + \frac{\varphi_{plasma} l}{k_{plasma}A}. \tag{3}$$

The values of all parameters in Eq. (3) are listed in Table 3 [18], with the only unknown being the blood cell conductivity. Using the values

Table 2
Blood cell concentration and size [17].

	Number/mm^3	Size (μm)	Cell volume percentage
Red blood cells (erythrocyte)	5×10^6	~8	97
White blood cells (leukocyte)	5×10^3	~15	2
Placket (thrombocyte)	3×10^5	~3	1

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