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Mixed convective heat transfer of water/alumina nanofluid inside a vertical microchannel

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A B S T R A C T

Mixed convective heat transfer of water/alumina nanofluid inside a vertical microchannel is investigated theoretically. A modified Buongiorno's model is employed for the nanofluid, which fully accounts for the effect of the nanoparticle migration. This model considers the Brownian motion and thermophoresis diffusivities as the predominant slip mechanism. Because of surface roughness in microscale channels, slip condition is considered at the walls, which appropriately represents the hydrodynamic boundary condition. The results obtained indicated that nanoparticles move from the heated walls (nanoparticle depletion) toward the core region of the channel (nanoparticle accumulation) and construct a non-uniform nanoparticle distribution. In addition, increasing the bulk mean volume fraction of nanoparticles ϕ_B, slip parameter λ and mixed convective parameter Ng enhances the heat transfer rate. Moreover, in contrast to λ, ϕ_B and Ng have a negative effect on the pressure drop of the system.

1. Introduction

Since higher heat transfer rates are desirable in modern industrial applications, conventional techniques are not appropriate any longer and heat transfer enhancement methods are of main concern for scientists working in this field. Generally, enhancement techniques can be divided into two groups: a) passive techniques which require special surface geometries [1], thermal packaging or fluid additives and b) active techniques which require external forces such as electrical and magnetic fields.

The passive techniques hold the advantage over the active techniques as they do not require any direct input of external power. These techniques generally use surface or geometrical modifications such as employing microchannels or altering the working fluid such as Newtonian or non-Newtonian fluids [2–4]. Usually channels with a hydraulic diameter below 5 mm are categorized as microchannels that are widely used in efficient new cooling systems such as electronic devices, automobile cooling systems and heat pipes. Many experimental and analytical studies have been conducted to compare the heat transfer characteristic of microscale tubes with conventional scales [5–12]. In addition, the idea behind the fluid additives is to improve the thermal conductivity of the most common fluids such as water, oil, and ethylene-glycol mixture, which emerged in 1873 [13]. Later, many researchers studied the influence of solid–liquid mixtures on potential heat transfer enhancement. However, they were confronted with problems such as abrasion, clogging, fouling and additional pressure loss of the system which make them unsuitable for heat transfer systems. In 1995, the word “nanofluid” was proposed by Choi [14] to indicate dilute suspensions formed by functionalized nanoparticles smaller than 100 nm in diameter which had already been created by Masuda et al. [15] as Al_2O_3–water. These nanoparticles are fairly close in size to the molecules of the base fluid and, thus, can enable extremely stable suspensions with only slight gravitational settling over long periods.

In line with the same proposition, theoretical studies emerged to model the nanofluid behaviors. At the outset, the proposed models were twofold: homogeneous flow models and dispersion models. In 2006, Buongiorno [16] demonstrated that the homogeneous models tend to underpredict the nanofluid heat transfer coefficient, whereas the dispersion effect is completely negligible due to the nanoparticle size. Hence, Buongiorno developed an alternative model to explain the anomalous convective heat transfer in nanofluids and so eliminate the shortcomings of the homogeneous and dispersion models. He asserted that the anomalous heat transfer occurs due to particle migration in the fluid. Investigating the nanoparticle migration, he considered seven slip mechanisms — the inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus forces, fluid drainage, and gravity — and maintained that, of these seven slip mechanisms, only Brownian diffusion and thermophoresis are important in nanofluids. Taking this finding as a basis, he proposed a two-component four-equation non-homogeneous equilibrium model for convective transport in nanofluids. The model has been used by Kuznetsov and Nield [17] for the study of the influence of nanoparticles on the natural

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Nomenclature

c_p	specific heat ($\mathrm{m^2/s^2\,K}$)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
h	heat transfer coefficient ($\mathrm{W/m^2 \cdot K}$)
H	height of the channel
HTC	dimensionless heat transfer coefficient
k	thermal conductivity ($\mathrm{W/m \cdot K}$)
k_{BO}	Boltzmann constant ($= 1.3806488 \times 10^{-23}\ \mathrm{m^2kg/s^2\,K}$)
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
Ng	mixed convection parameter
p	pressure (Pa)
q_w	surface heat flux ($\mathrm{W/m^2}$)
R	radius (m)
T	temperature (K)
u	axial velocity (m/s)
x, y	coordinate system

Greek symbols

ϕ	nanoparticle volume fraction
γ	ratio of wall and fluid temperature difference to absolute temperature
η	transverse direction
μ	dynamic viscosity ($\mathrm{kg/m \cdot s}$)
ρ	density ($\mathrm{kg/m^3}$)
λ	slip parameter

Subscripts

B	bulk mean
bf	base fluid
p	nanoparticle
w	condition at the heated wall

Superscripts

$*$	dimensionless variable

convection boundary-layer flow past a vertical plate, Tzou [18] for the analysis of nanofluid Bernard convection, and Hwang et al. [19] for the analysis of laminar forced convection. Then, a comprehensive survey of convective transport of nanofluids was conducted by Nield and Kuznetsov [20], Yang et al. [21], Malvandi et al. [22–26], Yang et al. [21], Sheikholeslami et al. [27–31], Hatami et al. [32,33], Rashidi et al. [34–36], and BÉG et al. [37].

The current study is a theoretical investigation of the fully developed mixed convective heat transfer of water/alumina nanofluid, using the modified Buongiorno model [38], inside a vertical microchannel. Uniform heat flux has been considered at the walls and because of the microscopic roughness in microchannels, the flow meets the Navier slip condition [39] instead of a conventional no-slip condition at the walls.

2. Problem description and governing equations

Consider a steady two-dimensional flow of the water/alumina nanofluid in a vertical microchannel with a prescribed wall heat flux, as shown in Fig. 1. A two-dimensional coordinate frame has been selected in which the x-axis is aligned vertically and the y-axis is normal to the walls. The nanofluid is treated as a two-component non-homogeneous mixture, including the base fluid and nanoparticles as introduced by Buongiorno [16], but this was modified according to Yang

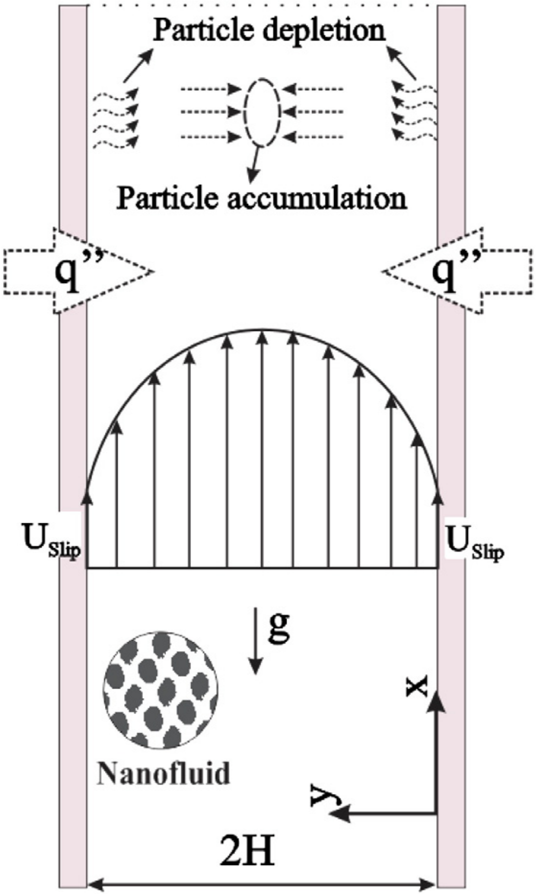

Fig. 1. The geometry of the physical model and coordinate system.

et al. [21] to fully account for the effects of nanoparticle migration. This modification was also employed by Malvandi et al. [38] for the theoretical investigation of the mixed convective flow of nanofluids inside vertical annuli. The viscous dissipation and axial conduction effects are assumed to be small. Consequently, the basic incompressible conservation equations of the mass, momentum, thermal energy, and nanoparticle fraction can be expressed in the following manner:

$$\partial_i(\rho u_i) = 0 \tag{1}$$

$$\partial_t(\rho u_i) + \partial_j\left(\rho u_i u_j\right) = -\partial_i p + \partial_j \mu\left(\partial_i u_j + \partial_j u_i\right) - \beta\rho g(T_w - T) \tag{2}$$

$$\partial_t(\rho c T) + \partial_i(\rho c u_i T) = \partial_i(k \partial_i T) + \rho_p c_p\left(D_B \partial_i \phi + \frac{D_T}{T}\partial_i T\right)\partial_i T \tag{3}$$

$$\partial_t(\phi) + \partial_i(u_i \phi) = \partial_i\left(D_B \partial_i \phi + \frac{D_T}{T}\partial_i T\right) \tag{4}$$

where u_i represents the velocity components; T is the local temperature; p is the pressure; and D_B and D_T are the Brownian diffusion and thermophoretic diffusion coefficients, respectively, which can be obtained as:

$$D_B = \frac{k_{BO} T}{3\pi \mu_{bf} d_p} \tag{5}$$