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Original Research Paper

Two-component heterogeneous mixed convection of alumina/water nanofluid in microchannels with heat source/sink

A. Malvandi [a],*, S.A. Moshizi [b], D.D. Ganji [c]

[a] *Department of Mechanical Engineering, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran*
[b] *Young Researchers and Elite Club, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran*
[c] *Mechanical Engineering Department, Babol Noshirvani University of Technology, Babol, Iran*

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ABSTRACT

The nanoparticle migration effects on mixed convection of alumina/water nanofluid in a vertical microchannel in the presence of heat source/sink with asymmetric heating wall are theoretically investigated. The modified two-component heterogeneous model of Buongiorno is employed for the nanofluid which considers Brownian diffusion and thermophoresis, the significant base of nanoparticle migration. Because of low dimensional structures and surface roughness of microchannels, a slip condition is considered at the surfaces to appropriately examine the non-equilibrium region at the fluid–solid interface. After the fluid flow is assumed as fully developed, the governing equations including continuity, momentum, energy, and nanoparticle volume fraction are simplified to ordinary differential equations and solved numerically. With the scale analysis of governing equations, it is revealed that the temperature-dependent buoyancy effects are negligible; however, the concentration-dependent buoyancy effects have significant impacts on flow and heat transfer characteristics. It is also shown that the imposed thermal asymmetry distorts the symmetry of velocity, temperature and nanoparticle volume fraction profiles and changes the direction of nanoparticle migration. In addition, the best performance is achieved under one-sided heating and a higher slip velocity at the surfaces.

1. Introduction

Economic incentives, energy reduction and space limitations have increased efforts to form more efficient heat exchange equipments. In the recent industrial applications, conventional techniques are not proper anymore and heat transfer enhancement techniques have become the main concerns of scientists. Basically, enhancement methods can be divided into two different groups: (a) passive techniques which require special surface geometries [1], thermal packaging and fluid additives and (b) active techniques which need external forces like electrical and magnetic forces. The active methods necessitate additional power that raises operational costs and initial capital of the equipment, while they usually represent a higher enhancement. However, the passive methods do not need any external power; therefore, they hold the advantage in comparison with the active methods. These methods, in general, use surface or geometrical modifications like microchannels or altering the working fluid such as Newtonian and non-Newtonian fluids. Typically, channels with a hydraulic diameter below 5 mm are categorized as microchannels that are commonly employed in efficient cooling equipments like electronic devices, automobile cooling systems and heat pipes.

The motivation behind the fluid additives represented in 1873 [2] was to enhance thermal conductivity of regular fluids like water, oil, and ethylene–glycol mixture. Then, several researchers studied the impact of solid–liquid mixtures on potential heat transfer enhancement. However, they confronted with some problems like abrasion, clogging, fouling and additional pressure loss which make this approach inappropriate for heat transfer equipments. Afterwards, in 1995, the term “nanofluid” was suggested by Choi [3] to signify dilute mixtures constructed by functionalized nanoparticles under 100 nm in-diameter which had been produced by Masuda et al. [4]. These nanoparticles are quite close in size to the base fluid molecules and therefore, can enable extremely stable suspensions with low gravitational settling over a long period.

In line with the same proposition, theoretical models emerged to study the nanofluid behaviors. Initially, the suggested models were twofold: homogeneous models and dispersion ones.

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* Corresponding author.
E-mail addresses: amirmalvandi@aut.ac.ir (A. Malvandi), s.a.moshizi@aut.ac.ir (S.A. Moshizi), ddg_davood@yahoo.com (D.D. Ganji).

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Nomenclature

c_p	specific heat (m^2/s^2 K)
D	diameter (m)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
h	heat transfer coefficient (W/m^2 K)
H	half of height of the channel (m)
k	thermal conductivity (W/m K)
k_{BO}	Boltzmann constant (= $1.3806488 \times 10^{-23}$ m^2 kg/s^2 K)
Nu	Nusselt number
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
Nr	mixed convection parameter
p	pressure (Pa)
q_w	surface heat flux (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 (kg/m s)
ρ	density (kg/m^3)
λ	slip parameter

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

Superscript	
$*$	dimensionless variable

Buongiorno [5], in 2006, proved that the homogeneous models underpredict the nanofluid heat transfer coefficient, while the dispersion effect can be neglected because of nanoparticle size. Consequently, Buongiorno presented an alternative model to explain abnormal convective heat transfer enhancement of nanofluids. He claimed that particle migration is the key reason of the abnormal enhancement of heat transfer coefficient. Then, he proposed a two-component four-equation non-homogeneous equilibrium model for convective transport in nanofluids. The model has been used by many authors which some of them are listed below: Sheikholeslami et al. [6–9], Rashidi et al. [10,11], Mahmoodi and Hashemi [12], Malvandi et al. [13,14], and Ashorynejad et al. [15]. Also, the convective heat transfer inside microchannels in the presence of an internal heat generation prevails in a wide range of engineering applications such as those dealing with chemical reactions and those concerned with dissociating fluids [16–19]. Moreover, the microchannel heat sink is a suitable choice for cooling such electronic devices. Therefore, an efficient cooling system is necessary to maintain the surface temperature in a safe range. Recent developments in nanotechnology show that nanofluids are efficient coolants for electronic devices [20].

Buongiorno's model has a significant problem; it assumes that the thermophysical variables are constant; hence, it cannot consider the effects of nanoparticle volume fraction distribution on thermophysical variables. Lately, Buongiorno's model was modified by Yang et al. [21,22] to consider the impacts of nanoparticle volume fraction distribution on thermophysical variables. Next, the modified Buongiorno's model was applied to different heat transfer problems including forced convection [23–29], mixed convection [30–33], and natural convection [34,35]. The results reveal that the modified model is a suitable model for simulating the impacts of nanoparticle migration in nanofluids. In the current study, the laminar fully developed mixed convective heat transfer of alumina/water nanofluid inside a vertical microchannel in presence of heat source/sink is investigated theoretically using the modified two-component heterogeneous model of Buongiorno [21,33]. Because of surface roughness and low dimensional structures in microchannels, the linear slip condition [13] has been considered at the surfaces to consider the non-equilibrium region near the interface. The parallel flat surfaces forming the microchannel boundaries are kept at constant with different heat fluxes. Therefore, the imposed thermal asymmetry changes the direction of nanoparticle migration which is one of the main aims of the current paper. Note that the current study can be considered as an extended version of the authors' previous work [30], where the scale analysis of the governing equations has been added and the effects of the thermal asymmetry and heat generation/absorption are the novel and distinctive outcomes of this study which have been considered.

2. Problem description and governing equations

Consider a laminar steady two-dimensional fully developed flow of alumina/water nanofluid through vertical microchannels in the presence of a heat source/sink. The physical model is depicted in Fig. 1, where the Cartesian coordinate x and y were aligned parallel and normal to surfaces respectively. The walls are heated uniformly by external means at a rate of q''_{wr} and q''_{wl} for the right and left walls, respectively. The ratio of the heat fluxes is $\varepsilon = q''_{wl}/q''_{wr}$, which characterizes the degree of the thermal asymmetry. From the numerical solutions conducted by Koo and Kleinstreuer [36] for the most standard nanofluid flows through a channel of about 50 μm, the viscous dissipation can be neglected. Therefore, the incompressible conservation equations of the mass, momentum, thermal energy, and nanoparticle fraction can be written in the following manner:

$$\frac{d}{dy}\left(\mu\frac{du}{dy}\right) - \frac{dP}{dx} + [(1-\phi_{wr})\rho_{f0}\beta(T-T_B) - (\rho_f - \rho_{f0})(\phi - \phi_{wr})]g = 0 \tag{1}$$

$$\rho c_p u\frac{\partial T}{\partial x} = \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + Q_0(T-T_B) + \rho_p c_p\left(D_B\frac{\partial \phi}{\partial y} + \frac{D_T}{T}\frac{\partial T}{\partial y}\right)\frac{\partial T}{\partial y} \tag{2}$$

$$\frac{\partial}{\partial y}\left(D_B\frac{\partial \phi}{\partial y} + \frac{D_T}{T}\frac{\partial T}{\partial y}\right) = 0 \tag{3}$$

where u, T and P represent the axial velocity, local temperature and pressure, respectively. Furthermore, the Brownian diffusion coefficient D_B and thermophoretic diffusion coefficient D_T can be written as

$$D_B = \frac{k_{BO}T}{3\pi\mu_{bf}d_p} \tag{4}$$

and