Particuology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

Nanoparticle migration effects on fully developed forced convection of TiO_2–water nanofluid in a parallel plate microchannel

F. Hedayati[a,*], G. Domairry[b]

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

ARTICLE INFO

Article history:
Received 9 September 2014
Received in revised form 4 November 2014
Accepted 9 November 2014

Keywords:
Nanofluid
Microchannel
Nanoparticles migration
Slip velocity
Brownian motion
Thermophoresis

ABSTRACT

This study considers the forced convection of laminar TiO_2–water nanofluid flow in a parallel plate microchannel. The small length scale associated with microchannels dictates the use of slip condition at the fluid–solid interface. The modified Buongiorno model was employed for the nanofluid to fully account for the effects of non-uniform viscosity and thermal conductivity. The partial differential equations associated with conservation laws were reduced to two-point ordinary boundary value differential equations before being numerically solved. Considering Brownian motion and thermophoresis, the effects of nanoparticle transport on concentration, velocity, and temperature profiles were analyzed for three different values of wall heat flux. To assess the efficiency of adding nanoparticles, the ratios of the pressure drop and the heat transfer coefficient of the nanofluid to that of the base fluid were studied in detail. From analyzing different heat flux ratios, one-sided heating was found to be most efficient at enhancing the heat transfer rate in the microchannel. Additionally, in the presence of the slip velocity, the increase in the value of the heat transfer coefficient for the nanofluid was smaller than that for the base fluid.

Introduction

The modern trend in miniaturizing devices requires a better understanding of heat transfer phenomena on small scales. Responding to this demand, many scientists and engineers are working on improving heat transfer techniques in micro-dimensions. Usually channels with hydraulic diameter below 1 mm are categorized as micro-channels, found wide use in efficient micro-sized cooling systems such as electronic devices, automobile cooling systems, and heat pipes. When dimensions are reduced to microscales, slip velocities at boundaries are inevitably encountered as the forces that keep fluid molecules in contact with a wall are not strong enough to overcome the local shear forces; such conditions may also take place at macroscales (Cohen & Metzner, 1985; Malvandi, Hedayati, & Ganji, 2014). Depending on application, microchannels may be designed with different cross-sectional geometries. Slip velocity in non-circular cross-sectional microchannels have been discussed by Duan and He (2014). Mohiuddin Mala and Li (1999) provided an experimental study on pressure drop and low rates for water in circular microchannels. Thermal performance of nanofluid flow in microchannels was studied by Li and Kleinstreuer (2008) where they concluded that nanofluids noticeably enhanced the thermal performance of microchannel mixture flow with a small increase in pumping power. The wide applications of microchannels can be gauged from numerous studies mentioned in reviews such as Salman, Mohammed, Munisamy, and Kherbeet (2013) and Talimi, Muzychka, and Kocabiyik (2012).

Changing the working fluid is of usual methods to enhance the efficiency of the system (Wen, Lin, Vafaei, & Zhang, 2009). When the higher heat transfer rate is desired, employing nanofluids can be one of the solutions (Farbod, Ahangarpour, & Etemad, 2014). Following Choi (1995), who first coined the name “nanofluid” for the mixture of nano-scaled particles with diameters between 1 and 100 nm and a base fluid, many researchers tried to study and model their behavior. Currently, there are two well-known models: the homogeneous flow model and the dispersion model. Buongiorno (2006) indicated that homogeneous models tend to underpredict values for the nanofluid heat-transfer coefficient, and because of nanoparticle size, the dispersion effect is completely negligible. Hence he developed an alternative model to explain the abnormal convective heat transfer enhancement in nanofluids and to

* Corresponding author. Tel.: +001 704 877 9456.
E-mail address: hedayati.faraz@live.com (F. Hedayati).

http://dx.doi.org/10.1016/j.partic.2014.11.012
1674-2001/

Please cite this article in press as: Hedayati, F., & Domairry, G. Nanoparticle migration effects on fully developed forced convection of TiO_2–water nanofluid in a parallel plate microchannel. *Particuology* (2015), http://dx.doi.org/10.1016/j.partic.2014.11.012

Nomenclature

c_p	specific heat (m^2/(s^2 K))
d_p	nanoparticle diameter (m)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
H	heat-transfer coefficient (W/(m^2 K))
H	channel height (m)
HTC	dimensionless heat-transfer coefficient
HTR	heat-transfer ratio
K	thermal conductivity (W/(m K))
k_{BO}	Boltzmann constant ($k_{BO} = 1.3806488 \times 10^{-23}$ J/K)
N	slip velocity factor
N_{BT}	ratio of the Brownian to thermophoretic diffusion coefficients
N_{dp}	pressure drop ratio
N_p	non-dimensional pressure drop
P	pressure (Pa)
q''	surface heat flux (W/m^2)
T	temperature (K)
U	axial velocity (m/s)
x, y	coordinate system

Greek symbols

ϕ	nanoparticle volume fraction
γ	relative temperature difference between wall and fluid with respect to wall temperature
η	transverse direction
μ	dynamic viscosity (kg/m s))
ρ	density (kg/m^3)
λ	slip parameter
ε	heat-flux ratio of the lower to the upper walls

Subscripts

B	bulk mean
bf	base fluid
nf	nanofluid
uw	condition at the upper wall
lw	condition at the lower wall
p	nanoparticle

Superscripts

*	dimensionless variable

eliminate the shortcomings of the homogeneous and dispersion models. He considered seven slip mechanisms—inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage, and gravity—and claimed that, of these seven, only Brownian diffusion and thermophoresis are the important slip mechanisms in nanofluids. Moreover, Buongiorno concluded that turbulence is not affected by nanoparticles. In this way, he was able to derive a two-component four-equation non-homogeneous equilibrium model for mass, momentum, and heat transfer in nanofluids that has been widely employed in the literature (Andarwa, Basirat Tabrizi, & Ahmadi, 2014; Garoosi, Garoosi, & Hooman, 2014; Garoosi, Jahanshaloo, & Garoosi, 2015; Kuznetsov & Nield, 2010; Karimipour et al., 2014; Malvandi, Ganji, Hedayati, & Yousefi Rad, 2013; Malvandi & Ganji, 2015a, Malvandi & Ganji, 2015b, in press; Salman, Mohammed, & Kherbeet, 2012; Safaei, Togun, Vafai, Kazi, & Badarudin, 2014; Sheikholeslami & Ganji, 2013).

Recently, Buongiorno's model has been modified by Yang, Li, and Nakayama (2013) to fully account for the effects of nanoparticle volume fraction distribution on the continuity, momentum, and energy equations. The modified model has the advantage of considering non-uniform distribution of viscosity and thermal conductivity over its original. Malvandi, Moshizi, Soltani, and Ganji (2014) then used the modified model to study mixed convection flow of nanofluids in a vertical annular pipe. They concluded that nanofluids can transfer heat more efficiently in the presence of slip condition than in a no-slip condition. In another study, Malvandi and Ganji (2014a) investigated the effects of magnetic field on nanoparticle distribution of alumina/water nanofluid in a microtube and reported that, in the presence of the magnetic field, the near wall velocity gradients increase, enhancing the slip velocity at the walls; thus the heat transfer rate and pressure drop intensify. More studies on the modified model may be found in Ganji and Malvandi (2014), Malvandi and Ganji (2014b, 2014c, 2014d, 2014e), and Malvandi, Moshizi, and Ganji (2014), Some other interesting studies using other models are Xu and Kleinstreuer (2014), and Sheikholeslami, Mustafa, and Ganji (2015).

Despite the accurate prediction of non-homogenous models (Buongiorno, 2006) and the frequent application of microchannels in modern engineering products, few theoretical studies have been conducted in this field. The present study is motivated by the need to determine the detailed behavior of nanoparticles motion in a parallel plate microchannel in the presence of asymmetric thermal boundary conditions. Nanoparticle arrangements in the mixture determine the rheological and thermophysical properties of the fluid which strongly affect velocity and temperature distributions. Because thermophoresis is the main mechanism in nanoparticle migration, different temperature gradients were imposed to fully account for the different modes of nanoparticle migration. In addition, because the length scale for microscopic roughness and the height of the microchannel are of the same order, slip velocity conditions at the walls were applied. The results presented a detailed accounting of the variation in the concentration profile and its effects on velocity and temperature distributions. Moreover, variations in pressure drop and heat transfer coefficient were analyzed in depth.

Problem definition and mathematical formulation

Let us consider a two-dimensional titania/water nanofluid flow in a parallel plate microchannel, which is assumed sufficiently long to achieve fully developed hydrodynamic and thermal flow. The x-axis is aligned horizontally and the y-axis is normal to the walls, which are subjected to different heat fluxes. Introducing the heat-flux ratio ε of the lower to the upper walls, three different values, specifically the adiabatic lower wall, $\varepsilon = 0$, unequal heat fluxes at the walls, $\varepsilon < 1$, and equal heat fluxes, $\varepsilon = 1$, are investigated (see schematics in Fig. 1). Furthermore, as the relative length scales of wall roughness and microchannel height are equal, slip velocities at the boundaries are chosen to be the most accurate. To fully account for the effects of nanoparticles migration, the modified Buongiorno model is employed. Viscous dissipation and axial conduction are assumed negligible. Consequently, the basic equations for incompressible flow and conservation of mass, momentum, thermal energy, and nanoparticle fraction can be expressed as (Hedayati, Malvandi, Kaffash, & Ganji, 2015):

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

$$\partial_j \left(\rho u_i u_j \right) = -\partial_i p + \partial_j \mu \left(\partial_i u_j + \partial_j u_i \right), \tag{2}$$

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

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