



Magnetic field effect on nanoparticles migration and heat transfer of water/alumina nanofluid in a channel



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ARTICLE INFO

Article history:

Received 3 January 2014

Received in revised form

28 February 2014

Available online 13 March 2014

Keywords:

Nanofluid

Nanoparticles' migration

Magnetic field

Slip velocity

Modified Buongiorno's model

ABSTRACT

The present study is a theoretical investigation of the laminar flow and convective heat transfer of water/alumina nanofluid inside a parallel-plate channel in the presence of a uniform magnetic field. A modified two-component, four-equation, nonhomogeneous equilibrium model was employed for the alumina/water nanofluid, which fully accounted for the effect of the nanoparticle volume fraction distribution. The no-slip condition of the fluid–solid interface is abandoned in favor of a slip condition which appropriately represents the non-equilibrium region near the interface at micro/nano channels. The results obtained indicated that nanoparticles move from the heated walls (nanoparticles depletion) toward the core region of the channel (nanoparticles accumulation) and construct a non-uniform nanoparticles distribution. Moreover, in the presence of the magnetic field, the near wall velocity gradients increase, enhancing the slip velocity and thus the heat transfer rate and pressure drop increase.

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1. Introduction

Enhancing the performance of conventional heat transfer has become a critical challenge for scientists and engineers. Generally, enhancement techniques can be divided into two groups: (a) active techniques which require external forces such as an electrical field and (b) passive techniques which require special surface geometries [1] or fluid additives. Concerning the latter alternative, which aims to improve the thermal conductivity of the most common fluids such as water, oil, and ethylene-glycol mixture, the idea of adding particles to the heat transfer fluids emerged in 1873 [2]. 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 makes these unsuitable for heat transfer systems. In 1995, the word 'nanofluid' was proposed by Choi [3] to indicate dilute suspensions formed by functionalized nanoparticles smaller than 100 nm in diameter which had already been created by Masuda et al. [4] 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. Likewise, in 1999, Lee et al. [5] measured the thermal conductivity of Al_2O_3 and CuO nanoparticle suspensions in water and ethylene glycol. In 2001, Eastman et al. [6] and Choi et al. [7] found an anomalous thermal conductivity enhancement of Cu and nanotube dispersions in ethylene glycol and oil, respectively. In the light of these pioneering works, numerous experimental investigations on the behaviors of nanofluids have been carried out which can be found in literature such as Fan and Wang [8].

Meanwhile, 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 [9] 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, only Brownian diffusion and thermophoresis are important slip mechanisms in nanofluids. Taking this finding as a basis, he

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Nomenclature

B_o	uniform magnetic field strength (T)
c_p	specific heat ($\text{m}^2/\text{s}^2 \text{K}$)
d	nanoparticle diameter (m)
D_B	Brownian diffusion coefficient (m^2/s)
D_T	thermophoresis diffusion coefficient (m^2/s)
h	heat transfer coefficient ($\text{W}/\text{m}^2 \text{K}$)
H	height of the channel (m)
Ha	Hartmann number
k	thermal conductivity ($\text{W}/\text{m K}$)
k_{BO}	Boltzmann constant ($= 1.3806488 \times 10^{-23} \text{ m}^2\text{kg}/\text{s}^2 \text{K}$)
Nu	Nusselt number
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
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/ms)
ρ	density (kg/m^3)
σ	electric conductivity ($1/\Omega\text{m}$)
λ	slip parameter

Subscripts

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

Superscripts

$*$	dimensionless variable
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proposed a two-component four-equation non-homogeneous equilibrium model for convective transport in nanofluids. The model has been used by Kuznetsov and Nield [10] to study the influence of nanoparticles on the natural convection boundary-layer flow past a vertical plate, by Tzou [11] for the analysis of nanofluid Bernard convection, and by Hwang et al. [12] for the analysis of laminar forced convection. Then, a comprehensive survey of convective transport of nanofluids was conducted by Nield and Kuznetsov [13], Malvandi et al. [14–16], Sheikholeslami et al. [17–22], Hatami et al. [23–25], Yang et al. [26,27], Malvandi and Ganji [28], and Matin and Pop [29].

Besides, the study of magnetic field has important applications in medicine, physics and engineering. Many industrial types of equipment, such as MHD generators, pumps, bearings and boundary layer control are affected by the interaction between the electrically conducting fluid and a magnetic field. The behavior of the flow strongly depends on orientation and intensity of the applied magnetic field. The exerted magnetic field manipulates the suspended particles and rearranges their concentration in the fluid which strongly changes heat transfer characteristics of the flow. The seminal study about MHD flows was conducted by Alfvén who won the Nobel Prize for his work. Later, Hartmann did a unique investigation on this kind of flow in a channel. Afterward, many researchers have emphasized this concept and the details can be found in literature such as Hatami et al. [30–32], Sheikholeslami et al. [33–39] and Mahian et al. [40].

In the present study we present a theoretical study of fully developed convective heat transfer of alumina/water nanofluid, using the modified Buongiorno's model [41], inside a channel in the presence of a uniform magnetic field. Uniform heat flux has been considered at the channel's walls and the flow meets the Navier's slip condition [42] instead of a conventional no-slip condition at the walls. The effects of a magnetic field, migration of nanoparticles and how these affect the thermal characteristics of the system are of particular interest. To the best of the author's knowledge, no study to date has examined this subject.

2. Problem description and governing equations

Consider the laminar, incompressible and two-dimensional flow of the water/alumina nanofluid in a parallel-plate channel. The geometry of the problem is shown in Fig. 1, where the wall's surfaces are subjected to the constant heat flux and a uniform magnetic field of strength B_o is applied normal to the main flow. A two-dimensional coordinate frame has been selected in which the x -axis is aligned horizontally and the y -axis is normal to the channel's walls. The nanofluid is treated as a two-component non-homogeneous mixture, including the base fluid and nanoparticles as introduced by Buongiorno [9], but this was modified according to Yang et al. [26] to fully account for the effects of nanoparticles' migration. This modification was also employed by Malvandi et al. [41] for the theoretical investigation of the mixed convective flow of nanofluids inside vertical annuli. The viscous dissipation, ohmic heating, and Hall effects are neglected as they are also 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:

$$\partial_i(\rho u_i) = 0 \quad (1)$$

$$\partial_t(\rho u_i) + \partial_i(\rho u_i u_j) = -\partial_i p + \partial_i \mu (\partial_i u_j + \partial_j u_i) - \sigma B_o^2 u_i \quad (2)$$

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

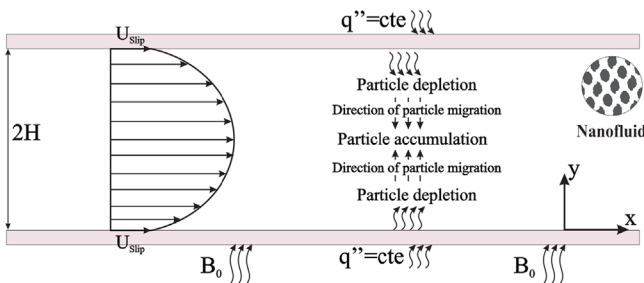


Fig. 1. The geometry of physical model and coordinate system.

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