International Journal of Thermal Sciences 84 (2014) 196–206

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Brownian motion and thermophoresis effects on slip flow of alumina/water nanofluid inside a circular microchannel in the presence of a magnetic field

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ARTICLE INFO

Article history:
Received 12 January 2014
Received in revised form
14 May 2014
Accepted 15 May 2014
Available online 20 June 2014

Keywords:
Nanofluid
Circular microchannel
Nanoparticles migration
Magnetic field
Slip velocity
Modified Buongiorno's model

ABSTRACT

The current study is a theoretical investigation of the laminar flow and convective heat transfer of alumina/water nanofluid inside a circular microchannel in the presence of a uniform magnetic field. A modified two-component four-equation nonhomogeneous equilibrium model was employed for nanofluids, which fully accounted for the effect of the nanoparticle volume fraction distribution. Because of the microscopic roughness in circular microchannels and also the non-adherence of the fluid–solid interface in the presence of nanoparticle migration, known as slip condition, the Navier's slip boundary condition is considered at the walls. The results indicated that nanoparticles migrate from the heated walls (nanoparticles depletion) towards the core region of the microchannel (nanoparticles accumulation) and construct a non-uniform nanoparticles distribution. The ratio of the Brownian to thermophoretic diffusivities (N_{BT}) has relatively significant effects both on the distribution of the nanoparticles and the convective heat transfer coefficient of nanofluids. It was further observed that for smaller nanoparticles, the nanoparticle volume fraction is more uniform and abnormal variations in the heat transfer rate vanish. 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.

1. Introduction

Enhancing the performance of conventional heat transfer has become a critical challenge for scientists and engineers. In general, 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.

In case of passive techniques, a number of major attempts have been conducted. The passive techniques can be divided in two groups: Geometry refinement (e.g., micro/nano channels) and fluid additives (e.g., micro/nano particles). With the recent progress in microfabrication-the process of fabrication of miniature structures of micrometer scales- a variety of micro-devices involving heat and fluid flows have been developed. Such devices found their application in various industries, such as microelectronics, biotechnology, and microelectromechanical systems (MEMS). Several research initiatives have been conducted to improve our understanding of the fluid flow and heat transfer at the micro level; these initiatives are thoroughly reviewed by Adham et al. [2] and Salman et al. [3]. In addition, the idea behind the fluid additives is to improve the thermal conductivity of common fluids, such as water, oil, and ethylene-glycol mixture which emerged in 1873 [4]. Later, many researchers studied the influence of solid–liquid mixtures on potential heat transfer enhancement. However, they faced a number of problems, such as abrasion, clogging, fouling, and additional pressure loss of the system, which made such mixtures unsuitable for heat transfer systems. In 1995, the word "nanofluid" was proposed by Choi [5] to indicate dilute suspensions formed by functionalized nanoparticles – smaller than 100 nm in diameter – which were already created by Masuda et al. [6] 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. [7] measured the thermal conductivity of Al_2O_3 and CuO nanoparticle suspensions in water and ethylene glycol. In 2001,

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http://dx.doi.org/10.1016/j.ijthermalsci.2014.05.013
1290-0729/

Nomenclature

B_o	uniform magnetic field strength
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)
Ha	Hartmann number
k	thermal conductivity (W/m K)
k_{BO}	Boltzmann constant (=1.3806488 × 10^{-23} m^2 kg/s^2 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, r	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)
σ	electric conductivity
λ	slip parameter

Subscripts

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

Superscripts

*	dimensionless variable

Eastman et al. [8] and Choi et al. [9] found an anomalous thermal conductivity enhancement for 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 has been carried out which can be found in literature such as Fan and Wang [10]. 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 [11] 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 proposed a two-component four-equation non-homogeneous equilibrium model for convective transport in nanofluids. The model has been used by Kuznetsov and Nield [12,13] to study the influence of nanoparticles on the natural convection boundary-layer flow past a vertical plate, Tzou [14] for the analysis of nanofluid Bernard convection, Hwang et al. [15] for the analysis of laminar forced convection. Then, a comprehensive survey of convective transport of nanofluids were conducted by Nield and Kuznetsov [16], Malvandi et al. [17–21], Haddad et al. [22], Pakravan and Yaghoubi [23], Sheikhzadeh et al. [24], Yang et al. [25], Ganji and Malvandi [26], Sheikholeslami et al. [27], Hatami and Ganji [28], MacDevette et al. [29], Akbarinia et al. [30] and Raisi et al. [31].

With reference to the latter alternative, the active techniques, 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 the 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 works. 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. [32,33], Sheikholeslami et al. [34–37], Rashidi et al. [38–40] and Mahian et al. [41].

Up to now, a lot of work has been conducted to study the fluid flow (gaseous or liquids) and heat transfer inside a circular microchannels [42–50]. Nevertheless, to the best of the author's knowledge, no study to date has examined on the effects of nanoparticle migration on the flow and thermal characteristics in the presence of a uniform magnetic field. Thus, in the current study we present a theoretical study of fully developed convective heat transfer of alumina/water nanofluid, using the modified Buongiorno's model [51], inside a circular microchannel in the presence of a uniform magnetic field. Uniform heat flux has been considered at the walls and because of the microscopic roughness at the wall of the microchannel and the nanoparticle migration in the fluid, instead of a conventional no-slip condition, the Navier's slip condition [52–54] has been employed at the walls. The effects of a uniform magnetic field, the migration of nanoparticles and how these affect the thermal characteristics of the system are of particular interest. One of the most significant of the present study is that it combines different methods of heat transfer enhancement, namely, passive (microchannel and nanofluid concepts) and active (presence of a magnetic field) techniques.

2. Problem description and governing equations

Consider the laminar, incompressible and two-dimensional flow of the alumina/water nanofluid inside a circular microchannel. The geometry of the problem is shown in Fig. 1, where the wall surfaces are subjected to a uniform heat flux and a uniform magnetic field of strength B_o is applied normal to the main flow (in the radial direction). A two-dimensional coordinate frame has been selected in which the x-axis is aligned horizontally and the r-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 [11], but this was modified according to Yang et al. [25] to fully account for the effects of nanoparticle migration. This modification was also employed by Malvandi et al. [51] for the theoretical investigation of the mixed convective flow