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Nanoparticles migration effects on magnetohydrodynamic (MHD) laminar mixed convection of alumina/water nanofluid inside microchannels

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ABSTRACT

This is a theoretical study on effects of nanoparticles migration on magnetohydrodynamic mixed convective heat transfer of alumina/water nanofluid inside a vertical microchannel. Walls are subjected to different heat fluxes; q''_{lw} for the left wall and q''_{rw} for the right wall, and nanoparticles are assumed to have a slip velocity relative to the base fluid, induced by Brownian diffusion and thermophoresis. Scale analysis of the governing equations indicates that buoyancy effects due to the temperature distribution is insignificant, however, the buoyancy effects due to concentration distribution of nanoparticles have vast effects on flow and heat transfer characteristics. Further, it is shown that nanoparticles eject themselves from the heated walls and accumulate in the core region, but they are more likely to accumulate near the wall with lower heat flux. Also, the non-uniform nanoparticle distribution causes velocities to move toward the wall with higher heat flux and enhances heat transfer rate there. Moreover, while the nanoparticle volume fraction is smaller than 0.1, the maximum increase in the values of heat transfer rate is 37% for small nanoparticles which drops to 14% for larger nanoparticles. Applying a magnetic field leads to 42% and 30% increase in the values of heat transfer rate for small and large nanoparticles respectively. Additionally, one-sided heating serves as another causing factor for increasing the heat transfer rate which boosts it up to 80% for large nanoparticles.

1. Introduction

Economic incentives, energy saving and space considerations have increased efforts to construct more efficient heat exchange equipment. Many techniques have been presented by researchers to improve heat transfer performance, which is referred to as heat transfer enhancement, augmentation, or intensification. Bergles [1] was the first to classify heat transfer enhancement techniques to (a) active techniques which require external forces to maintain the enhancement mechanism such as an electrical field or vibrating the surface and (b) passive techniques which do not require external forces, including geometry refinement (*e.g.*, micro/nano channels), special surface geometries [2], or fluid additives (*e.g.*, micro/nano particles).

The idea of adding particles to heat transfer fluids as an effective method of passive techniques, emerged in 1873 [3]. The motivation was to improve thermal conductivity of the most common fluids such as water, oil, and ethylene–glycol mixture, with solid particles which have intentionally higher thermal conductivity. Then, 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 [4] to indicate dilute suspensions formed by functionalized nanoparticles smaller than 100 nm in diameter which had already been created by Masuda et al. [5] 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. Then, theoretical studies emerged to model nanofluid behaviors. At the outset, the proposed models were twofold: homogeneous flow models and dispersion models. In 2006, Buongiorno [6] demonstrated that homogeneous flow models are in conflict with experimental observations and tend to underpredict the nanofluid heat transfer coefficient, whereas the dispersion effect is completely negligible due to nanoparticle size. Hence, Buongiorno developed an alternative model to explain the anomalous convective heat transfer in nanofluids and so eliminate the shortcomings of homogeneous and dispersion models. He asserted that anomalous heat transfer occurs due to particle migration in the fluid. Investigating nanoparticle migration, he considered seven slip mechanisms (inertia, Brownian diffusion, thermophoresis, diffusiophoresis, magnus

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Nomenclature

B	uniform magnetic field strength
c_p	specific heat (m^2/s^2 K)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
h	heat transfer coefficient (W/m^2 K)
H	channel height (m)
Ha	Hartmann number
HTC	dimensionless heat transfer coefficient
k	thermal conductivity (W/m K)
k_{BO}	Boltzmann constant (= $1.3806488 \times 10^{-23}$ m^2 kg/ s^2 K)
Nr	mixed convective parameter due to nanoparticle distribution
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
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	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
lw	condition at the left wall
p	nanoparticle
rw	condition at the right wall
Superscripts	
$*$	dimensionless variable

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. This model has been used by Kuznetsov and Nield [7] to study influence of nanoparticles on natural convection boundary-layer flow past a vertical plate, Tzou [8] for analysis of nanofluid Bernard convection, Hwang et al. [9] for analysis of laminar forced convection. Then, a comprehensive survey of convective transport of nanofluids was conducted by Mushtaq et al. [10] for nonlinear radiative heat transfer in flow of nanofluid due to solar energy, Safaei et al. [11] for heat transfer enhancement in a forward-facing contradicting channel, Karimipour et al. [12] for mixed convection of Cu–water nanofluid in a shallow inclined lid driven cavity, Sheikholeslami et al. [13–15] for CFD simulation of free convection of nanofluids in enclosures, and Goodarzi et al. [16] for two-phase simulation of nanofluids in a shallow cavity.

Recently, Buongiorno's model was modified by Yang et al. [17,18] to fully account for effects of the nanoparticle volume fraction. Next, Malvandi et al. [19] consider the modified model for fully developed mixed convection of nanofluids in a vertical annulus. They indicate that the modified model is suitable for considering effects of nanoparticle migration in nanofluids. Then, the modified Buongiorno's model has been applied to different heat transfer concepts including forced [20–23], mixed [24–27], and natural convection [28,29].

Recent progress in microfabrication—the process of fabrication of miniature structures of micrometer scales—has resulted in the development of a variety of micro-devices involving heat and fluid flows. Such devices have 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 thoroughly reviewed by Adham et al. [30] and Salman et al. [31] have resulted in increased interest in the possibility of a slip boundary condition. Adherence of fluid to solid at the boundaries, known as "no-slip" boundary condition, is one of the commonplace assumptions of Navier–Stokes theory which is not valid at microscale channels [32]. Slippage of liquids near the walls of microscale channels has been encountered as a result of interaction between a coated solid wall (hydrophobic, hydrophilic or superhydrophobic materials) and the adjacent fluid particle. In fact, because of the repellent nature of the hydrophobic and superhydrophobic surfaces, fluid molecules close to the surface do not follow the solid boundary, resulting in an overall velocity slip. More discussion on slip effects can be found in open literature, *e.g.* [20,33].

Active techniques commonly present higher augmentation thought and they need additional power that increases initial capital and operational costs of the system. In this class, 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 interaction between electrically conducting fluid and a magnetic field. The behavior of 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 works. Later, Hartmann did a unique investigation on this kind of flow in a channel. Effects of MHD on nanofluids have been considered by Sheikholeslami et al. [34–36] on free convection of nanofluids in enclosures, Selimefendigil and Oztop [37] for mixed convection of nanofluid inside a partially heated triangular enclosure with a rotating adiabatic cylinder, Nadeem et al. [38] for boundary layer flow of a Maxwell fluid over a stretching sheet, and Malvandi et al. [39–41] for considering the effects of a uniform magnetic field on nanoparticle migration.

The current progress on theoretical modeling of nanofluids has resulted in an increased interest in explaining the thermophysical characteristics of nanofluids. Lately, it has been shown that nanoparticle migration has considerable effects on the flow and heat transfer characteristics of nanofluids, and it is responsible for the abnormal heat transfer characteristics of nanofluids [6,17,18]. To the best of our knowledge, very few studies have been investigated on theoretical modeling of nanofluids in microchannels, most of which used homogeneous models for nanofluids [42], while effects of nanoparticle migration have commonly been ignored. In the current research, distribution of the nanoparticle volume fraction is obtained considering nanoparticle fluxes due to Brownian diffusion and thermophoresis in order to take into account effects of nanoparticle migration on fully developed mixed convective heat transfer of Al_2O_3–water nanofluid inside a vertical microchannel in the presence of a uniform magnetic field. Walls are subjected to different heat fluxes; q''_{lw} for the left wall and q''_{rw} for the right wall and because of microscopic roughness at the surface walls, instead of a conventional no-slip condition, the Navier's slip condition has been employed at the walls. The modified Buongiorno's model [19] has been used for nanofluids that fully account for effects of nanoparticle volume fraction distribution. Effects of a uniform magnetic field, asymmetric heating effects, the migration of nanoparticles, and how these affect hydrodynamic and thermal