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Effects of nanoparticle migration and asymmetric heating on magnetohydrodynamic forced convection of alumina/water nanofluid in microchannels

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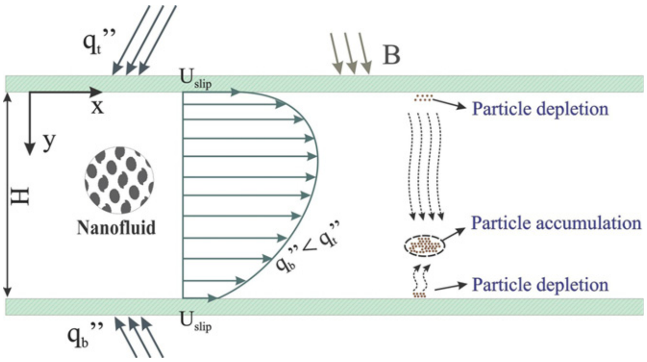
HIGHLIGHTS

- Magnetohydrodynamic forced convection of alumina/water nanofluid in microchannels.
- Nanoparticles migration effects on rheological and thermophysical characteristics.
- Brownian motion and thermophoresis effects on nanoparticles migration.
- Effects of asymmetric heating on the heat transfer enhancement.
- Describing the anomalous heat transfer enhancement in nanofluids.

GRAPHICAL ABSTRACT



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ABSTRACT

The present paper is a theoretical investigation on effects of nanoparticle migration and asymmetric heating on forced convective heat transfer of alumina/water nanofluid in microchannels in presence of a uniform magnetic field. Walls are subjected to different heat fluxes; q_t'' for top wall and q_b'' for bottom wall, and because of non-adherence of the fluid–solid interface due to the microscopic roughness in microchannels, Navier's slip boundary condition is considered at the surfaces. A two-component heterogeneous mixture model is used for nanofluid with the hypothesis that Brownian motion and thermophoretic diffusivities are the only significant slip mechanisms between solid and liquid phases. Assuming a fully developed flow and heat transfer, the basic partial differential equations including continuity, momentum, and energy equations have been reduced to two-point ordinary boundary value differential equations and solved numerically. It is revealed that nanoparticles eject themselves from heated walls, construct a depleted region, and accumulate in the core region, but more likely to accumulate near the wall with lower heat flux. Also, the non-uniform distribution of nanoparticles causes velocities to move toward the wall with a higher heat flux and enhances heat transfer rate there. In addition, inclusion of nanoparticles in a very strong magnetic field and slip velocity at the walls has a negative effect on performance.

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 tech-

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niques 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/nanoparticles). 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. Likewise, in 1999, Lee et al. [6] measured the thermal conductivity of Al_2O_3 and CuO nanoparticle suspensions in water and ethylene glycol. In 2001, Eastman et al. [7] and Choi et al. [8] 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 has been carried out which can be found in literature such as Fan and Wang [9]. 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 [10] demonstrated that the homogeneous flow models are in conflict with the experimental observations and 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. Then, Savino and Patterson [11] presented a similar model accounting for the gravitational effects. These models have 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, the model considered by many researchers, for example [16–18]. Recently, Buongiorno's model has been modified by Yang et al. [19,20] to fully account for the effects of the nanoparticle volume fraction. Then, Li and Nakayama [21] obtained an exact solution for fully developed flow of nanofluid in a tube subject to constant heat flux, with and without accounting for the temperature dependency of thermophysical properties. The comparison reveals that the effects of temperature-dependent thermophysical properties on both dimensionless velocity and temperature profiles are not as sensitive as those of the nanoparticle volume fraction. Furthermore, they indicated that the temperature dependency on thermophysical properties only alters the level of the Nusselt number. Accordingly, the behavior of heat transfer rate can easily be understood with considering the nanoparticle volume fraction distribution. The modified Buongiorno's model has been applied to different heat transfer concepts including forced [22–24], mixed [25–30], and natural convection [31,32]. The results indicated that the modified model is suitable for considering the effects of nanoparticle migration in nanofluids.

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 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 which thoroughly reviewed by Adham et al. [33] and Salman et al. [34] have resulted in an 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 the Navier–Stokes theory which is not valid at microscale channels. Slippage of liquids near the walls of microscale channels has encountered as a result of the 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, the fluid molecules closed to the surface do not follow the solid boundary, resulting in an overall velocity slip. More discussion on the slip effects can be found in open literature, e.g. [35–38].

On the other hand, active techniques commonly present higher augmentation though they need additional power that increases initial capital and operational costs of the system. In this class, the study of the 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 [39–48].

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 [10,19,20]. Up to now, very few studies have been investigated on theoretical modeling of nanofluids in microchannels, most of which used homogeneous models for nanofluids [49–51], while the effects of nanoparticle migration have commonly been ignored. In the current research, the distribution of the nanoparticle volume fraction is obtained considering the nanoparticle fluxes due to the Brownian diffusion and thermophoresis in order to take into account the effects of nanoparticle migration on fully developed forced convective heat transfer of alumina/water nanofluid in microchannels in the presence of a uniform magnetic field. Walls are subjected to different heat flux; q_t'' for the top wall and q_b'' for the bottom wall and because of the microscopic roughness at the wall of the microchannel, instead of a conventional no-slip condition, Navier's slip condition has been employed at the walls. The modified Buongiorno's model [26] has been used for nanofluids that fully account for the