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Fully developed forced convection of alumina/water nanofluid inside microchannels with asymmetric heating

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ABSTRACT

The effects of nanoparticle migration and asymmetric heating on the forced convective heat transfer of alumina/water nanofluid in microchannels have been investigated theoretically. Walls are subjected to different heat fluxes; q_t'' for the top wall and q_b'' for the bottom wall to form the asymmetric heating. Because of the microscopic roughness in microchannels, Navier's slip boundary condition is considered at the fluid–solid interface. A two-component mixture model is used for nanofluids 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, energy, and nanoparticle distribution equations) have been reduced to two-point ordinary boundary value differential equations and solved numerically. It is revealed that nanoparticles eject themselves from the heated walls, construct a depleted region, and accumulate in the core region, but they are more likely to accumulate toward the wall with the lower heat flux. In addition, the non-uniform nanoparticle distribution makes the velocities move toward the wall with the higher heat flux and enhances the heat transfer rate there. Moreover, the advantage of nanofluids is increased in the presence of a slip velocity at the walls.

1. Introduction

Nowadays, the efficiency of heat exchangers is not only determined by the enhancements in the heat transfer rate, but also depends on economic and accommodating considerations. Responding to this demand, many scientists have been involved in improving heat transfer performance, which is referred to as heat transfer enhancement, augmentation, or intensification. Heat transfer enhancement techniques were originally classified by Bergles [1] 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/nanochannels), special surface geometries [2], or fluid additives (e.g., micro/nanoparticles).

Among the different passive techniques, particles as additives in the working fluids have burst onto the scene of engineering research which emerged in 1873 [3] and is developing rapidly. The motivation was to improve the thermal conductivity of the most common fluids such as water, oil, and ethylene–glycol mixture, with the solid particles which have intentionally higher thermal conductivity. Then, many researchers studied the influence of solid–liquid mixtures on potential heat transfer enhancement. But they were confronted with problems such as abrasion, clogging, fouling and additional pressure loss of the system, which make 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

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Nomenclature

c_p	specific heat (m^2/s^2 K)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
h	heat transfer coefficient ($W/m^2 \cdot K$)
h_p	specific enthalpy of nanoparticles
H	channel height (m)
HTC	dimensionless heat transfer coefficient
J_p	nanoparticle flux
k	thermal conductivity ($W/m \cdot K$)
k_{BO}	Boltzmann constant ($= 1.3806488 \times 10^{-23}\ m^2\ kg/s^2\ K$)
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
N_p	non-dimensional pressure drop
N_{dp}	pressure drop ratio
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 ($kg/m \cdot s$)
ρ	density (kg/m^3)
λ	slip parameter

Subscripts

B	bulk mean
bf	base fluid
b	condition at the bottom wall
nf	nanofluid
t	condition at the top wall
p	nanoparticle

Superscripts

*	dimensionless variable

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. These models have been used by Kuznetsov and Nield [11] to study the influence of nanoparticles on the natural convection boundary-layer flow past a vertical plate. Then, many researchers employed this model, such as [12–15]. Recently, Buongiorno's model has been modified by Yang et al. [16,17] to fully account for the effects of the nanoparticle volume fraction. The modified Buongiorno's model has been applied to different heat transfer concepts including forced [18–23], mixed [24–26], and natural convection [27,28]. The results indicated that the modified model is suitable for considering the effects of nanoparticle migration in nanofluids. Rigorous authors can find more discussion on nanofluids in open literature, e.g. [29–39].

As mentioned above, minimizing the scales of the devices – microfabrication – is one of the main goals to improve the performance of a system and many devices are on the way to being produced in micro sizes; thus, traditional technologies are becoming obsolete for heat removal processes. 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. [40] and Salman et al. [41] 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 close 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. [42,43].

Recently, it has been shown that nanoparticle migration has considerable effects on the flow and heat transfer characteristics of nanofluids [44], and it is responsible for the abnormal heat transfer characteristics of nanofluids [10,16,17]. Up to now, very few studies have investigated on theoretical modeling of nanofluids in microchannels, most of which used homogeneous models for nanofluids [45–47], 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. Walls are subjected to different heat fluxes; q_t'' for the top wall and q_b'' for the bottom wall and because of the microscopic roughness on the wall of the microchannel, instead of a conventional no-slip condition, the Navier's slip condition has been employed at the walls. The modified Buongiorno's model [25] has been used for nanofluids that fully account for the effects of nanoparticle volume fraction distribution. The asymmetric heating effects, the migration of nanoparticles, and how these affect the hydrodynamic and thermal characteristics of the system are of particular interest.

2. Nanoparticle migration

It is known that different nanoparticle migration mechanisms can be relevant in flowing suspensions, Brownian diffusion, inertia, thermophoresis, diffusiophoresis, the Magnus effect, fluid drainage, and gravity, but here (with a very small nanoparticle dimension of <100 nm) only the Brownian and thermophoretic diffusivities are considered under conditions at which the other five mechanisms are not significant, as Buongiorno [10] stated. It has been suggested that Brownian diffusion can be observed due to random drifting of suspended nanoparticles within the base fluid, which comes from continuous collisions between nanoparticles and liquid molecules. The Brownian diffusion is proportional to the concentration gradient and described by the Brownian diffusion coefficient, D_B, which is given by the Einstein–Stokes' equation

$$D_B = \frac{k_B T}{3\pi \mu_{bf} d_p} \tag{1}$$