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Natural convection of nanofluids inside a vertical enclosure in the presence of a uniform magnetic field

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ABSTRACT

The present study is a theoretical investigation of natural convective heat transfer of nanofluids, inside a vertical enclosure, in the presence of a uniform magnetic field. A modified Buongiorno's model is employed for the nanofluid, which fully accounts for the effect of nanoparticle migration. The behavior of the nanofluid is investigated for two different nanoparticles in the water-base fluid, namely alumina and titania. It was observed that the nanoparticles move from the heated walls (nanoparticles' depletion) toward the cold wall (nanoparticles' accumulation) and construct a non-uniform nanoparticle distribution. The results also indicate that for smaller nanoparticles, the nanoparticle volume fraction is more uniform and there is no abnormal variation in the heat transfer rate. Moreover, Nu_B is reduced in the presence of the magnetic field for alumina/water nanofluid; however, for titania/water nanofluid it is vice versa.

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 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, Tzou [11] for the analysis of nanofluid Bernard convection, and Hwang et al. [12] for the analysis of laminar forced convection. Then, a comprehensive survey of convective transport of nanofluids were conducted by Nield and Kuznetsov [13], Malvandi et al. [14–19], Hatami et al. [20–22], Li et al. [23], Kefayati et al. [24], Yang et al. [25], Rashidi et al. [26], and Sheikholeslami et al. [27–30].

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Nomenclature

B_o	uniform magnetic field strength
c_p	specific heat (m^2/s^2K)
d	nanopaticle diameter (m)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
h	heat transfer coefficient ($W/m^2 \cdot K$)
H	width of the channel
H_a	Hartmann number
k	thermal conductivity ($W/m \cdot K$)
k_{BO}	Boltzmann constant ($=1.3806488 \times 10^{-23} m^2 kg/s^2 K$)
N_u	Nusselt number
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
Nr	buoyancy ratio
p	pressure (Pa)
q_w	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)
σ	electric conductivity

Subscripts

B	bulk mean
bf	base fluid
p	nanoparticle
cw	condition at the cold wall
hw	condition at the hot wall

Superscripts

Ci	dimensionless variable

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 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 the 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. Afterwards, many researchers have emphasized this concept and the details can be found in literature such as Hatami et al. [31,32], Rashidi et al. [33–35], Malvandi and Ganji [36], Sheikholeslami et al. [37–39] and Kefayati [40,41].

In the current study we present a theoretical study of the fully developed natural convective heat transfer of nanofluids, using the modified Buongiorno's model [42], inside a vertical enclosure in the presence of a uniform magnetic field. The behavior of the nanofluid is investigated for two different nanoparticles in the water based fluid, namely alumina and titania. The effects of a uniform magnetic field, nanoparticle concentration, migration of nanoparticles and how these affects the thermal characteristics of the system are of particular interest. To the best of the author's knowledge, no study to date has examined on this subject.

2. Problem description and governing equations

Consider the laminar, incompressible and two-dimensional flow of nanofluids inside a vertical enclosure where a uniform magnetic field of strength B_o is applied normal to the side walls, as shown in Fig. 1. A two-dimensional coordinate frame has been selected in which the x-axis is aligned vertically and the y-axis is normal to the side walls. The left and right (side) walls are maintained isothermally at high and low temperatures, respectively; whereas both the top and bottom walls are kept insulated. The height of the enclosure is sufficiently large (narrow channel) such that the free convective flow can be assumed to be hydrodynamically and thermally fully developed in the entire field excluding in the vicinity of the top and bottom ends. 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. [25] to fully account for the effects of nanoparticle migration. This modification was also employed by Malvandi et al. [42] for 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 [23,42]:

$$\partial_i(\rho u_i) = 0 \tag{1}$$

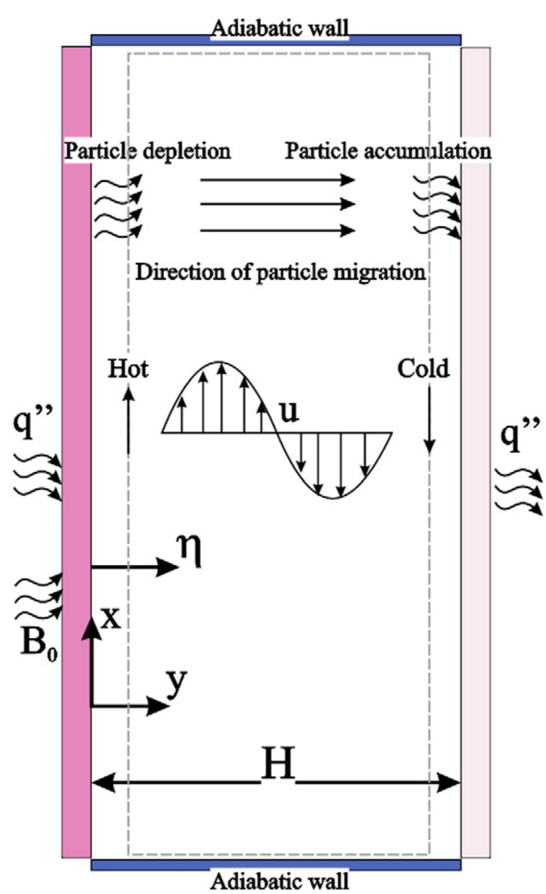

Fig. 1. The geometry of physical model and coordinate system.