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Modeling the natural convective flow of micropolar nanofluids

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ABSTRACT

A micropolar model for nanofluidic suspensions is proposed in order to investigate theoretically the natural convection of nanofluids. The microrotation of the nanoparticles seems to play a significant role into flow regime and in that manner it possibly can interpret the controversial experimental data and theoretical numerical results over the natural convection of nanofluids. Natural convection of a nanofluid in a square cavity is studied and computations are performed for Rayleigh number values up to 10^6, for a range of solid volume fractions ($0 \leqslant \varphi \leqslant 0.2$) and, different types of nanoparticles (Cu, Ag, Al_2O_3 and TiO_2). The theoretical results show that the microrotation of the nanoparticles in suspension in general decreases overall heat transfer from the heated wall and should not therefore be neglected when computing heat and fluid flow of micropolar fluids, as nanofluids. The validity of the proposed model is depicted by comparing the numerical results obtained with available experimental and theoretical data.

1. Introduction

Over the last decade there has been a significant growth in the use of colloids manufactured by nanosized particles dispersed in a base fluid. These engineered colloids have numerous applications such as in micro electromechanical systems (MEMS), nano electromechanical systems (NEMS), biomedical engineering (imaging and ablation), nuclear reactors, extraction of geothermal power, etc. [1–6]. Our ability to design novel materials at the nanoscale level led to technologies capable of measuring and manipulating nanomaterials. A nanofluid is a mixture consists of nanometer-sized particles and fibers dispersed in a liquid, having altered physical properties, such as viscosity, density and heat transfer among others, compared to those of the base fluid. The concept of nanofluid, in its primitive form, was first reported in the middle of the 18th century and has been used in oil drilling, civil engineering construction, pharmaceutical and food processing over the last century. Nevertheless, a tremendous expansion of the applications of nanotechnologies has occurred during the last few decades [7,8].

Nanofluids posses some unique features when compared with other mixtures, such as stability, since particles are small comparable to the dimensions of the base fluid molecules, low weight and thus have less prone to settle [9]. Additionally, nanofluids have been found to possess enhanced thermophysical properties such as increased thermal conductivity, thermal diffusivity, viscosity and convective heat transfer coefficients compared to those of base fluids like oil or water [10]. The most important characteristic of nanofluids is their high thermal conductivity relative to the base fluids. In fact, Choi [8] was the first who introduced the thermal conductivity enhancement and presented experimental measurements for the thermal conductivity of nanofluids.

Despite the numerous theoretical models related to the physical properties of the nanofluids, experimental results will finally show the performance of the nanofluids in real world applications. Numerous experimental results for forced and mixed convection [11–14] show the improved performance of heat transfer of nanofluids compared against the base fluid. Nevertheless, there is a striking lack of experimental data for natural convection [15]. Natural convection is initiated by a density difference induced by temperature differences within the fluid. In most buoyancy-driven convection problems, flow is generated by either a temperature variation or a concentration variation in the fluid, which leads to local density differences. Furthermore, natural convection in enclosures has been of considerable research interest in recent years due to the coupling of fluid flow and energy transport. Putra et al. [12] experimentally studied natural convection in a horizontal cylinder with the vertical ends heated and cooled. They used two different types of nanofluids, Al_2O_3/water and CuO/water, and they examined the influence of the volume fraction of the nanoparticles on the Nusselt number, which is the ratio of convective to conductive heat transfer normal the boundary/interface of solid and fluid.

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They found that the Nusselt number in nanofluids decreases by increasing volume fraction of nanoparticles. Wen and Ding [14,16] investigated experimentally natural convection of TiO_2/water between two disks, heated from bottom and cooled from top and reported similar trend to that shown in Putra et al. [12]. These experimental studies showed that the effect of variable volume fraction in natural convective heat transfer of nanofluids is important.

In the numerical studies for natural convective heat transfer of nanofluids conducted by several researchers, nanofluids were treated as a single-phase fluid and conventional equations of mass, momentum and energy were solved [12–16]. The effect of nanofluid relies on its thermal conductivity and viscosity which are obtained from the theoretical models or experimental data. Khanafer et al. in [17] studied natural convection of Cu–water nanofluid in a two-dimensional enclosure assuming uniform volume fraction. They solved the governing equations in their stream function-vorticity formulation and showed that Nusselt number increases with an increase of the volume fraction of the nanoparticles. Additionally, in a numerical study on natural convection with different aspect ratios of the enclosure, Jou and Tzeng [18] showed a similar trend. Abu-Nada et al. in [19] studied natural convection in horizontal annuli using different nanofluids and showed that the heat transfer is enhanced by using nanofluids and, Ho et al. [20], studying natural convection in a square enclosure, showed that the Nusselt number increases with increasing nanoparticles volume fraction. In fact this result can be reproduced for different models of effective viscosity and thermal conductivity.

The numerical studies and experimental findings in the case of natural convection in enclosures are controversial. The theoretical model predictions have a trend that contradicts experimental observations. Therefore, it is possible that the assumptions made in the theoretical models lead to false outcomes. The numerical studies depicted above, assumed that nanoparticles are in thermal equilibrium with the fluid and, no slip between the nanoparticles and fluid molecules, thus they have a uniform mixture of nanoparticles. Trying to predict theoretically the experimental results of nanofluids in natural convection, Polidori et al. in [15] investigated natural convective heat transfer of Al_2O_3–water nanofluid in an external boundary layer. They found that natural convection heat transfer depends on, both, the effective thermal conductivity of the nanofluid along to the viscosity model used. In fact, Abuali and Falahatpisheh in [21] studied natural convection on Al_2O_3–water nanofluid in vertical annuli and they reported a decreasing Nusselt number as the nanoparticles volume fraction increases, using different models of thermal conductivity and viscosity as well as considering the effect of temperature on the nanofluids properties.

It is clear that the theoretical outcomes based on the assumptions of no-slip velocities between nanoparticles and fluid molecules and concentration uniformity have to be reconsidered. In fact, the nanoparticle are moving (translate and rotate) and since they cannot accompany fluid molecules (mainly in the natural convection regime) due to some slip mechanisms (Brownian motion, thermophoresis) the volume fraction of nanofluids may not be uniform. This will results to a mixture with variable concentration of nanoparticles, initiating several physical phenomena such as the Dufour effect, that is important in heat transfer of nanofluids, the Soret effect or thermophoresis, which is the occurrence of heat flux due to a concentration gradient [22,23]. Ahuja in [24] experimentally demonstrated that heat transfer enhancement may occur from particle rotation, since under the effect of the shear stress, the suspended particles can rotate about an axis perpendicular to the main flow direction. This rotation creates a three-dimensional hydrodynamic boundary layer and the fluid flow towards the wall is then increased.

A fluid flow theory that takes into consideration the microrotation of the nanoparticles could potentially explain the theoretically and the experimental results. This theory is called micropolar fluid theory. Micropolar fluids, introduced by Eringen [25], can be considered as a generalization of the Navier–Stokes equations. In fact they are a subclass of microfluids, since they take into account the microstructure of the fluid along with the inertial characteristics of the substructure particles, which are allowed to undergo rotation. Using Eringen's definition on microfluids, a simple microfluid is a fluid medium whose properties and behavior are strongly influenced by the local motions of the material particles contained in each of its volume elements. In other words, a microfluid is an isotropic viscous fluid that possesses local inertia. From the physical part of view, this model introduces a new kinematic variable, called microrotation, which describes the rotation of particles. Due to its complex formulation, microfluids are divided into subclasses, which allow a simplified description of the effects arising from particle micromotions. Especially in micropolar fluids, a subclass of microfluids, rigid particles contained in a small volume element can rotate about the center of the volume element, which is described by the microrotation vector [26,27], being independent of the mean fluid flow and its local vorticity field. The mathematical background of the micropolar fluid flow theory is presented in [28] and, as it is pointed out, the theory of micropolar fluids is expected to successfully describe non-Newtonian behavior of certain fluids, such as liquid crystals, ferro-liquids, colloidal fluids, liquids with polymer additives, animal blood carrying deformable particles (platelets), clouds with smoke, suspensions, and slurries. The research area of micropolar fluids has been of great interest mainly because the Navier–Stokes equations for Newtonian fluids cannot successfully describe the characteristics of fluid with suspended particles.

In the present article experimental nanofluids models are incorporated into the micropolar theory framework and, a micropolar model for nanofluidic suspensions is proposed in order to investigate theoretically the natural convection of nanofluids. Moreover, the paper is presented as follows. In Section 2, the governing equations of the proposed micropolar nanofluid model are presented, while in Section 3 the validation first of the numerical method used for the solution of the equations of the flow and second of the proposed miropolar nanofluid model, are depicted. The agreement of the proposed model with available experimental data is emphasized. In Section 4, the heat transfer performance of a micropolar nanofluid enclosed in a rectangular cavity is studied for a range of solid volume fractions ($0 \leqslant \varphi \leqslant 0.2$), Rayleigh numbers ($10^3 - \leqslant Ra \leqslant 10^6$) and choice of nanoparticles (Cu, Ag, Al_2O_3 and TiO_2). For all simulations, pure water is considered as the base fluid with $Pr = 6.2$. Finally, in Section 5, the conclusions complete the paper.

2. Governing equations

Consider the natural convection flow in a square cavity of length L filled with a micropolar nanofluid of Al_2O_3/water, as shown in Fig. 1. The coordinates x and y are chosen in such way that x measures the distance along the bottom horizontal wall, while y measures the distance along the left vertical wall, respectively. Regarding to the boundary conditions, it is assumed that the horizontal walls are adiabatic, while the vertical walls are kept at constant temperatures T_H and T_C on the left and right sides, respectively, where $T_H > T_C$. In order to describe the incompressible viscous fluid flow, conservation laws of mass, momentum and energy with appropriate rheological models and equations of state are used. For a micropolar fluid flow the conservation of mass, linear momentum, angular momentum and in the case of natural