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Full Length Article

Mixed convection from a discrete heat source in enclosures with two adjacent moving walls and filled with micropolar nanofluids

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ABSTRACT

This paper examines numerically the thermal and flow field characteristics of the laminar steady mixed convection flow in a square lid-driven enclosure filled with water-based micropolar nanofluids by using the finite volume method. While a uniform heat source is located on a part of the bottom of the enclosure, both the right and left sidewalls are considered adiabatic together with the remaining parts of the bottom wall. The upper wall is maintained at a relatively low temperature. Both the upper and left sidewalls move at a uniform lid-driven velocity and four different cases of the moving lid ordinations are considered. The fluid inside the enclosure is a water based micropolar nanofluid containing different types of solid spherical nanoparticles: Cu, Ag, Al_2O_3, and TiO_2. Based on the numerical results, the effects of the dominant parameters such as Richardson number, nanofluid type, length and location of the heat source, solid volume fractions, moving lid orientations and dimensionless viscosity are examined. Comparisons with previously numerical works are performed and good agreements between the results are observed. It is found that the average Nusselt number along the heat source decreases as the heat source length increases while it increases when the solid volume fraction increases. Also, the results of the present study indicate that both the local and the average Nusselt numbers along the heat source have the highest value for the fourth case (C4). Moreover, it is observed that both the Richardson number and moving lid ordinations have a significant effect on the flow and thermal fields in the enclosure.

1. Introduction

Mixed (free and forced) convection flow and heat transfer in enclosures has received much attention in the recent years due to its many important practical applications such as thermal design of buildings, electronics cooling, solar collectors, commercial refrigeration and float glass production. During the mixed free and forced convection, it is necessary to add the contributions of the free and forced convection in assisting flows and to subtract them in opposing flows. Also, the mixed convection phenomena becomes very important when the forced velocity induced by a mechanical device like a fan has an effect equal to the free stream velocity induced by the buoyancy force which appears due to the density variation [1,2]. From the other hand, nanofluids are dilute liquid suspensions of nanoparticles with at least one critical dimension smaller than 100 nm which is firstly utilized by Choi [3]. Nowadays, more attention was considered to this new type of composite materials because of its enhanced properties and behavior associated with the heat transfer. They have received more attention as a new generation of heat transfer fluids in building heating, heat exchangers, plants and automotive cooling applications, because of their excellent thermal performance. Many studies indicate that the dispersion of a small amount of solid nanoparticles in conventional fluids increase remarkably their thermal conductivity. Compared to the existing techniques for enhancing heat transfer, the nanofluids show a superior potential for increasing heat transfer rates in a variety of cases. Various advantages of nanofluid applications include: improved heat transfer, heat transfer system size reduction, micro channel cooling and miniaturization of systems [4]. Various numerical and experimental studies related with the mixed convection in lid-driven square or rectangular cavities with and without nanofluids have been studied extensively in the literature. Iwatsu et al. [5] studied the mixed convection in a driven cavity with a stable vertical temperature gradient. Khanafer and Chamkha [6] extended the work of Iwatsu et al. [5] and studied the mixed convection flow in a lid-driven enclosure filled with a fluid-saturated porous medium in the presence of the heat generation effects. Sivasankaran

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et al. [7] investigated numerically by using the finite volume method the mixed convection in a square lid-driven cavity with a corner heating and an internal heat generation or absorption. The results were obtained for different lengths of the heaters, Richardson numbers and internal heat generation or absorption parameters. It was observed that the heat transfer rate was enhanced at forced convection dominated regime when the vertical length of the heater was higher than that of the horizontal length. Tiwari and Das [8] investigated numerically the heat transfer augmentation in a two sided lid-driven differentially heated square cavity utilizing copper–water nanofluid. They considered different cases characterized by the direction of wall movement. They concluded that both the Richardson number and the direction of moving walls influenced the fluid flow and thermal behaviors. Muthtamilselvan et al. [9] studied numerically the mixed convection in a lid-driven enclosure filled with copper–water nanofluids for various aspect ratios. It was found that both the aspect ratio and the solid volume fraction affected the fluid flow and the heat transfer in the lid-driven enclosure. Waheed [10] studied the mixed convective heat transfer in rectangular enclosures driven by a continuously moving horizontal plate while Ouertatani et al. [11] studied the mixed convection in a double lid-driven cubic cavity. Mahmoudi et al. [12] studied numerically using the finite volume approach the mixed convection flow and temperature fields in a vented square cavity subjected to an external copper–water nanofluid. In order to investigate the effect of inlet and outlet locations, four different placement configurations of the inlet and outlet ports were considered. In each of them, both the inlet and outlet ports were alternatively located either on the top or the bottom of the sides and external flow entered into the cavity through an inlet opening in the left vertical wall and exits from another opening in the opposite wall. The remaining boundaries were considered adiabatic. Their study had been carried out for Reynolds number in the range of $50 \le Re \le 1000$, Richardson number in the range of $0 \le Ri \le 10$ and solid volume fraction in the range of $0 \le \varphi \le 0.05$. Results were presented in the form of streamlines, isotherms and average Nusselt number. Talebi et al. [13] investigated numerically the mixed convection flows in a lid-driven square cavity utilizing the copper–water nanofluid. They showed that at a given Reynolds number and Rayleigh number, solid concentration had a positive effect on the heat transfer enhancement. Abu-Nada and Chamkha [14] solved numerically the steady laminar mixed convective flow and heat transfer of a nanofluid made up of water and Al_2O_3 in a lid-driven inclined square enclosure using a second-order accurate finite-volume method. It was found that the heat transfer mechanisms and the flow characteristics inside the cavity were strongly dependent on the Richardson number. Shahi et al. [15] executed a numerical investigation of the mixed convection flows through a copper–water nanofluid in a square cavity with inlet and outlet ports. Their study had been carried out for Reynolds number in the range of $50 \le Re \le 1000$, Richardson number in the range of $0 \le Ri \le 10$ and for solid volume fraction in the range of $0 \le \varphi \le 0.05$. Results were presented in the form of streamlines, isotherms, average Nusselt number and average bulk temperature. The results indicated that the increase in the solid concentration caused to increase the average Nusselt number at the heat source surface and a decrease in the average bulk temperature. Hussein et al. [16] investigated numerically the mixed convection in a rectangular inclined lid-driven cavity filled with water-based nanofluids. While, a uniform heat source was located on a part of the left inclined sidewall of the cavity, the right inclined sidewall was considered adiabatic together with the remaining parts of the left inclined sidewall. The top and bottom walls were maintained at a low temperature and the top wall moved from left to right with a uniform lid-driven velocity. It was found that the local Nusselt number was decreased as the inclination angle and the solid volume fraction were increased. Moreover, it was observed that the shape of the circulation vortex was sensitive to the inclination angle and the addition of nanofluids. Mansour and Ahmed [17] investigated numerically by using the finite volume method the mixed convection in double lid-driven enclosures with the heat source embedded in the left sidewall and filled with Al_2O_3–water nanofluid. Four cases were considered depending on the direction of the movement of the walls. Their study had been carried out for Richardson number ($Ri = 0.1–100$), nanoparticles volume fraction ($\varphi = 0–4\%$), the heat source length ($B = 0.2, 0.4, 0.6, 0.8$) and Reynolds number ($Re = 10–316.2278$). It was found that the fluid flow and heat transfer characteristics depended strongly on the direction of the horizontal wall movement. Also, a significant heat transfer enhancement was obtained by using the Al_2O_3–water nanofluid. Esfe et al. [18] studied numerically the mixed convection within nanofluid-filled cavities with two adjacent moving walls by using the finite volume approach. It was found that by adding nanoparticles to the fluid, the strength of the vortices was increased. Also, they concluded that the average Nusselt number was increased by increasing the volume fraction of nanoparticles. Another useful research had been conducted to simulate the mixed convection heat transfer using nanofluid under different conditions [19–23].

A number of experimental studies have been conducted to investigate the flow field and heat transfer characteristics of lid-driven cavity flow in the past several decades. Kuhlmann et al. [24] presented a numerical and experimental investigation of a steady flow in rectangular two sided lid-driven enclosures. Their results indicated that the basic two dimensional flow was not always unique. For low Reynolds numbers it consist two separate co-rotating vortices adjacent to the moving walls. The problem of an incompressible fluid flow in a rectangular container driven by two facing side walls which move steadily in anti-parallel for Reynolds numbers up to 1200 was studied experimentally by Blohm and Kuhlmann [25]. The moving sidewalls are realized by two rotating cylinders of large radii tightly closing the cavity. They found that beyond a first threshold robust, steady, three-dimensional cells bifurcate supercritically out of the basic flow state. If both side walls move with same velocity (symmetrical driving) the oscillatory instability was found to be tricritical.

Recently, much attention are devoted to the micropolar fluids due to their many practical applications such as liquid crystal, low-concentration suspension flow, blood rheology, the presence of dust or smoke, exotic lubricants and the effect of dirt in a journal bearing. In fact, micropolar fluids are those with microstructure belonging to a complex class of the non-Newtonian fluids with a non-symmetrical stress tensor. Physically, they represent fluids consisting of random particles suspended in a viscous medium [26]. The theory of the micropolar fluid was first suggested by Eringen [27] to take into account the effects of the local structure and micro-motions of the fluid particles which cannot be described by the classical models. Recently, a micropolar model for nanofluidic suspensions is proposed by Bourantas and Loukopoulos [28] and Bourantas et al. [29] in order to investigate theoretically the natural convection of nanofluids. They observed that by keeping the microrotation number K constant, the average Nusselt number increases with increasing Rayleigh number. Anyway, limited investigations are considered the mixed convention in enclosure filled with micropolar fluid such as Hsu and Wang [30]. A literature survey indicates that no studies have been done on the mixed convection in a lid-driven square enclosure partially heated from its bottom wall and filled with a micropolar nanofluid. Most of the published papers are related with the mixed convection heat transfer in enclosures filled with the Newtonian nanofluids. The extension to the non-Newtonian or micropolar nanofluids are not considered previously anywhere. To reach this goal, the objective of the present work is to examine the effects of Richardson number, nanofluid type, length and location of the heat source, solid volume fractions, moving lids orientations and