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Simulation of double diffusive MHD (magnetohydrodynamic) natural convection and entropy generation in an open cavity filled with power-law fluids in the presence of Soret and Dufour effects (Part I: Study of fluid flow, heat and mass transfer)

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ABSTRACT

In this paper, double diffusive natural convection of non-Newtonian power-law fluids in an open cavity in the presence of a horizontal magnetic field, studying Soret and Dufour parameters has been analyzed by FDLBM (Finite Difference Lattice Boltzmann method). This study has been performed for the certain pertinent parameters of Rayleigh number ($Ra = 10^4$ and 10^5), Hartmann number ($Ha = 0$, 15, and 30), power-law index ($n = 0.6$, 1, and 1.4), Lewis number ($Le = 2.5$ and 5), Dufour parameter ($D_f = 0$, 1, and 5), Soret parameter ($S_r = 0$, 1, and 5) and the buoyancy ratio ($N = -1$and 1). Results indicate that the augmentation of the Hartmann number provokes heat and mass transfer to drop for different power-law indexes. As the Soret and Dufour numbers equal zero, the heat and mass transfer decrease with the increment of the power-law index in different Rayleigh numbers for various Hartmann numbers. The heat transfer increases with the rise of the Dufour parameter and the mass transfer enhances as the Soret parameter increases for different power-law indexes and Rayleigh numbers. The augmentation of Soret and Dufour parameters alters the behavior of heat and mass transfer against the change of the power-law index.

1. Introduction

1.1. Background

Flow in an enclosure driven by buoyancy force is a fundamental problem in fluid mechanics. This type of flow can be used as validation in academic researches and various applications of engineering [1–3]. Natural convection in open cavities have received a considerable attention [4–9] due to their applications in various industries of high-performance insulation for buildings, injection molding, chemical catalytic reactors, packed sphere beds, grain storage, float glass production, heat exchangers, microchannel, air-conditioning in rooms, cooling of electronic devices, and such geophysical problems. The flow of an electrically conducting fluid in a magnetic field is influenced by MHD (magnetohydrodynamic) forces resulting from the interaction of induced electric currents with the applied magnetic field. An externally imposed magnetic field is a widely used tool for the process of manufacturing metals. The molten flows in this process behave usually like non-Newtonian power-law fluid; therefore, it is not possible practically to be studied as a Newtonian fluid. For example, a magnetic field is applied on the melt during solidification process in injection molding in Magnesium Injection Molding. Moreover, as we know the dominant heat transfer process in injection molding is convection while the melt behaves like power-law non-Newtonian fluid [10].

The effect of magnetic field on the convection process in cavities on different fluids and boundary conditions has been studied by various numerical methods widely [11–14]. In addition, several investigations on natural convection for non-Newtonian power-law fluids in a cavity were conducted by researchers with different models and numerical methods [15–21]. However, some limited studies of the MHD natural convection of power-law fluids in an enclosure have been conducted in the absence of the mass transfer [22–24].

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Moreover, the mass transfer plays a crucial role in the mentioned applications and therefore it is significant that the double diffusive natural convection on the problem to be investigated. On the other hand, in the double diffusive natural convection of different enclosures, the important parameters of Soret and Dufour have been usually neglected while it has demonstrated [25–30] they affect heat and mass transfer considerably. Hence, the significant topic has been studied in this paper. One of the main applications of this study is observable in the magnetic refrigerators using microchannel regenerators [31] where the water-glycol can be applied as the basic fluid [32]. In this application, a relative and changing magnetic field is applied into the micro-channel regenerators and creates an external magnetic field. The external magnetic field can affect the heat and mass transfer in the microchannel. In addition, the viscosity of the water-glycol demonstrates a power-law manner [33] in a wide range of temperatures.

In the following sections of the introduction part, the previous studies have been explained and also the main aims of this investigation have been stated.

1.2. Literature review

Kahveci and Oztuna [11] investigated MHD natural convection flow and heat transfer in a laterally heated partitioned enclosure. They showed that the x-directional magnetic field is more effective in damping convection than the y-directional magnetic field, and the average heat transfer rate decreases with an increase in the distance of the partition from the hot wall. Furthermore, they demonstrated the average heat transfer rate decreases up to 80% if the partition is placed at the midpoint. Pirmohammadi and Ghassemi [12] studied the effect of a magnetic field on convection heat transfer inside a tilted square enclosure. They found that for a given inclination angle, as the value of Hartmann number increases, the convection heat transfer reduces. In addition, they obtained that at Ra $= 10^4$, value of Nusselt number depends strongly upon the inclination angle for relatively small values of Hartmann number. Sathiyamoorthy and Chamkha [13] conducted a numerical study for natural convection flow of electrically conducting liquid gallium in a square cavity as the bottom wall is uniformly heated and the left and right vertical walls are linearly heated while the top wall kept thermally insulated. They exhibited that the magnetic field with inclined angle has effects on the flow and heat transfer rates in the cavity. Kefayati et al. [14] investigated the Prandtl number effect on MHD natural convection in an open cavity which has been filled with liquid Gallium, Air and Water by Lattice Boltzmann Method. They exhibited heat transfer declines with the increment of Hartmann number, while this reduction is marginal for Ra $= 10^3$ by comparison with other Rayleigh numbers. Ohta et al. [15] examined the natural convective heat transfer of pseudoplastic fluids in a square cavity with a heated bottom and cooled top walls by a direct numerical analysis. They mentioned that the heat transfer rate of pseudoplastic fluids become larger than that of a Newtonian fluid under thermal conditions where stable vortex flows are formed. Kim et al. [16] studied the transient natural convection of non-Newtonian power-law fluids in a square enclosure with differentially heated vertical side walls subjected to constant wall temperatures. They studied a range of nominal Rayleigh numbers from Ra $= 10^5$-10^7 and Prandtl numbers from Pr $= 10^2$-10^4 and demonstrated that the mean Nusselt number increases with decreasing power-law index for a given set of values of Rayleigh and Prandtl numbers. Lamsaadi et al. [17] performed a study of natural convection, in a vertical rectangular cavity filled with a non-Newtonian fluid and subjected to uniform heat flux along the vertical side walls numerically. They found that compared with the Newtonian case, shear-thinning behavior enhances the fluid flow heat transfer rate, while shear-thickening behavior causes an opposite effect. Turan et al. [18] simulated two-dimensional steady-state of laminar natural convection in square enclosures with differentially heated sidewalls subjected to constant wall temperatures where the enclosures are considered to be completely filled with non-Newtonian fluids obeying the power-law model. They proved that the mean Nusselt number rises with increasing values of the Rayleigh number for both Newtonian and power-law fluids. The Nusselt number was found to decrease with increasing power-law index, and, for large values of it, the value of mean Nusselt number settled to unity as the heat transfer took place principally by conduction. Moreover, the simulation results displayed that the mean Nusselt number is marginally affected by the increase in Prandtl number for Newtonian and power-law fluids for a given set of values of the Rayleigh number and power law index.

Natural convection of Newtonian and non-Newtonian power law type fluids in two-dimensional rectangular tilted enclosures was investigated numerically by Khezzar et al. [19]. They indicated shear thinning and thickening result in significant increases and decreases, respectively, in the heat transfer rate in comparison to the heat transfer rate of a Newtonian fluid. The increase and

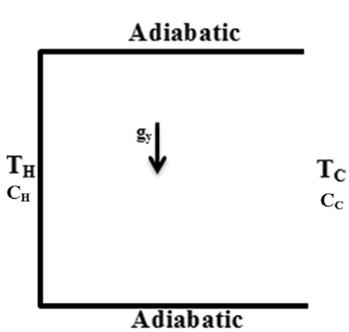

Fig. 1. Geometry of the present study.

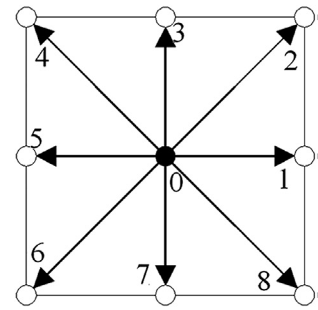

Fig. 2. Discrete velocity distribution in D2Q9.

Table 1
Grid independence study at Ra $= 10^5$, n = 0.6, N = 1, Ha = 0, Le = 5, $D_f = 0$ and $S_r = 0$.

Mesh size	Nu_{avg}	Sh_{avg}
100*100	10.0301	23.4907
110*110	10.0866	23.5286
120*120	10.1566	23.5509
130*130	10.2095	23.6021
140*140	10.2378	23.6181
150*150	10.2583	23.6255
160*160	10.2583	23.6255