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Full Length Article

Numerical investigation of double diffusive buoyancy forces induced natural convection in a cavity partially heated and cooled from sidewalls

Rasoul Nikbakhti [a,*], Javad Khodakhah [b]

[a] Mashhad Aviation of Applied Science and Technology Training Center, P.O. Box No. 91895-1466, Mashhad, Iran
[b] Faculty of Engineering, Ferdowsi University of Mashhad, P.O. Box No. 91775-1111, Mashhad, Iran

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This paper deals with a numerical investigation of double-diffusive natural convective heat and mass transfer in a cavity filled with Newtonian fluid. The active parts of two vertical walls of the cavity are maintained at fixed but different temperatures and concentrations, while the other two walls, as well as inactive areas of the sidewalls, are considered to be adiabatic and impermeable to mass transfer. The length of the thermally active part equals half of the height. The non-dimensional forms of governing transport equations that describe double-diffusive natural convection for two-dimensional incompressible flow are functions of temperature or energy, concentration, vorticity, and stream-function. The coupled differential equations are discretized via FDM (Finite Difference Method). The Successive-Over-Relaxation (SOR) method is used in the solution of the stream function equation. The analysis has been done for an enclosure with different aspect ratios ranging from 0.5 to 11 for three different combinations of partially active sections. The results are presented graphically in terms of streamlines, isotherms and isoconcentrations. In addition, the heat and mass transfer rate in the cavity is measured in terms of the average Nusselt and Sherwood numbers for various parameters including thermal Grashof number, Lewis number, buoyancy ratio and aspect ratio. It is revealed that the placement order of partially thermally active walls and the buoyancy ratio influence significantly the flow pattern and the corresponding heat and mass transfer performance in the cavity.

1. Introduction

In nature and many industrial applications, there is a diversity of transport processes where simultaneous heat and mass transfer is a common phenomenon. Fluid flows generated by combining temperature and concentration buoyancy forces are called double-diffusive convection. Double diffusion convection occurs in a wide range of fields such as oceanography, astrophysics, geology, biology, chemical processes and, geophysical problems. It also happens in many engineering applications such as solar ponds, natural gas storage tanks, crystal manufacturing, material processing, food processing, etc. To have an overview of the phenomenon see some relevant fundamental works [1–3]. A comprehensive early overview of the literature was reported by Bejan [4], Viskanta et al. [5] and Fernando [6].

More recently the enthusiasm for double diffusive convection is to study the phenomenon in the square and rectangular enclosures. Makayssi et al. [7] performed both analytical and numerical analyses of natural double-diffusive convection in a shallow enclosure filled with a non-Newtonian power-law fluid. In their case, both short vertical walls were submitted to uniform heat and mass fluxes whereas the top and bottom sides were insulated and impermeable to mass transfer. The authors examined the influence of different parameters (aspect ratio, Lewis number, Buoyancy ratio number, power-law behavior index, Prandtl number, thermal Rayleigh number) on the fluid flow and heat and mass transfer characteristics. The effect of variable density on thermosolutal natural convection in a binary mixture of ideal gasses contained in a vertical enclosure was numerically investigated by Sun et al. [8]. The results showed that the effects of non-Boussinesq were more significant in the opposing flow than in the aiding flow where both solutal and thermal forces are equal in intensity.

Al-Farhany and Turan [9] studied numerically steady conjugate double-diffusive natural convective in a two-dimensional porous cavity sandwiched between two finite thickness walls filled with anisotropic porous medium. Investigations for a variable porosity medium with a wide range of the modified Rayleigh number ($10 \le Ra \le 1000$), buoyancy ratio ($-2 \le N \le 2$), Lewis number

* Corresponding author. Tel.: +98 915 500 0903; fax: +98 513 890 5220.
E-mail address: rasoul_nikbakhti@yahoo.com (R. Nikbakhti).
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($0.1 \le Le \le 10$), thermal conductivity ratio ($0.1 \le Kr \le 10$), and ratio of wall thickness to its height ($0.1 \le D \le 0.4$) were performed by the authors. They concluded that the increase in the Rayleigh leads to increase in the Nusselt number while it decreases with increasing thermal conductivity ratio, Lewis number, and the wall thickness number. Bera et al. [10] have presented a numerical study to understand the effect of local thermal non-equilibrium (LTNE) state on the phenomenon of double-diffusive natural convection in a square enclosure filled with porous medium. A finite volume method that has been proposed by Patankar [11] was employed. The results indicated that LTNE state had a significant influence on the rate of heat transfer and thermal distribution while its impact on the mass transfer rate and solute distribution was negligible. Harzallah et al. [12] numerically studied double-diffusive natural convection in a porous vertical enclosure using an LTNE model. The cavity was bounded by finite thickness walls with opposing temperature, concentration gradients on vertical walls as well as adiabatic and impermeable horizontal ones. The porous medium was assumed to be hydrodynamically anisotropic. Calculations were performed for various parameters to analyze the effects of two main factors including finite thickness conducting walls and the mechanical anisotropy on the unsteady double-diffusive natural convection. At another work, the impacts of radiative parameters such as the particular emissivity ε, and the optical thickness τ_D on fluid flow, heat and mass transfer by natural convection and thermal radiation in a cavity filled with a fluid saturated porous medium has been studied by Jbara et al. [13]. It was observed from their results that with the increase in particular emissivity ε and the optical thickness τ_D, temperature and velocity values were found to be increased while it led to the reduction in concentration values.

Teamah [14] performed a numerical study to investigate the effect of magnetic field on double diffusive natural convection in a two-dimensional rectangular enclosure. Constant temperatures and concentration were imposed along the left and right walls of the enclosure while the upper and lower surfaces were adiabatic and impermeable to mass transfer. Besides, a uniform magnetic field was applied in a horizontal direction. The laminar regime was considered under steady state condition. The author covered a wide range of Ra_T ($10^3 \le Ra_T \le 10^6$), N ($-10 \le N \le 10$), Ha ($0 \le Ha \le 200$), and ($-50 \le \phi \le +25$) for the fixed Lewis number $Le = 1$ and Prandtl number $Pr = 0.7$. The results indicated that the magnetic field caused the reduction in heat transfer and fluid circulation within the cavity. It was also observed that the average Nusselt number tended to be increased in the presence of a heat sink while heat source was found to decrease it. Later, Teamah et al. [15] analyzed the double-diffusive natural convective flow in an inclined rectangular cavity in the presence of magnetic field and heat source. Their cavity and conditions were similar to that of Teamah [14]. They found that the inclination angle had a considerable influence on heat and mass transfer rate so that the maximum average Nusselt and Sherwood numbers were obtained at two inclination angles, $\gamma = 45°$ and 135°.

Islam et al. [16] numerically examined laminar mixed convection in a lid-driven square cavity having a square internal blockage. In their experiment, the blockage was maintained at a hot temperature and four surfaces of the cavity (including the lid) were maintained at a cold temperature. A finite volume method of the ANSYS FLUENT commercial CFD code was used to solve the problem. The results indicated that both blockage ratios (defined as the ratio of blockage size to cavity height), as well as placement locations of the blockage inside the cavity, have significant effects on the average Nusselt number. The authors concluded that the most effective heat transfer was obtained when the blockage was located at the top-left and the bottom-right corners of the enclosure. They also observed that as the blockage ratio increases, the average Nusselt number tends to decrease up to a certain value of the blockage ratio. Morshed et al. [17] did an extension for Islam et al.'s [16] study with two isothermally heated square internal blockages. Their cavity and conditions were similar to that of Islam et al. [16]. The numerical results were reported for blockage ratio, Reynolds number, and Richardson number at a fixed Prandtl number (0.71). The placement order of the blockages had a significant influence on heat and mass transfer rate; to explore this effect three different blockage placement cases were studied. The results revealed that the highest average Nusselt number was obtained in Case III while Case I was the least favorable blockage placement in terms of the heat transfer performance. Double-diffusive laminar mixed convection in a two-dimensional inclined enclosure with the moving top lid considered to move in both upward and downward directions was investigated numerically by Teamah et al. [18]. The results indicated that the flow field was characterized by a primary circulating bubble with its place depending on the direction of the moving lid.

The above literature surveys show that most of the works concerned with the heat and mass transfer convection in rectangular geometries are because of either vertical or horizontal temperature and concentration difference. However, some engineering applications such as solar energy collection, prevention of subsoil water pollution, cooling of electronic components, fluidized bed chemical reactor are subjected to partial heating and cooling zones. In fact, the complete active walls are not optimized for the heat and mass transfer in such practical applications. In other words, the relative position of the hot and cold wall regions plays a more significant role in optimizing heat and mass transfer rate in the cavity. Therefore, it is required to study the convective heat and mass transfer in the enclosures with partially active thermal and solutal walls in order to obtain the results that give a better understanding of these applications.

Natural convection in a partial heating and cooling cavity has been extensively studied in the literature [19–23].

However, less attention has been given to the phenomenon of the double-diffusive natural convection with partial thermal and concentration sources. Nithyadevi and Yang [24] studied the effect of double-diffusive natural convection of water filled in a partially heated square cavity with Soret and Dufour coefficients around the density maximum. The results demonstrated that the temperature of maximum density leaves strong effects on the heat and mass transfer because of the formation of bi-cellular structure. Also, it was found that the increase in the thermal Rayleigh number leads to increase in heat and mass transfer rate irrespective of the thermal source section. A steady laminar flow of double-diffusive convective heat transfer and fluid flow in a square cavity with three heaters situated at equal pitches on the left side wall has been studied by Teamah et al. [25]. Investigations for various Rayleigh number, Prandtl number, buoyancy ratio, and dimensionless heater lengths at a Lewis number of 2 were performed by the authors. They concluded that the heat and mass transfer increases with increasing the Rayleigh and Prandtl numbers. Moreover, they found that the average Nusselt and Sherwood numbers increase as the heater length increases. Oueslati et al. [26] have numerically investigated double-diffusive natural convection with entropy generation in an enclosure partially heated and salted from the left vertical sidewall. They concentrated their study on influences of the major parameters (Rayleigh number, buoyancy ratio, source length, Lewis number and source location) on the rate of heat and mass transfer in the rectangular cavity with an aspect ratio ($Ar = 4$).

The present investigation is an extension of Nikbakhti and Rahimi [27] study. They analyzed different thermally active locations to obtain the optimum combinations in terms of the heat and mass transfer performance in the cavity. However, it is worth to note that the heat and mass transfer performance could also depend on other important factors such as the orientation of the thermal and solutal