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Conjugated effect of joule heating and magneto-hydrodynamic on double-diffusive mixed convection in a horizontal channel with an open cavity

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ABSTRACT

A finite element analysis is performed on the conjugated effect of joule heating and magneto-hydrodynamic on double-diffusive mixed convection in a horizontal channel with an open cavity. Homogeneous flows are imposed throughout the channel. Consistent high temperatures and concentrations are imposed at the bottom wall of the cavity. The other sides of the cavity along with the channel walls are considered as adiabatic. The effects of the various parameters (Richardson number, Hartmann number, joule heating, buoyancy ratio and Lewis number) on the contours of streamline, temperature, concentration and density have been depicted. Moreover, the average Nusselt and Sherwood numbers as well as bulk temperature is presented for the aforementioned parameters. The results show that the aforesaid parameters have noticeable effect on the flow pattern and heat and mass transfer.

1. Introduction

Mixed convection is that type of heat transfer in which there is a noteworthy interaction between free and forced convection. Mixed convective heat transfer in open cavities has long been studied and has received increases attention due to its application of practical interest, such as nuclear reactors, solar receiver, thermal storage and open cavity packaging of semiconductors. Studies associated with mixed convection in open cavities have received increasing consideration. Pavlovic and Penot [1] performed an experimental investigation of the mixed convection heat transfer in an open isothermal cubic cavity. They concluded that the convective heat loss for the central solar receiver. Fusegi [2] carried out a numerical study on convective heat transfer from periodic open cavities in a channel with oscillatory through flow. Khanafer et al. [3] made a numerical investigation on mixed convection heat transfer in open-ended enclosures for three different flow angles. They found that, thermal insulation of cavity can be achieved through the use of high horizontal velocity flow. A numerical analysis of laminar mixed convection in a channel with an open cavity and a heated wall bounded by a horizontally insulated plate was presented by Manca et al. [4], where the authors considered three heating modes: assisting flow, opposing flow and heating from below. Later, a similar problem for the case of assisting forced flow configuration was tested experimentally by Manca et al. [5]. Leong et al. [6] performed a numerical study on the mixed convection from an open cavity in a horizontal channel. Authors found that the heat transfer rate was reduced, and the flow became unstable in the mixed convection regime. Aminossadati and Ghasemib [7] performed a numerical study on the mixed convection in a horizontal channel with a discrete heat source in an open cavity. They considered three different heating modes and found noticeable differences among the indicated three heating modes. Wong and Saeid [8] numerically investigated the opposing mixed convection arises from jet impingement cooling of a heated bottom surface of an open cavity in a horizontal channel filled with porous medium.

Magneto-hydrodynamics (MHD) is that branch of science, which studies the dynamics of electrically conducting fluids in the presence of electromagnetic fields. MHD is usually regarded as a very up to the date subject, because it has many engineering applications such as liquid–metal cooling of nuclear reactors and electromagnetic casting, etc. MHD studies are mostly focused on convection heat transfer in closed cavities. Piazza and Ciofalo [9] carried out a numerical investigation on buoyancy-driven magneto-hydrodynamic flow in a liquid–metal filled in a cubic enclosure. The authors found that increasing Hartmann number suppressed the convective motions. Chamkha [10] made a study for mixed convection in a square cavity in the presence of magnetic field and an internal heat generation and absorption. He concluded

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Nomenclature

B_0 strength of the magnetic field, (Tesla)
Br buoyancy ratio $(\beta_c(c_h - c_L)/\beta_T(T_h - T_i))$
c mass concentration (kg m^{-3})
c_p specific heat (J kg^{-1} k^{-1})
c_h high mass concentration (kg m^{-3})
c_L low mass concentration (kg m^{-3})
C dimensionless mass concentration $(c - c_L)/(c_h - c_L)$
D mass diffusivity (m^2 s^{-1})
g gravitational acceleration (ms^{-2})
H height of the cavity (m)
Ha Hartmann number $(B_0 L\sqrt{\sigma/\mu})$
J joule heating parameter $(\sigma B_0^2 u_i L/\rho c_p(T_h - T_i))$
k fluid conductivity (Wm^{-1} k^{-1})
L cavity length (m)
Le Lewis number (α/D)
Nu average Nusselt number
p dimensional pressure (kg m^{-1} s^{-2})
P non-dimensional pressure $((p + \rho g y)L^2/\rho u_i^2)$
Pr Prandtl number(ν/α)
Re Reynolds number $(u_i L/\nu)$
Ri Richardson number $(g\beta_T(T_h - T_i)L/u_i^2)$
Sh average Sherwood number
T temperature (K)
T_h heat source temperature (K)
T_i inlet flow temperature (K)
(u, v) velocity components (ms^{-1})
(U, V) dimensionless velocity component $(U = u/u_i, V = v/u_i)$
w height of the channel (m)
(x, y) dimensional coordinates (m)
(X, Y) dimensionless coordinates $(X = x/L, Y = y/L)$

Greek symbols
α thermal diffusivity (m^{2}s^{-1})
β_T coefficient of thermal expansion (K^{-1})
β_c coefficient of mass expansion (m^3 kg^{-1})
μ dynamic viscosity (kg m^{-1} s^{-1})
ν kinematic viscosity (m^2 s^{-1})
Θ bulk temperature
θ non-dimensional temperature $(T - T_i)/(T_h - T_i)$
ρ density (kg m^{-3})
ρ^* dimensionless density $(BrC - \theta)$
σ electrical conductivity (S m^{-1})
γ penalty constraint
ψ stream function

Subscriptv
i inlet state

Abbreviations
MHD magneto-hydrodynamic
CBC convective boundary conditions

that the flow behavior inside the cavity and heat transfer rate is strongly affected by the magnetic field. Sarries et al. [11] performed a numerical study on unsteady natural convection of an electrically conducting fluid in a laterally and volumetrically heated square cavity under the influence of a magnetic field. Xu et al. [12] completed an experimental study on natural convection of a molten metal contained in a rectangular enclosure in the presence of an external magnetic field. Oztop et al. [13] studied the effects of sinusoidal temperature boundary conditions on magnetohydrodynamic buoyancy-induced flow in a non-isothermally heated square enclosure. Rahman et al. [14] made a numerical investigation on the conjugate effect of joule heating and magneto-hydrodynamics mixed convection in an obstructed lid-driven square enclosure. Recently, Rahman et al. [15] numerically studied magneto-hydrodynamic mixed convection in a horizontal channel with an open cavity. They used Galerkin weighted residual method for the numerical simulation and showed a significant effect of the considered parameters on the flow and thermal fields inside the cavity. Bhuvaneswari et al. [16] carried out a computational study of convective flow and heat transfer in a cavity in the presence of uniform magnetic field. Ogot [17] made an analysis of heat and fluid flow transport due to natural convection and magneto-hydrodynamic flows in a square enclosure with a finite length heater using differential quadrature technique. Sposito and Ciofalo [18] studied fully developed mixed magneto-hydrodynamic convection in a vertical square duct.

The double-diffusive mixed convection in a channel with an open enclosure has also found wide applications in engineering, such as cooling of electronic components, finned heat exchangers, cavity of solar central receivers, chemical processing, thermal and pollution control, evaporative cooling and fire control in buildings. There are several studies related to mixed convection for combined heat, and mass transfer. Deng et al. [19] made a numerical study for a laminar double diffusive mixed convection in a two-dimensional ventilated enclosure with discrete heat and contaminant sources. They investigated the characteristics of the airflow and heat/contaminant transport structures in the indoor air environment by means of a convection transport visualization technique. Costa [20] carried out a numerical study for double-diffusive natural convection in parallelogrammic enclosures filled with moist air. Chamkha and Naser [21] studied the problem of unsteady, laminar double-diffusive convective flow of a binary gas mixture in an inclined rectangular enclosure filled with a uniform porous medium. A numerical simulation of double diffusive natural convection in rectangular enclosure in the presence of magnetic field and heat source was performed by Teamah [22]. Teamah and El-Maghlany [23] numerically simulated double-diffusive mixed convective flow in a rectangular enclosure with insulated moving lid. Brown and Lai [24] numerically investigated a horizontal channel with an open cavity and obtained correlations for combined heat and mass transfer which covered the entire convection regime from natural, mixed to forced convection. Chamkha and Naser [25] made an examination on hydromagnetic double-diffusive convection in a rectangular enclosure with opposing temperature and concentration gradients.

A detailed literature survey reveals that the majority of existing numerical investigations are restricted in cavities with or without a magnetic field in detail. In view of the abovementioned statements, it is also seemed that the conjugate effect of joule heating and magneto-hydrodynamic double-diffusive mixed convection in a horizontal channel with an open cavity has not been addressed yet. In the present study, we undertake this task varying the Hartmann number Ha $(10 \leqslant Ha \leqslant 100)$, joule heating parameter J $(0.0 \leqslant J \leqslant 3.0)$, buoyancy ratio Br $(0.5 \leqslant Br \leqslant 5.0)$ and Lewis number Le $(2.0 \leqslant Le \leqslant 10.0)$ for Reynolds number $Re = 100$, Richardson number $Ri = 1.0$ and Prandtl number $Pr = 0.7$. A comprehensive study of the flow field, temperature and concentration distribution with detailed analysis on heat and mass transfer evaluation will be done. The results are shown in terms of parametric presentations on the contours of streamlines, isotherms, concentration and density for the considered pertinent dimensionless parameters.