International Journal of Research Publication and Reviews, Vol 4, no 3, pp 4115-4119, March 2023

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Numerical Investigation on the Effect of Magnetic Field and Semicircular Porous Medium in a Square Enclosure on Thermal Traits

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ABSTRACT

In the present study, the effect of hot permeable semicircular porous body and a horizontal magnetic field in a square cavity on flow structure and heat transfer characteristics are analyzed numerically. For the numerical study, the Lattice-Boltzmann method is used, and the flow properties in the porous body are obtained by the Darcy-Brinkmann-Forchheimer term. The numerical algorithm is solved using the SRT model in addition to the D2Q9 mesh model. The main objective of the present study is to evaluate the effect of permeability and magnetic field on heat transfer characteristics. The analysis is carried out for different range of parameters such as Darcy number ($Da = 10^{-5}$, 10^{-4}, and 10^{-3}) and Hartmann number (Ha = 0, 25, and 50) on the quantitative and qualitative outcomes. The Rayleigh number (Ra), Prandtl number (Pr), and Lewis number (Le) are fixed as 10^5, 7.0 and 5, respectively. The flow is driven by the buoyancy force caused by the temperature gradient between the porous body and the walls of the casing. Increasing Ha impedes the intensity of the flow field and thus the heat transfer rate is reduced while Ha is increased. In addition, Da increases the energy of fluid flow and hence the mean Nusselt number and Sherwood number increase.

Keywords: LBM; MHD; Porous body; Semi-circular cylinder; Kinetic energy.

Introduction

Magnetic Field Effect on Entropy Generation at Thermo-solutal Convection in a Square Cavity analyse by Mounir *et.al* [1]. They mention total entropy generation increases for high thermal Gr number and with BR. Barik and Dash [2] study the heat and mass transfer effect flow over a sheet in the presence of a heat source and said that inclusion of viscous dissipation in flow through porous is beneficial for gaining temperature. Mishra *et.al* [3] studied the effect of heat transfer on electrically conducting MHD micropolar fluid with radiation and heat source. Noted that presence/absence of MHD generates back flow with velocity profile. MHD flow and heat transfer of viscous fluid through porous body has been investigated by Petrovic *et.al* [4]. They said increase of the porosity parameter reduces the velocity and induced magnetic field.

Stamenkovi *et.al* [5] studied the micro polar fluid flow in porous media between two plates and noted that for smaller values of the porosity R, viscous heating increases the temperature near plates. Three-dimensional free convective MHD flow and heat transfer through a porous medium discussed by R N Jat and Anuj [6] and said the heat transfer rate increases with the increasing values of these parameters are Re and M. Geridonmez and Hakan [7] investigated Natural convection in a cavity filled with porous medium under effect of a partial magnetic field. Mentioned that the effect of partial magnetic field disappears as Da decreases. Mustafa and Khawatreh [8] performed Unsteady MHD Flow and Heat Transfer Through Porous Medium Between Parallel Plates with Periodic Magnetic Field and noted that the velocity of the fluid decreases due to an increase in Pr, magnetic field strength or permeability.

Laminar natural convection in power-law liquids from a heated semi-circular cylinder with its flat side oriented downward studied by Anurag and Chhabra [9] and reported at fixed values of Gr and Pr, shear-thinning behavior can enhance the rate of heat transfer. Avinash and R.P. Chhabra [10] reported Laminar free convection from a horizontal semi-circular cylinder to power-law fluids. They elucidated under conditions of Gr, Pr, and n, it is indeed possible to enhance the rate of heat transfer by two to three folds over and above that in Newtonian fluids. Double diffusion convection in a cavity with a hot square obstacle inside is simulated using LBM Method by Mohsen Nazari *et.al* [11]. They mentioned as the Ra and Le increase, more negative N is needed for vortices to join the main flow and the multi-cell flow converts to double-cell flow. Influence of porous circular cylinder on MHD double-diffusive natural convection and entropy generation analyzed by T.R. Vijaybabu [12] and mentioned that amalgamation of buoyancy force, permeability, magnetic field intensity and its direction can greatly regulate the flow, heat, and concentration characteristics.

For the first time, the focus of the study is the investigation of the heat transfer properties of a porous material under the influence of a magnetic field. Due to the wide range of applications of porous bodies with corners and bulges, the semicircular shape was considered. The purpose of the numerical simulation is to analyze the effect of the porous semicircular body and the magnetic field on the flow and heat transfer properties.

Problem description

The physical model considered for this study comes from Fig.1. It consists of a square cavity of side L and a porous circular cylinder of diameter W. The diameter of the porous cylinder is kept constant at *0.4L*.

The following assumptions are considered to simplify the current analysis and make it acceptable for the numerical simulations:

- Fluid flow is assumed to be steady, two-dimensional, and incompressible.
- Fluid flow driven by density variation offered by the thermal gradient between the porous circular cylinder and the housing walls.
- The local thermal equilibrium state is assumed in the porous area. The ratio of the viscosity of the porous medium to the thermal conductivity of the porous medium to the fluid is assumed to be one.

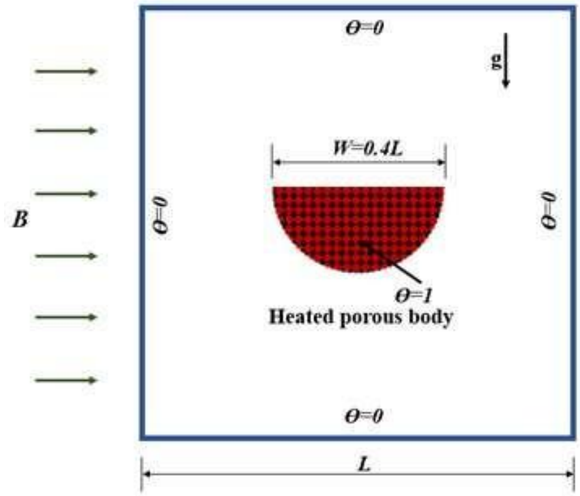

Figure 1. Schematic diagram

Parameters considered:

- Hartmann Number, $Ha = 0, 25, \& 50$
- Darcy Number, $Da = 10^{-3}, 10^{-4}, \& 10^{-5}$
- Porosity, $\varepsilon = 0.977, 0.935, \& 0.824$
- Rayleigh Number, $Ra = 10^{5}$
- Prandtl Number, $Pr = 7$
- Lewis Number, $Le = 5$

Lattice Boltzmann Method

LBM is used to assess the current issue because of its straightforward approach to numerous hydrodynamic problems. LBM has demonstrated its capacity to solve complicated geometry and multi-phase flow through porous bodies. The distribution of grouped particles is used to illustrate the flow in this technique. The FORTRAN computer language is used to create a lattice Boltzmann code for the current numerical inquiry. Combining the Darcy-Brinkmann-Forchheimer term with the LBM's flow evolution equation yields the porous characteristics. The numerical technique was solved by combining the D2Q9 lattice model with the SRT model.

LBM employs sequential operations such as collision, streaming, determining boundary conditions, and computing macroscopic attributes. The flow field collision equation, which incorporates magnetic intensity and porous characteristics, is applied to the whole computational domain, and is borrowed from [12]. The collision equation directly incorporates the porous media, and the force terms correspond to the buoyancy force. The equation for flow field collision may be expressed as [12].

$$f_i\,(x + e_i\Delta t,\, t + \Delta t) - f_i\,(x,\, t) = -1/r\,[\, f_i\,(x,\, t) - f_i^{eq}\,(x,\, t)] + \Delta t F_i + \Delta t F_M. \qquad (1)$$

Results and Discussions

Effect of Ha

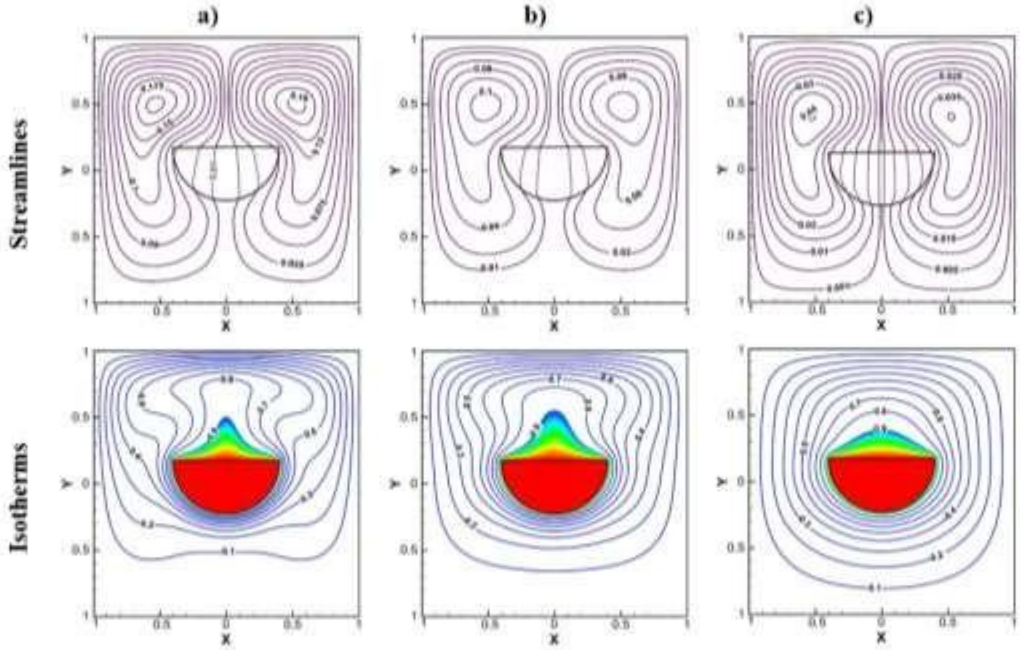

Figure 2. effect of Hartmann number on streamlines and isotherms at *Da* = 0. a) *Ha* = 0, b) *Ha* = 25, & c) *Ha* = 50

Hartmann number indicates the intensity of magnetic field or in other words it is the ratio of magnetic force to the viscous force. Increase in *Ha* indicates intensification of magnetic field. Fig. 2. represents the effect of *Ha* on streamlines and isotherms. At *Ha* = 0, the kinetic energy of the fluid is high because at this *Ha* the intensity of the magnetic field is zero. Further augmentation in *Ha* reduced the kinetic energy of the fluid because the horizontal component of the velocity of the fluid increases and as a result the tendency of the fluid to flow decreases. On other hand increase in *Ha* resulted in cross wise distribution of the isotherm and isotherms get spread all over the cavity. The thermal boundary layer became thicker while increasing in *Ha* which indicates decrease in heat transfer rate. To sum up, increase in *Ha* reduces the kinetic energy of the fluid as a result the heat transfer rate decrease.

Effect of Da

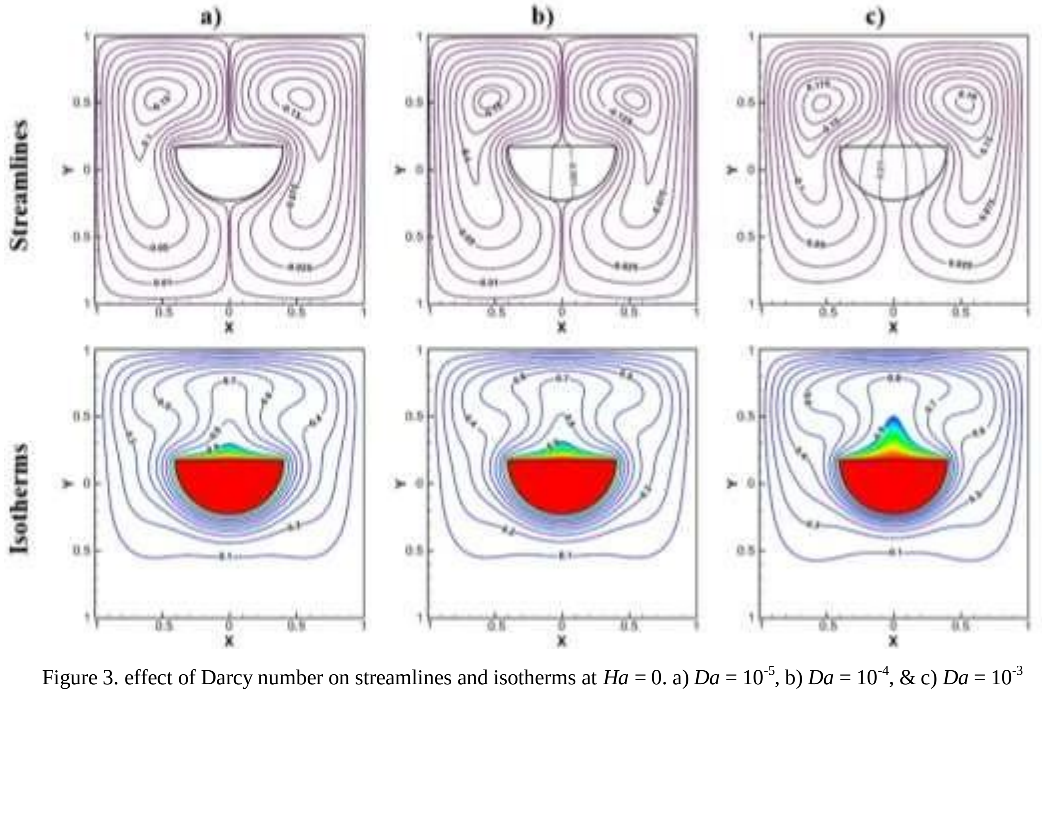

Figure 3. effect of Darcy number on streamlines and isotherms at *Ha* = 0. a) *Da* = 10^{-5}, b) *Da* = 10^{-4}, & c) *Da* = 10^{-3}

Darcy number indicates permeability offered by the porous body, increase in *Da* increases the permeability of porous body and allows more amount of fluid to pass through it. The effect of *Da* on isotherms and streamlines is represented in the fig. 3. At 10^{-5}, less amount of fluid enters the porous body because, the viscous resistance offered by porous body is high. The porous body acts like a solid body at this *Da*. Further increase in Da ($Da = 10^{-4}$), little amount of fluid passes through the porous body. At the value of 10^{-3}, flow intensity and kinetic energy increase due to viscous resistance becomes low. Increase in *Da*, the thermal boundary layer at the bottom of the porous body became thinner which indicates at the bottom of the porous body the heat transfer increase. And it is noteworthy to mention that the plume above the porous body get stretched with increase in *Da* because the amount of hot fluid coming out increase. To sum up, increase in Darcy number increases kinetic energy of the fluid and which increases rate of heat transfer significantly.

Average Nusselt number (Nu_M)

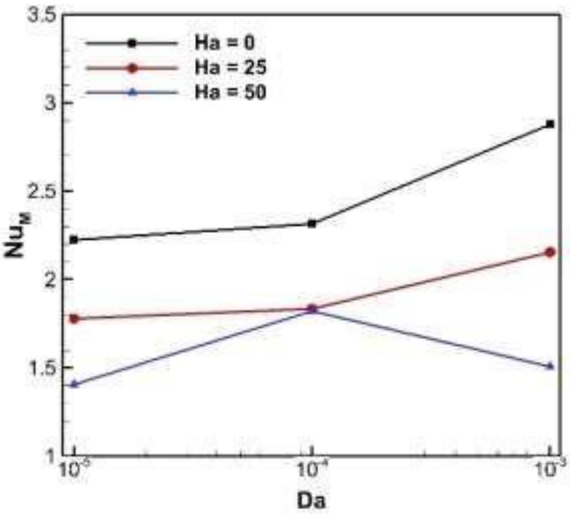

Figure 4. Effect of *Da* and *Ha* on mean Nusselt number

Mean Nusselt number (Nu_M) indicates the amount of heat transfer through convection to the conduction. In our case we concentrate on convective heat transfer. Fig. 4. represents the variation of mean Nusselt number with *Da* and *Ha*. Increase in *Da*, the average Nusselt number increased significantly. This is because increase in *Da* allows more amount of fluid to pass through it hence more amount of fluid interact and carry heat from the hot porous body. On other hand increase in *Ha*, the average Nusselt number reduced trivially. This is because increase in *Ha* reduces the kinetic energy of the fluid as a result the intensity of fluid flow drops a little. It is to be mentioned that at $Ha = 50$ for $Da = 10^{-4}$, the mean Nusselt number is maximum when compared to other *Da*. The percentage increment in Nu_M with refence to $Da = 10^{-5}$ are 4.13%, and 29.37% for $Da = 10^{-4}$, and 10^{-3} with reference to $Ha = 0$. And The percentage decrement in Nu_M with refence to $Ha = 0$ are 25.07%, and 47.66% for $Ha = 25$, and $Ha = 50$ with reference to $Da = 10^{-3}$. The maximum mean Nusselt number is found at $Ha = 0$ and $Da = 10^{-3}$.

Conclusion

LBM investigation on the influence on magnetic field and porous body on heat and flow characteristics are elucidated in the present study. For analysis the parameters considered are Hartmann number (Ha = 0, 25, & 50) and Darcy number ($Da = 10^{-5}$, 10^{-4}, & 10^{-3}). The obtained interesting results are mentioned below:

- Increase in *Da*, porous body offered more amount of fluid to pass through it. As a result, kinetic energy of the fluid improved significantly.
- Augmentation in *Da* hindered the fluid flow intensity which implies diminution in kinetic energy of the fluid.
- The mean Nusselt number has decreased with increase in *Ha*, and increase with increase in *Da*.
- The maximum values of Nu_M are found for the case $Da = 10^{-3}$ at $Ha = 0$, where the kinetic energy of the fluid is maximum.
- It is noted that at maximum *Da* and minimum *ss* the heat transfer is maximum.

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