Journal of Magnetism and Magnetic Materials 357 (2014) 53–60

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Effects of a magnetic quadrupole field on thermomagnetic convection of air in a porous square enclosure

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ARTICLE INFO

Article history:
Received 3 September 2013
Received in revised form
18 December 2013
Available online 21 January 2014

Keywords:
Thermomagnetic convection
Numerical simulation
Porous medium
Magnetic quadrupole field
Magnetic force

ABSTRACT

The thermomagnetic convection of air in a two-dimensional porous square enclosure under a magnetic quadrupole field is investigated numerically. The scalar magnetic potential method is used to calculate the magnetic field. A generalized model, which includes a Brinkman term, a Forcheimmer term and a nonlinear convective term, is used to solve the momentum equations. The flow and temperature fields for the air thermomagnetic convection are presented and the local and average Nusselt numbers on the walls are calculated and compared. The results show that the magnetic field intensity, Darcy number and Rayleigh number have a significant effect on the flow field and heat transfer in a porous square enclosure.

1. Introduction

Natural convection heat transfer in porous enclosures continues to be an active research area, due to its significance for both fundamental interests and engineering applications, such as solar receivers, cooling of electronic devices, solidification of materials and so on. There are many open literature related to natural convection in porous enclosures [1–3]. Anandalakshmi et al. [4] have investigated the heat distribution and thermal mixing during steady laminar convection flow inside right-angled triangular enclosure filled with porous media. The heat transfer distribution and thermal mixing enhances due to isothermal heating of walls. Ellahi et al. [5–8] have analyzed the influence of variable viscosity and viscous dissipation on the non-Newtonian flow in porous medium using the homotopy analysis method. Numerical investigation of natural convection within porous square enclosures for various thermal boundary conditions has been done by Ramakrishna et al. [9]. It is found that thermal boundary conditions have an important influence on the flow and heat transfer characteristics during natural convection within porous square cavities.

Magnetohydrodynamic (MHD) flow has taken a great interest in recent years due to its numerous important applications in science and engineering, such as electronic packaging, microelectronic mechanical devices, crystal growth in liquids, and solar energy technology. The MHD natural convection has been investigated by many researchers using experimental, analytical and numerical methods [10–17]. Kakarantzas et al. [10–13] investigated buoyancy-driven magnetoconvection flow in an enclosure with different boundary conditions. Magnetohydrodynamic natural convection in a rectangular cavity under a uniform magnetic field at different angles with respect to horizontal plane has been investigated by Yu et al. [14]. They concluded that the heat transfer is not only determined by the strength of the magnetic field, but also influenced by the inclination angle. Especially, when the aspect ratio is less or more than 1, it is found that the inclination angle plays a great role on flow and heat transfer. Ellahi et al. [15,16] investigated the magnetohydrodynamic (MHD) flow of non-Newtonian nanofluid in a pipe or a channel. At the same time, they also studied the effect of magnetic field on natural convection heat transfer of Cu–water nanofluid in an enclosure with hot elliptic cylinder [17]. Their results showed that increasing Rayleigh number leads to increase heat transfer enhancement. Costa et al. [18] studied natural convection flow in differentially heated square enclosures filled with fluid-saturated porous media under the effect of a magnetic field induced by two electric currents. It is shown that induced magnetic field reduces the overall heat transfer crossing the enclosure. Hasanpour et al. [19] used the lattice Boltzmann method to depict the Prandtl number effect on MHD mixed convection flow in a porous lid-driven cavity.

In recent years, with the development of superconducting magnet providing strong magnetic induction of 10 T or more, the natural convection of paramagnetic fluids like oxygen gas and air under magnetic field has been an interesting research topic

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http://dx.doi.org/10.1016/j.jmmm.2014.01.027

Nomenclature

$\boldsymbol{b}$	magnetic flux density, T
b_0	reference magnetic flux density, $b_0=Br$, T
$\boldsymbol{B}$	dimensionless magnetic flux density
C	$C=1+(1/T_0\beta)$
Da	Darcy number, $\frac{\kappa}{L^2}$
$\boldsymbol{f}_m$	magnetic force
$\boldsymbol{g}$	gravitational acceleration, m s^{-2}
$\boldsymbol{H}$	magnetic field intensity
L	length of the enclosure, m
Nu_m	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
p_0	pressure at reference temperature, Pa
p'	pressure difference due to the perturbed state, Pa
Pr	Prandtl number, $Pr=\frac{\nu}{\alpha}$
Ra	Rayleigh number, $Ra=\frac{g\beta(T_h-T_c)L^3}{\alpha\nu}$
T_0	$T_0=\frac{T_h+T_c}{2}$, K
T_c	temperature of the cold wall, K
T	temperature, K
T_h	temperature of the hot wall, K
u,v	velocity components, m s^{-1}
U,V	dimensionless velocity components
$\boldsymbol{U}$	velocity vector
x,y	Cartesian coordinates
X,Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity, m s^{-1}
β	thermal expansion coefficient, K^{-1}
γ	dimensionless magnetic strength parameter, $\gamma=\frac{\chi_0 b_0^2}{\mu_m gL}$
θ	dimensionless temperature, $\theta=\frac{T-T_0}{T_h-T_c}$
μ_0	magnetic permeability of vacuum, H m^{-1}
μ_m	magnetic permeability, H m^{-1}
ν	kinematic viscosity, m^2 s^{-1}
ρ	fluid density, kg m^{-3}
χ	mass magnetic susceptibility, m^3 kg^{-1}
χ_m	volume magnetic susceptibility
ε	porosity
μ	fluid kinematic viscosity, kg m^{-1} s^{-1}
φ_m	scalar magnetic potential
κ	permeability, m^2

Subscripts

0	reference value
c	hot
h	cold

investigated by many researchers. Many research works about magnetically induced natural convection have been reported [20]. The effect of magnetic buoyancy force on the convection of paramagnetic fluids was first reported by Braithwaite et al. [21], they used the magnetic field both to enhance and suppress the Rayleigh–Benard convection in a solution of gadolinium-nitrate in a shallow layer heated from below and cooled from above and showed that the influence depends on the relative orientation of magnetic force and temperature gradient. Carruthers and Wolfe [22] studied the thermomagnetic convection of oxygen gas in a rectangular container with thermal and magnetic field gradients theoretically and experimentally. They found that the magnetic buoyancy force canceled out the influence of gravitational buoyancy force when the rectangular enclosure heated from one vertical wall and cooled from opposing wall was located in the horizontal magnetic field with vertical magnetic field gradient. They also found the horizontal magnetic field could enhance or suppress the Rayleigh–Benard convection when the rectangular enclosure heated from below and cooled from above was located with the same mode. Wakayama and coworkers found some various interesting phenomena under the magnetic field, such as enhancing combustion flames and sustaining flames under microgravity, magnetic control of thermal convection [23]. Tagawa's group [24] derived a model equation for magnetic convection using a method similar to the Boussinesq approximation and studied natural convection of paramagnetic, diamagnetic and electrically conducting fluids in a cubic enclosure with thermal and magnetic field gradients at different thermal boundaries numerically and experimentally. Ozoe and co-workers [25] studied natural convection of paramagnetic and diamagnetic fluids in a cylinder under gradient magnetic field at different thermal boundaries numerically and experimentally and found that the magnetic force due to gradient magnetic field could be used to control heat transfer rate of paramagnetic and diamagnetic fluids. Yang et al. [26] investigated the thermomagnetic convection of air or oxygen gas in a enclosure by using the gradient magnetic field available from the neodymium–iron–boron permanent magnet systems, and pointed out that the enhancement or suppression of thermomagnetic convection of air or oxygen gas could be achieved by a gradient magnetic field. Tomasz and co-workers [27] studied natural convection of paramagnetic fluids in a cubic enclosure under magnetic field by an electric coil. They found that the inclined angle of electric coil, location of electric coil and *Ra* number have an important influence on heat transfer rate of paramagnetic fluids.

Above studies are concerned with the effect of magnetic force on natural convection of paramagnetic fluids. However, only a few studies are paid on the combined effects of both magnetic and gravitational forces on the natural convection of paramagnetic fluids in porous medium. Natural convection in an enclosure filled with a paramagnetic or diamagnetic fluid-saturated porous medium under strong magnetic field was numerically investigated by Wang et al. [28,29]. Considering the effect of Darcy number, Rayleigh number and magnetic force number, the results of numerical investigation showed that the magnetic force had a significant effect on the flow field and heat transfer in a paramagnetic or diamagnetic fluid-saturated porous medium. The application of strong magnetic field for porous medium may be found in the field of medical treatment, metallurgy, materials processing, and combustion. There may be plenty of applications in engineering field in the near future. Thus, the study of effect of magnetic force on natural convection in porous media is very important for both scientific research and engineering application.

2. Physical model

The schematic of the system under consideration is shown in Fig. 1. The system consists of a porous cubic enclosure which is kept in a horizontal position and four permanent magnets which generate a magnetic field. The porous cubic enclosure filled with air is heated isothermally from the left-hand side vertical wall and