International Journal of Heat and Mass Transfer 90 (2015) 418–426

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effect of induced electric field on magneto-natural convection in a vertical cylindrical annulus filled with liquid potassium

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ARTICLE INFO

Article history:
Received 4 April 2015
Received in revised form 18 June 2015
Accepted 21 June 2015

Keywords:
Cylindrical annulus
Magnetic field
Magneto-natural convection
Electric field
CFD

ABSTRACT

Laminar steady magneto-natural convection in a vertical cylindrical annulus formed by two coaxial cylinders filled with liquid potassium is studied numerically. The cylindrical walls are isothermal, and the other walls are assumed to be adiabatic. A constant horizontal magnetic field is also applied on the enclosure. The results show that flow is axisymmetric in the absence of the magnetic field; but by applying the horizontal magnetic field, it becomes asymmetric. This is due to the growth of Roberts and Hartmann layers near the walls parallel and normal to the magnetic field, respectively. The applied magnetic field results in a reduction in the Nusselt number in most of the regions of the annulus. This reduction is high in the Hartmann layers but low in the Roberts layers. Moreover, it was found that for a given value of Hartman number, the average Nusselt number is greater in the case of solving the electric potential equation. The results show that there is a large difference in the Nusselt number obtained by solving the electric potential equation, compared with by neglecting the electric potential.

1. Introduction

Magnetic field is widely used in many applications such as the military and aerospace industries [1], measuring [2], pumping [3], and electric generation [4]. In the crystal growth process, the temperature difference between the wall and the melt region causes buoyancy forces that result in a natural convection flow. Buoyancy force causes the motions that can generate undesirable microscopic heterogeneities in production. Therefore, in such processes reduction in natural convection is taken it consideration. The use of magnetic field is an effective method for reducing the natural convection in liquid metals [5–8]. Many authors numerically studied the convective heat transfer in a rectangular cavity exposed to a magnetic field and showed that with an increase in the magnetic field, natural convective heat transfer is reduced [9–17].

Some researchers have numerically studied the effect of magnetic fields on convective heat transfer in 2D cylindrical enclosures. Steady and unsteady mixed convection in a 2D cylindrical annulus with a rotating outer cylinder under a radial magnetic field was investigated numerically by Mozayyeni and Rahimi [18]. They investigated the effect on heat transfer of various dimensionless numbers such as Reynolds number, Rayleigh number, Hartmann number, Eckert number, and radii ratio. Numerical results showed that the flow and heat transfer are significantly suppressed by applying an external magnetic field. In another study, Afrand et al. [19] studied numerically a steady natural convection under different directions of magnetic field in a 2D cylindrical annulus filled with liquid gallium. Their results showed that by increasing the Hartmann number, natural convection is decreased. They found that at low Rayleigh numbers with an increase in Hartmann number, natural convection in the annulus is frequently due to the conduction mode.

Moreover, some researchers have to pay attention to experimental investigation of natural convective heat transfer in cylindrical annuluses containing magnetic fluid. For example, natural convective heat transfer in a horizontal cylindrical annulus containing magnetic fluid was experimentally investigated by Sawada et al. [20]. The cylindrical walls were maintained at a constant temperature, and a nonuniform magnetic field was applied to the annulus. Results revealed the influence of the magnetic field changes the heat transfer. Experimental and numerical analyses of a thermo-magnetic convective flow of paramagnetic fluid in the space between two vertical cylinders influenced by the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.06.059
0017-9310/

Nomenclature

A	aspect ratio
B_0	magnitude of the external magnetic field (kg/s^2 A)
D	annulus gap ($D = r_o - r_i$ (m))
E	dimensional induced electric field (m kg/s^3 A)
E^*	dimensionless induced electric field
F	Lorentz force (N/m^3)
g	acceleration due to gravity (m/s^2)
Ha	Hartmann number
J	electric current density (A/m^2)
L	height of the annulus
Nu	Nusselt number
p	pressure (N/m^2)
P	dimensionless pressure
Pr	Prandtl number
Ra	Rayleigh number
T	dimensional temperature (K)
T^*	dimensionless temperature
(r, z)	radial and axial co-ordinates
(R, Z)	dimensionless radial and axial co-ordinates
(r_i, r_o)	radii of inner and outer cylinders (m)
(u, v, w)	dimensional velocity components in (r, θ, z) direction (m/s)
(U, V, W)	dimensionless velocity components in (r, θ, z) direction
(x, y, z)	Cartesian co-ordinate components

Greek letters

α	thermal diffusivity (m^2/s)
β	fluid coefficient of thermal expansion (1/K)
ϕ	dimensional electrical potential (m^{2}kg/s^{3}A)
Φ	dimensionless electrical potential
γ	inclination angle
λ	radii ratio
μ	dynamic viscosity (kg/ms)
θ	azimuthal angle
ρ	fluid density (kg/m^3)
σ	fluid electrical conductivity (s^3 A^2/m^3 kg)

Subscripts

c	condition at cold wall
h	condition at hot wall

magnetic field were carried out by Wrobel et al. [21]. They showed that the effect of the Hartmann number on the heat transfer rate is four times greater than the effect of Rayleigh number.

In the last decade, several studies have been performed on the effect of magnetic fields on convective heat transfer in 3D cylindrical enclosures. In this regard, by focusing on the directions of magnetic field, Sankar et al. [22] numerically studied the effect of magnetic fields on natural convection in the space between two vertical concentric cylinders. This study was carried out for electrically conducting fluid (Pr = 0.054) under a constant axial or radial magnetic field. The inner and outer cylinders were kept at constant temperatures. The results show that flow and heat transfer are suppressed more effectively by a radial magnetic field in tall enclosures, whereas in shallow enclosures, an axial magnetic field is more effective. Furthermore, the effect of a radial or axial magnetic field on double-diffusive natural convection in a vertical cylindrical annulus was presented by Venkatachalappa et al. [23]. They claimed that for small buoyancy ratios, the magnetic field suppresses double diffusive convection. Kumar and Singh [24] considered a vertical cylindrical annulus filled with an electrically conducting fluid in the presence of a radial magnetic field. The effect of the Hartmann number and buoyancy force distribution parameters on the fluid velocity, induced magnetic field, and induced current density was numerically analyzed. It was observed that the fluid velocity and induced magnetic field rapidly decrease with the increase in the value of Hartmann number. Kakarantzas et al. [25] used numerical methods to study the magneto-natural convection in a vertical cylindrical enclosure with sinusoidal upper wall temperature under a tilted magnetic field. The computational results demonstrated that the Nusselt number is decreased more effectively by an axial magnetic field compared to a horizontal one. In another research, Kakarantzas et al. [26] performed a numerical study on the effect of a horizontal magnetic field on unsteady natural convection in the vertical annulus containing liquid metal. They reported that by increasing the magnetic field, the flow becomes laminar. Moreover, it can be observed that the horizontal magnetic field causes the loss of axisymmetry of flow. Recently, Afrand et al. [27] carried out a 3D numerical investigation of natural convection in a tilted cylindrical annulus filled with molten potassium and controlled it by using various magnetic fields. Their results revealed the effect of the magnetic field direction on temperature distribution, Lorentz force, and induced electric field.

According to the above-mentioned works [1–27], it was found that some of these studies reported the effect of magnetic field on the Lorentz force and on heat transfer. Several other works demonstrated electric field distribution in the enclosure by solving electric potential equations. Scant attention has been given to induced electric field and how it affects the amount of heat transfer in a vertical cylindrical annulus in the presence of a horizontal magnetic field. The aim of the present work is to examine the effect of induced electric field on the natural convection in a vertical cylindrical annulus filled with liquid potassium ($Pr = 0.072$). Such a study helps in understanding the electric field induced by the motion of electrically conducting fluid exposed to a magnetic field, which has some relevance in material processes.

2. Mathematical formulation

2.1. Problem statement

In this work, laminar steady natural convection in a 3D vertical cylindrical annulus filled with liquid potassium ($Pr = 0.072$) is studied. The annulus formed by two coaxial cylinders is displayed in Fig. 1. In this figure, r_i and r_o are the radii of the inner and outer cylinders, respectively, and L is the length of the annulus. The cylindrical walls are isothermal, and the other walls are assumed to be adiabatic. B is the horizontally applied uniform magnetic field while the induced magnetic field is assumed negligible.

2.2. Governing equations

The governing equations of steady laminar natural convection flow of an incompressible electrically conducting fluid by using Boussinesq approximation after neglecting viscous and ohmic dissipations in the 3D cylindrical coordinate are defined below:

Continuity equation:

$$\nabla.\mathbf{v} = 0 \tag{1}$$

Momentum equation:

$$\rho(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla p + \mu\nabla^2\mathbf{v} + \rho\mathbf{g} + \mathbf{F} \tag{2}$$