International Journal of Thermal Sciences 118 (2017) 12–23

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Using a magnetic field to reduce natural convection in a vertical cylindrical annulus

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ARTICLE INFO

Article history:
Received 3 April 2016
Received in revised form
10 April 2017
Accepted 11 April 2017

Keywords:
Vertical cylindrical annulus
Nusselt number
Hartman number
Prandtl number
Induced electric field
Numerical simulation

ABSTRACT

This paper presents the investigation of laminar natural convection in 3D vertical cylindrical annulus containing electrically conductive fluids under a horizontal magnetic field. The model was composed of two isothermal coaxial cylinders. Both ends of the cylinders were supposed adiabatic and all walls were assumed electrically insulated. Complex nonlinear governing equations were solved numerically by means of the finite volume method. The effects of different parameters such as the strength of the magnetic field, the radii ratio, aspect ratio, and Prandtl number on the temperature distribution, average Nusselt number, distribution of Lorentz forces as well as induced electric field were investigated. Results showed that for aspect ratios lower than about 1, the average Nusselt number increased as aspect ratio was increased. When aspect ratio was greater than about 1, the average Nusselt number decreases as aspect ratio was enlarged. Moreover, results showed that the average Nusselt number increased as radii ratio was increased. Results also revealed that a stronger magnetic field was needed to achieve pure conduction in the case of thick annulus. The presence of magnetic field induced an electric field which affected the Lorentz force. Distributions of Lorentz force and induced electric field indicated respectively the formation of Hartmann and Roberts layers. Furthermore, the average Nusselt number increased with increasing Prandtl number at all Hartmann numbers. It was also found that with increasing Hartmann number, the effect of Prandtl number on the average Nusselt number decreased.

1. Introduction

Nowadays, magnetic fields are widely used in most important industries. In cooling or heating applications, increasing the heat transfer is considered by the magnetic field. For this purpose, researchers have also introduced magnetic nanofluids [1–7]. In some heat transfer applications, magnetic fields are for nuclear reactor cooling systems, pumping, stirring, and levitation of magnetic materials [8–11]. Magnetic fields also could be employed to attenuate the fluid flows caused by natural convection [12–14].

During crystal growth processes, the temperature gradient in the melt, which is due to the temperature difference between the solid wall of the container and the melt, causes Buoyancy forces in the melt. In most practical cases, the random and irregular motions caused by this effect lead to microscopic inhomogeneity of the manufactured materials. Hence, in such applications, reduction of convection heat transfer is of great interest. As mentioned above, the use of magnetic fields is an effective method to reduce this type of heat transfer in electrically conducting fluids. Since the interactions between the magnetic field and the fluid flow cause Lorentz forces, which always oppose the direction of fluid motion. Nonetheless, the magnetic fields can also cause electric potential, which counteracts the Lorentz forces. Hence, the induced electric potential can negatively affect the desired objectives of the magnetic field [15,16].

Since magnetic control of fluid flows in annulus can be used in different applications, the convection heat transfer in fluids subject to magnetic fields has been intensely studied. For instance, Mozayyenin and Rahimi [17] numerically investigated the mixed convection heat transfer in cylindrical annulus of constant wall temperature subject to a radial magnetic field. Different combination of dimensionless numbers including Reynolds number, Hartmann number, Rayleigh number, Eckert number, and the ratio of the annulus gap width was considered in their study. Their numerical results indicated that the fluid flow and heat transfer were significantly suppressed by applying the magnetic field. Teimouri et al. [18] numerically studied free convection in a long horizontal

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.04.012
1290-0729/

Nomenclature

A	aspect ratio
B	magnitude of the external magnetic field (kg/s^2A)
D	annulus gap $(D = r_o - r_i(m))$
E	dimensional induced electric field (mkg/s^3A)
E^*	dimensionless induced electric field
F	Lorentz force (N/m^3)
F^*	dimensionless Lorentz force
g	acceleration due to gravity (m/s^2)
H	height of the annulus
Ha	Hartmann number
J	electric current density (A/m^2)
n	normal vector (m)
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^2kg/s^3A)
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^3A^2/m^3kg)

Subscripts

c	condition at cold wall
h	condition at hot wall
i	inner cylinder
o	outer cylinder

cylindrical annulus filled with molten potassium exposed to a radial magnetic field. Their results revealed that with increasing radii ratio, the influence of magnetic field on free convection decreased. Sankar et al. [19] studied the effect of magnetic field on natural convection between two vertical concentric cylinders. Their study was performed on electrically conducting fluid with Prandtl numbers of 0.054 subject to axial and radial magnetic fields of constant strength. The temperatures of the inner and outer cylinders were kept constant. They used numerical approaches and demonstrated the effect of Rayleigh and Hartmann numbers on the isotherms and streamlines. Their results also indicated that in shallow annuluses the natural convection was repressed more effectively by an axial magnetic field, while in tall annuluses a radial magnetic field is more impressive. Wrobel et al. [20] conducted experimental and numerical studies on the fluid flow and heat transfer of a paramagnetic fluid between two vertical cylinders subject to a magnetic field. They concluded that the effect of Hartmann number on heat transfer was four times stronger than that of the Rayleigh number. Kabier et al. [21] analytically studied the heat and mass transfer in an impenetrable horizontal cylinder containing a non-Newtonian fluid in a porous media. The studied cavity was subject to a horizontal magnetic field. Many assumptions were made in their work, and the effect of different parameters including the strength of the magnetic field was investigated. Venkatachalappa et al. [22] studied the effect of radial and axial magnetic field on convection heat transfer and mass transfer in a hollow vertical cylinder using numerical methods. They demonstrated the effect of Hartmann number on isotherms as well as streamlines when subjected to radial or axial magnetic fields. Kumar and Singh [23] investigated the effect of radial magnetic field on laminar natural convective a viscous electrically conducting fluid between two concentric vertical cylinders. They observed that the fluid velocity and induced magnetic field were reduced with augmenting Hartmann number. Their results showed that this decreasing was more when one of the cylinders is conducting compared to when both cylinders are non-conducting. Kakarantzas et al. [15] studied the unsteady state effect of a constant horizontal magnetic field on a specific vertical annulus (with specific dimensions), and demonstrated the effect of magnetic field on isotherms and velocity. Numerical methods were used in their studies, and the Prandtl Number of the modeled fluid was 0.0321. According to their results, applying a magnetic field causes an electrical field, eliminating symmetry in the tangential direction. Afrand et al. [24] numerically investigated natural convection of electrically conducting fluid in an inclined cylindrical annulus under various magnetic fields. Their results revealed that the effect of transverse magnetic field on the average Nusselt number is more effective than that of the axial magnetic field. Further, Afrand et al. [25] performed 3D numerical simulation of natural convection of molten potassium in an inclined cylindrical annulus exposed to a magnetic field. They reported that a magnetic field can control the natural convection of molten potassium. Their results also revealed that the direction and strength of the magnetic field could have different effects on the suppression of natural convection. They also observed that increasing the strength of the magnetic field caused the loss symmetry.

According to the literature review, most studies have been conducted to examine the conditions that the induced electric potential caused by the magnetic field was not created or considered. Moreover, the effect of different parameters on various aspects of heat transfer and fluid flow in a vertical annulus under magnetic field were investigated, while their effects on the distribution of Lorentz forces and the induced electric potential were not considered. Hence, in the present study, the effect of different parameters such as the strength of the magnetic field, the radii ratio, length of annulus, and Prandtl number on the temperature distribution, distribution of Lorentz forces as well as induced electric field is investigated.

2. Mathematical formulation

In the present study, laminar natural convection heat transfer in 3-dimensional vertical cylindrical annuluses containing an electrically conductive fluid is investigated. The studied annulus are composed of cylinders with inner and outer radii as well as height of r_i, r_o, and H, respectively, as illustrated in Fig. 1. Since numerous