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EFFECT OF INDUCED MAGNETIC FIELD ON MHD FLOW BETWEEN TWO PARALLEL POROUS PLATES AT CONSTANT TEMPERATURE GRADIENT IN PRESENCE OF INCLINED MAGNETIC FIELD

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The paper studies effect of induced magnetic field on laminar convection flow of a viscous electrically conducting incompressible fluid between two parallel porous plates at constant temperature gradient in presence of a uniform inclined magnetic field. An angle (θ) is formed with the vertical line by applying a magnetic field in that direction and field is strong enough to induce another field along the line of flow. Using the proper similarity transformations, the flow equations are converted into ordinary differential equations, which are then numerically solved by using MATLAB's bvp4c solver. Plotting of the graphs allows one to examine the effects of several critical parameters such as Hartmann number, Darcy number, Magnetic Reynolds number, Prandtl number, and Field inclination on velocity field, induced magnetic field, temperature field at the plates. The acquired results demonstrate that the flow system is effectively influenced by the field inclination, the magnetic parameter, and the plate porosity. The rise in field inclination leads to an increase in magnetic drag force.
Keywords: *Induced magnetic field; Free convection; Porous plate; MHD; Temperature gradient*
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INTRODUCTION

Since last two decades, many researchers have studied on the Magnetohydrodynamics viscous incompressible flow in the presence of an external magnetic field (magnetohydrodynamic flow) and receiving great attention because of its large number of applications such as in the field of industry, technology, energy generation, geophysics and geo-thermal activities, astrophysics, nuclear science, combustion modelling, plasma studies, oil exploration and many others. For example, nowadays MHD generators are widely used for power generation, MHD pumps are used in chemical energy technology for pumping electrically conducting fluids at atomic energy entre, pinching hot plasma, purification of crude oil, in the case of manufacturing of glass, use of MHD flow meter in measuring the speed of a ship etc. Such kind of flow are normally designed under the supposition of unchanged temperature and constant heat flow rate intensity in presence of externally applied magnetic field. However, the flow is always influenced by the imposed magnetic field by means of its induced magnetic field. The field induces electromotive magnetic force that in turn effects the velocity field and ultimately controls the flow. Further, direction of applied magnetic field is always important, because in comparison to a magnetic field that applied along the flow, a transversed magnetic field acts differently, it generates more drag force and thereby dissipates much energy. The magnetic drag force acts upon the suspended particles and rearrange them according to their concentration depending upon the strengths of the field. This also strongly changes the pattern of heat transfer and energy density within the flow system. Thus, the behaviour of flow system highly depends upon the strength of the applied magnetic field and its inclination with respect to the direction of flow. This is why the consideration of effect of induced magnetic field and its inclination are highly important both in terms of theoretical and experimental point of view. In MHD flow, energy balance is considered by the internal energy due to conduction and convection of heat with the stream, generation and dissipation of heat due to viscous friction and porosity friction, and energy dissipation due to effect of induced magnetic field. Although the effect of heat radiation is always there, but its contribution is much smaller and negligible within the moderate range of temperature.

There has been a significant undivided attention in research activities in MHD free convection flow within vertical parallel plates. As far our knowledge goes, the most relevant problem of magnetohydrodynamic flow in the presence of applied transverse magnetic field between two parallel plates was first discussed by Hartmann [1]. Later on, by Schercliff [2], Soundalgekar [3], Raptis and Singh [4]. Between two vertical plates, laminar convection flow through a porous media was examined by Soundalgekar and Bhatt [5]. In their discussion of laminar convection flow between two vertical porous plates in the presence of uniform magnetic field under varying medium permeabilities, Das and Sanyal [6] addressed conducting incompressible fluid flow behaviour. A vertical channel with constant temperature and constant heat flux on the walls was studied by Paul et al. [7] for transient free convective flow. Chakraborty and Borkakati [8] had studied unstable free convection MHD flow.

Pop et al. [9] have discussed the laminar boundary layer flow due to a continuously moving flat plate. Unsteady magnetohydrodynamic free convective flow and heat transfer along a vertical porous plate with variable suction and internal heat generation was studied by Sharma and Singh [10]. Palani and Srikanth [11] also studied the hydrodynamic

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flow past a semi-infinite vertical with mass transfer. A numerical analysis of the hydromagnetic free convective flow in the presence of induced magnetic field has been studied by Singh et al., [12]. Jha and Sani [13] have investigated the symmetric heating caused by induced magnetohydrodynamic natural convection flow of an electrically conducting and viscous incompressible fluid in a vertical channel. Kumer and Singh [14] have discussed the unsteady magnetohydrodynamic free convective flow past a semi-infinite vertical wall by taking into account the induced magnetic field. Sarveshanand and A.K. Singh [15] studied the MHD free convection between vertical parallel porous plates in the presence of induced magnetic field. Hamza [16] studied the free convection slip flow of an exothermic fluid in a convectively heated vertical channel. Recently, Goswami et al. [17] have studied unsteady MHD free convection flow between two heated vertical parallel plates in the presence of a uniform magnetic field. Induced magnetic field effect on MHD free convection flow in nonconducting and conducting vertical microchannel walls has been investigated by Goud [18]. In a vertical annular micro-channel with a radial magnetic field, B.K. Jha and Babatunde Aina investigate the effect of an induced magnetic field on magnetohydrodynamic (MHD) natural convection flow. A discussion of Jumanne Mng'ang'a [20] is found in Effect of chemical reaction and joule heating on MHD generalized couette flow between two parallel vertical porous plates with induced magnetic field and Newtonian heating/cooling.

In this paper, we have studied the laminar convection flow of a viscous electrically conducting incompressible fluid between two parallel plates in presence of a uniform inclined magnetic field at constant temperature gradient. Magnetic field is applied in the direction making an angle θ to the vertical line and field is strong enough to induce another field along the line of flow. In almost all the previous such kind of studies, the inclination of the applied magnetic field and heat dissipation due to porosity of the medium are ignored, so we have considered those along with the effect of induced magnetic field. The aim of this paper is to make computational study and analysis of velocity field, induced magnetic field, temperature field at the plates for different values of non-dimensional physical quantities such as Hartmann Number, Darcy number, Magnetic Reynolds number, Prandtl number and the field inclination $\lambda(=\cos\theta)$. The problem has its significant in numerous applications, including the extrusion of polymers in the production of nylon and rayon, the pulp and textile industries, in power technology, in petroleum industry on purification of crude oil, solid fuel rocket nozzles used in guided missile system, flow of polymer solutions in industry, construction of wet-bulb thermometer, and in many other engineering and industrial fields. When such a conducting fluid flows in presence of a magnetic field, the flow is influenced not only by the applied magnetic field but also the induced magnetic field. There are interactions among the conducting fluid particles with the magnetic flux that in turn modifies the flow pattern, flow properties, and the heat transfer. It is also possible to control effectively the flow by adjusting the magnitude and direction of the applied magnetic field applied. Understanding the dynamics of such kind of flow, may be a help in controlling technology involving MHD flow and devices, such as MHD power generator, thermonuclear power devices including industrial, geophysical, astronomical, and in variety of geophysical and geothermal settings.

MATHEMATICAL ANALYSIS

In the horizontal direction, we have studied a laminar convection flow of an electrically conducting viscous incompressible fluid between two porous parallel plates (Fig. 1); the X-axis is taken horizontally along the fluid motion, and the Y-axis is perpendicular to it. Allowing a uniform magnetic field B_0 to be applied in a direction that forms an angle with the vertical line, this will cause B to induce another magnetic field along the fluid's motion.

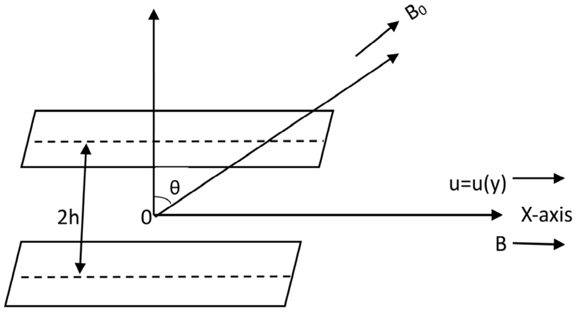

Figure 1. Physical Model of the Problem.

The distance between the plates is '2h'. The plates are maintained at constant temperature gradient (Γ /h). We considered the plate temperature T_w as $T_w = T_0 + (\Gamma/h)\,x$, where, T_0 is the temperature at the origin. The fluid temperature is assumed to be vary along vertical direction while temperature gradient is supposed to be constant along horizontal direction. Let u be the fluid velocity along X-axis, therefore the fluid velocity, magnetic field and induced magnetic field are $\{u(y), v_0, 0\}$, $\{B_0(\sqrt{1-\lambda^2}), B_0(\lambda), 0\}$ and $\{B(y), 0, 0\}$ respectively.

The investigation is carried out on the following basic assumptions,

- Hall effects and polarization effects are neglected.
- The fluid moves with the uniform velocity so that all the physical variables are assumed to be time independent.

The governing equations representing flow are as follows:

$$\frac{\partial u}{\partial x} = 0, \tag{1}$$

$$\vartheta\left(\frac{\partial^2 u}{\partial y^2}\right) - v_0\left(\frac{\partial u}{\partial y}\right) + \left(\frac{B_0\lambda}{\rho\mu_e}\right)\left(\frac{\partial B}{\partial y}\right) - k_0 - \frac{\vartheta}{k_1}u = 0, \tag{2}$$

$$\vartheta_m\left(\frac{\partial^2 B}{\partial y^2}\right) - v_0\left(\frac{\partial B}{\partial y}\right) + B_0\lambda\left(\frac{\partial u}{\partial y}\right) = 0, \tag{3}$$

$$\rho C_p\left(u\frac{\partial T}{\partial x} + v_0\frac{\partial T}{\partial y}\right) = k\frac{\partial^2 T}{\partial y^2} + \rho\vartheta\left(\frac{\partial u}{\partial y}\right)^2 + \left[\frac{1}{\sigma{\mu_e}^2}\left(\frac{\partial B}{\partial y}\right)^2\right] + \frac{\mu}{k_1}u^2 = 0. \tag{4}$$

Where k_0 is constant.

The boundary conditions associated with physics of the problem are

$$u=0, \quad B=0, \quad T=T_w \quad \text{at } y = \pm h. \tag{5}$$

Equations (2)-(4) can be converted to a system of non-linear ordinary differential equations via the similarity variables,

$$x^* = \frac{x}{h}, y^* = \frac{y}{h}, u^* = \frac{uh}{\alpha}, \phi = \left(\frac{T_w - T}{\Gamma}\right), B^* = \left(\frac{B}{B_0}\right). \tag{6}$$

After removing asterisks, the transformed equations are

$$\frac{\partial^2 u}{\partial y^2} - Re\frac{\partial u}{\partial y} + \frac{M^2\lambda}{R_m}\frac{\partial B}{\partial y} - k_0 - \frac{1}{Da}u = 0, \tag{7}$$

$$\frac{\partial^2 B}{\partial y^2} - Re\frac{\partial B}{\partial y} + \lambda R_m\frac{\partial u}{\partial y} = 0, \tag{8}$$

$$\frac{\partial^2 \phi}{\partial y^2} - Pr[Re\frac{\partial \phi}{\partial y} + E\{\left(\frac{\partial u}{\partial y}\right)^2 + \frac{M^2}{{R_m}^2}\left(\frac{\partial B}{\partial y}\right)^2 + \frac{1}{Da}u^2\}] - Ku = 0. \tag{9}$$

It is notable that the continuity equation (1) is identically satisfied i.e. the proposed velocity is suitable with the continuity equation.

The boundary conditions (5) in terms of the similarity variables (6) becomes

$$u=0, \quad B=0, \quad \phi=0 \quad \text{at} \quad y = \pm 1. \tag{10}$$

SOLUTIONS OF THE EQUATIONS

In this paper, solutions of the nonlinear coupled equations (7)-(9) subject to the boundary conditions (10) are solved by using "MATLAB built-in bvp4c solver technique" for different values of physical parameters. Therefore, we have transformed the ordinary differential equations into a set of first order differential equations as given below:

Let,

$$u = y(1),\ u' = y(2),\ B = y(3),\ B' = y(4),\ \phi = y(5),\ \phi' = y(6). \tag{11}$$

The transformed first order differential equations are

$$y'(2) = Re * y(2) - \frac{M^2\lambda}{R_m} * y(4) + k_0 + \frac{1}{Da} * y(1), \tag{12}$$

$$y'(4) = Re * y(4) - \lambda * R_m * y(2), \tag{13}$$

$$y'(6) = \text{Pr}\ [Re * y(6) + E\{y(2)^2 + \frac{M^2}{{R_m}^2} * y(4)^2 + \frac{1}{Da}y(1)^2 + K * y(1). \tag{14}$$

The transformed boundary conditions are:

$$y0(1) - 0,\ y0(3) - 0,\ y0(5) - 0,\ y1(1) - 0,\ y1(3) - 0,\ y1(5) - 0. \tag{15}$$

RESULTS AND DISCUSSIONS

In order to get the physical insight of the problem, the non-dimensional physical quantities representing velocity field (u), induced magnetic field (B) and temperature field (ϕ) are computed for different values of the other parameters such as Hartmann Number (M), Magnetic Reynolds Number (R_m), Darcy Number (Da), Prandtl Number (Pr), and inclination of the field λ(=cos θ). The effect of these different parameters is shown and analysed graphically in the Figures (2-13).

Velocity Profiles

Figures 2–5 present the variation of the u with λ, Da, M and R_m respectively. The nature of variation within the channel from lower to upper plate are in almost parabolic shape. Figure 2 elucidates the effect inclination of the applied field λ on u; at a point within the channel, with the rise λ (from 0.1 to 1.0) i.e. as the field inclined more and more towards vertical, u increases gradually. This is because of decrease of magnetic drag force acting on the flow as the field shifted towards vertical from horizontal. Figure 3 show that the variation of u for different values of Da where with the increase of Da, fluid velocity (u) decreases within the channel. Figure 4 shows velocity distribution with respect to M; with the increase of M maintaining R_m fixed (≅1.0), u increases. Figure 5 shows the effect of R_m on fluid velocity u; with increase of with R_m, fluid velocity decreases significantly. This is due to the force, called Lorentz force, which causes reduction in the fluid velocity.

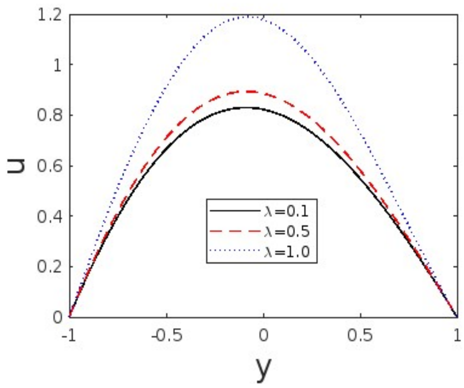

Figure 2. Variation of u with λ
for Re=1.5; M=3.5; R_m=1.0; Da=1.0

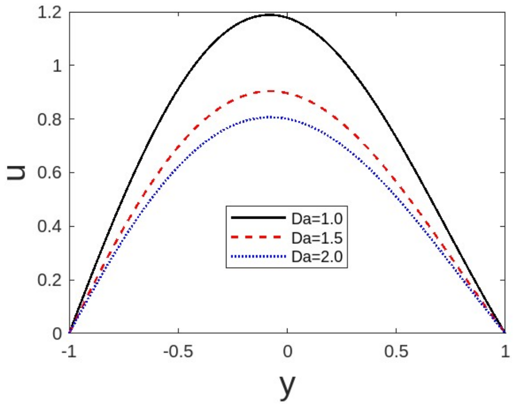

Figure 3. Variation of u with Da
for Re=1.5; M=3.5; R_m=1; λ=1

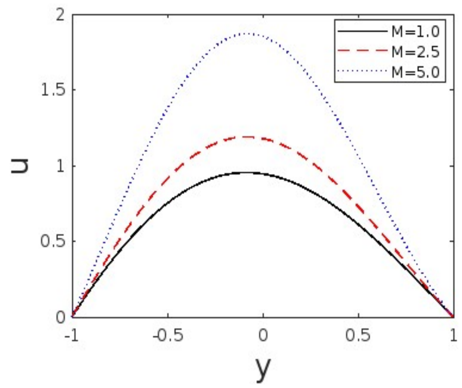

Figure 4. Variation of u with M
for; Re=1.5; R_m=1.0; Da=1.0

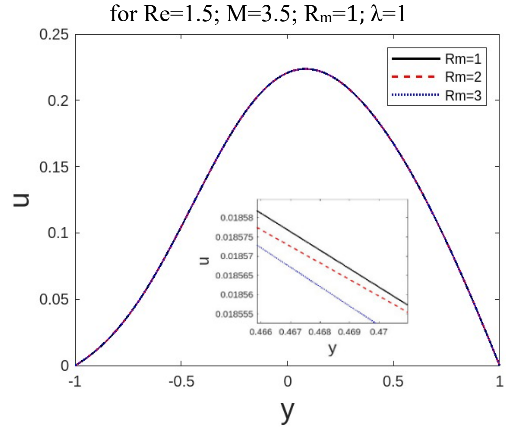

Figure 5. Variation of u with R_m
for Re=1.5; M=3.5; Da=1.0; λ=1.0

Induced Magnetic field profiles

Figure 7 presents distribution of induced magnetic field (B) within the channel for different values of λ; Within the channel, from lower to upper plate, the variation of B seems to be sinusoidal where the magnitude of B increases as it inclined more and more towards vertical i.e. field inclination has an effect on generation of induced magnetic field. Figure 8 presents distribution of B within the channel for different values of R_m; with the increase of R_m the magnitude of B also increases within the channel.

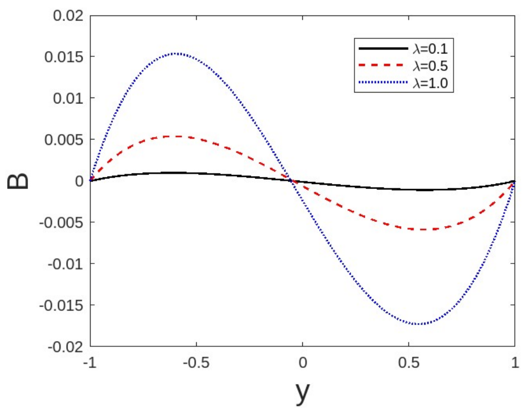

Figure 7. Variation of B with λ
for Re=1.5; M=3.5; R_m=1.0

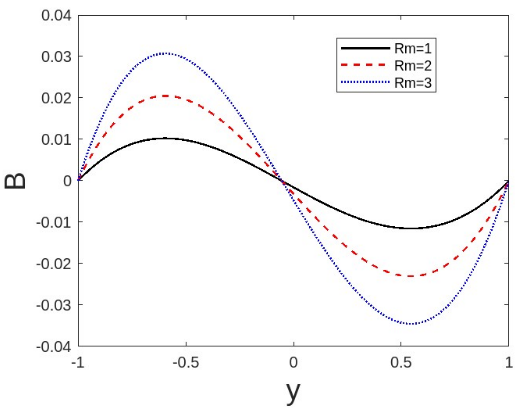

Figure 8. Variation of B with R_m
for Re=1.5; λ=1.0; M=3.5

Temperature profiles

Figure 9-13 each of them illustrates the variation of temperature profile (ϕ) with Da, M, R_m, K and Pr respectively, which are also seen to be almost parabolic shape within the channel form lower to upper plate. Figure 9 elucidates the temperature profile (ϕ) within the channel for various values of Da, ϕ increases with the rise of Da. There is an increase in the temperature profile across the wall as the Darcy number increases. This is because of the increased permeability of the material; the convective mode becomes stronger as the Darcy number rises. The rate of variation of fluid temperature (ϕ) is more in upper half than the lower one within the channel. Figure 10 depicts the temperature profile with M, it is seen that, an increases of Hartman M leads to a decrease in the temperature profile. Figure 11 shows the variation of temperature with Rm. It is observed that with rises of Rm, fluid temperature (ϕ) increases. Figure 12 shows the variation of temperature profiles (ϕ) within the channel for various values of K; (ϕ) increases with the rise of K. The rate of variation of fluid temperature (ϕ) is more in upper half than the lower one within the channel. Figure 13 shows that the impact of Pr on temperature profile (ϕ); fluid temperature decreases with the increase of Pr.

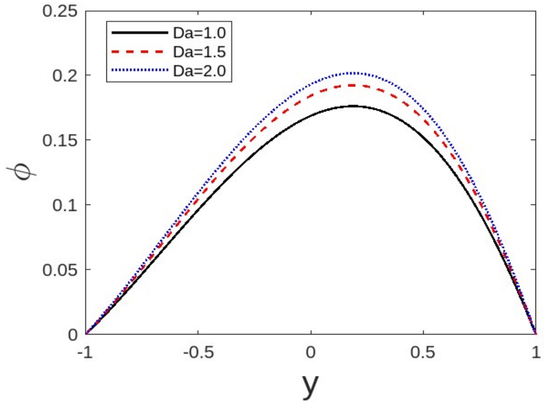

Figure 9. Variation of ϕ with Da for M=1.5; K=1.5; Pr=0.71; R_m=1.0

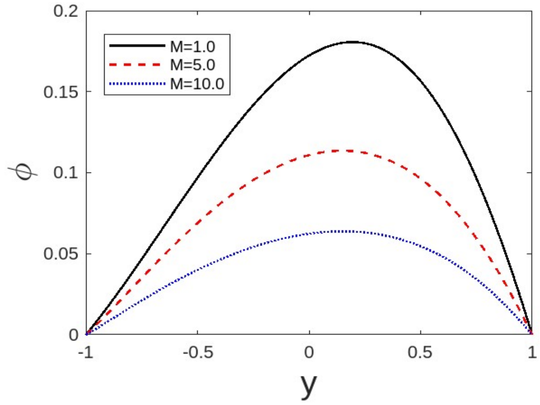

Figure 10. Variation of ϕ with M for Pr=0.71; Da=1.0; R_m=1; K=1.5

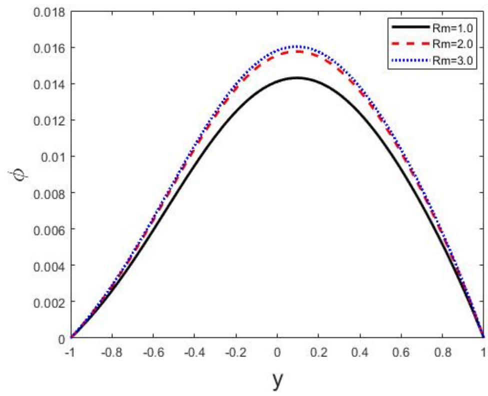

Figure 11. Variation of ϕ with R_m for Pr=0.71; Da=1; M=3.5; K=1.5

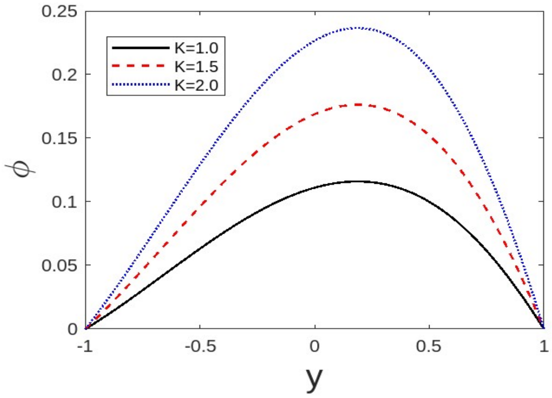

Figure 12. Variation of ϕ with K for Pr=0.71; Da=1.0; R_m=1.0; M=1.5

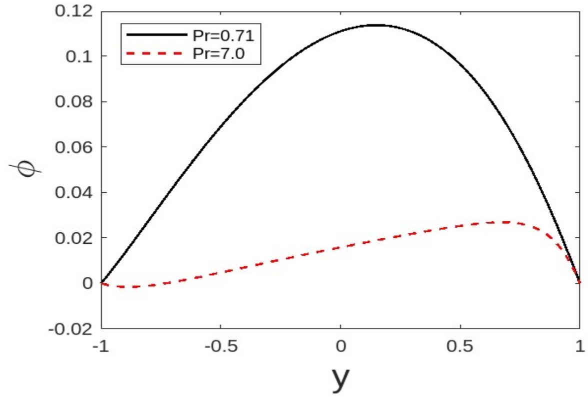

Figure 13. Variation of ϕ with Pr for Da=1.0; R_m=1.0; K=1.5; M=1.5

CONCLUSIONS

We have studied the effect of magnetic field inclination under the action of induced magnetic field on laminar convection flow of a viscous electrically conducting incompressible fluid between two parallel porous plates at constant temperature gradient. From above results and discussion, it can be concluded that fluid velocity increases with rise of field inclination of the applied magnetic field from horizontal to vertical. Induced magnetic field and permeability of the medium have influence on fluid velocity, fluid temperature as well. Fluid velocity decreases with the increase of the Darcy number and magnetic Reynold number. In the present physical setup of the problem, within the channel the induced field varies sinusoidally from lower to upper plate; magnitude of which increases with the rise of field inclination from horizontal to vertical. Medium permeability and induced magnetic field affects the fluid temperature significantly. Fluid temperature increases with the increase of the medium Permeability, Magnetic Reynolds number and the temperature gradient but decreases with the rise of Hartmann number and Prandtl number. Such kind of hydrodynamic behaviour often occurs in a fluid motion where a conducting fluid flows in presence of magnetic field that induces another field where working velocity, temperature and other flow parameters may be manageable by adjusting the magnitude and direction of the applied magnetic field. The results have relevance in the applications advent of technology that involves MHD flow system and devices such as MHD power generator, thermonuclear power devices, in petroleum industry, on purification of crude oil, solid fuel rocket nozzles used in guided missile system, flow of polymer solutions in industry (in case of extrusion of polymers in the production of nylon and rayon), construction of wet-bulb thermometer, and in many such fluid flow relating to engineering and industrial fields.

Nomenclature

$\vartheta = \frac{\mu}{\rho}$, Kinematic viscosity;

$Re = (\frac{v_0 h}{\vartheta})$, Reynolds number;

$Pr = (\frac{\vartheta}{\alpha})$, Prandtl number,

$E = \frac{\alpha^2}{\Gamma c_p h^2}$, Eckert number;

$Da = \frac{k_1}{h^2}$, Darcy number;

$\frac{\partial \phi}{\partial x} = K$, Temperature gradient.

$M = B_0 h \sqrt{\frac{\sigma}{\rho \vartheta}}$, Magnetic parameter

$R_m = (\alpha \mu_e \sigma)$, Magnetic Reynolds number;

$\vartheta_m = \frac{1}{(\sigma \mu_e)}$, Magnetic diffusivity.

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ВПЛИВ ІНДУКОВАНОГО МАГНІТНОГО ПОЛЯ НА МГД ПОТІК МІЖ ДВОМА ПАРАЛЕЛЬНИМИ ПОРИСТИМИ ПЛАСТИНАМИ ПРИ НАЯВНОСТІ ПОСТІЙНОГО ГРАДІЄНТА ТЕМПЕРАТУРИ НАХИЛЕНОГО МАГНІТНОГО ПОЛЯ

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Досліджено вплив індукованого магнітного поля на ламінарну конвекцію в'язкої електропровідної нестисливої рідини між двома паралельними пористими пластинами при постійному градієнті температури за наявності однорідного похилого магнітного поля. Кут (θ) утворюється з вертикальною лінією шляхом застосування магнітного поля в цьому напрямку, і поле є достатньо сильним, щоб індукувати інше поле вздовж лінії потоку. За допомогою належних перетворень подібності рівняння потоку перетворюються на звичайні диференціальні рівняння, які потім чисельно розв'язуються за допомогою розв'язувача bvp4c MATLAB. Побудова графіків дозволяє досліджувати вплив кількох критичних параметрів, таких як число Гартмана, число Дарсі, магнітне число Рейнольдса, число Прандтля та нахил поля на поле швидкості, індуковане магнітне поле, температурне поле на пластинах. Отримані результати демонструють, що на систему течії ефективно впливають нахил поля, індуковане магнітне поле та пористість пластини. Підвищення нахилу поля призводить до збільшення сили магнітного опору.
Ключові слова: *індуковане магнітне поле; вільна конвекція; плита пористого типу; МГД; температурний градієнт*