[Volume 4 issue 03 March 2016]
PageNo.1283-1295 ISSN : 2320-7167

INTERNATIONAL JOURNAL OF MATHEMATICS AND COMPUTER RESEARCH

The Hall Effects in the Viscous Flow of an Ionized Gas through an Inclined Porous Layer

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ABSTRACT

The paper considers the viscous flow of an ionized gas through a porous medium between two parallel plates separated by height 2h in an inclined channel with angle of inclination θ. Analytical expressions for primary and secondary velocities have been obtained. The influence of various physical parameters like Hartmann number M, Hall parameter m, viscosity ratio parameter φ_1 and Darcy number Da on the flow field have been discussed. It is found that the primary and the secondary velocities decrease with an increase in Hartmann number M in both partially and fully ionized cases. It is also found that both the primary and the secondary velocities increase in both partially and fully ionized cases with an increase in the Hall parameter m, viscosity ratio parameter φ_1 and Darcy number Da.

Key words: MHD, Ionized Gas, Porous Medium, Permeability, Hall current.

1. INTRODUCTION

The flow of fluids through porous media is encountered in a wide range of engineering and industrial applications in recovery or extraction of crude oil, geothermal systems, thermal insulation, heat exchangers, storage of nuclear wastes, packed bed catalytic reactors, atmospheric and oceanic circulations and in hydrological problems. In biomechanics, the blood vessel is often modeled as a circular tube lined with porous material, where the finite circular porous layer represents the tissue region surrounding the blood. Channabasappa, Umapathy and Nayak [1] proposed a theoretical model for the study of flow and heat transfer in a parallel plate channel, one of whose walls is lined with non-erodible porous material.

The study of flow of electrically conducting fluid in the presence of magnetic field, the so-called Magnetohydrodynamics (MHD) has a lot of attention due to its diverse applications. In astrophysics and geophysics, it is applied to the study of stellar and solar structures, interstellar matter and radio propagation through the ionosphere. In engineering, it finds its application in MHD pumps, MHD bearings, nuclear reactors, MHD generators and MHD flow meters etc. MHD also has important applications in biomedical engineering including cardiac, MRI and ECG. More recently, many researchers have focused attention on MHD applications where the operating temperatures are high.

Dileep Singh Chauhanand and Priyanka Rastogi [2] studied unsteady MHD flow of viscous incompressible and electrically conducting fluid and heat transfer through a porous medium adjacent to an accelerated horizontal plate in a rotating system. Israel-Cookey *et al*. [3] investigated on steady hydromagnetic flow of a radiating viscous fluid through a horizontal channel in a porous medium. Makinde and Mhone [4] investigated the effect of thermal radiation on MHD oscillatory flow in a channel filled with saturated porous medium and non-uniform wall temperatures.

Ionized gas is plasma which is the fourth state of matter. It starts as a gas and then becomes ionized. It is a gas consisting of charged ions and electrons. Ionizing is the process by which an electrically neutral atom, molecule or radical loses or gains one or more electrons and becomes an ion. Ionization can occur in gases, liquids or solids. The degree of ionization refers to the proportion of neutral particles, such as those in a gas or aqueous solution that are ionized into charged particles.

Ahdanov [5] and Soo [6] studied transport phenomena in a partially Ionized gases. The effects of hall currents in the viscous flow of an ionized gas between two parallel walls, under the action of a uniform transverse magnetic field are first studied by Sato [7]. Following this analysis, Raju and Rao [8] have studied the Hall effects on temperature distribution in a rotating ionized hydromagnetic flow between parallel walls.

Abdul Maleque and Abdul Sattar [9] studied the effects of variable properties and Hall current on steady MHD laminar convective fluid flow due to a porous rotating disk. Ghosh *et al*. [10] investigated Hall effects on heat transfer and MHD flow in a rotating channel. Sharma *et al*. [11] studied the Hall Effect on MHD mixed convective flow of a viscous incompressible fluid past a vertical porous plate immersed in porous medium with heat source/sink whereas Linga Raju and Murthy [12] studied MHD heat transfer aspects between two parallel conducting porous walls in a rotating system with Hall currents. Singh et al. [13] have studied hydromagnetic oscillatory flow of a viscous liquid past a vertical porous plate in a rotating system. Yaminishi [14] have discussed the Hall effects on the steady hydromagnetic flow between two parallel plates.

Many experiments are performed in laboratory using an inclined channel since this geometry is very close to practical situations encountered in industry or environment. In hydraulics, a large amount of literature is devoted to the computation of flows in inclined channels (Chow [15]). Yih [16] has studied the stability of liquid flowing down an inclined plane. Lin [17] has studied the instability of a liquid film flowing down an inclined plane.

In view of these facts, it is interesting to study the effects of Hall current on flow of ionized gas through an inclined porous layer bounded by two parallel plates. The aim of the present paper is to study the combined effects of Hartmann number *M*, Hall parameter *m* and Darcy number Da on the steady MHD flow of an ionized gas in the porous channel.The results are discussed through graphs.

Nomenclature

u, w	Velocity components along x and z- directions.
$\bar{q}$	Velocity vector
$\vec{B}$	The magnetic flux density.
$\vec{E}$	The electric field.
$\bar{J}$	The current density.
p	Pressure.
E_x, E_z	Electric fields along x and z-directions.
$s = \frac{p_e}{p}$	Ionization parameter (the ratio of the electron pressure to the total pressure)
σ_0	The coefficient of proportionality between the current density J and collision term in the equation of motion of charged particles.
σ_1, σ_2	The modified conductivities parallel and normal to the direction of electric field.
$u_p = -\left(\frac{\partial p}{\partial x}\right).\frac{h^2}{\rho \upsilon}$	Characteristic velocity.

$m = \dfrac{w_e}{\left(\dfrac{1}{\tau_e} + \dfrac{1}{\tau}\right)}$	Hall parameter.
w_e	The gyration frequency of electron.
τ , τ_e	The mean collision time between electron, ion and electron, neutral particles respectively.
$M = \sqrt{\dfrac{B_0^2 h^2 \sigma_0}{\rho \upsilon}}$	Hartmann Number.
μ	Coefficient of viscosity ($\mu = \rho\nu$)
$\overline{\mu}$	Effective viscosity of the fluid in porous medium
ρ	Density of the fluid.
ν	Kinematic Viscosity
k	Permeability of the medium.
$\varphi_1 = \dfrac{\overline{\mu}}{\mu}$	Viscosity ratio.
$N = \dfrac{Fr}{\mathrm{Re}} = \dfrac{gh^2}{u_p \upsilon}$	Non dimensional parameter.

2. MATHEMATICAL FORMULATION OF THE PROBLEM

The viscous flow of ionized gas through a porous medium between two parallel plates is considered. The channel is inclined at an angle θ with the horizontal. The permeability of the porous medium is taken as k. The width of the channel is denoted by 2h. Fig. 1 shows the coordinate system.

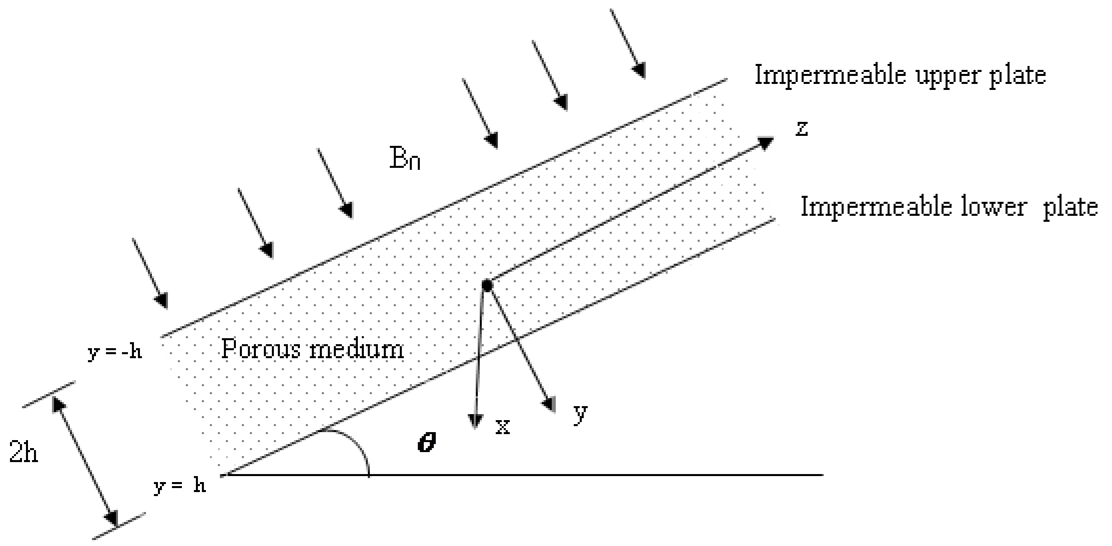


Fig. 1 Physical model

The x-axis is taken in the direction of hydrodynamic pressure gradient in the plane parallel to the channel walls, but not in the direction of flow. The fluid flow is along y-direction. A parallel uniform magnetic field B_0 is applied in the y-direction and the Hall currents are taken into account while, the fluid is driven by a constant pressure gradient $-\dfrac{\partial p}{\partial x}$. All physical quantities except pressure become functions of y only, as the walls are infinite in extent along x- and z-directions. Further to obtain the governing equations, the following assumptions are made following Sato [7] and Dileep Singh Chauhanand and Priyanka Rastogi [2].

(i) The density of gas is everywhere constant.
(ii) The ionization is in equilibrium which is not affected by the applied electric and magnetic fields.
(iii) The effect of space charge is neglected.
(iv) The flow is fully developed and stationary, that is, $\frac{\partial(\ )}{\partial x}=0,\ \frac{\partial(\ )}{\partial z}=0$ except $-\frac{\partial p}{\partial x}\neq 0$.
(v) The magnetic Reynolds number is small (so that the externally applied magnetic field is undisturbed by the flow). The induced magnetic field is small when compared with the applied field. Therefore, components in the conductivity tensor are expressed in terms of B_0.
(vi) The flow is two-dimensional so that $\frac{\partial(\ )}{\partial z}=0,$
(vii) The porous medium is homogeneous and isotropic so that its permeability k is same throughout the medium.

The physical configuration and the nature of the flow suggest the following forms of velocity vector $\bar{q}$, the magnetic flux density $\bar{B}$, the electric field $\bar{E}$ and the current density $\bar{J}$:
$\bar{q}=[u,0,w]$, $\bar{B}=[0,B_0,0]$, $\bar{E}=[E_x,0,E_z]$ and $\bar{J}=[j_x,0,j_z]$

Under the above assumptions, the governing equations of flow reduce to

$$-\frac{1}{\rho}\frac{\partial p}{\partial x}\left[\left(1-s\left(1-\frac{\sigma_1}{\sigma_0}\right)\right)\right]+\phi_1\upsilon\frac{d^2u}{dy^2}+\frac{B_0}{\rho}\left[-\sigma_1\left(E_z+uB_0\right)+\sigma_2\left(E_x-wB_0\right)\right]-\frac{\upsilon}{k}u+g\ Sin\theta=0 \tag{1}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial x}\left(s\frac{\sigma_2}{\sigma_0}\right)+\phi_1\upsilon\frac{d^2w}{dy^2}+\frac{B_0}{\rho}\left[\sigma_1\left(E_x-wB_0\right)+\sigma_2\left(E_z+uB_0\right)\right]-\frac{\upsilon}{k}w-g\ Cos\theta=0 \tag{2}$$

in which $s=p_e/p$ is the ratio of the electron pressure to the total pressure. The value of s is 0.5 for neutral fully-ionized plasma and approximately zero for a weakly-ionized gas. u, w and E_x, E_z are x- and z- components of velocity $\bar{q}$ and electric field $\bar{E}$ respectively.

$$\sigma_1=\frac{\sigma_0}{1+m^2}\ ;\ \sigma_2=\frac{\sigma_0 m}{1+m^2}\ ;\ m=\frac{w_e}{\left[\frac{1}{\tau}+\frac{1}{\tau_e}\right]}$$

Here, $\varphi_1=\frac{\bar{\mu}}{\mu}$ is the viscosity ratio; $\bar{\mu}$ is the effective viscosity of the gas in porous medium.

The boundary conditions are

$u = 0, w = 0$ at $y = h$

$u = 0, w = 0$ at $y = -h$

We introduce the following non dimensional variables and parameters to make the basic equations and boundary conditions dimensionless.

$$u^* = \frac{u}{u_p},\ w^* = \frac{w}{u_p},\ y^* = \frac{y}{h},\ u_p = -\left(\frac{\partial p}{\partial x}\right)\frac{h^2}{\rho\upsilon},\ L_1 = \left(1 - s\left(1 - \frac{\sigma_1}{\sigma_0}\right)\right)\ ;\ L_2 = \left(-s\frac{\sigma_2}{\sigma_0}\right)\ ;\ m_x = \frac{E_x}{B_0 u_p},\ m_z = \frac{E_z}{B_0 u_p},$$

$$M^2 = \frac{B_0^2 h^2 \sigma_0}{\rho\upsilon},\ N = \frac{Fr}{\mathrm{Re}} = \frac{gh^2}{u_p \upsilon} \text{ and } Da = \frac{k}{h^2}$$

In view of the above dimensionless quantities, Eqns. (1) and (2) take the following form. Neglecting the asterisks (*), we get,

$$L_1 + \phi_1 \frac{d^2u}{dy^2} - \frac{\sigma_1}{\sigma_0} M^2 (m_z + u) + \frac{\sigma_2}{\sigma_0} M^2 (m_x - w) - \frac{u}{Da} + N\,Sin\theta = 0 \tag{3}$$

$$L_2 + \phi_1 \frac{d^2w}{dy^2} + \frac{\sigma_1}{\sigma_0} M^2 (m_x - w) + \frac{\sigma_2}{\sigma_0} M^2 (m_z + u) - \frac{w}{Da} - N\,Cos\theta = 0 \tag{4}$$

The corresponding boundary conditions are

$u = 0, w = 0$ at $y = \pm 1$

Further, writing $q = u + iw,\ \ L = L_1 + iL_2,\ E = m_x + im_z$

The equations (3) and (4) can be written in complex form as

$$\phi_1 \frac{d^2q}{dy^2} + \left[-\frac{\sigma_1}{\sigma_0} M^2 + i\frac{\sigma_2}{\sigma_0} M^2 - \frac{1}{Da}\right] q = -L - N\left(Sin\theta - i\,Cos\theta\right) - i\frac{\sigma_1}{\sigma_0} M^2 \bar{E} - \frac{\sigma_2}{\sigma_0} M^2 E \tag{5}$$

The boundary conditions become

$$q = 0 \text{ at } y = \pm 1 \tag{6}$$

3. SOLUTION OF THE PROBLEM

If the side walls are made up of conducting material and short circuited by an external conductor, the induced electric current flows out of the channel. In this case no electric potential exists between the side walls. If we assume zero electric field also in the x- and z- directions, then E=0(m_x= 0, m_z= 0). In this case, equation (5) becomes

$$\frac{d^2q}{dy^2} + aq = k \tag{7}$$

Solving equation (7) subject to the boundary condition (6), the expression for q is obtained as follows:

$$q = A\,Cosh\sqrt{a}\,y + \frac{k}{a} \tag{8}$$

Expanding real and imaginary parts, we get solutions for u and w. They all are dependent on s. The primary and the secondary velocities (u and w) are obtained as follows:

$$u = A_1 Cosh\, a_3 y\ Cos\, a_4 y - A_2 Sinh\, a_3 y\ Sin\, a_4 y + k_3 \tag{9}$$

$$w = A_2 Cosh\, a_3 y\ Cos\, a_4 y + A_1 Sinh\, a_3 y\ Sin\, a_4 y + k_4 \tag{10}$$

where

$$a = a_1 + ia_2\,,\; k = k_1 + k_2\,,\; A = A_1 + iA_2\,,\; a_1 = \left(\frac{1}{\varphi_1}\right)\left[\left(-\frac{\sigma_1}{\sigma_0}\right)M^2 - \frac{1}{Da}\right],\; a_2 = \left(\frac{1}{\varphi_1}\right)\left[\left(\frac{\sigma_2}{\sigma_0}\right)M^2\right],\; k_1 = \left(\frac{1}{\phi_1}\right)\left(-L_1 - N\,Sin\theta\right),$$

$$k_2 = \left(\frac{1}{\phi_1}\right)\left(-L_2 + N\,Cos\theta\right),\; \frac{\sigma_1}{\sigma_0} = \frac{1}{1+m^2},\;\; \frac{\sigma_2}{\sigma_0} = \frac{m}{1+m^2},\; k_3 = \frac{k_1a_1 + k_2a_2}{a_1^2 + a_2^2},\;\; k_4 = \frac{k_2a_1 - k_1a_2}{a_1^2 + a_2^2},\; a_3 = \frac{\sqrt{\sqrt{a_1^2 + a_2^2} + a_1}}{2},$$

$$a_4 = \frac{\sqrt{\sqrt{a_1^2 + a_2^2} - a_1}}{2},\;\; f_1 = Cosh\,a_3 Cos\,a_4\,,\; g_1 = Sinh\,a_3 Sin\,a_4\,,\; A_1 = \frac{-k_3 f_1 - k_4 g_1}{f_1^2 + g_1^2},\; A_2 = \frac{-k_4 f_1 + k_3 g_1}{f_1^2 + g_1^2}$$

We note that when $\varphi_1 = 1$ (i. e $\overline{\mu} = \mu$), g = 0 and $k \to \infty$ (i.e non-porous medium), the results coincide with those of Sato [7].

4. RESULTS AND DISCUSSION

The closed form solutions for both the velocity distributions, such as primary velocity(u) and secondary velocity(w) distributions in the porous medium are obtained. The results are depicted graphically in figures 2 to 13. The graphs are given for two cases, viz., partially ionized (s = 0) and fully ionized (s=0.5) cases.

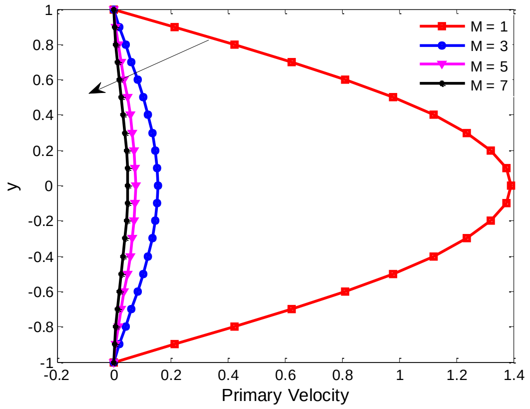


Fig. 2. Variations of primary velocity with y for different values of M with s = 0, m = 1 $\theta = \pi/6$, $\varphi_1 = 2$, Da = 0.1 , N = 0.1

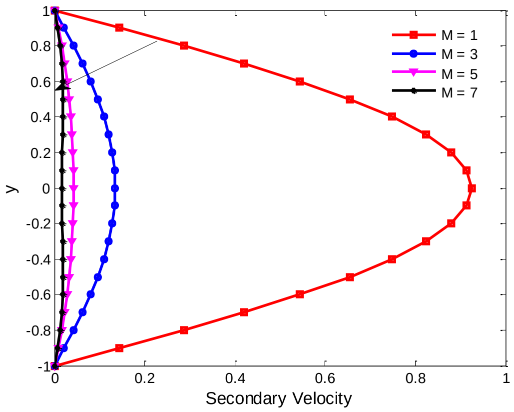
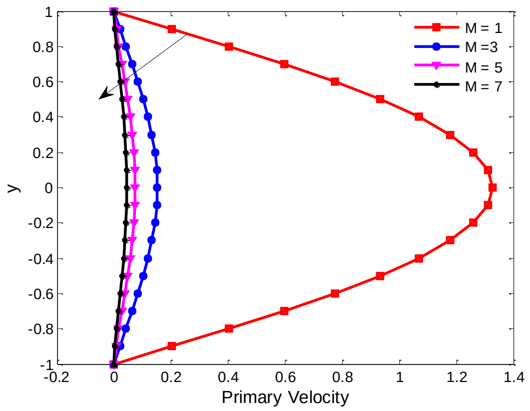


Fig.3.Variations of secondary velocity with y for different values of M with s = 0, m = 1, $\theta = \pi/6$, $\varphi_1 = 2$, Da = 0.1 , N = 0.1



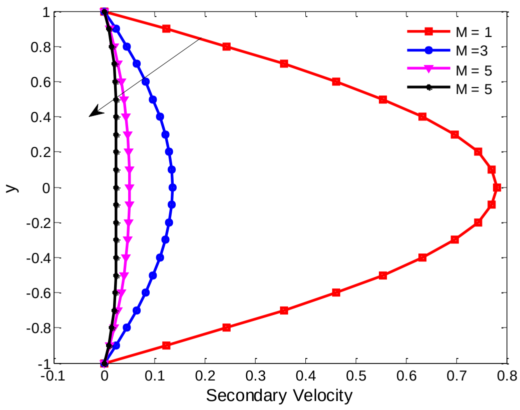


Fig. 4. Variations of primary velocity with y for different values of M with $s = 0.5$, $m = 1$, $\theta = \pi/6$, $\varphi_1 = 2$, $Da = 0.1$, $N = 0.1$

Fig. 5. Variations of secondary velocity with y for different values of M with $s = 0.5$, $m = 1$, $\theta = \pi/6$, $\varphi_1 = 2$, $Da = 0.1$, $N = 0.1$

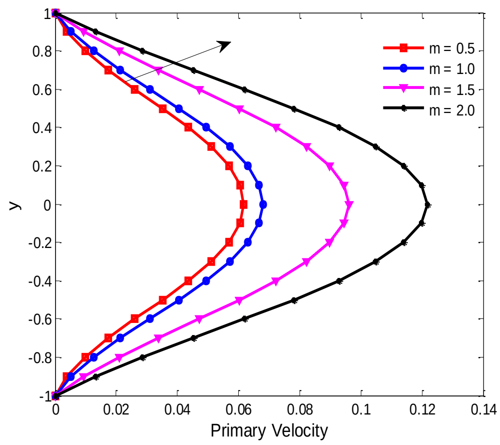


Fig. 6. Variations of primary velocity with y for different values of m with $s = 0$, $M = 5$, $\theta = \pi/6$, $\varphi_1 = 2$, $Da = 0.1$, $N = 0.1$

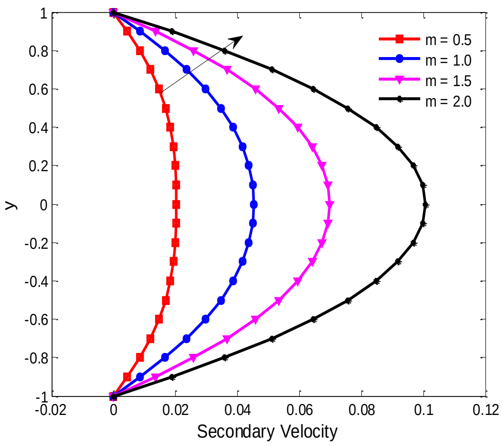


Fig. 7. Variations of secondary velocity with y different values of m with $s = 0$, $M = 5$ $\theta = \pi/6$, $\varphi_1 = 2$, $Da = 0.1$, $N = 0.1$

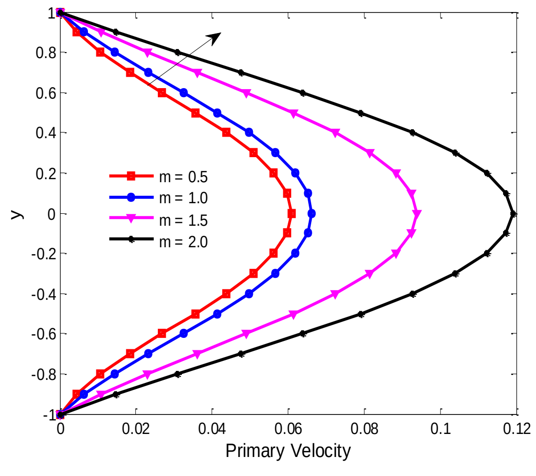


Fig. 8. Variations of primary velocity with y for different values of m with $s = 0.5$, $M = 5$ $\theta = \pi/6$, $\varphi_1 = 2$, $Da = 0.1$, $N = 0.1$

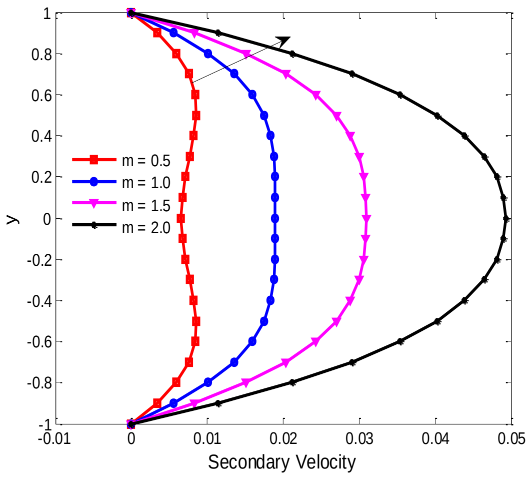


Fig.9.Variations of secondary velocity with y different values of m with $s = 0.5$, $M = 5$ $\theta = \pi/6$, $\varphi_1 = 2$, $Da = 0.1$, $N = 0.1$

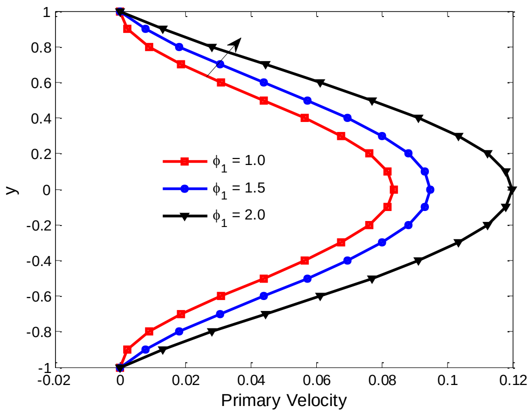


Fig. 10. Variations of primary velocity with y for different values of ϕ_1 with $s = 0$, $M = 5, \theta = \pi/6, m = 2$, $Da = 0.1$, $N = 0.1$

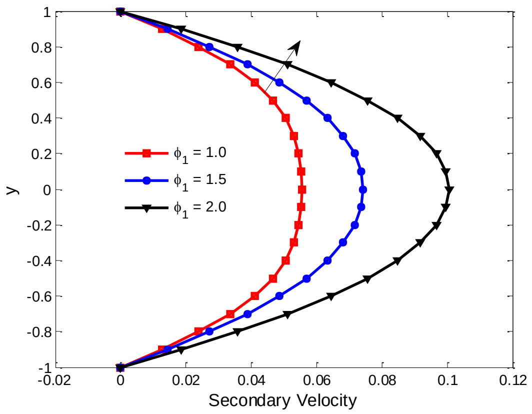


Fig. 11. Variations of secondary velocity with y for different values of ϕ_1 with $s = 0$, $M = 5, \theta = \pi/6, m = 2$, $Da = 0.1$, $N = 0.1$

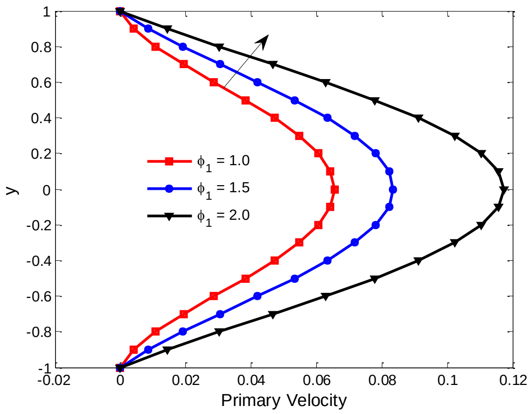


Fig. 12. Variations of primary velocity with y for different values of ϕ_1 with $s = 0.5$, $M = 5$, $\theta = \pi/6, m = 2$, $Da = 0.1$, $N = 0.1$

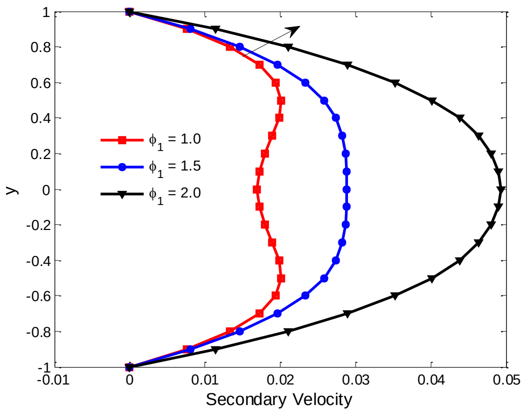


Fig. 13. Variations of secondary velocity with y for different values of ϕ_1 with $s = 0.5$, $M = 5$, $\theta = \pi/6, m = 2$, $Da = 0.1$, $N = 0.1$

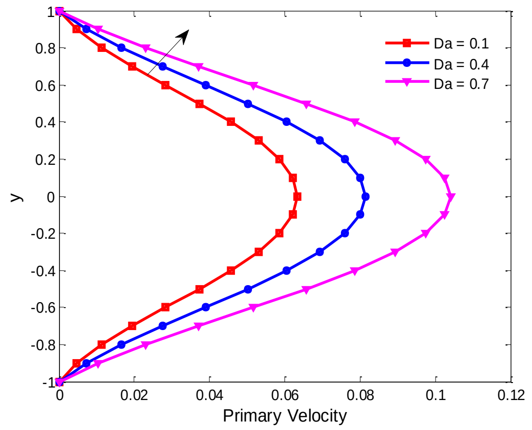


Fig.14. Variations of primary velocity with y for different values of Da with $s = 0.5$, $M = 5$, $\theta = \pi/6$, $m = 1$, $\varphi_1 = 2$, $N = 0.1$

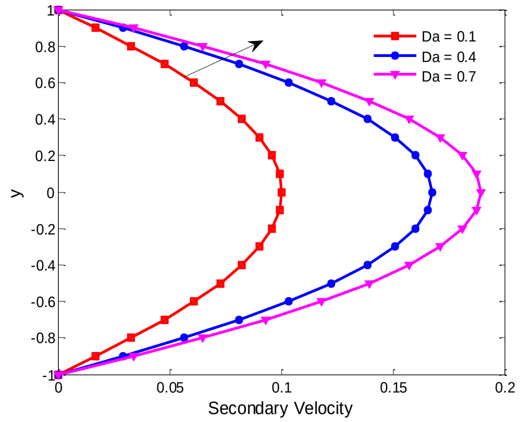


Fig15. Variations of secondary velocity with y different values of M with $s = 0.5$, $M = 5$, $\theta = \pi/6$, $m = 1$, $\varphi_1 = 2$, $N = 0.1$

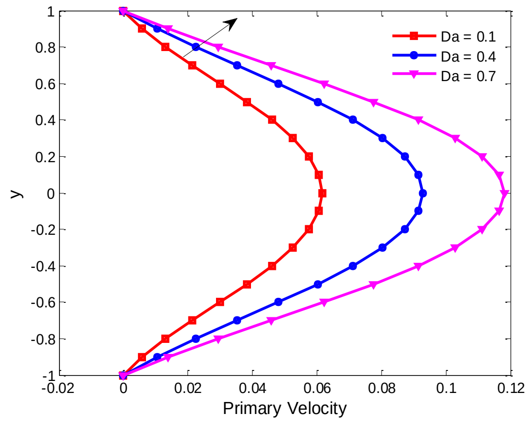


Fig.16. Variations of primary velocity with y for different values of Da with $s = 0.5$, $M = 5$, $\theta = \pi/6$, $m = 1$, $\varphi_1 = 2$, $N = 0.1$

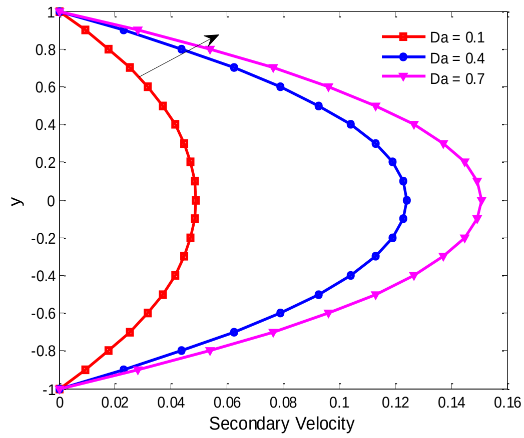


Fig. 17. Variations of secondaryvelocity with y for different values of Da with $s = 0.5$, $M = 5$, $\theta = \pi/6$, $m = 1$, $\varphi_1 = 2$, $N = 0.1$

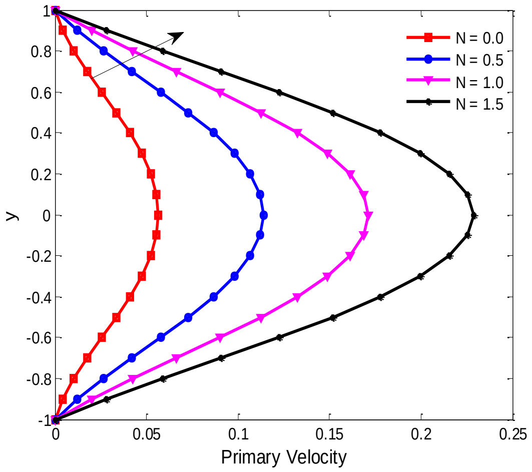


Fig. 18. Variations of primary velocity with y for different values of N with $s = 0$, $M = 5, \theta = \pi/6, m = 2, \varphi_1 = 2$, Da= 0.1

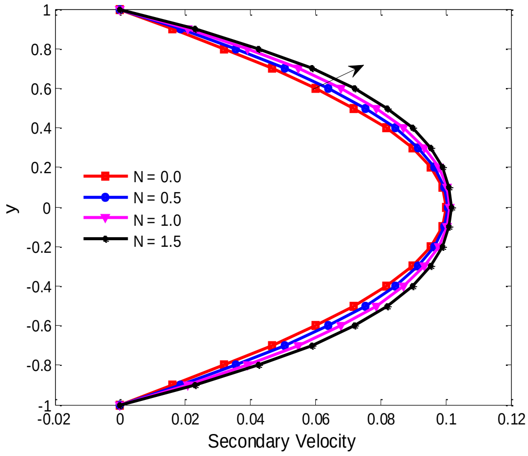


Fig19. Variations of secondary velocity with y different values of N with $s = 0$, $M = 5, \theta = \pi/6, m = 2, \varphi_1 = 2$, Da= 0.1

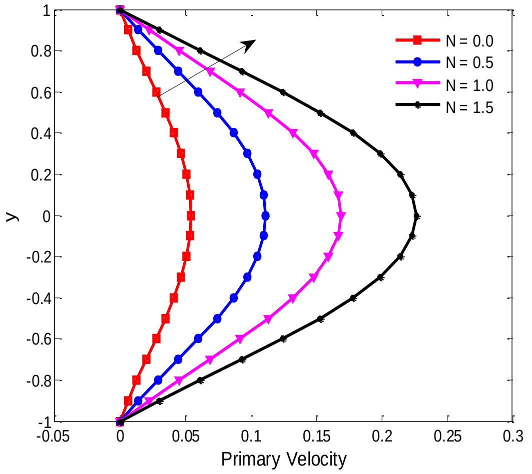


Fig. 20. Variations of primary velocity with y or different values of N with $s = 0.5$, $M = 5, \theta = \pi/6, m = 2, \varphi_1 = 2$, Da= 0.1

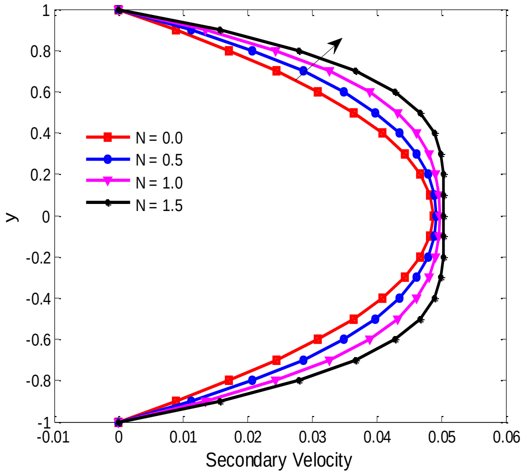
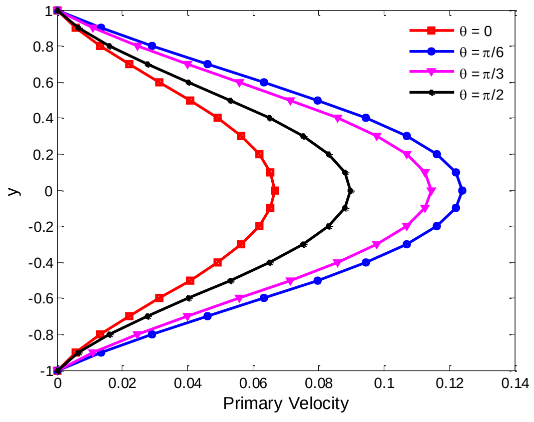


Fig. 21. Variations of secondary velocity with y for different values of N with $s = 0.5$, $M = 5, \theta = \pi/6, m = 2, \varphi_1 = 2$, Da= 0.1



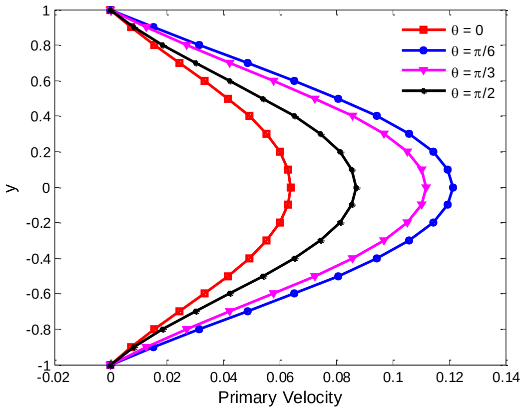
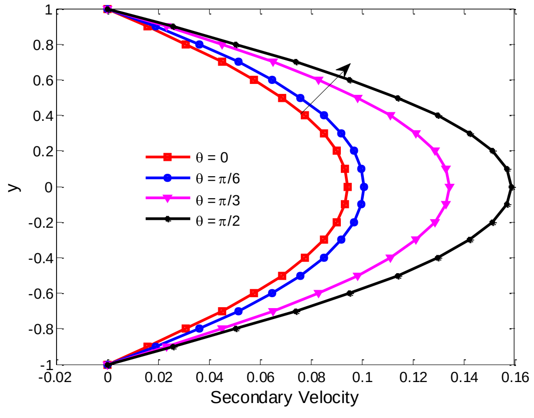


Fig. 22. Variations of primary velocity with y for different values of θ with $s = 0.5$, $M = 5$, N=0.1 , $m = 2$, $\varphi_1 = 2$, Da= 0.1

Fig23. Variations of secondary velocity with y or different values of θ with $s = 0$, $M = 5$,N=0.1, $m = 2$, $\varphi_1 = 2$, Da= 0.1



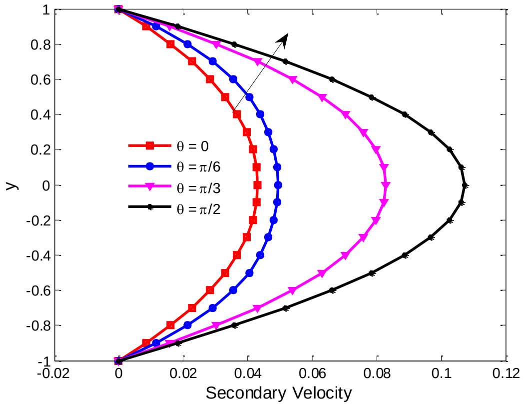


Fig. 24. Variations of primary velocity with y for different values of θ with $s = 0.5$, $M = 5$, $\theta = \pi/6$, $m = 2$, $\varphi_1 = 2$, Da= 0.1

Fig. 25. Variations of secondary velocity with y for different values of θ with $s = 0.5$, $M = 5$, $\theta = \pi/6$, $m = 2$, $\varphi_1 = 2$, Da= 0.1

Figs. 2 to 5 show the variation in primary and secondary velocities for different values of Hartmann number *M* and for fixed Da, N, θ, m and φ_1. It is observed that for partially and fully ionized cases, primary and secondary velocities decrease with an increase in the Hartmann number *M*. This is because the increase in the magnetic field gives rise to reduction in velocity in the channel.

Figs. 6 to 9 show the variation in primary and secondary velocities for different values of Hall parameter *m* and for fixed Da, N, θ, M and φ_1. It is observed that for partially and fully ionized cases, primary and secondary velocities increase with an increase in the Hall parameter *m*.

Figs. 10 to 13 show the variation in primary and secondary velocities for different values of φ_1 and for fixed *M*, N, θ, m and Da. It is observed that for partially and fully ionized cases, both primary and secondary velocities increase with an increase in the viscosity ratio φ_1

Figs. 14 to 17 show the variation in primary and secondary velocities for different values of Darcy number *Da* and for fixed *M*, N, θ, m and φ_1. It is observed that for partially and fully ionized cases, both primary and secondary velocities increase with an increase in the Darcy number *Da.*

Figs. 18 to 21 show the variation in primary and secondary velocities for different values of N and for fixed *M*, Da, θ, m and φ_1. It is observed that for partially and fully ionized cases, both primary and secondary velocities increase with an increase in the N.

Figs. 22 to 24 show the variation in primary and secondary velocities for different values of θ and for fixed *M*, Da, N, m and φ_1. It is observed that for partially and fully ionized cases, primary velocity increases from $\theta = 0$ to $\theta = \pi/6$ and then decreases up to $\theta = \pi/2$ but secondary velocities increase with an increase in the θ from 0 to $\pi/2$.

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