Hall Effect on Ionized Hydromagnetic Slip-Flow Between Parallel Walls in a Rotating System

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ABSTRACT

We discuss the effects of Hall currents on an ionized hydromagnetic slip-flow between two parallel walls in a rotating system, when the walls are made up of non-conducting and conducting materials. Exact solutions for the primary and secondary velocity distributions and their corresponding mean velocities are obtained by assuming that the magnetic Reynolds number is small by applying the first order velocity slip conditions at both the walls. Also discussed the flow features for different values of the governing parameters involved such as, the rotation parameter, Hartmann number, Hall parameter, slip parameter and the ionization parameter (that is, the ratio of electron pressure to the total pressure).

Keywords: MHD flow, Hall currents, Rotating fluids, Slip flow regime

§ 1. INTRODUCTION

The problem of hydromagnetic channel flow has been attracted by a number of researchers, notably, Hartmann- Lazarus (15), Shercliff (40), Cowling (6), Chang and Yen (5), Cramer (7), Tao (47), Sutton and Sherman (44) and many more, on account of its numerous applications in engineering science, in industrial applications, such as in MHD generators, nuclear reactors and geothermal energy extractions, also in plasma studies etc. With the impetus given by these authors and many more, the study of hydromagnetic flows on different aspects and in different geometries has gained a good deal of studies by several authors, namely Rossow (34), Kakuktani (17), Ong and Nicholls (25), Ludford (21), Gupta (12), Singh (40), Soundalgekar (41, 42), Datta (8), Pop (26-28), Messiha (24), Rao (31), Verma and Mathura (48), Mathur (22).

In the above mentioned investigations, the effects of Hall currents are not considered. But it is well known in literature that, when the working fluid is an ionized gas, where the density is low/or the magnetic field is very strong, one cannot neglect the resulting effects of Hall currents, since the study of hydromagnetic flows with Hall currents has important applications in designing the magnetohydrodynamic generators, Hall accelerators and in flight magnetohydrodynamics etc. The problems relating to the effects of Hall currents on specific flow problems under the influence of a very strong magnetic field have been studied by several researchers, such as, Broer (3), Sato (36), Sutton and Sherman (44), Tani (46), Katagiri (16), Pop (29), Gupta (13), Mathur (22), Datta and Jana (9), Debnath et al (10), Rao and Krishna (32), Raptis and Ram (35), Ghosh (11), Ram (33), Helmy (15), Rajasekhar et. al (30), Chand et. al (4) and many more. In which, LingaRaju and Rao (19) have studied the Hall effects on temperature distribution in a rotating ionized hydromagnetic flow between parallel walls. Later on, LingaRaju and Murthy (20) have studied the quasi-state solutions of MHD ionized flow and heat transfer with Hall currents between parallel walls in a rotating system.

But, in most of these investigations, the authors have considered the no-slip conditions at the boundary walls. However there exists, the cases where partial slip on the wall does occur. These situations may include rarefied gas flows, rough or porous walls. In such cases, the no-slip condition must be replaced by the partial slip condition with the modified Navier-Stokes equations describing the flow field and many such investigations are also made available in the literature. Mention may be made due to the works of: Basset (1), Michael and Stephen (23), Tamada and Murali (45), Bhatt and Sacheti (2), Street (43), Lance and Rogers (18), Sastry and Bhadram (37), Schaaf and Chambre (38) with slip boundary conditions.

In this paper, an attempt is made to discuss how LingaRaju and Rao's (19) results get modified when their no-slip boundary conditions at the walls are replaced by the first order velocity slip condition?. We discuss the effects of Hall currents on an ionized hydro-magnetic slip-flow between two parallel walls in a rotating system, when the walls are made up of non-conducting and conducting materials. Exact solutions for the primary and secondary velocity distributions and their corresponding mean velocities are obtained by assuming that the magnetic Reynolds number is small by applying the first order velocity slip boundary conditions at both the walls. Also, it is discussed the flow features for different values of the governing parameters involved such as, the rotation parameter T, the Hartmann number M, the Hall parameter m, slip parameter β and the ionization parameter "s", that is, the ratio of the electron pressure to the total pressure. In § 1, formulation of the problem is mentioned. In § 2, the basic governing equations of motion with relevant boundary conditions and mathematical analysis of the problem are given. Section §3, deals with the solutions of the problem in two cases of study, one for non-conducting(insulating) and the other for conducting walls. While in section §4, discussion of the results is made in detail from the graphs as shown in figures 1 to 24.

§ 2. Formulation of the problem, basic equations with boundary conditions and mathematical analysis of the problem

We consider the steady two-dimensional viscous flow of an ionized gas between two parallel walls extent along x- and z-directions situated at a distance 2h apart, in presence of a uniform transverse magnetic field by taking Hall currents into account. 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. A uniform magnetic field of intensity H_0 is applied in the direction of the y-axis. The whole system is rotated with an angular velocity $\overline{\Omega}$ about an axis normal to the xz-plane, i.e., about y-axis, where $\overline{\Omega} = (0, \Omega, 0)$. Since, the plates are infinite in length, so all physical quantities except pressure depend only on y. We assume that the magnetic Reynolds number is very small, so that the induced magnetic field produced by the motion of the electrically conducting fluid is negligible and we applied an electric field in x- and z-directions. Further, to simplify the theoretical analysis, the following assumptions as in Sato (36), Linga Raju and Rao (19) are considered: (i) The density of gas is always constant, (ii) The ionization is in equilibrium which is not affected by the applied magnetic and electric fields, (iii) The effect of space charge is neglected (iv) The flow is fully developed and stationary, that is $\partial/\partial t = 0$, $\partial/\partial x = 0$ except $\partial p/\partial x \neq 0$, (v) The magnetic Reynolds number is small (so that the externally applied magnetic field is undisturbed by the fluid), namely the induced magnetic field is small compared with the applied field (Shercliff (40)) and (vi) The flow is two-dimensional, namely $\partial/\partial z = 0$. With these assumptions, the governing equations of motion and current are formulated and are simplified as

$$-\left[1-s(1-\frac{\sigma_1}{\sigma_0})\right]\frac{\partial p}{\partial x}+\rho\nu\frac{d^2u}{dy^2}+B_0[-\sigma_1(E_z+uB_0)+\sigma_2(E_x-wB_0)] = 2\rho\Omega w,$$

(1)

$$(s\frac{\sigma_2}{\sigma_0})\frac{\partial p}{\partial x}+\rho\nu\frac{d^2w}{dy^2}+B_0[\sigma_1(E_x-wB_0)+\sigma_2(E_z+uB_0)]=-2\rho\Omega u\,.$$

(2)

The slip boundary conditions are given by u = $\beta\frac{du}{dy}$ and w = $\beta\frac{dw}{dy}$ at y = $\pm$ h.

(3)

In the above equations, Ω represents the angular velocity with which the whole system is rotated about y-axis and s = p_e/p is the ratio of the electron pressure to the total pressure. The value of s is 1/2 for neutral fully–ionized plasma and approximately zero for a weakly–ionized gas. u, w and E_x and E_z are x- and z- components of velocity $\overline{V}$ and electric field $\overline{E}$ respectively, β is the first order velocity slip parameter . Also,

$$\sigma_1 = \frac{\sigma_0}{1+m^2}, \quad \sigma_2 = \frac{\sigma_0 m}{1+m^2} \quad \text{and} \quad m = \frac{\omega_e}{\left[\frac{1}{\tau}+\frac{!}{\tau_e}\right]}.$$

(4)

where ω_e is the gyration frequency of electron, τ and τ_e are the mean collision time between electron and ion, electron and neutral particles respectively; σ_1, σ_2 are the modified conductivities parallel and normal to the direction of electric field. The above expression for m which is valid in the case of partially–ionized gas agrees with that of fully–ionized gas when τ_e approaches infinity.

The equations (1) and (2) are non–dimensionalised using the characteristic length h and velocity

u_P = - $\left(\frac{\partial p}{\partial x}\right)\left(\frac{h^2}{\rho\nu}\right)$. Using the notation u, w for u/u_p and w/u_P and y for y/h, we obtain the non–dimensional equations:

$$k_1 + \frac{d^2u}{dy^2} - \frac{\sigma_1}{\sigma_0} M^2 (m_z + u) + \frac{\sigma_2}{\sigma_0} M^2 (m_x - w) = 2T^2 w,$$

(5)

$$k_2 + \frac{d^2w}{dy^2} + \frac{\sigma_1}{\sigma_0} M^2 (m_x - w) + \frac{\sigma_2}{\sigma_0} M^2 (m_z + u) = -2T^2 u,$$

(6)

In which, $k_1 = 1 - s\,(1 - \frac{\sigma_1}{\sigma_0})$, $k_2 = -s\,(\sigma_2/\sigma_0)$, $m_x = E_x/(B_0 u_P)$, $m_Z = E_z/(B_0 u_P)$, the Hartmann number, M is defined as $M^2 = \frac{B_0{}^2 h^2 \sigma_0}{\rho \nu}$ and T^2 (Taylor number) $= \frac{\Omega h^2}{\nu}$.

(7)

Further, writing $q = u + iw$, $K = k_1 + ik_2$, $E = m_x + im_z$; the equations (5) and (6) can be written in complex form as :

$$\frac{d^2q}{dy^2} + \left(\frac{-\sigma_1}{\sigma_0} M^2 + i\frac{\sigma_2}{\sigma_0} M^2 + 2iT^2 \right) q = -K - i\frac{\sigma_1}{\sigma_0} M^2 E - \frac{\sigma_2}{\sigma_0} M^2 E.$$

(8)

The eq. (8) is to be solved subject to the following slip boundary conditions at the walls:

$$q = \beta \frac{dq}{dy} \text{ at } y = \pm 1, \quad (9)$$

Also, I_x and I_z defined by $J_X/(\sigma_0 B_0 u_P)$ and $J_Z/(\sigma_0 B_0 u_P)$ respectively, are given in complex notation as

$$I = I_X + iI_Z = \frac{\sigma_2 + i\sigma_1}{\sigma_0} \left(q - iE - \frac{s}{M^2} \right) + \frac{is}{M^2}. \quad (10)$$

The non–dimensional electric field m_x and m_z are to be determined by boundary conditions at large x and z.

§ 3. Solutions of the problem

The solution of the problem considered is carried out in the following two cases.

3.1 Solutions for non-conducting(insulating) walls:

When the side walls are kept at large distance in x and z-directions and are made up of non-conducting material, the induced electric current does not go out of the channel, but circulates in the fluid. Therefore, the additional conditions for current can be defined as in Sato (36) and hence the resulting solutions are found. Solutions for velocity and current distributions u, w, u_m, w_m, respectively are all independent of the partial pressure of electron gas 's'and are obtained as

$u=C_1 \cosh py \cos qy + C_2 \sinh py \sin qy+(1/M^2)(1+\gamma/\varepsilon)$

(11)

$w=C_2 \cosh py \cos qy - C_1 \sinh py \sin qy+(1/M^2)(m-\delta/\varepsilon)$

(12)

The mean velocity in the complex notation is given by $q_m = u_m + i\, w_m$, where the primary mean velocity is given by

$u_m=C_1 a_4 + C_2 a_5 + A$
(13)

and the secondary mean velocity is given by

$w_m= C_2 a_4 - C_1 a_5 + B$ (14)

The constants involved in the above solutions (11) to (14) are given by

$p = \sqrt{[\sqrt{\{[M^2/(1+m^2)]^2+[mM^2/(1+m^2) +2T^2]^2\}} -[M^2/(1+m^2)]]}/\sqrt{2}$

$q = \sqrt{[\sqrt{\{[M^2/(1+m^2)]^2+[mM^2/(1+m^2)+2T^2]^2\}}+[M^2/(1+m^2)]]}/\sqrt{2}$

$a_1 = \sinh^2 p \sin^2 q + \cosh^2 p \cos^2 q + [\beta^2 (p^2+q^2)](\sinh^2 p \cos^2 q + \cosh^2 p \sin^2 q)$
$+2\beta q \sin q \cos q + 2 \beta$ □$p \sinh p \cosh p$,

$a_2 = \sinh p \sin q+ \beta q \sinh p \cos q+$□ $\beta p \cosh p \sin q$, $a_3 = \cosh p \cos q - \beta q \cosh p \sin q + \beta p \sinh p \cos q$

$a_4 = [p/(p^2+q^2)]\sinh p \cos q+[q/(p^2+q^2)]\cosh p \sin q$, $a_5 = [p/(p^2+q^2)]\cosh p \sin q-[q/(p^2+q^2)]\sinh p \cos q$

$\gamma = -(a_2a_4)^2 -(a_3a_5)^2-(a_3a_4)^2-(a_2a_5)^2+a_1a_3a_4+a_1a_2a_5+m(a_1a_2a_4-a_1a_3a_5)$

$\delta = (a_1a_2a_4-a_1a_3a_5)+m((a_2a_4)^2+(a_3a_5)^2+(a_3a_4)^2+(a_2a_5)^2-a_1a_3a_4-a_2a_4a_5))$

$\zeta = (a_2a_4)^2+(a_3a_5)^2+(a_3a_4)^2+(a_2a_5)^2$, $A = (1/M^2)[1+(\gamma/\zeta)]$, $B = (1/M^2)[m-(\delta/\zeta)]$

$C_1 = -[Aa_3-Ba_2]/a_1$., $C_2 = -[Aa_2+Ba_3]/a_1$.
(15)

3.2 Solutions for conducting walls:

When the side walls are made up of conducting material and short-circuited by an external conductor, the indeed 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, we have m_x=0, m_z=0. Constants in the solution are determined by these two conditions. The solutions for u, w, $u_{m,}$ $w_{m,}$ are all depend on 's' and are obtained as

u=C_1 coshpy cosqy + C_2 sinhpy sinqy + A (16)

w=C_2 coshpy cosqy – C_1 sinhpy sinqy + B (17)

The primary mean velocity is given by

u_m==C_1 a_4 + C_2 a_5 + A (18)

and the secondary mean velocity is given by

w_m= C_2 a_4 - C_1 a_5 + B (19)

the constants involve in the above solutions(16) to (19) are given by

$p =\sqrt{[\sqrt{\{[M^2/(1 + m^{2)}]^2 + [mM^2/(1 + m^2) + 2T^2]^2\}} - [M^2/(1 + m^2)]]} /\sqrt{2}$

$q = \sqrt{[\sqrt{[M^2/(1 + m^2)]^2 + [mM^2/(1 + m^2) +2T^2]^2\}} + [M^2/(1 + m^2)]]} /\sqrt{2}$

$a_1 = \sinh^2p \sin^2q + \cosh^2p \cos^2q + [\beta^2 (p^2+q^2)](\sinh^2p \cos^2q + \cosh^2p \sin^2q)$
$+2\beta q \sin q \cos q + 2 \beta \square p \sinh p \cosh p,$

a_2 =sinhp sinq + βq sinhp cosq +□ β pcoshp sinq, a_3 = coshp cosq - β q sinhp cosq + β p sinhp cosq

a_4 = $[p/(p^2+q^2)]$sinhpcosq+$[q/(p^2+q^2)]$coshp sinq, a_5 = $[p/(p^2+q^2)]$coshp sinq-$[q/(p^2+q^2)]$sinhpcosq

$\gamma =-(a_2a_4)^2 -(a_3a_5)^2-(a_3a_4)^2-(a_2a_5)^2+a_1a_3a_4+a_1a_2a_5+m(a_1a_2a_4-a_1a_3a_5)$

$\delta = (a_1a_2a_4-a_1a_3a_5)+m((a_2a_4)^2+(a_3a_5)^2+(a_3a_4)^2+(a_2a_5)^2-a_1a_3a_4-a_2a_4a_5))$

$\zeta = (a_2a_4)^2+(a_3a_5)^2+(a_3a_4)^2+(a_2a_5)^2$, A=1/$M^2$, $B = m(1\text{-}s)/M^2$, $C1= -[Aa3\text{-}Ba2]/a1$,

$C_2 = -[Aa_2+Ba_3]/a_1$.

$$I=\left(\frac{\sigma_2 + i\sigma_1}{\sigma_0}\right)\left(q - \frac{s}{M^2}\right) + \frac{i\,s}{M^2}, \qquad (20)$$

in which u_m and w_m are the mean velocities of the primary and secondary velocity distributions u and w respectively.

§ 4. Results and discussion

The closed form solutions are obtained for both primary and secondary velocity distributions, that is, u and w, when both walls are made up of non-conducting (insulated) and conducting materials. The numerical computations for u and w are carried out and the corresponding mean velocities are calculated to plot their graphs. We note that when β= 0 (i.e., for no-slip condition at the walls), the analysis is in agreement with the solution of LingaRaju and Rao (19). When β = 0 and T = 0 (that is, for no-slip and without rigid rotation), these results coincide with those of Sato (36). Also, the velocity distributions thus obtained are found independent of s (ratio of electron pressure to the total pressure) in case of non-conducting walls and depending on "s" in the case of conducting walls. The graphs for velocity distributions are shown in figures 1 to 24 for both the cases. Fig. 1 and 2 exhibit the primary and secondary velocity distributions u and w respectively for different values of the Hartmann number M and for fixed Hall parameter m=2, Rotation parameter T = 2 and β = 0.01. From fig.1, It is observed that when m, β and T are fixed, u decreases with an increase in M. From fig. 2, for fixed when m, β and T , as M increases, w also decreases. Fig. 3 and 4 show the primary and secondary velocity distributions u and w respectively for fixed values of Hartmann number M=10, rotation parameter T=2, β = 0.01 and for different Hall parameter m. Here, it is noticed that, for small m(say upto 2), both u and w are decreasing in nature while for values of m above 2, they tend to increase. Figures 5 and 6 show the primary and secondary velocity distributions u and w respectively for different values of rotation parameter T with fixed M=10, m=2, β=0.01. It is found that, both these distributions increase as the rotation increases. Figures 7 and 8 exhibit the primary and secondary velocity profiles u and w respectively for fixed values of M=10, m=T=2 and different slip parameter β. These profiles, also found to increase as β increases.

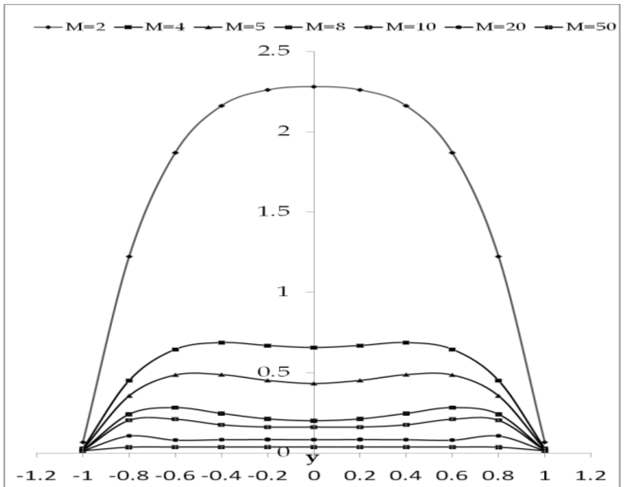

Fig.2.1 Primary Velocity distribution of Non-Conducting Plates for different M and Fixed with T=m=2, B=0.01

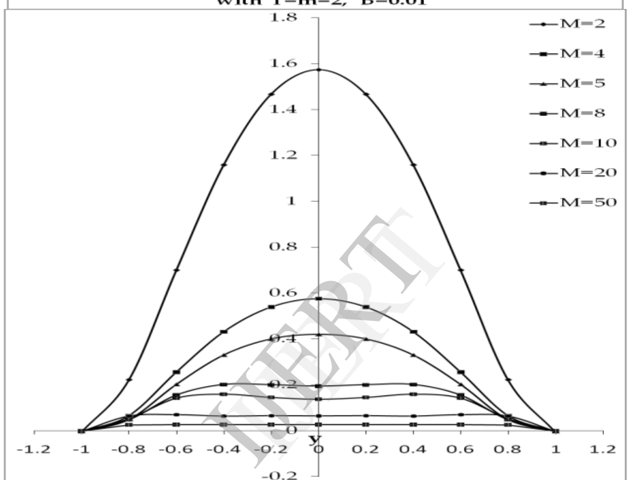

Fig.2.2 Secondary Velocity distribution of Non-Conducting Plates for different M Fixed with T=m=2, B=0.01

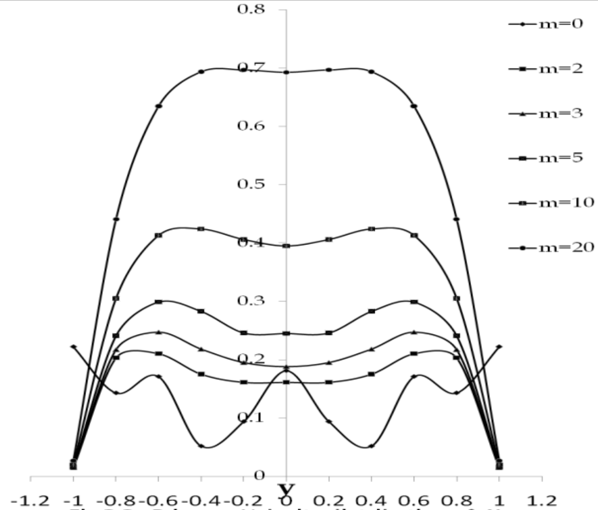

Fig.2.3 Primary Velocity distribution of Non-conducting Plates for different **m** and Fixed with T=2, M=10, Beta=0.01

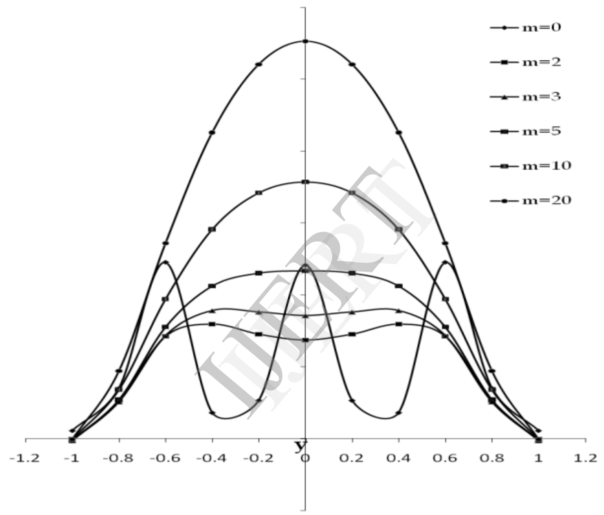

Fig.2.4 Secondary Velocity distribution of Non-conducting Plates for different **m** and Fixed with T=2,M=10,Beta=0.01

ISSN: 2278-0181
Vol. 2 Issue 9, September - 2013

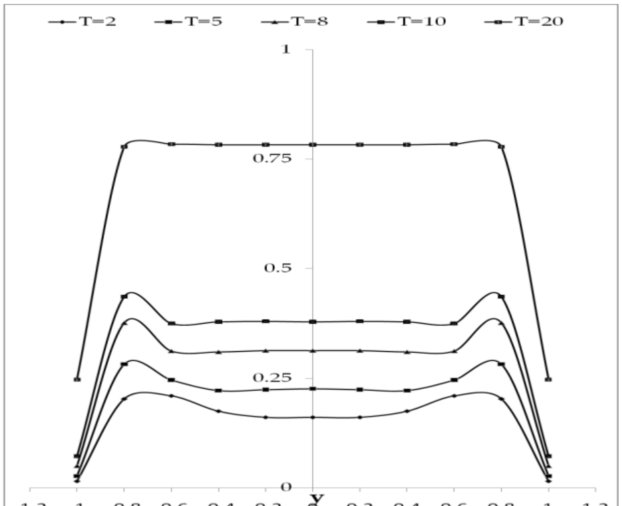

Fig.2.5 Primary Velocity distribution of Non-conducting Plates for differentT and Fixed with M=10, m=2, B=0.01

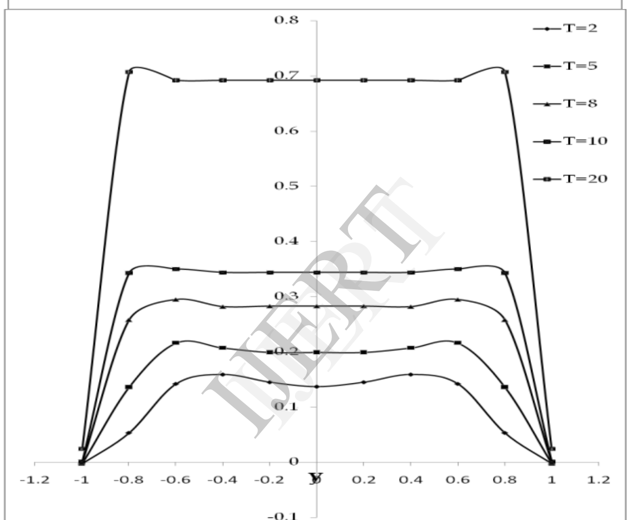

Fig.2.6 Secondary Velocity distribution of Non-Conducting Plates for different T and Fixed with M=10, m=2, B=0.01

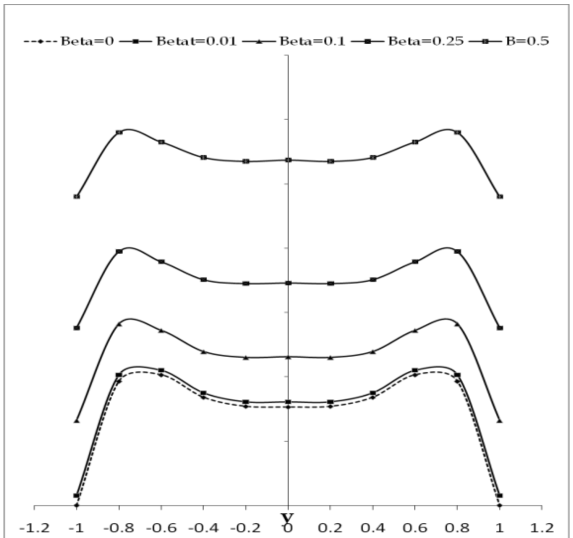

Fig.2.7 Primary Velocity distribution of Non-conducting Plates for different **Beta** Values and Fixed with T=m=2,M=10,

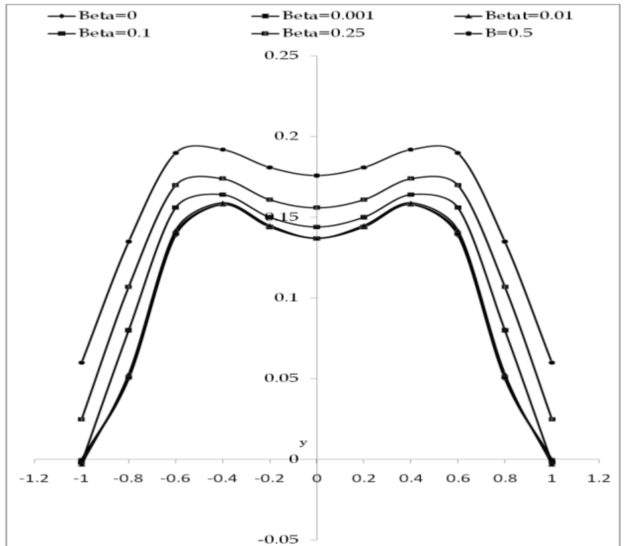

Fig 2.8 Secondary velocity distribution of Non-conducting Plates for different **Beta** values and fixed with T=m=2, M=10.

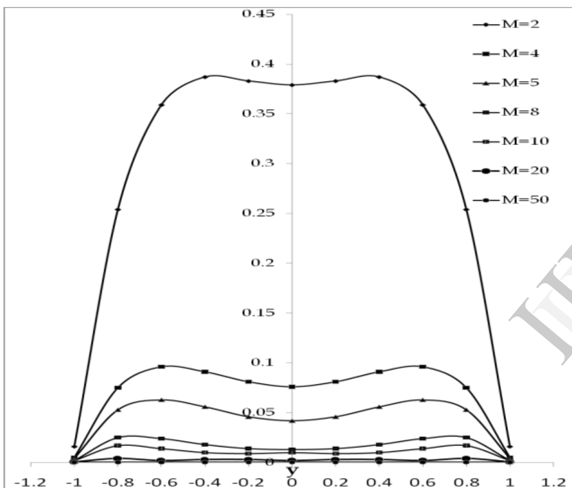

Fig.2.9 Primary Velocity distribution of Conducting Plates for different **M** and Fixed with T=m=2, Beta=0.01, **s=0**

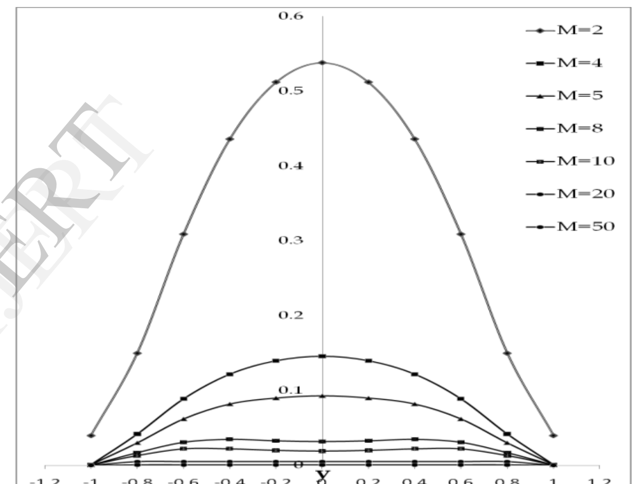

Fig.2.10 secondary Velocity distribution of Conducting Plates for different **M** and Fixed with T=m=2, Beta=0.01, s=0

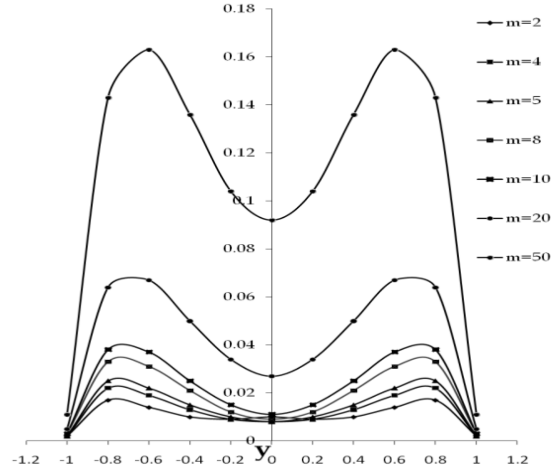

Fig.2.11 Primary Velocity distribution of Conducting Plates for different **m** and Fixed with T=2, M=10, Beta=0.01 ,s=0

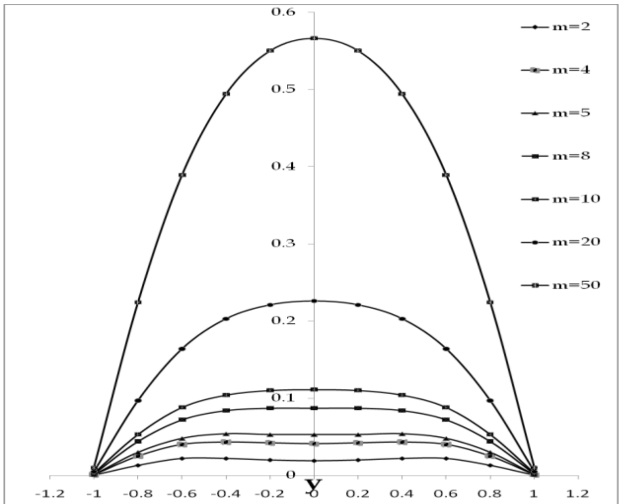

Fig.2.12 secondary Velocity distribution of Conducting Plates for different **m** and Fixed with T=2, M=10, Beta=0.01, s=0

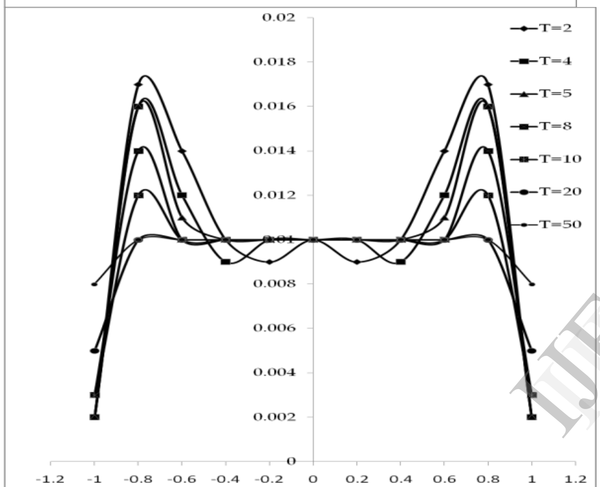

Fig.2.13 Primary Velocity distribution of Conducting Plates for different **T** and Fixed with M=10, m=2, Beta=0. 01, s=0

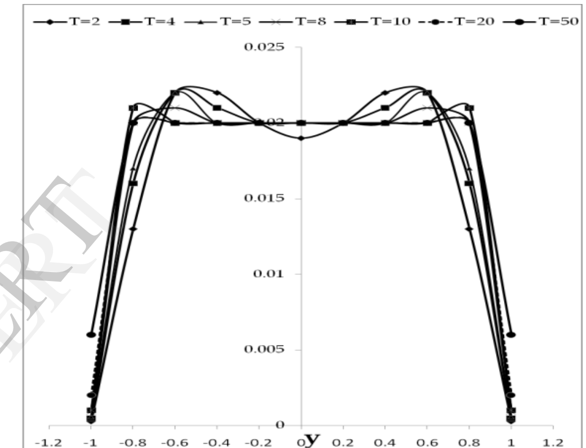

Fig.2.14 Secondary Velocity distribution of Conducting Plates for different **T** and Fixed with M=10, m=2, Beta=0.01 , s=0.

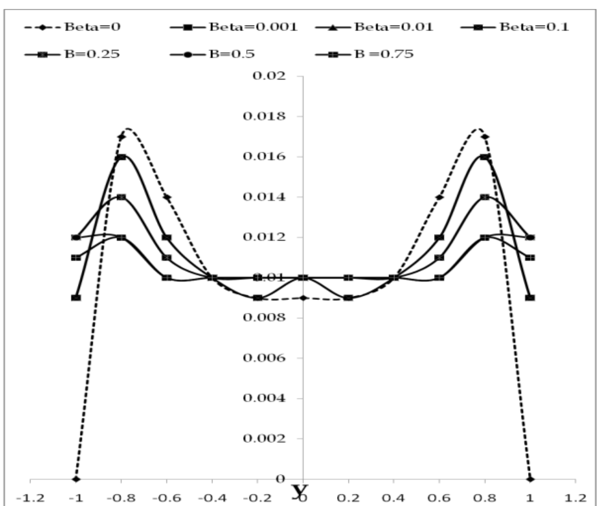

Fig.2.15 Primary Velocity distribution of Conducting Plates for different **Beta** values and Fixed with T=m=2, M=10, s=0

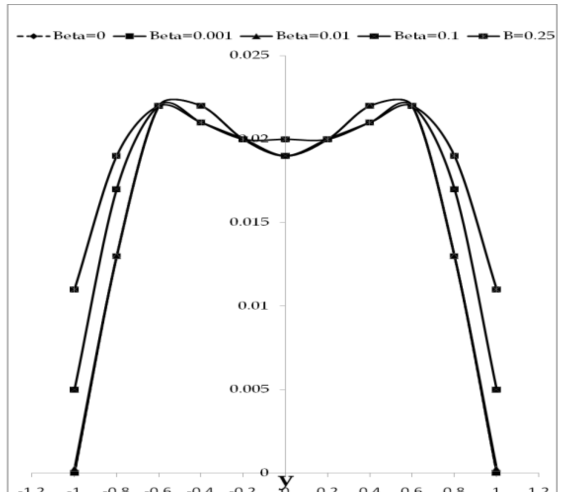

Fig.2.16 secondary Velocity distribution of Conducting Plates for different **Beta** values and Fixed with T=m=2, M=10, s=0

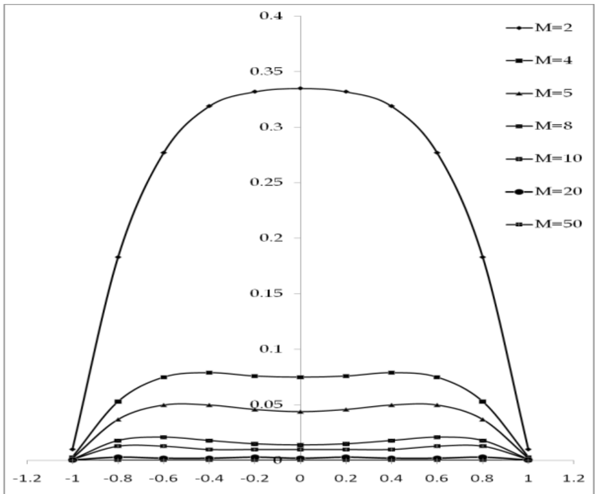

Fig.2.17 Primary Velocity distribution of Conducting Plates for different M and Fixed with T=m=2, Beta=0.01, s=0.5

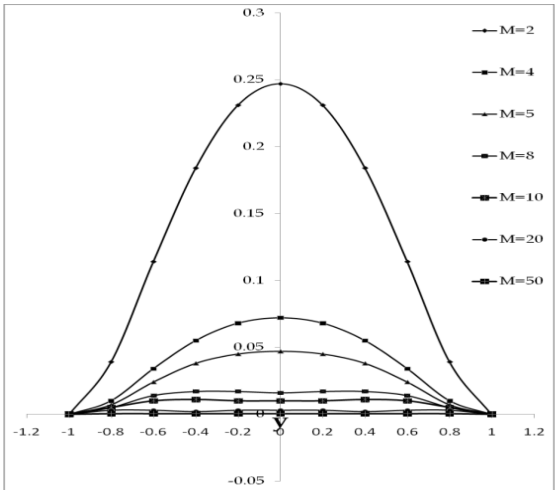

Fig.2.18 Secondary Velocity distribution of Conducting Plates for different M and Fixed with T=m=2, Beta=0.01 , s=0.5

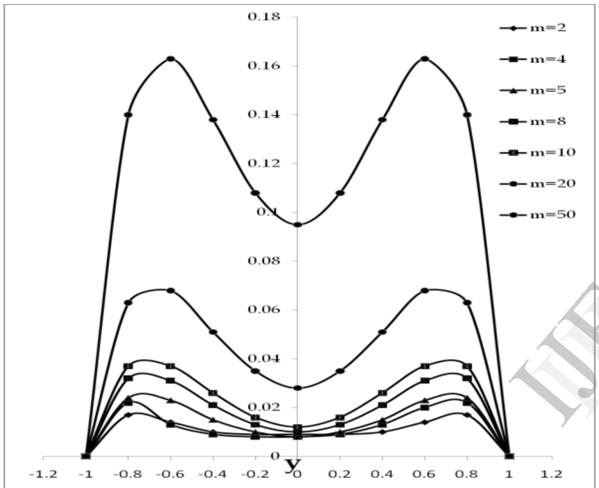

Fig.2.19 Primary Velocity distribution of Conducting Plates for different m and Fixed with T=2, M=10, Beta=0.01, s=0.5

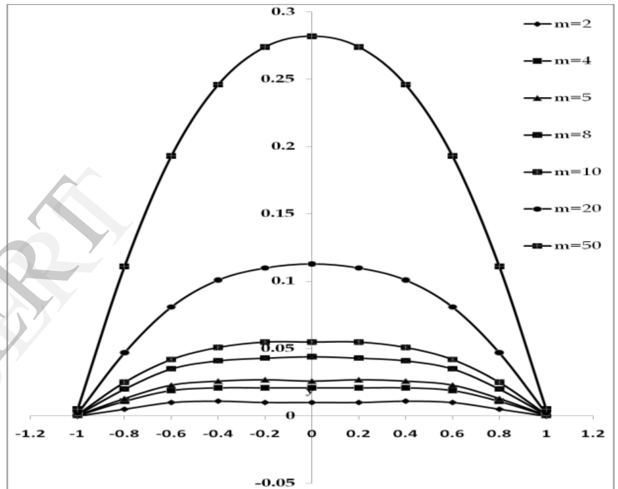

Fig.2.20 secondary Velocity distribution of Conducting Plates for different m and Fixed with T=2,M=10,Beta=0.01,s=0.5

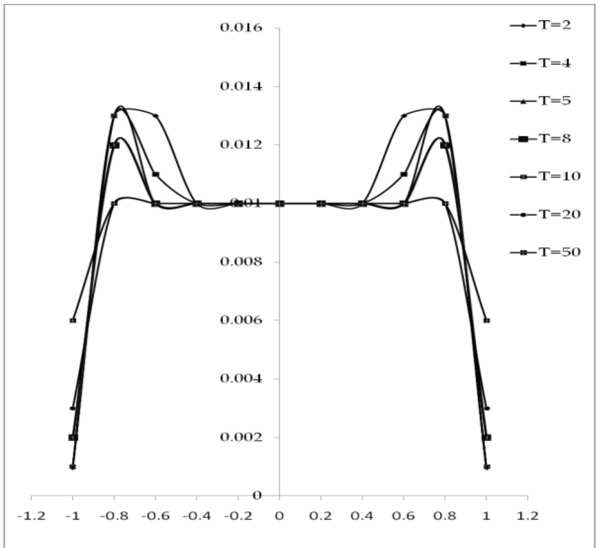

Fig 2. 21 Primary Velocity distribution of Conducting Plates for different **T** and Fixed with M=10, m=2, Beta=0.01, s=0.5

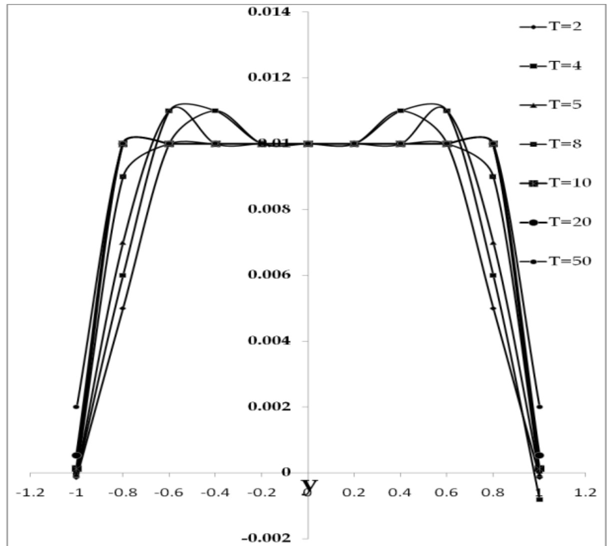

Fig.2.22 Secondary Velocity distribution of Conducting Plates for different **T** and Fixed with M=10, m=2, Beta=0.01, s=0.5

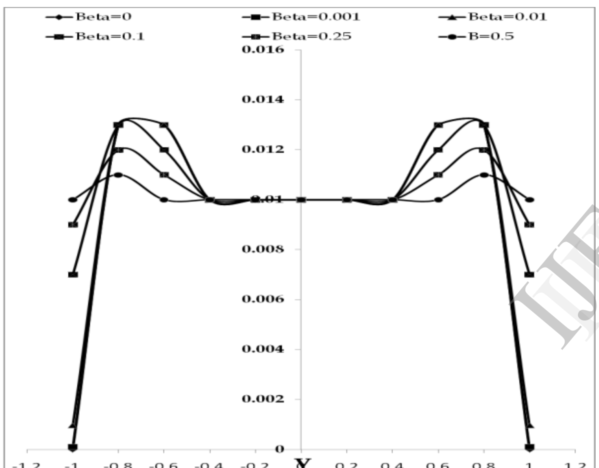

Fig.2.23 Primary velocity distribution of Conducting Plates for different **Beta** values and Fixed with T=2,m=2 M=10, s=0.5

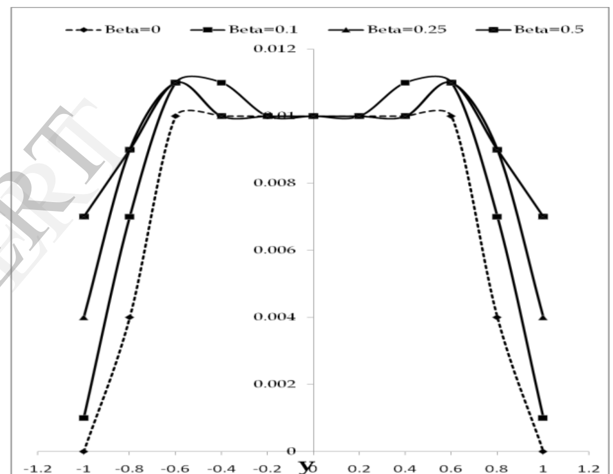

Fig.2.24 secondary Velocity distribution of Conducting Plates for different **Beta** values and Fixed with T=m=2, M=10, s=0.5

Figures 9 to 16 and 17 to 24 represent the graphs for both primary and secondary velocity distributions in two cases of s=0 and s=1/2 respectively. For the case when s=0 and s=1/2, it is noticed that both the distributions tend to decrease as M increases with fixed m, T and β. While for fixed M, T, β and an increase in m increases the primary and secondary velocity distributions. But with an increase in T, there is no significant variation in the primary velocity distributions for the cases when s=0 and s=1/2. While the secondary velocity distribution decreases in case of s=0 and it increases in case of s = ½. Further it is concluded that, the primary velocity distribution u decreases but the secondary velocity distribution increases as the slip parameter β increases with a fixed values of M, m and T in both the cases s=0 and s=1/2.

§ 6 Conclusion

The problem of an ionized hydromagnetic slip-flow between two parallel walls in a rotating system, when both the walls are made up of non-conducting (insulating) and conducting materials is considered by taking the effects of Hall currents in to account. It is assumed that the magnetic Reynolds number is small. Exact solutions for the primary and secondary velocity distributions and their corresponding mean velocities are obtained by applying the slip boundary conditions at both the walls. Also discussed the flow features for different values of the governing parameters involved such as, the rotation parameter T, the Hartmann number M, the Hall parameter m, slip parameter β and the ionization parameter s (the ratio of the electron pressure to the total pressure). The velocity distributions are found to be independent of s, in case of non-conducting walls and are depending on this parameter s, in the case of conducting walls. In case of the non-conducting walls, it is observed that, an increase in the Hartmann number is to decrease both the primary and secondary velocity distributions for fixed Hall parameter, Rotation parameter and slip parameter. It is noticed that, the small Hall parameter (say upto 2), diminishes the velocity distributions, while for values of this parameter (say, above 2), they tend to enhance. It is found that, the profiles of the velocity distributions tend to increase with an increase in the rotation or the slip parameter.

In case of conducting walls and for the cases when the ionization parameter, s= 0 and 1/2, it is noticed that, both the distributions tend to decrease as the Hartmann number increases with fixed Hall parameter, Taylor number and slip parameter. While, an increase in Hall parameter increases the primary and secondary velocity distributions for fixed Hartmann number, Taylor number, slip parameter. But with an increase in Taylor number, there is no significant variation in the primary velocity distributions. While the secondary velocity distribution decreases in case of ionization parameter equal to zero and it increases in case of ionization parameter equal to half. Further it is concluded that, the primary velocity distribution decreases, but the secondary velocity distribution increases as the slip parameter increases with the increasing values of Hartmann number, Hall parameter and Taylor number.

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