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An Unsteady MHD Flow Past a Porous Flat Plate on Taking Hall Currents into account

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Abstract- **study of an unsteady hydro-magnetic flow of a viscous incompressible electrically conducting fluid bounded by an infinitely long porous flat plate in the presence of Hall currents taken into account has been investigated. Initially ($t = 0$), the fluid at infinity moves with a uniform velocity in the direction of the flow. At time $t > 0$, the plate suddenly moves with the same uniform velocity in the direction of the flow. The governing equations are solved analytically using the Laplace transform technique. The solutions are also obtained for small and large times. The effects of pertinent parameters on the velocity field and the shear stress at the porous plate are exhibited with the help of graphs and tables. It is interesting to note that the series solution of fluid motion converge more quickly than the exact solution for small times.**

Keywords: *Magnetic Parameter, Hall Currents, Suction parameter, time, general solution and solutions for small time.*

1 INTRODUCTION

The effects of transversely applied magnetic field on the flow of an electrically conducting viscous fluids have been discussed widely owing to their astrophysics, geophysical and engineering applications. When the strength of the magnetic field is strong, one cannot neglect the effects of Hall current. In an ionized gas where the density is low and/or the magnetic field is very strong, the conductivity normal to the magnetic field is reduced due to the free spiraling of electrons and ions about the magnetic lines of force before suffering collisions and a current is induced in a direction normal to both the electric and the magnetic fields. This phenomenon, well known in the literature, is called the Hall effect. The study of hydromagnetic viscous flows with Hall currents has important engineering applications in problems of magnetohydrodynamic generators and of Hall accelerators as well as in flight magnetohydrodynamics. The unsteady hydromagnetic flow of an incompressible electrically conducting viscous fluid induced by a porous plate is of considerable interest in the technical field due to its frequent occurrence in industrial and technological applications. Pop and Soundalgekar [1] have investigated the effects of Hall currents on hydromagnetic flow near a porous plate. The hydromagnetic flow past a porous flat plate with Hall effects has been studied by Gupta[2]. Debnath et al.[3] have discussed the effects of Hall current on an unsteady hydromagnetic flow past a porous plate in a rotating fluid system. Hossain[4] has studied the effect of Hall current on an unsteady hydromagnetic free convection flow near an infinite vertical porous plate. The effect of Hall current on hydromagnetic free convection flow near an accelerated porous plate has been studied by Hossain and Mohammad [5]. Mazumder[6] has studied the combined effect of Hall current and rotation on hydromagnetic flow over an oscillating porous plate. Maji et al. [7] have studied the Hall effects on hydromagnetic flow on an oscillatory porous plate. Hall effects on the magnetohydrodynamic shear flow past an infinite porous flat plate subjected to uniform suction or blowing have been investigated by Gupta et al. [8]. Hall effects on unsteady hydromagnetic flow past an accelerated porous plate in a rotating system have been studied by Das et al. [9]. Das et al. [10] have investigated Hall effects on unsteady MHD rotating flow past a periodically accelerated porous plate with slippage. Hall effect on MHD transient flow past an impulsively started infinite horizontal porous plate in a rotating system has been studied by Reddy [11]. Characteristics of MHD Casson fluid past an inclined vertical porous plate have been investigated by Reddy et al. [12].

The objective of the present paper is to analyze the effects of Hall currents on an unsteady hydromagnetic flow of a viscous incompressible electrically conducting fluid induced by an infinitely long porous flat plate in the presence of a uniform transverse magnetic field. Initially $t = 0$ the fluid at infinity moves with uniform velocity U_0. At time $t > 0$, the plate suddenly moves with uniform velocity U_0 in the direction of the flow. An exact solution of the governing equation has been obtained by using Laplace transform technique. In order to verify the results obtained exactly another solution which is valid for small times is also obtained. The solution for the flow describing the large time is also derived.

2 FORMULATION

Consider an unsteady MHD flow of a viscous incompressible electrically conducting fluid filling the semi infinite space $z \geq 0$ confined to the an infinitely long flat porous plate of finite dimension. Consider the cartesian coordinates system with x-axis along the plate , y-axis is perpendicular to the plate and z axis is normal to the xy plane in the vertically upward direction [See Fig.1]. A uniform magnetic field of strength B_0 is imposed perpendicular to the plane of the plate. Initially, the fluid flows past an infinitely long porous flat plate with free-stream velocity U_0 along x-axis. At time $t > 0$, the plate suddenly starts to move with same uniform velocity as that of the free stream velocity U_0. Since the plates are infinitely long, all physical variables, except pressure, depend on z only.

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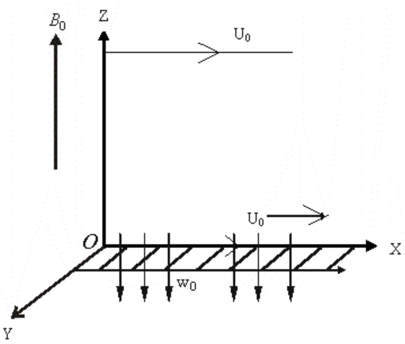

Fig.1: Geometry of the problem.

At time $t = 0$, for the velocity components u, v, w in the directions x, y and z axes, the momentum equations for the steady flow are

$$-w_0 \frac{du}{dz} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu \frac{d^2u}{dz^2} + \frac{B_0}{\rho} j_y, \qquad (1)$$

$$-w_0 \frac{dv}{dz} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu \frac{d^2v}{dz^2} - \frac{B_0}{\rho} j_x, \qquad (2)$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z}, \qquad (3)$$

where p is the modified pressure including centrifugal force, ρ the density of the fluid, ν the kinematic coefficient of viscosity and $\vec{j} \equiv (j_x, j_y, j_z)$ the current density vector.

The boundary conditions are

$$u = 0, v = 0 \text{ at } z = 0 \text{ and } u \to U_0, v \to 0 \text{ as } z \to \infty. \qquad (4)$$

The generalized Ohm's law, on taking Hall currents into account and neglecting ion-slip and thermo-electric effect, is (see Cowling [13])

$$\vec{j} + \frac{\omega_e \tau_e}{B_0}\left(\vec{j} \times \vec{B}\right) = \sigma\left(\vec{E} + \vec{q} \times \vec{B}\right), \qquad (5)$$

where $\vec{B}$ is the magnetic field vector, $\vec{E}$ the electric field vector, ω_e the cyclotron frequency, τ_e the collision time of electron and σ the electrical conductivity.

We shall assume that the magnetic Reynolds number for the flow is small so that the induced magnetic field can be neglected. This assumption is justified since the magnetic Reynolds number is generally very small for partially ionized gases. The solenoidal relation $\nabla . \vec{B} = 0$ for the magnetic field gives $B_z = B_0 =$ constant everywhere in the fluid where $\vec{B} \equiv (B_x, B_y, B_z)$. The equation of conservation of the charge $\nabla \cdot \vec{j} = 0$ gives $j_z =$ constant. This constant is zero since $j_z = 0$ at the plate which is electrically non-conducting. Thus $j_z = 0$ everywhere in the flow. Since the induced magnetic field is neglected, the Maxwell's equation $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ becomes $\nabla \times \vec{E} = 0$ which in turn gives $\frac{\partial E_x}{\partial z} = 0$ and $\frac{\partial E_y}{\partial z} = 0$. This implies that $E_x =$ constant and $E_y =$ constant everywhere in the flow.

In view of the above assumption, equation (5) gives

$$j_x + m j_y = \sigma(E_x + vB_0), \qquad (6)$$

$$j_y - m j_x = \sigma\left(E_y - uB_0\right), \qquad (7)$$

where $m = \omega_e \tau_e$ is the Hall parameter. Since the magnetic field is uniform in the free stream so that there is no current and hence, we have

$$j_x \to 0, j_y \to 0 \text{ as } z \to \infty. \qquad (8)$$

On the use of (8), equations (6) and (7) give

$$E_x = 0, E_y = 0, \qquad (9)$$

everywhere in the flow. Substituting the above values of E_x and E_y in the equations (6) and (7) and solving for j_x and j_y, we get

$$j_x = \frac{\sigma B_0}{1+m^2}(v + m\, u), \qquad (10)$$

$$j_y = -\frac{\sigma B_0}{1+m^2}(u - m\, v). \qquad (11)$$

Under usual boundary layer approximations and on the use of (10) and (11), equations (1) and (2) become

$$-w_0 \frac{du}{dz} = \nu \frac{d^2u}{dz^2} - \frac{\sigma B_0^2}{\rho(1+m^2)}[(u - U_0) - m\, v], \qquad (12)$$

$$-w_0 \frac{dv}{dz} = \nu \frac{d^2v}{dz^2} - \frac{\sigma B_0^2}{\rho(1+m^2)}[v + m(u - U_0)]. \qquad (13)$$

Introducing the non-dimensional variables

$$\eta = \frac{U_0 z}{\nu}, (u_1, v_1) = \frac{(u,v)}{U_0}, \quad i = \sqrt{-1}, \qquad (14)$$

equations (12) and (13) become

$$-S\frac{du_1}{d\eta} = \frac{d^2u_1}{d\eta^2} - \frac{M^2}{(1+m^2)}[(u_1 - 1) - m\, v_1], \qquad (15)$$

$$-S\frac{dv_1}{d\eta} = \frac{d^2v_1}{d\eta^2} - \frac{M^2}{(1+m^2)}[v_1 + m\,(u_1 - 1)], \qquad (16)$$

where $S = \frac{w_0}{U_0}$ is the suction parameter and $M^2 = \frac{\sigma \nu B_0^2}{\rho U_0^2}$ the magnetic parameter.

Corresponding boundary conditions become

$$u_1 = 0 = v_1 \text{ at } \eta = 0 \text{ and } u_1 \to 1, v_1 \to 0 \text{ as } \eta \to \infty.$$

Combining equations (15) and (16), we get

$$-S\frac{dF}{d\eta} = \frac{d^2F}{d\eta^2} - \frac{M^2(1+im)}{1+m^2}(F - 1), \qquad (18)$$

where

$$F = u_1 + i\, v_1. \qquad (19)$$

Corresponding boundary conditions are

$$F = 0 \text{ at } \eta = 0 \text{ and } F \to 1 \text{ as } \eta \to \infty. \qquad (20)$$

The solutions of the equation (18) subject to the boundary conditions (20) are given by

$$u_1 = 1 - e^{-\alpha\eta}\cos\beta\eta, \qquad (21)$$

$$v_1 = e^{-\alpha\eta}\sin\beta\eta, \qquad (22)$$

where

$$\alpha = \frac{S}{2} + \frac{1}{\sqrt{2}}\left[\left\{\left(\frac{S^2}{4} + \frac{M^2}{1+m^2}\right)^2 + \left(\frac{mM^2}{1+m^2}\right)^2\right\}^{\frac{1}{2}} + \left(\frac{S^2}{4} + \frac{M^2}{1+m^2}\right)\right]^{\frac{1}{2}},$$

$$\beta = \frac{1}{\sqrt{2}}\left[\left\{\left(\frac{S^2}{4} + \frac{M^2}{1+m^2}\right)^2 + \left(\frac{mM^2}{1+m^2}\right)^2\right\}^{\frac{1}{2}} - \left(\frac{S^2}{4} + \frac{M^2}{1+m^2}\right)\right]^{\frac{1}{2}}. \qquad (23)$$

The solutions given by (21) and (22) is valid for both suction $(S > 0)$ and blowing $(S < 0)$ at the plate.

At time $t > 0$, the plate suddenly moves with uniform velocity U_0 along x-axis in the direction of flow. Then the unsteady fluid flow be governed by the following system of equations:

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$$\frac{\partial u}{\partial t} - w_0\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{\partial^2 u}{\partial z^2} - \frac{\sigma B_0^2}{\rho(1+m^2)}(u - mv), \quad (24)$$

$$\frac{\partial v}{\partial t} - w_0\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\frac{\partial^2 v}{\partial z^2} - \frac{\sigma B_0^2}{\rho(1+m^2)}(v + mu), \quad (25)$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z}. \quad (26)$$

Corresponding initials and boundary conditions are

$$u = U_0, v = 0 \text{ at } z = 0, \quad t > 0 \text{ and}$$
$$u \to U_0, \quad v \to 0 \text{ as } z \to \infty, \quad t \geq 0. \quad (27)$$

Using infinity conditions equations (24) and (25) become

$$\frac{\partial u}{\partial t} - w_0\frac{\partial u}{\partial z} = \nu\frac{\partial^2 u}{\partial z^2} - \frac{\sigma B_0^2}{\rho(1+m^2)}[(u - U_0) - mv] \quad ,(28)$$

$$\frac{\partial v}{\partial t} - w_0\frac{\partial v}{\partial z} = \nu\frac{\partial^2 v}{\partial z^2} - \frac{\sigma B_0^2}{\rho(1+m^2)}[v + m(u - U_0)]. \quad (29)$$

Introducing the non-dimensional variables

$$\eta = U_0 z/\nu, (u_1, v_1) = \frac{(u,v)}{U_0}, \tau = U_0^2 t/\nu, i = \sqrt{-1}, \quad (30)$$

Equations (28) and (29) become

$$\frac{\partial u_1}{\partial \tau} - S\frac{\partial u_1}{\partial \eta} = \frac{\partial^2 u_1}{\partial \eta^2} - \frac{M^2}{(1+m^2)}[(u_1 - 1) - mv_1], \quad (31)$$

$$\frac{\partial v_1}{\partial \tau} - S\frac{\partial v_1}{\partial \eta} = \frac{\partial^2 v_1}{\partial \eta^2} - \frac{M^2}{(1+m^2)}[v_1 + m(u_1 - 1)], \quad (32)$$

Combining equations (31) and (32) we get

$$\frac{\partial F}{\partial \tau} - S\frac{\partial F}{\partial \eta} = \frac{\partial^2 F}{\partial \eta^2} - \frac{M^2(1+im)}{1+m^2}F, \quad (33)$$

where

$$F = u_1 + iv_1 - 1. \quad (34)$$

Corresponding initial and the boundary conditions for $F(\eta, \tau)$ are

$$F(\eta, 0) = F(\eta)\eta \geq 0, \quad (35)$$
$$F(0, \tau) = 0 \text{ for } \tau > 0,$$
$$F(\infty, \tau) = 0 \text{ for } \tau \geq 0, \quad (36)$$

where $F(\eta)$ is given by (19).

To solve the equation (33), we assume

$$F(\eta, \tau) = H(\eta, \tau)e^{-\lambda\tau}, \quad (37)$$

where

$$\lambda = \frac{M^2(1+im)}{1+m^2}. \quad (38)$$

Using (37), the equation (33) becomes

$$\frac{\partial H}{\partial \tau} - S\frac{\partial H}{\partial \eta} = \frac{\partial^2 H}{\partial \eta^2}, \quad (39)$$

with the initial and boundary conditions

$$H(\eta, 0) = F(\eta) \text{ for } \eta \geq 0, \quad (40)$$
$$H(0, \tau) = 0 \text{ for } \tau > 0,$$
$$H(\infty, \tau) = 0 \text{ for } \tau \geq 0. \quad (41)$$

Taking Laplace transformation of (39) and solving the resulting equation subject to the initial and boundary conditions (40) and (41), we get

$$\bar{H}(\eta, s) = \frac{e^{-(S/2+\sqrt{S^2/4+s})\eta}}{s-\lambda} - \frac{e^{-(\alpha+i\beta)\eta}}{s-\lambda}. \quad (42)$$

where

$$\bar{H}(\eta, s) = \int_0^\infty H(\eta, \tau)e^{-s\tau}\, d\tau \quad (43)$$

The inverse Laplace transformation of (42) on using (37) and (34), we get

$$u_1 + i\,v_1 = 1 - e^{-(\alpha+i\beta)\eta} + \frac{1}{2}e^{-\frac{S}{2}\eta}[e^{(a+ib)\eta}\text{erfc}\left(\frac{\eta}{2\sqrt{\tau}} + (a + ib)\sqrt{\tau}\right) + e^{-(a+ib)\eta}\,\text{erfc}\left(\frac{\eta}{2\sqrt{\tau}} - (a + ib)\sqrt{\tau}\right)], \quad (44)$$

where

$$a, b = \frac{1}{\sqrt{2}}\left[\left\{\left(\frac{S^2}{4} + \frac{M^2}{1+m^2}\right)^2 + \left(\frac{mM^2}{1+m^2}\right)^2\right\}^{\frac{1}{2}} \pm \left(\frac{S^2}{4} + \frac{M^2}{1+m^2}\right)\right]^{\frac{1}{2}}. \quad (45)$$

On separating into real and imaginary parts one can easily obtain the velocity components u_1 and v_1 from the equation (44). The solution given by (44) is valid for both suction ($S > 0$) and blowing ($S < 0$) at the plate.

SOLUTION AT SMALL TIMES:

In this case, we use the method which is previously used by Carslaw and Jaegar [14] since it converges rapidly for small times. For small time $\tau(<< 1)$ and large $S(>> 1)$ on taking inverse Laplace transformation of (42) we get,

$$H(\eta, \tau) = e^{-\frac{S}{2}\eta - \frac{1}{4}S^2\tau}\sum_{n=0}^{\infty}\left(\frac{S^2}{4} + \lambda\right)^n(4\tau)^n i^{2n}\text{erfc}(\eta/2\sqrt{\tau}) - e^{-(\alpha+i\beta)\eta+\lambda\tau}. \quad (46)$$

On the use of (37), equation (46) becomes

$$F(\eta, \tau) = e^{-\frac{S}{2}\eta - \frac{S^2}{4}\tau - \lambda\tau}\sum_{n=0}^{\infty}\left(\frac{S^2}{4} + \lambda\right)^n(4\tau)^n i^{2n}\text{erfc}(\eta/2\sqrt{\tau}) - e^{-(\alpha+i\beta)\eta},$$

where $i^n\text{erfc}(.)$ denotes the repeated integrals of the complementary error function given by

$$i^n\,\text{erfc}(x) = \int_x^\infty i^{n-1}\text{erfc}(\xi)d\xi, n = 0,1,2,\cdots,$$
$$i^0\,\text{erfc}(x) = \text{erfc}(x), \quad (47)$$
$$i^{-1}\text{erfc}(x) = \frac{2}{\sqrt{\pi}}e^{-x^2}$$

On separating real and imaginary parts, we have the velocity components as

$$u_1 = 1 - e^{-\alpha\eta}\cos\beta\eta + e^{-\left(\frac{S}{2}\eta + \alpha_1\tau\right)}[A(\eta, \tau)\cos\beta_1\tau + B(\eta, \tau)\sin\beta_1\tau], \quad (48)$$

$$v_1 = e^{-\alpha\eta}\,\sin\beta\eta + e^{-\left(\frac{S}{2}\eta + \beta_1\tau\right)}\,[B(\eta, \tau)\cos\beta_1\tau - A(\eta, \tau)\sin\beta_1\tau], \quad (49)$$

where

$$A(\eta, \tau) = T_0 + \alpha_1(4\tau)T_2 + \left(\alpha_1{}^2 - \beta_1{}^2\right)(4\tau)^2 T_4 + \left(\alpha_1{}^3 - 3\alpha_1\beta_1{}^2\right)(4\tau)^3 T_6 + \cdots,$$

$$B(\eta, \tau) = \beta_1(4\tau)T_2 + 2\alpha_1\beta_1(4\tau)^2 T_4 + \left(3\alpha_1{}^2\beta_1 - \beta_1{}^3\right)(4\tau)^3 T_6 + \cdots,$$

$$\alpha_1 = \frac{S^2}{4} + \frac{M^2}{1+m^2}, \beta_1 = \frac{mM^2}{1+m^2}. \quad (50)$$

The above equations show that the Hall effects become important only when terms of order τ is taken into account.

SOLUTION AT LARGE TIMES

For large time τ, the expression (44) can be written as

$$u_1 + i\,v_1 = 1 + \frac{1}{2}e^{-\frac{S}{2}\eta}[e^{(a+ib)\eta}\,\text{erfc}((a + ib)\sqrt{\tau} + \frac{\eta}{2\sqrt{\tau}}) - e^{-(a+ib)\eta}\,\text{erfc}\,((a + ib)\sqrt{\tau} - \frac{\eta}{2\sqrt{\tau}})]. \quad (51)$$

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Further, if $\eta \ll 2\sqrt{\tau}$, $\tau \gg 1$ then the solution becomes

$$u_1 = 1 + \frac{e^{-\frac{S}{2}\eta-(a^2-b^2)\tau}}{(a^2+b^2)\sqrt{\pi\tau}}\left[(a\cos 2ab\,\tau - b\sin 2ab\,\tau)\sinh a\eta\cos b\eta + (b\cos 2ab\,\tau + a\sin 2ab\,\tau)\cosh a\eta\,\sin b\eta\right], \quad (52)$$

$$v_1 = \frac{e^{-\frac{S}{2}\eta-(a^2-b^2)\tau}}{(a^2+b^2)\sqrt{\pi\tau}}\left[(a\cos 2ab\,\tau - b\sin 2ab\,\tau)\cosh a\eta\sin b\eta - (b\cos 2ab\,\tau + a\sin 2ab\,\tau)\sinh a\eta\cos b\eta\right]. \quad (53)$$

The above equations (52) and (53) show the existence of inertial oscillations. The frequency of these oscillations is given by

$$\omega = 2ab = \frac{mM^2}{1+m^2}, \quad (54)$$

which does not occur in the absence of Hall currents.

It is observed from equations (52) and (53) that the Hall parameter not only induced a cross flow but also occurs inertial oscillations of the fluid velocity.

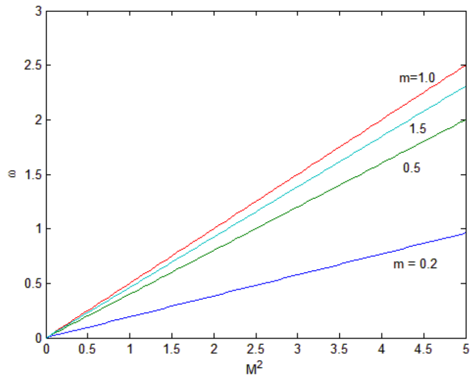

Fig.2: Frequency of oscillations ω for M^2 and m

It is seen from Fig.2 that the frequency of these oscillations ω increases with increase in magnetic field M^2. On the other hand, with an increase in Hall Currents m, the frequency of oscillations ω at first increases, reaches a maximum at $m = 1$ and then decreases.

3 RESULTS AND DISCUSSION

4

In order to gain a clear insight of the physical problem, we have discussed the effects of various physical parameters such as magnetic parameter M^2, Hall parameter m, suction parameter S and time t on the fluid velocity profiles and shear stress at the porous plate. The fluids velocity profiles are shown in Figs.3-12. It is seen from the Figs. 3-12 that the optimum fluid velocity occur in the vicinity of the plate and asymptotically approaches to zero in the free stream region for both the primary and secondary velocity components. It is seen from Figs.3 and 4 that the primary fluid velocity component u_1 increases whereas the secondary fluid velocity component v_1 decreases with an increase in magnetic parameter M^2. That means Magnetic field has accelerating influence on primary flow and retarding influence on secondary flow. Magnetic field regulates the motion. It is observed from Figs.5 and 6 that the primary velocity u_1 decreases whereas the secondary velocity v_1 increases with increase in Hall parameter m. This indicates that the activity of Hall currents on the velocity components opposite to the activity of magnetic field on the velocity components. Figs.7 and 8 indicate the variations of suction parameter S on the primary and secondary flows. It is found that the primary velocity u_1 increases whereas the secondary velocity v_1 decreases with increase in suction parameter S. It is seen from Figs.9 and 10 that the primary velocity u_1 increases whereas the secondary velocity v_1 decreases as time τ progresses. For small values of time, we have drawn the velocity components u_1 and v_1 on using the exact solution given by equation (44) and the series solution given by equations (48) and (49) in Figs.11 and 12. It is seen that the series solution given by (48) and (49) converge more quickly than the exact solution given by (44) for small time.

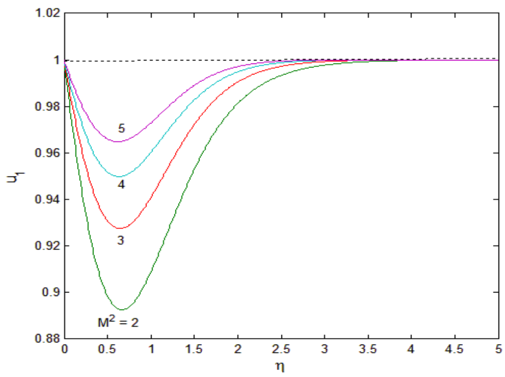

Fig.3: Primary velocity for M^2 when $m = 0.5$, $\tau = 0.2$ and $S = 1.0$

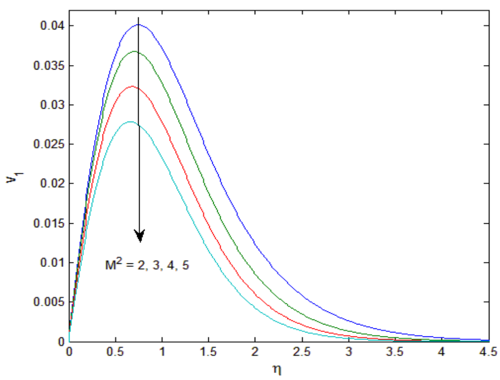

Fig.4: Secondary velocity for M^2 when $m = 0.5$, $\tau = 0.2$ and $S = 1.0$

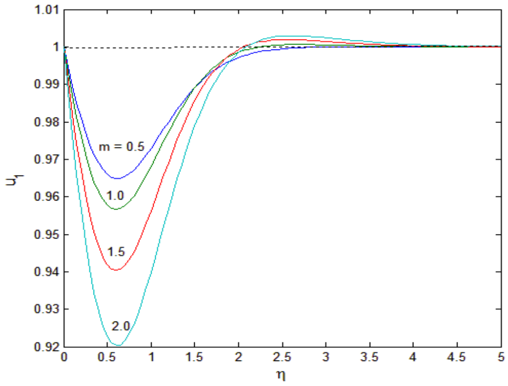

Fig.5: Primary velocity for m when $M^2 = 5, \tau = 0.2$ and $S = 1.0$

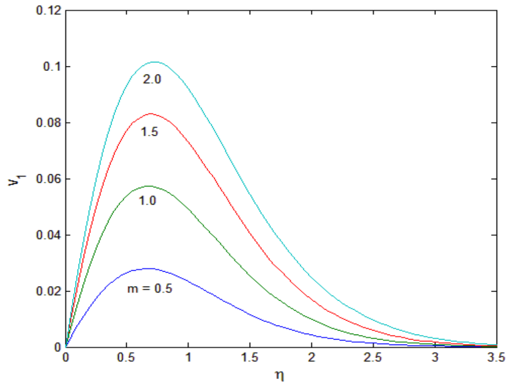

Fig.6: Secondary velocity for m when $M^2 = 5, \tau = 0.2$ and $S = 1.0$

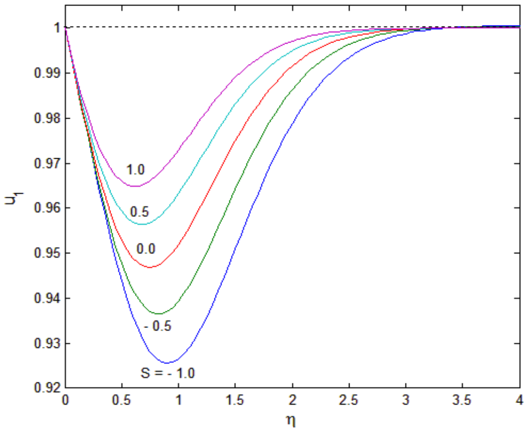

Fig.7: Primary velocity for S when $M^2 = 5, \tau = 0.2$ and $m = 0.5$

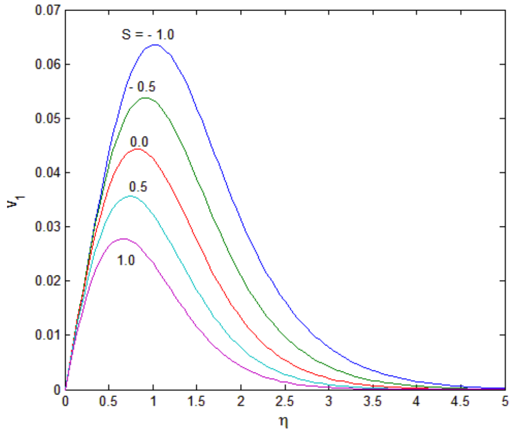

Fig.8: Secondary velocity for S when $M^2 = 5, \tau = 0.2$ and $m = 0.5$

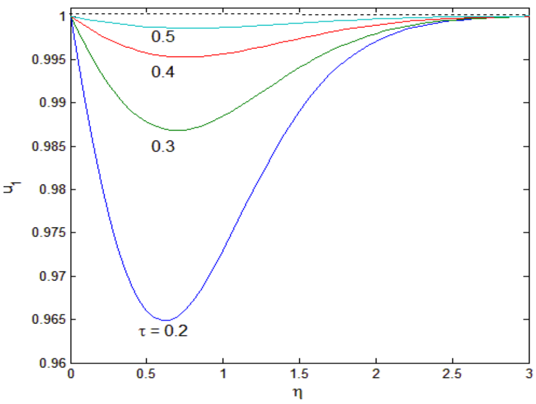

Fig.9: Primary velocity for τ when $M^2 = 5$, $m = 0.5$ and $S = 1.0$

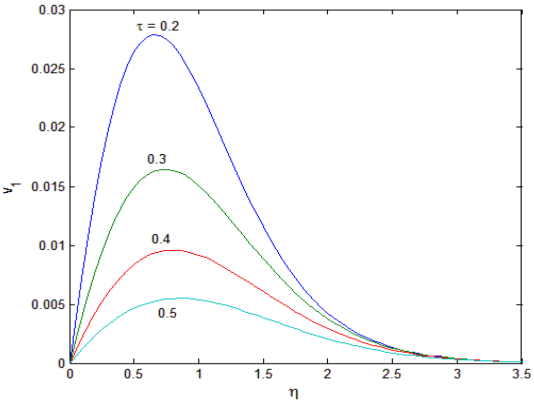

Fig.10: Secondary velocity for τ when $M^2 = 5$, $m = 0.5$ and $S = 1.0$

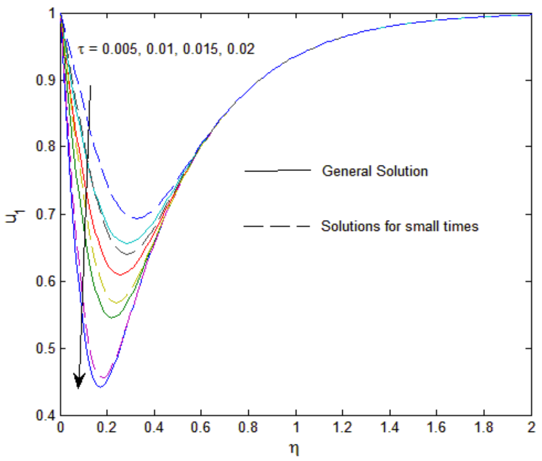

Fig.11: Primary velocity for τ for the general solution and solution for small times when $M^2 = 5$, $m = 0.5$ and $S = 1.0$

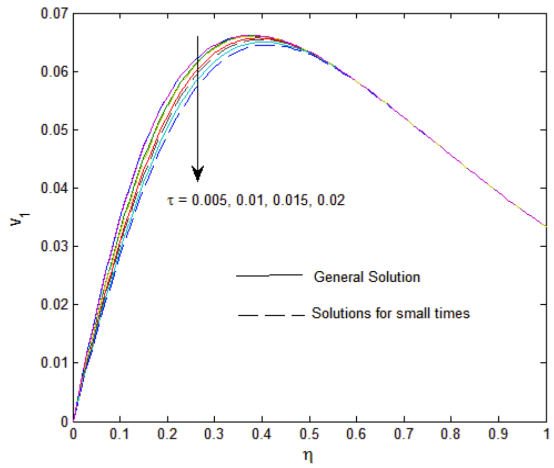

Fig.12: Secondary velocity for τ for the general solution and solution for small times when $M^2 = 5$, $m = 0.5$ and $S = 1.0$

The shear stresses at the plate $\eta = 0$ due to the primary and secondary flow are given by

$$\tau_x + i\tau_y = \left[\frac{\partial F}{\partial \eta}\right]_{\eta=0} = \alpha + i\beta - \left[\frac{S}{2} + (a+ib)\,\mathrm{erf}(a+ib)\sqrt{\tau} + \frac{1}{\sqrt{\pi\tau}} e^{-(a+ib)^2\tau}\right]. \quad (55)$$

The numerical results of the shear stress components τ_x and τ_y are shown in Figs.13 and 14 for different values of Hall parameter m and time τ. It is seen that the magnitude of the shear stress component τ_x and the component τ_y decrease as time τ progresses whereas they increase with an increase in Hall parameter m.

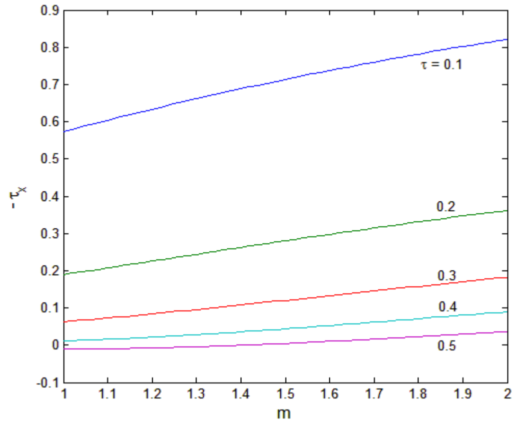

Fig.13: shear stress τ_x at the plate $\eta = 0$ due to the primary flow when $M^2 = 5$ and $S = 1.0$

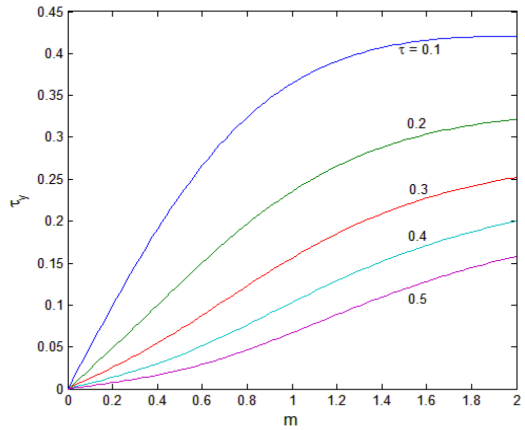

Fig.14: shear stress τ_y at the plate $\eta = 0$ due to the Secondary flow when $M^2 = 5$ and $S = 1.0$

For small times, the shear stress at the plate $\eta = 0$ due to primary and the secondary flows can be obtained as

$$\tau_x = \left[\frac{\partial u_1}{\partial \eta}\right]_{\eta=0} = \alpha - \frac{1}{2} e^{-\alpha_1 \tau}[P(0,\tau)\cos\beta_1\tau + Q(0,\tau)\sin\beta_1\tau], \quad (56)$$

$$\tau_y = \left[\frac{\partial v_1}{\partial \eta}\right]_{\eta=0} = \beta - \frac{1}{2} e^{-\alpha_1 \tau}[Q(0,\tau)\cos\beta_1\tau - P(0,\tau)\sin\beta_1\tau], \quad (57)$$

where

$$P(0,\tau) = \left(ST_0 + Y_{-1}/\sqrt{\tau}\right) + \alpha_1(4\tau)\left(ST_2 + Y_1/\sqrt{\tau}\right) + \left({\alpha_1}^2 - {\beta_1}^2\right)(4\tau)^2\left(ST_4 + Y_3/\sqrt{\tau}\right) + \left({\alpha_1}^3 - 3\alpha_1{\beta_1}^2\right)(4\tau)^3\left(ST_6 + Y_5/\sqrt{\tau}\right) + \cdots, \quad (58)$$

$$Q(0,\tau) = \beta_1(4\tau)\left(ST_2 + Y_1/\sqrt{\tau}\right) + 2\alpha_1\beta_1(4\tau)^2\left(ST_4 + Y_3/\sqrt{\tau}\right) + \left(3{\alpha_1}^2\beta_1 - {\beta_1}^3\right)(4\tau)^3\left(ST_6 + Y_5/\sqrt{\tau}\right) + \cdots, \quad (59)$$

with

$$\frac{dT_{2n}}{d\eta} = -\frac{Y_{2n-1}}{2\sqrt{\tau}},$$

where $Y_{2n-1} = i^{2n-1}erfc(\eta/2\sqrt{\tau})$. (60)

We compare the the numerical values of the shear stress components for general solution and the solution for small times. It is observed from Tables-1 and 2 that for small time, values of shear stresses give higher result than the values of shear stresses for general solution.

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Table-1

Shear stress due to primary flow for $M^2 = 5, S = 1.0$

	$-\tau_x$(For General solution)			$-\tau_x$(Solution for small times)		
m\τ	0.005	0.010	0.015	0.005	0.010	0.015
0.0	5.896093	3.644242	2.673381	5.896093	3.644238	2.673358
0.5	6.032860	3.765285	2.782767	6.032872	3.765358	2.782959
1.0	6.290388	3.998794	2.998242	6.290404	3.998886	2.998493
1.5	6.515985	4.208713	3.196242	6.515995	4.208762	3.196378

Table-2

Shear stress due to secondary flow for $M^2 = 5, S = 1.0$

	τ_y(For General solution)			τ_y(Solution for small times)		
m\τ	0.005	0.010	0.015	0.005	0.010	0.015
0.0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.5	0.393570	0.361540	0.337486	0.393615	0.361790	0.338174
1.0	0.595888	0.555407	0.524776	0.595908	0.555517	0.525087
1.5	0.660252	0.622620	0.594005	0.660258	0.622650	0.594089

4 CONCLUSION

The goal of this paper is to investigate the effect of Hall currents on an unsteady hydromagnetic flow of a viscous incompressible electrically conducting fluid bounded by an infinitely long flat porous plate in the presence of a uniform transverse magnetic field. The non-dimensional form of the governing equations of the fluid flow have been solved by the Laplace transform technique. Some conclusions of the study are as below:

• The optimum fluid velocity occur in the vicinity of the plate and asymptotically approaches to zero in the free stream region for both the velocity components.

• Magnetic field regulates the fluid motion.

• Hall currents reduces the primary flow whereas it accelerates the secondary flow.

• As time progresses or if we enhance the porosity of the porous plate the primary flow increases but the secondary flow decreases.

• The series solution of fluid motion converge more quickly than the exact solution for small time.

• The magnitude of the shear stress component due to primary flow and the component due to secondary flow decrease as time progresses whereas they increase as Hall current increases.

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