

MHD Transient Flow with Hall Current Past an Accelerated Horizontal Porous Plate in a Rotating System

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ABSTRACT

An exact solution to the problem of an MHD transient flow with Hall current past a uniformly accelerated horizontal porous plate in a rotating system has been presented. The dimensionless governing equations of the flow problem are solved by Laplace transform technique in closed form. A uniform magnetic field is assumed to be applied transversely to the direction of the flow. The expressions for velocity fields and skin-frictions are obtained in non-dimensional form. The primary and secondary velocity distributions and skin-frictions at the plate due to primary and secondary velocity field are demonstrated graphically and the effects of the different parameters namely, rotational parameter, Hartmann number, Hall parameter and acceleration parameter are discussed and the results are physically interpreted.

Keywords: MHD; Rotating System; Transient; Hall Current; Mass Transfer; Skin-Friction

1. Introduction

Many engineering problems are susceptible to MHD analysis. The study of MHD flow problems has achieved remarkable interest due to its application in MHD generators, MHD pumps and MHD flow meters etc. The study of effects of magnetic field on free convection flow is important in liquid metals, electrolytes and ionized gases. Geophysics encounters MHD phenomena in interactions of conducting fluids and magnetic fields. The rotating flow of an electrically conducting fluid in presence of magnetic field has got its importance in Geophysical problems. The study of rotating flow problems are also important in the solar physics dealing with the sunspot development, the solar cycle and the structure of rotating magnetic stars. It is well known that a number of astronomical bodies possess fluid interiors and magnetic fields. Changes that take place in the rate of rotation, suggest the possible importance of hydro magnetic spin-up. The general theory of rotating fluids has received growing interest during last decade because of its application in Cosmic and Geophysical science. In this regard, we may cite the works done by Raptis [1], Singh [2,3], Alam *et al.* [4] and Debnath [5].

MHD in the present form is due to the pioneer contribution of several notable authors like Alfven [6], Cowling [7], Ferraro and Pulmpton [8] etc. It was emphasized by Cowling (1975) that when the strength of the applied magnetic field is sufficiently large, Ohm's law needs to be modified to include Hall current. The Hall effect is due merely to the sideways magnetic force on the drifting free charges. The electric field has to have a component transverse to the direction of the current density to balance this force. In many works of Plasma physics, it is not paid much attention to the effect caused due to Hall current. However, the Hall effect can not be completely ignored if the strength of the magnetic field is high and the number density of electrons is small as it is responsible for the change of the flow pattern of an ionized gas. Hall effect results in a development of an additional potential difference between opposite surfaces of a conductor for which a current is induced perpendicular to both the electric and magnetic field. This current is termed as Hall current. It was discovered in 1879 by Edwin Herbert Hall while working on his doctoral degree at the Johns Hopkins University in Baltimore, Maryland, USA. Pop [9], Kinyanjui *et al.* [10], Archrya *et al.* [11]

and Ahmed and Kalita [12] etc. have presented some model studies on the effect of Hall current on MHD convection flow because of its possible application in the problems of MHD generators and Hall accelerators. An unsteady MHD free convective flow past a vertical porous plate immersed in a porous medium with Hall current, thermal diffusion and heat transfer have been studied by Ahmed *et al.* [13]. Recently, Ahmed and Sarmah [14] have carried out an investigation of MHD transient flow past an impulsively started infinite horizontal porous plate in a rotating system with Hall current.

Due to the importance of studying MHD flow problems in rotating fluid with Hall current, we have proposed in the present paper to investigate an unsteady MHD transient flow with Hall currents past a uniformly accelerated porous plate in a rotating system.

2. Basic Equations

The equations governing the motion of an incompressible viscous electrically conducting fluid in a rotating system in presence of a magnetic field are as under:

Equation of continuity:

$$\nabla \cdot \mathbf{q} = 0 \tag{1}$$

Momentum equation:

$$\rho \left[\frac{\partial \mathbf{q}}{\partial t'} + 2\boldsymbol{\Omega} \times \mathbf{q} + \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r}) + (\mathbf{q} \cdot \nabla) \mathbf{q} \right] = -\nabla p + \mathbf{J} \times \mathbf{B} + \mu \nabla^2 \mathbf{q} \tag{2}$$

Kirchhoff's first law:

$$\nabla \cdot \mathbf{J} = 0 \tag{3}$$

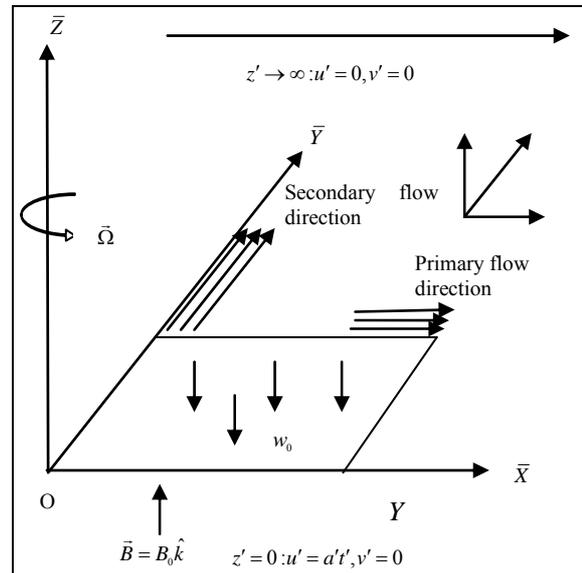
General Ohm's law:

$$\mathbf{J} + \frac{\omega_e \tau_e}{B_0} (\mathbf{J} \times \mathbf{B}) = \sigma \left[\mathbf{E} + \mathbf{q} \times \mathbf{B} + \frac{1}{e\eta_e} \nabla p_e \right] \tag{4}$$

Gauss's law of magnetism:

$$\nabla \cdot \mathbf{B} = 0 \tag{5}$$

where \mathbf{q} is the velocity vector, $\boldsymbol{\Omega}$ the angular velocity of the fluid, \mathbf{r} the position vector of the fluid particle P considered, ρ the fluid density, p the pressure, \mathbf{J} the current density, \mathbf{B} the magnetic induction vector, μ the co-efficient of viscosity, σ the electrical conductivity, t' the time, B_0 the strength of the applied magnetic field, ω_e the electron frequency, τ_e the electron collision time, e the electron charge, η_e the number density of electron, p_e the electron pressure, \mathbf{E} the electric field, $2\boldsymbol{\Omega} \times \mathbf{q}$ is the Coriolis acceleration, $\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r})$ is the centripetal acceleration and the other



Flow configuration

symbols have their usual meanings and the other symbols have their usual meanings.

We now consider an unsteady flow of an incompressible viscous electrically conducting fluid past a suddenly started infinite horizontal porous plate relative to a rotating system with constant suction in presence of a uniform transverse magnetic field taking into account the effect of Hall current. Our investigation is restricted to the following assumptions:

- All the fluid properties are constants and the buoyancy force has no effect on the flow.
- The plate is electrically non-conducting.
- The entire system is rotating with angular velocity $\boldsymbol{\Omega}$ about the normal to the plate and $|\boldsymbol{\Omega}|$ is so small that $|\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r})|$ can be neglected.
- The magnetic Reynolds number is so small that the induced magnetic field can be neglected.
- p_e is constant.
- $\mathbf{E} = \mathbf{0}$.

Initially the plate and the fluid were rotating in unison with a constant angular velocity $\boldsymbol{\Omega}$ about the normal to the plate. At time $t' > 0$, the plate is moved in its own plane relative to the rotating system with acceleration a' . We introduce a coordinate system (x', y', z') with X-axis horizontally in the direction of the plate velocity, Y-axis horizontally perpendicular to the direction of the plate velocity and Z-axis along the normal to the plate which is the axis of rotation. Let $\mathbf{q} = \hat{i}u' + \hat{j}v' + \hat{k}w'$ be the fluid velocity, $\mathbf{J} = J'_x \hat{i} + J'_y \hat{j} + J'_z \hat{k}$ be the current density at the point $P(x', y', z', t')$ and $\mathbf{B} = B_0 \hat{k}$ be the applied magnetic field, $\hat{i}, \hat{j}, \hat{k}$ being the unit vectors along X-axis, Y-axis and Z-axis respectively. As the plate is infinite in X-direction and Y-direction, therefore

all the quantities except possibly the pressure are independent of x' and y' .

The Equation (1) gives

$$\frac{\partial w'}{\partial z'} = 0 \tag{6}$$

which is trivially satisfied by

$$\bar{w} = -w'_0 \tag{7}$$

Therefore the velocity vector \mathbf{q} is given by

$$\mathbf{q} = u'\hat{i} + v'\hat{j} - w'_0\hat{k} \tag{8}$$

The Equation (5) is satisfied by

$$\mathbf{B} = B_0\hat{k} \tag{9}$$

The Equation (3) reduces to

$$\frac{\partial J'_z}{\partial z'} = 0$$

which shows that

$$J'_z = 0 \tag{10}$$

(as the plate is electrically non-conducting).

Hence the current density is given by

$$\mathbf{J} = J'_x\hat{i} + J'_y\hat{j} \tag{11}$$

Under the above assumptions, the Equation (4) takes the form:

$$\mathbf{J} + \frac{m}{B_0}(\mathbf{J} \times \mathbf{B}) = \sigma(\mathbf{q} \times \mathbf{B}) \tag{12}$$

where $m = \omega_e \tau_e$ is the Hall parameter.

The Equations (8)-(12) yield,

$$J'_x = \frac{\sigma B_0 (v' + mu')}{1 + m^2} \tag{13}$$

$$J'_y = \frac{\sigma B_0 (mv' - u')}{1 + m^2} \tag{14}$$

With the foregoing assumptions and under the usual boundary layer approximation the Equation (2) reduces to

$$\frac{\partial u'}{\partial t'} - w'_0 \frac{\partial u'}{\partial z'} - 2\Omega'v' = \nu \frac{\partial^2 u'}{\partial z'^2} + \frac{\sigma B_0^2 (mv' - u')}{\rho(1 + m^2)} \tag{15}$$

$$\frac{\partial v'}{\partial t'} - w'_0 \frac{\partial v'}{\partial z'} + 2u'\Omega' = \nu \frac{\partial^2 v'}{\partial z'^2} - \frac{\sigma B_0^2 (mu' + v')}{\rho(1 + m^2)} \tag{16}$$

with $\frac{\partial p'}{\partial z'} = 0$.

where w'_0 is the constant suction velocity and ν is the kinematic viscosity

The relevant initial and boundary conditions are

$$u' = 0, v' = 0 \text{ for } t' \leq 0, \forall z \tag{17}$$

$$\left. \begin{aligned} u' = at', v' = 0 \text{ at } z' = 0; \\ u' = 0, v' = 0 \text{ at } z' \rightarrow \infty \end{aligned} \right\} \forall t' > 0 \tag{18}$$

We introduce the following non-dimensional variables and parameters:

$$z = \frac{w'_0 z'}{\nu}, t = \frac{w'^2_0 t'}{\nu}, u = \frac{u'}{U'_0}, v = \frac{v'}{U'_0},$$

$$M = \frac{\sigma B_0^2 \nu}{\rho w'^2_0}, \Omega = \frac{2\Omega' \nu}{w_0^2}, a = \frac{a' \nu}{w_0^3}$$

The non-dimensional form of the Equations (15) and (16) are

$$\frac{\partial u}{\partial t} - \frac{\partial u}{\partial z} - \Omega v = \frac{\partial^2 u}{\partial z^2} + \frac{M}{1 + m^2}(mv - u) \tag{19}$$

$$\frac{\partial v}{\partial t} - \frac{\partial v}{\partial z} + \Omega u = \frac{\partial^2 v}{\partial z^2} - \frac{M}{1 + m^2}(mu + v) \tag{20}$$

Subject to the initial and boundary conditions:

$$u = 0, v = 0 \text{ for } t \leq 0, \forall z \tag{21}$$

$$\left. \begin{aligned} u = at, v = 0 \text{ at } z = 0 \\ u = 0, v = 0 \text{ at } z \rightarrow \infty \end{aligned} \right\} \forall t > 0 \tag{22}$$

3. Method of Solution

Let us introduce the complex variable q defined by $q = u + iv$ where $i^2 = -1$.

The non-dimensional forms of the equation governing the flow can be rewritten as follows:

$$\frac{\partial q}{\partial t} = \frac{\partial^2 q}{\partial z^2} + \frac{\partial q}{\partial z} - Aq \tag{23}$$

where $A = i\Omega + \frac{M(1 + im)}{1 + m^2}$

Subject to the boundary conditions:

$$q = 0 \text{ for } t \leq 0 \tag{24}$$

$$\left. \begin{aligned} q = at, v = 0 \text{ at } z = 0 \\ q = 0, v = 0 \text{ at } z \rightarrow \infty \end{aligned} \right\} \forall t \tag{25}$$

On applying Laplace Transform to the Equation (23), the following ordinary differential equation is derived

$$\frac{d^2 \bar{q}}{dz^2} + \frac{d\bar{q}}{dz} - (A + s)\bar{q} = 0 \tag{26}$$

with relevant boundary conditions :

$$\bar{q} = \frac{a}{s^2} \text{ at } z = 0 \tag{27}$$

$$\bar{q} = 0 \text{ at } z \rightarrow \infty \tag{28}$$

The solution of the Equation (26) under the conditions

(27) and (28) is

$$\bar{q} = \frac{a}{s^2} e^{-\xi z} \tag{29}$$

Taking inverse Laplace transforms of the Equation (29) we derive the following:

$$q = ae^{-\eta\sqrt{t}} \left[\left(\frac{t}{2} - \eta \frac{\sqrt{t}}{2\sqrt{b}} \right) e^{-2\eta\sqrt{bt}} \operatorname{erfc}(\eta - \sqrt{bt}) + \left(\frac{t}{2} + \eta \frac{\sqrt{t}}{2\sqrt{b}} \right) e^{2\eta\sqrt{bt}} \operatorname{erfc}(\eta + \sqrt{bt}) \right] \tag{30}$$

where, $b = \frac{4A+1}{4}$, $\xi = \frac{1+\sqrt{1+4(A+s)}}{2}$, $\eta = \frac{z}{2\sqrt{t}}$

and $A = i\Omega + \frac{M(1+im)}{1+m^2}$

4. Skin Friction

The non-dimensional skin-friction at the plate is given by

$$\begin{aligned} \tau &= -\frac{1}{2\sqrt{t}} \left(\frac{\partial q}{\partial \eta} \right)_{\eta=0} \\ &= \frac{a}{2} \left[\frac{1}{\sqrt{b}} \operatorname{erf}(\sqrt{bt}) + 2t\sqrt{b} \operatorname{erf}(\sqrt{bt}) + \frac{2t}{\sqrt{\pi}} e^{-bt} + t \right] \\ &= \tau_x + i\tau_y \end{aligned}$$

where τ_x and τ_y are the skin-frictions at the plate due to the primary and the secondary velocity fields. The expressions for τ_x and τ_y are obtained but not presented here for the sake of brevity.

5. Results and Discussion

In order to get the physical insight into the problem we have carried out numerical calculations for the representative velocity field and skin-friction at the plate for different values of the physical parameters involved and these values have been demonstrated in different graphs. Our investigation is restricted to t equal to 1 and the other parameters namely, rotational parameter (Ω), Hartmann number (M), Hall parameter (m) and accelerating parameter (a) has been considered arbitrarily.

Figure 1 depicts the variation in skin-friction τ_x due to the primary velocity field versus Hall parameter m for different values of rotational parameters Ω . It is noticed that τ_x decreases with increasing values of Hall parameter m whereas a rise in the values rotational parameter Ω results a growth in τ_x .

The influence of Hartmann number M on skin-friction τ_x against Hall parameter m is presented in **Figure 2**. It is observed that a growth in the Hartmann number M leads to an increase of τ_x . Moreover, it is seen

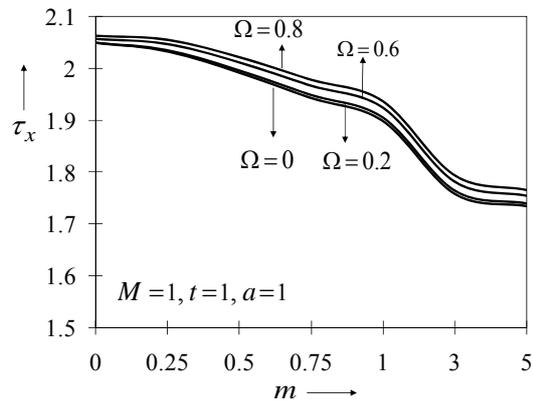


Figure 1. The behavior of τ_x versus m under the effect of Ω .

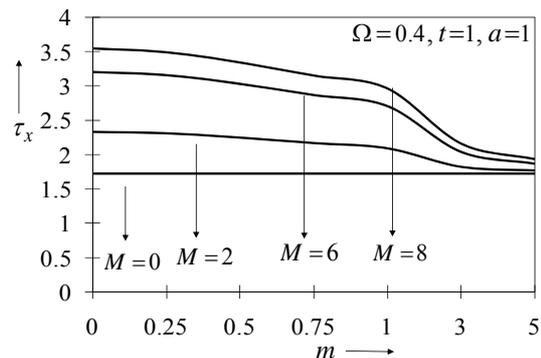


Figure 2. The behavior of τ_x versus m under the effect of M .

that τ_x decreases very slowly and steadily as the Hall parameter m rises. In other words, an increase in the Hall parameter or a decrease in Hartmann number results a decrease in drag force at the plate due to the primary velocity.

Figure 3 demonstrates the nature of τ_x against Hall parameter m under the effect of accelerating parameter a . **Figure 3** exhibits a substantial growth in τ_x with increasing values of accelerating parameter a . It is also seen that τ_x is unalterable for small values accelerating parameter or in absence of plate acceleration. That is, τ_x (drag force) due to the primary velocity is undisturbed whenever the plate is at rest as well for the slow movement of the plate. However, for higher values of the accelerating parameter (a) skin-friction τ_x decreases gradually with increasing values of Hall parameter m .

The behaviour of τ_y (drag force per unit area) due to the secondary velocity field versus Hall parameter m under the effects of Hartmann number M , rotational parameter Ω and acceleration parameter a respectively are depicted in **Figures 4-6**. It is noticed that a rise in M , Ω and accelerating parameter (a) results a growth in τ_y . Moreover τ_y is undisturbed by

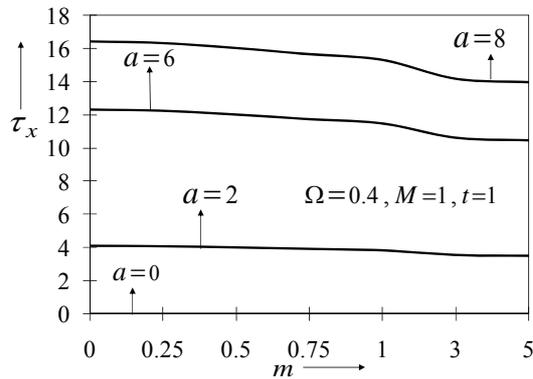


Figure 3. The behavior of τ_x versus m under the effect of a .

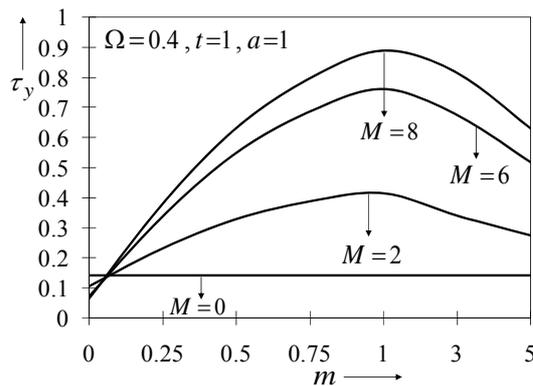


Figure 4. The behavior of τ_y under the effect of M versus m .

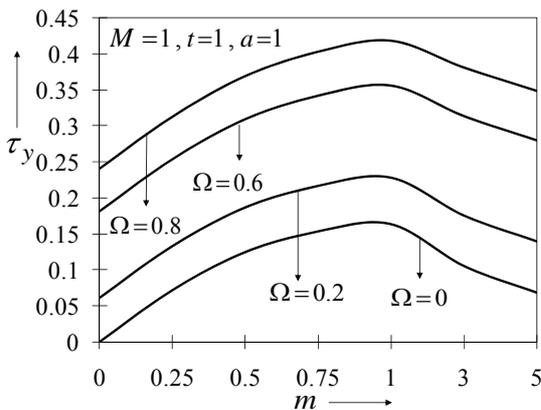


Figure 5. The behavior of τ_y versus m under the effect of Ω .

Hall effect in absence of magnetic field and acceleration of the plate. The same figures also indicate the growth of τ_y for small and moderate values of Hall parameter ($m \leq 1$) and afterwards a reversal trend on τ_y is noticed.

The effect of Hartmann number M on primary velocity field is presented in Figure 7. This figure clearly

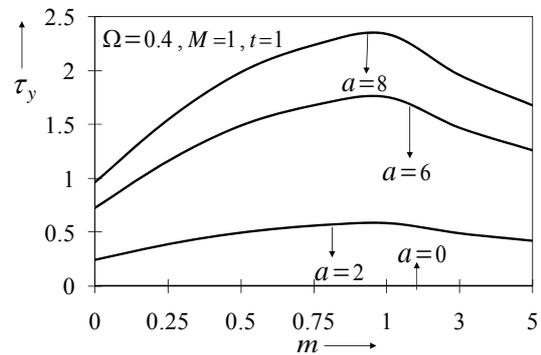


Figure 6. The behavior of τ_y versus m under the effect of a .

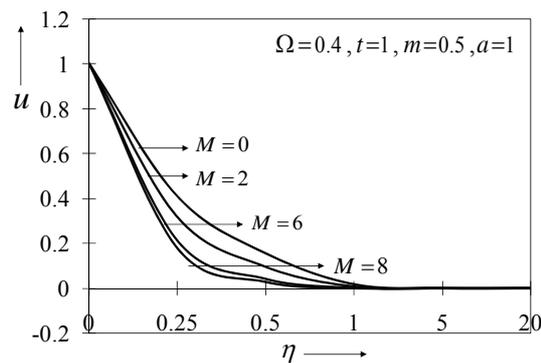


Figure 7. The variation of u versus η under the effect of M .

shows that the primary velocity sharply decreases in a thin layer of the fluid adjacent to the plate surface and then it decreases slowly and steadily to its minimum value $u=0$ as $\eta \rightarrow \infty$. The same figure also indicates that an increase in the Hartmann number M has an inhibiting effect on the primary velocity u . The primary fluid velocity u gets continuously reduced with increasing M . That is the application of the transverse magnetic field retards the primary motion. This phenomenon has an excellent agreement with the physical fact that the Lorentz force generated in present flow model due to interaction of the transverse magnetic field and the fluid velocity acts as a resistive force to the fluid flow which serves to decelerate the flow. As such the magnetic field is an effective regulatory mechanism for the flow regime.

Further, it is worthwhile to mention that the effect of Hartmann number M on primary velocity u is negligible for large η . In other words the fluid motion far away from the plate is undisturbed due to imposition of the magnetic field.

Figure 8 indicates that an increase in the plate acceleration causes the primary flow to retard comprehensively near the plate. That is the role of accelerating parameter a on primary velocity field is almost similar to

the role of Hartmann number M . However, in absence of acceleration a very small growth of primary velocity is noticed in a thin fluid region adjacent to the plate surface and afterwards it falls slowly and steadily to its free stream value as $\eta \rightarrow \infty$.

Figures 9-12 demonstrate the behaviour of the secondary velocity field (v) under the effects of rotational parameter (Ω), Hartmann number (M), Hall parameter (m) and accelerating parameter (a) respectively. From these figures, it is interesting to observe that the magnitude of v increases from its zero value at the plate surface into a fluid region adjacent to

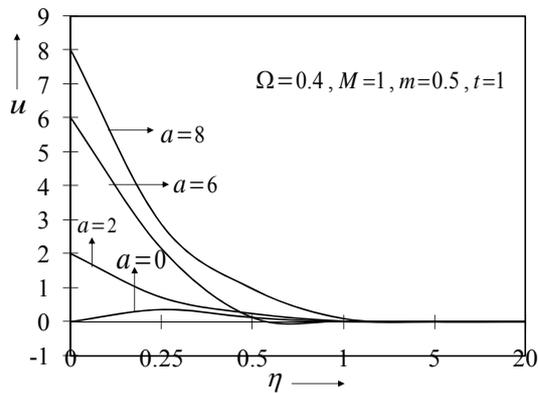


Figure 8. The variation of u versus η under the effect of a .

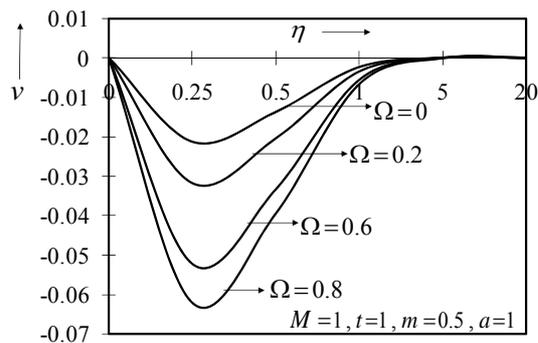


Figure 9. The behavior of v under the effect of Ω , versus η .

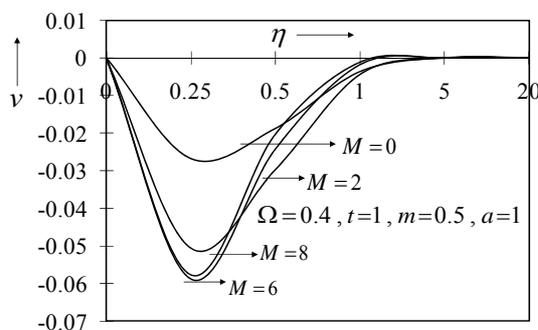


Figure 10. The behavior of v under the effect of M , versus η .

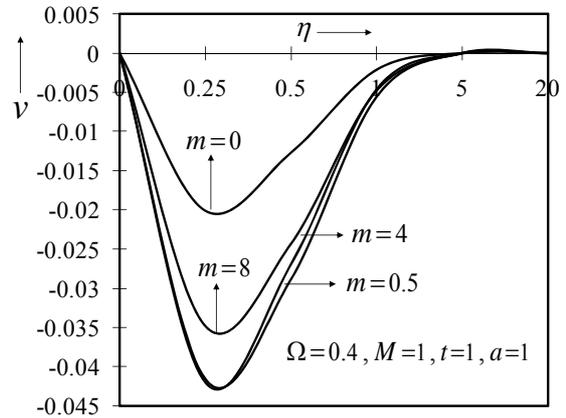


Figure 11. The behavior of v under the effect of m , versus η .

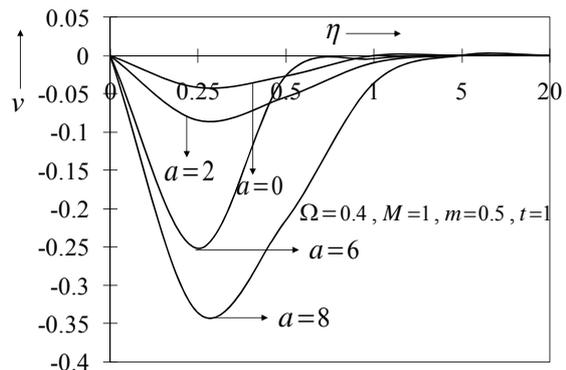


Figure 12. The behavior of v under the effect of a , versus η .

the plate and then it decreases to zero value (attainable at possibly large distances from the plate surface). This clearly agrees with the boundary conditions of the present flow problem. Figures 9 and 12 indicate that a rise in the values of rotational parameter Ω and accelerating parameter a causes a growth in the magnitude of secondary velocity. However, this effect seems to be negligible in the fluid region far away from the plate. Further, it is worthwhile to mention that for small and moderate values of Hartmann number M and Hall parameter m , the behaviour of secondary velocity field is identical to its behaviour under the effects of Ω and accelerating parameter a whereas, for higher values of Hartmann number M and Hall parameter m the behaviour of secondary velocity v takes a reverse trend.

It is inferred from Tables 1 and 2 that a rise in rotational parameter (Ω), and Hall parameter (m) results in a growth in the primary velocity u .

6. Conclusions

- The main flow velocity u decreases with an imposition of magnetic field.

Table 1. Behavior of u under the effect of Ω , versus η . ($M = 1, t = 1, m = 0.5, a = 1$).

η	$u(\Omega = 0)$	$u(\Omega = 0.6)$	$u(\Omega = 0.8)$
0	1	1	1
0.25	0.3611287	0.3550634	0.3519596
0.5	0.1239504	0.1185953	0.1158712
1	0.0121564	0.0108471	0.0101901
5	0	0	0

Table 2. Behavior of u under the effect of m , versus η . ($M = 1, t = 1, \Omega = 0.4, a = 1$).

η	$u(m = 0)$	$u(m = 4)$	$u(m = 8)$
0	1	1	1
0.25	0.3508695	0.4021751	0.4063124
0.5	0.1174215	0.1507741	0.1539457
1	0.0110595	0.0168414	0.0175416
5	0	0	0

- An increase in accelerating parameter a results in a remarkable growth in the main flow velocity u in a thin layer adjacent to the plate.
- The drag force due to primary velocity (τ_x) rises due to rotation or imposition of the transverse magnetic field or the acceleration of the plate.
- The skin friction τ_y (drag force due to secondary velocity) shows a growth for increasing each of Hartmann number M , rotational parameter Ω as well as accelerating parameter a .

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Units for Physical Properties

Symbol	Quantity	SI unit
a'	Acceleration of the plate	m/s^2
a	Dimensionless acceleration	
B_0	magnetic flux density, magnetic induction	Tesla
m	Hall parameter	
M	Hartmann number	
t'	time	s
t	Dimensionless time	
$(\bar{u}, \bar{v}, \bar{w})$	Velocity components	m/s
(u, v, w)	Dimensionless velocity components	
w_0	Suction velocity	m/s
$(\bar{x}, \bar{y}, \bar{z})$	Cartesian coordinates	m
Ω'	Angular velocity	s^{-1}
Ω	Dimensionless angular velocity	
ρ	Fluid density	kg/m^3
σ	Electrical conductivity	$(\text{ohm} \times \text{meter})^{-1}$
ν	Kinematic viscosity	m^2/s
(τ_x, τ_y)	Components of skin friction	