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# Hall effect on MHD forced convection from an infinite porous plate with dissipative heat in a rotating system

**Nazibuddin AHMED and Jiwan Krishna GOSWAMI**
*Department of Mathematics, Gauhati University,*
*Guwahati-781014, Assam-INDIA*
*e-mails: saheel_nazib@yahoo.com, jkg_gurs@rediffmail.com*

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**Abstract**

An attempt has been made to study the Hall effect on MHD forced convection from an infinite horizontal porous plate with dissipative heat in a rotating system with uniform free stream when the temperature at the plate varies periodically with time. The entire system rotates with a constant angular velocity about the normal to the plate. A uniform magnetic field is assumed to be applied along the normal to the plate directed into the fluid region. The governing equations are solved analytically. The expressions for the velocity and temperature field are obtained in non-dimensional form. The skin friction due to primary and secondary velocity field, the rate of heat transfer in terms of Nusselt number with their amplitudes and phases of fluctuating parts at the plate are demonstrated graphically and the effects of Hall current and magnetic field on these fields are discussed.

**Key Words:** Hall current, forced convection, skin-friction, MHD, rotating system

**AMS Subject Classification:** 76W05

## 1. Introduction

The study of MHD flow problems has achieved remarkable interest due to its applications in MHD generators, MHD pumps and MHD flow meters etc. Convection problems of electrically conducting fluids in presence of transverse magnetic field has got much importance because of its wide application in Geophysics, Astrophysics, Plasma physics, Missile technology etc. MHD in the present form is due to the pioneer contribution of several notable authors like Alfven [1], Cowling [2], Ferraro and Pulmpton [3], Shercliff [4] and Crammer and Pai [5].

When the strength of the applied magnetic field is sufficiently large, Ohm's law needs to be modified to include Hall current and this fact was initially emphasized by Cowling [2]. 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. Model studies on the effect of Hall current on MHD convection flow problems have been carried out by many scholars because of its possible applications in the problems of MHD generators and Hall accelerators. Pop [6], Kinyanjui et al. [7], Archrya et al. [8], Datta et al. [9] and Maleque and Sattar [10] are some of them.

The rotating flow of an electrically conducting fluid in presence of magnetic field has developed its importance from Geophysical problems. The study of rotating flow problems are also important in the solar physics dealing with sunspot development, the solar cycle and the structure of rotating magnetic stars. It is well known that a number of astronomical bodies possesses fluid interiors and magnetic fields. Changes that take place in the rate of rotation, suggest the possible importance of hydro magnetic spin-up. Debnath [11], Singh [12] and Takhar et al. [13] have studied the problems of spin-up in MHD under different conditions.

The object of the present work is to investigate the effect of Hall current and magnetic field on an electrically conducting fluid past an infinite horizontal porous plate with dissipative heat in a rotating system due to importance of such problems in many space and temperature related phenomena.

## 2. Mathematical formulation

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

Equation of continuity:

$$\vec{\nabla} \cdot \vec{q} = 0. \tag{2.1}$$

Momentum equation:

$$\rho \left[ \frac{\partial \vec{q}}{\partial t'} + 2\vec{\Omega} \times \vec{q} + \vec{\Omega} \times \left( \vec{\Omega} \times \vec{r} \right) + (\vec{q} \cdot \vec{\nabla})\vec{q} \right] = -\vec{\nabla} p + \vec{J} \times \vec{B} + \mu \nabla^2 \vec{q}. \tag{2.2}$$

Energy equation:

$$\rho C_p \left[ \frac{\partial \bar{T}}{\partial t'} + (\vec{q} \cdot \vec{\nabla})\bar{T} \right] = K \nabla^2 \bar{T} + \Phi + \frac{\vec{J}^2}{\sigma}. \tag{2.3}$$

Kirchhoff's first law:

$$\vec{\nabla} \cdot \vec{J} = 0. \tag{2.4}$$

General Ohm's law:

$$\vec{J} + \frac{\omega_e \tau_e}{B_0} (\vec{J} \times \vec{B}) = \sigma \left[ \vec{E} + \vec{q} \times \vec{B} + \frac{1}{e \eta_e} \vec{\nabla} p_e \right]. \tag{2.5}$$

Gauss's law of magnetism:

$$\vec{\nabla} \cdot \vec{B} = 0. \tag{2.6}$$

We now consider an unsteady flow of a viscous and incompressible fluid past a porous horizontal plate with constant suction velocity $-w_0$ (say). Choose the origin on the plate and the X-axis parallel to the direction of the flow and the Y-axis along the width of the plate. The Z-axis is considered perpendicular to the plate and directed into the fluid region and it is the axis of rotation about which the fluid rotates with angular velocity $\bar{\Omega}$. A uniform magnetic field is applied in the transverse direction of the flow. Since the plate is infinite in length in X- and Y-direction, therefore all physical quantities except possibly the pressure are independent of $\bar{x}$ and $\bar{y}$ . Let $(\bar{u}, \bar{v}, \bar{w})$ be the fluid velocity at a point $(\bar{x}, \bar{y}, \bar{z})$. Our investigation is restricted to the following assumptions:

i) All the fluid properties are constants and the buoyancy force has no effect on the flow.

ii) The plate is electrically non-conducting.

iii) The entire system is rotating with angular velocity $\overrightarrow{\Omega}$ about the normal to the plate and $|\overrightarrow{\Omega}|$ is so small that $\left|\vec{\Omega} \times \left(\vec{\Omega} \times \vec{r}\right)\right|$ can be neglected.

iv) The magnetic Reynolds number is so small that the induced magnetic field can be neglected.

v) $p_e$ is constant.

vi) $\vec{E} = 0$.

The equation of continuity gives

$$\frac{\partial \bar{w}}{\partial \bar{z}} = 0, \text{ with } \bar{w} = -w_0 = a \text{ constant} = \text{suction velocity.} \tag{2.7}$$

With the foregoing assumptions and under the usual boundary layer approximations, the equations governing the flow and heat transfer are

$$\frac{\partial \bar{u}}{\partial \bar{t}} = \upsilon \frac{\partial^2 \bar{u}}{\partial \bar{z}^2} + \frac{\partial \bar{U}}{\partial \bar{t}} + 2\bar{\Omega}\bar{v} + w_0 \frac{\partial \bar{u}}{\partial \bar{z}} + \frac{\sigma B_0^2}{\rho}\left(\frac{m\bar{v} - \bar{u} + \bar{U}}{1+m^2}\right) \tag{2.8}$$

$$\frac{\partial \bar{v}}{\partial \bar{t}} = \upsilon \frac{\partial^2 \bar{v}}{\partial \bar{z}^2} + 2\bar{\Omega}\left(\bar{U} - \bar{u}\right) + w_0 \frac{\partial \bar{v}}{\partial \bar{z}} - \frac{\sigma B_0^2}{\rho}\left(\frac{m(\bar{u} - \bar{U}) + \bar{v}}{1+m^2}\right) \tag{2.9}$$

$$\begin{aligned} \frac{\partial \bar{T}}{\partial \bar{t}} = \; & \alpha \frac{\partial^2 \bar{T}}{\partial \bar{z}^2} + w_0 \frac{\partial \bar{T}}{\partial \bar{z}} + \frac{\upsilon}{C_p}\left\{\left(\frac{\partial \bar{u}}{\partial \bar{z}}\right)^2 + \left(\frac{\partial \bar{v}}{\partial \bar{z}}\right)^2\right\} \\ & + \frac{\sigma B_0^2}{\rho C_p (1+m^2)}\left\{\left(\bar{U} - \bar{u}\right)^2 + \bar{v}^2\right\}. \end{aligned} \tag{2.10}$$

The relevant boundary conditions are

$$\begin{aligned} &\text{at } \bar{z} = 0 : \bar{u} = 0, \, \bar{v} = 0, \, \bar{T} = \bar{T}_w + \varepsilon\left(\bar{T}_w - \bar{T}_\infty\right) e^{i\bar{\omega}\bar{t}} \\ &\text{at } \bar{z} \to \infty : \bar{u} = \bar{U} = U_0\left(1 + \varepsilon e^{i\bar{\omega}\bar{t}}\right), \, \bar{v} = 0, \, \bar{T} = \bar{T}_\infty \end{aligned} \tag{2.11}$$

We introduce the following non-dimensional quantities:

$$u = \frac{\bar{u}}{U_0}, \; v = \frac{\bar{v}}{U_0}, \; U = \frac{\bar{U}}{U_0}, \; t = \frac{\bar{t} w_0^2}{\upsilon}, \; \omega = \frac{\upsilon \bar{\omega}}{w_0^2}, \quad \Omega = \frac{2\bar{\Omega}\upsilon}{w_0^2}, \; z = \frac{\bar{z} w_0}{\upsilon}, \; M = \frac{\sigma B_0^2 \upsilon}{\rho w_0^2},$$

$$P_r = \frac{\upsilon}{\alpha}, \; T = \frac{\bar{T} - \bar{T}_\infty}{\bar{T}_w - \bar{T}_\infty}, \; E = \frac{U_0^2}{C_p(\bar{T}_w - \bar{T}_\infty)}.$$

The non-dimensional governing equations and boundary conditions are

$$\frac{\partial u}{\partial t}=\frac{\partial^2 u}{\partial z^2}+\Omega v+\frac{\partial U}{\partial t}+\frac{\partial u}{\partial z}+\frac{M}{(1+m^2)}\left(mv-(u-U)\right), \tag{2.12}$$

$$\frac{\partial v}{\partial t}=\frac{\partial^2 v}{\partial z^2}+\Omega\left(U-u\right)+\frac{\partial v}{\partial z}-\frac{M}{(1+m^2)}\left(m(u-U)+v\right), \tag{2.13}$$

$$\begin{aligned}P_r\frac{\partial T}{\partial t}=\;&\frac{\partial^2 T}{\partial z^2}+P_r\frac{\partial T}{\partial z}+EP_r\left\{\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right\}\\&+\frac{EMP_r}{1+m^2}\left\{\left(U-u\right)^2+v^2\right\}\end{aligned} \tag{2.14}$$

subject to the boundary conditions

$$\bar{z}=0: \quad u=0,\, v=0,\, T=1+\varepsilon e^{i\omega t} \tag{2.15}$$

$$\bar{z}\to\infty: \quad u=U=1+\varepsilon e^{i\omega t},\, v=0,\, T=0.$$

## 3. Solution of the problem

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

$$\frac{\partial q}{\partial t}=\frac{\partial^2 q}{\partial z^2}+\frac{\partial U}{\partial t}+\frac{\partial q}{\partial z}+\left(\frac{M}{1+m^2}+i\Omega\right)\left(U-q\right)-\frac{imM}{1+m^2}\left(q-U\right) \tag{3.1}$$

$$P_r\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial z^2}+P_r\frac{\partial T}{\partial z}+EP_r\left(\left|\frac{\partial q}{\partial z}\right|^2\right)+\frac{EMP_r}{1+m^2}\left(U-q\right)\left(U-\bar{q}\right), \tag{3.2}$$

subject to the boundary conditions

$$z=0: q=0,\; T=1+\varepsilon e^{i\omega t}, \tag{3.3}$$

$$z\to\infty: q=1+\varepsilon e^{i\omega t},\; T=0$$

Assuming the small amplitude oscillation $\varepsilon << 1$, we represent the velocity $q$ and temperature $T$ as

$$q=q_0(z)+\varepsilon e^{i\omega t}q_1(z)+O(\varepsilon^2) \tag{3.4}$$

$$T=T_0(z)+\varepsilon e^{i\omega t}T_1(z)+O(\varepsilon^2). \tag{3.5}$$

Substituting the expressions from (3.4) and (3.5) in equations (3.1) and (3.2) and by equating the harmonic terms and neglecting $\varepsilon^2$ the following differential equations are obtained:

$$q_0''+q_0'-\left(\frac{M}{1+m^2}+i\Omega+i\frac{mM}{1+m^2}\right)q_0=-\left(\frac{M}{1+m^2}+i\Omega+i\frac{mM}{1+m^2}\right), \tag{3.6}$$

$$q_1''+q_1'-\left(\frac{M}{1+m^2}+i\Omega+i\frac{mM}{1+m^2}+i\omega\right)q_1=-\left(\frac{M}{1+m^2}+i\Omega+i\frac{mM}{1+m^2}+i\omega\right), \tag{3.7}$$

$$T_0'' + P_r T_0' = -EP_r \left| \frac{dq_0}{dz} \right|^2 - \frac{EP_r M}{1+m^2}(1-q_0)(1-\bar{q}_0), \tag{3.8}$$

$$\begin{aligned} T_1'' + P_r T_1' - i\omega P_r T_1 = \ & -EP_r \left( q_0' \bar{q}_1' + q_1' \bar{q}_0' \right) \\ & - \frac{EP_r M}{1+m^2} \left( (1-q_0)(1-\bar{q}_1) + (1-q_1)(1-\bar{q}_0) \right). \end{aligned} \tag{3.9}$$

The relevant boundary conditions are:

$$\text{at } z = 0: \ \ q_0 = 0, \ q_1 = 0, \ T_0 = 1, \ T_1 = 1 \tag{3.10}$$

$$\text{at } z \to \infty: \ \ q_0 = 1, \ q_1 = 1, \ T_0 = 0, \ T_1 = 0 \tag{3.11}$$

Here, $\bar{q}_0$ and $\bar{q}_1$ indicate the conjugate of the complex numbers $q_0$ and $q_1$, respectively.

The solutions of the equations (3.6), (3.7), (3.8) and (3.9) subject to boundary conditions (3.10) and (3.11) are

$$q_0 = 1 - e^{-\lambda_1 z}, \tag{3.12}$$

$$q_1 = 1 - e^{-\lambda_2 z}, \tag{3.13}$$

$$T_0 = L_2 e^{-P_r z} + L_1 e^{-(\lambda_1 + \bar{\lambda}_1) z}, \tag{3.14}$$

$$T_1 = L_5 e^{-\lambda_3 z} + L_3 e^{-(\lambda_1 + \bar{\lambda}_2) z} + L_4 e^{-(\bar{\lambda}_1 + \lambda_2) z}, \tag{3.15}$$

where

$$\lambda_1 = \frac{1 + \sqrt{1 + 4\left( \frac{M}{1+m^2} + i\Omega + i\frac{mM}{1+m^2} \right)}}{2},$$

$$\lambda_2 = \frac{1 + \sqrt{1 + 4\left( \frac{M}{1+m^2} + i\Omega + i\frac{mM}{1+m^2} + i\omega \right)}}{2},$$

$$\lambda_3 = \frac{P_r + \sqrt{P_r^2 + 4i\omega P_r}}{2},$$

$$L_1 = \frac{-EP_r \left( \lambda_1 \bar{\lambda}_1 + \frac{M}{1+m^2} \right)}{\left( \lambda_1 + \bar{\lambda}_1 \right)^2 - P_r \left( \lambda_1 + \bar{\lambda}_1 \right)},$$

$$L_2 = 1 - L_1$$

$$L_3 = \frac{-EP_r \left( \lambda_1 \bar{\lambda}_2 + \frac{M}{1+m^2} \right)}{\left( \lambda_1 + \bar{\lambda}_2 \right)^2 - P_r \left( \lambda_1 + \bar{\lambda}_2 \right) - i\omega P_r},$$

$$L_4 = \frac{-EP_r \left( \bar{\lambda}_1 \lambda_2 + \frac{M}{1+m^2} \right)}{(\bar{\lambda}_1 + \lambda_2)^2 - P_r(\bar{\lambda}_1 + \lambda_2) - i\omega P_r}$$

$$L_5 = 1 - L_3 - L_4.$$

# 4. Velocity and temperature field

The non-dimensional velocity field is given by

$$q = q_0(z) + \varepsilon e^{i\omega t} q_1(z). \tag{4.1}$$

By splitting into real and imaginary parts the primary and secondary velocity components are derived as

$$u = u_0 + \varepsilon \left| A \right| Cos(\omega t + \alpha) \tag{4.2}$$

$$v = v_0 + \varepsilon \left| A \right| Sin(\omega t + \alpha) \tag{4.3}$$

where

$u_0 + iv_0 = q_0, \quad |A| = |q_1|$ and $\alpha = \arg(q_1)$.

The temperature in the non-dimensional form is given by

$$\begin{aligned} T = \quad & T_0(z) + \text{Real part of} \left\{ \varepsilon e^{i\omega t} T_1(z) \right\} \\ & = T_0(z) + \varepsilon \left| B \right| \cos(\omega t + \beta), \end{aligned} \tag{4.4}$$

where $|B| = |T_1(z)|$ and $\beta = \arg\left(T_1(z)\right)$.

# 5. Skin-friction

The skin friction at the plate in the direction of primary and secondary velocities are respectively given by

$$\tau_x = \left[ \frac{du}{dz} \right]_{z=0} = \tau_{x0} + \varepsilon \left| G \right| \cos(\omega t + \gamma), \tag{5.1}$$

$$\tau_y = \left[ \frac{dv}{dz} \right]_{z=0} = \tau_{y0} + \varepsilon \left| G \right| sin(\omega t + \gamma), \tag{5.2}$$

where $|G| = |q_1'(0)|$, $\gamma = \arg\left(q_1'(0)\right)$, $\tau_{x0} = u_0'(0)$ and $\tau_{y0} = v_0'(0)$.

# 6. Coefficient of Heat-Transfer

The rate of heat transfer in terms of Nusselt number from the plate to the fluid is given by

$$\begin{aligned} Nu = \quad & -\text{Real part of} \left( \tfrac{\partial T}{\partial z} \right)_{z=0} \\ & = -\text{Real part of} \left\{ T_0'(0) + \varepsilon e^{i\omega t} T_1'(0) \right\} \\ & = -T_0'(0) - \varepsilon \text{Real part of} \left\{ e^{i\omega t} T_1'(0) \right\} \\ & = N_{u_0} + \varepsilon \left| H \right| \cos\left(\omega t + \delta\right), \end{aligned}$$

where $|H| = |T_1'(0)|$ and $\delta = \arg\left(T_1'(0)\right)$.

## 7. Results and discussions

In order to study the effects of Hall current and magnetic field on skin friction, heat transfer, the amplitudes and phases of the fluctuating parts of skin friction and heat transfer, we have plotted skin friction amplitude $|G|$, heat transfer amplitude $|H|$, skin friction phase $\tan\gamma$, rate of heat transfer phase $\tan\delta$, skin friction due to primary velocity $\tau_x$ and skin friction due to secondary velocity $\tau_y$ against Hartmann number $M$ for different values of Hall parameter $m$. We have restricted our investigation to $P_r$ (Prandtl number) equal to 0.7, which correspond to air at 298 K and 1 atmospheric pressure and the Eckert number $E$ is selected to be 0.05. The value of rotation parameter $\Omega$ is taken to be 0.2. Throughout our investigation, $\omega$ and $t$ are chosen in such a way that $\omega t = \frac{\pi}{2}$ and the frequency of oscillation $\varepsilon$ is taken to be equal to 0.001. The values of Hartmann number $M$ and Hall parameter m are chosen arbitrarily.

Figures 1 and 2, respectively, depict the effects of the Hartmann number $M$ and Hall parameter $m$ on the amplitude $|G|$ and phase $\tan\gamma$ of the skin friction at the plate. It is observed from these figures that for increasing values of Hall parameter $m$, the amplitude of the skin friction $|G|$ decreases whereas the phase of the skin friction $\tan\gamma$ increases. Further, we can also conclude that for low strength magnetic field, $|G|$ and $\tan\gamma$ are not affected by Hall current. This phenomenon is clearly supported from physical reality. Moreover for increasing values of the Hartmann number $M$, the amplitude of the skin friction $|G|$ increases whereas phase of the skin friction $\tan\gamma$ is decreased. That is the application of the transverse magnetic field increases the amplitude $|G|$ of the skin friction and decreases the phase $\tan\gamma$ of the skin friction.

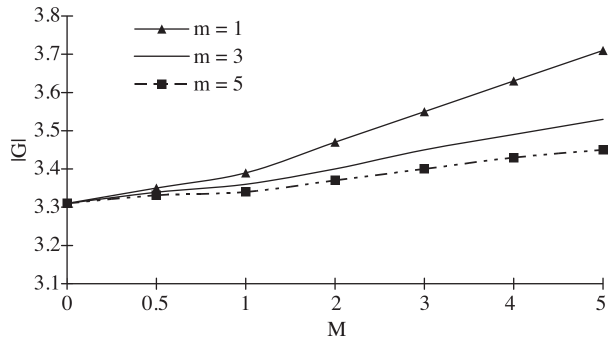


**Figure 1.** The skin friction amplitude $|G|$ versus Hartmann number $M$.

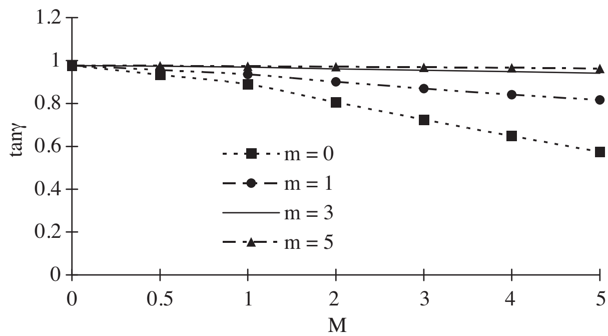


**Figure 2.** The skin-friction phase $\tan\gamma$ against Hartmann number.

The behaviour of the skin friction $\tau_x$ at the plate (due to the primary velocity) and $\tau_y$ (due secondary velocity) under the influence of Hartmann number $M$ and the Hall parameter m are presented respectively in Figures 3 and 4. It is inferred from these two figures that the effect of Hall current causes $\tau_x$ to decrease and $\tau_y$ to increase. The same figures also indicate that for low strength magnetic field, the Hall current does not have any influence on the viscous drag on the plate. It is also seen that due to the application of the magnetic field, $\tau_x$ increases and for small values of Hall parameter, $\tau_y$ decreases. In other words, the application of the transverse magnetic field causes the viscous drag at the plate to increase in the direction of the primary velocity and decrease in the direction of the secondary velocity.

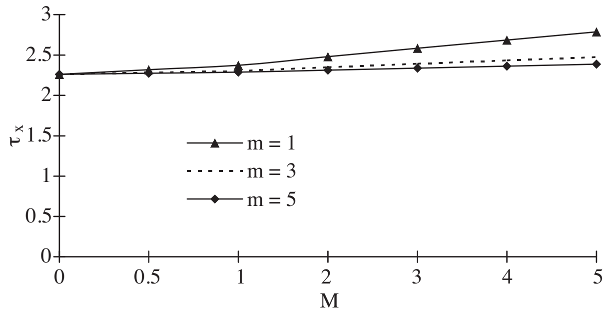


**Figure 3.** The skin-friction $\tau_x$ due to primary velocity versus Hartmann number.

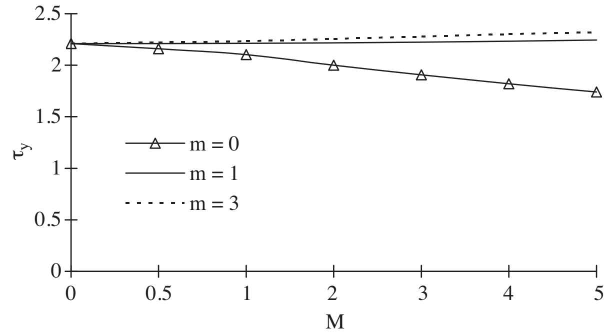


**Figure 4.** The skin-friction $\tau_y$ due to secondary velocity versus Hartmann number at the plate $y$=0.

The effects of Hartmann number $M$ and Hall current $m$ on the amplitude of the rate of heat transfer $|H|$ and its phase $\tan\delta$ at the plate are demonstrated in Figures 5 and 6. It is noticed that the application of magnetic field leads |H| to decrease and $\tan\delta$ to increase. The same figures further indicate that |H| increases but $\tan\delta$ decreases under the influence of Hall current.

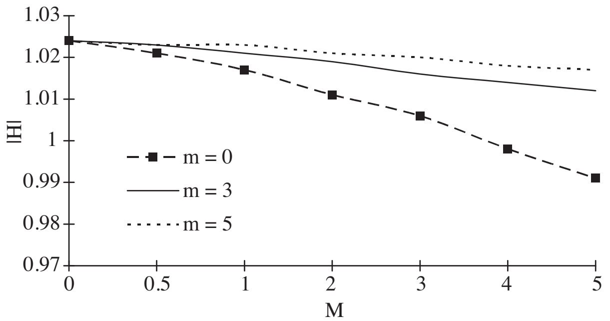


**Figure 5.** The Heat transfer amplitude $|H|$ versus Hartmann number $M$.

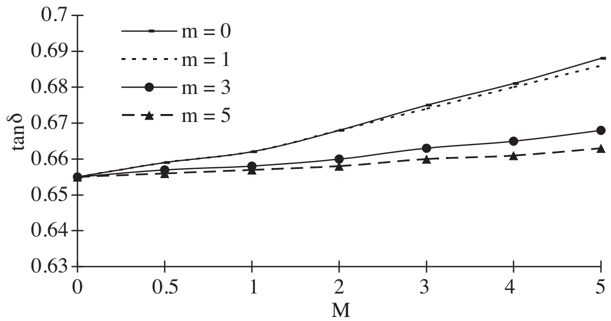


**Figure 6.** The Heat transfer phase $\tan\delta$ against Hartmann number $M$.

Finally, Figure 7 exhibits the behaviour of the Nusselt number (Nu) versus Hartmann number M for different values of Hall parameter $m$. It is noticed from this figure that the rate of heat transfer from the plate to the fluid falls due to the magnetic field and it rises under the effect of Hall current.

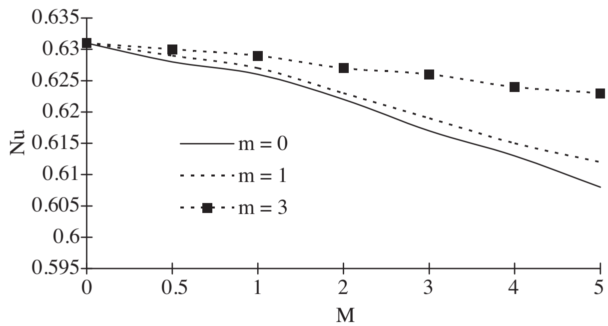


**Figure 7.** The Nusselt number $Nu$ versus Hartmann number $M$.

# 8. Conclusion

The present investigation leads to the following conclusions:

1. The Hall current causes $|G|$ to decrease and $\tan\gamma$ to increase.

2. The skin friction $\tau_x$ due to the primary velocity decreases and the skin friction $\tau_y$ due to the secondary velocity increases under Hall current.

3. The Hall current causes $|H|$ to increase and $\tan\delta$ to decrease.

4. The application of the magnetic field leads the amplitude $|H|$ of the rate of heat transfer from the plate to the fluid to fall and $\tan\delta$, the phase of rate of heat transfer to rise.

5. The rate of heat transfer from the plate to the fluid is increased under the effect of Hall current and it is reduced due to the application of the magnetic field.

# Nomenclature

$\vec{q}$ is the velocity vector
$\vec{\Omega}$ is the angular velocity of the fluid
$\rho$ is the fluid density
$\vec{r}$ is the position vector of the fluid particle considered
$p$ is the pressure
$\vec{J}$ is the current density
$\vec{B}$ is the magnetic induction vector
$\mu$ is the co-efficient of viscosity
$\sigma$ is the electrical conductivity
$t'$ is the time
$B_0$ is the strength of the applied magnetic field
$C_p$ is the specific heat at constant pressure
$\bar{T}$ is the temperature
$K$ is the thermal conductivity
$\phi$ is the frictional heat
$\omega_e$ is the electron frequency
$\tau_e$ is the electron collision time
$e$ is the electron charge
$\eta_e$ is the number density of electron
$p_e$ is the electron pressure
$\vec{E}$ is the electric field
$\nu$ is the kinematic viscosity
m is the Hall parameter
$\overline{U}$ is the dimensional free stream velocity
$\alpha$ is the thermal diffusivity
$u$ is the non-dimensional primary velocity
$v$ is the non-dimensional secondary velocity
$\bar{\omega}$ is the frequency of oscillation
$M$ is the Hartmann number
$P_r$ is the Prandtl number
$E$ is the Eckert number and the other symbols have their usual meaning.

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