Natural convection unsteady magnetohydrodynamic mass transfer flow past an infinite vertical porous plate in presence of suction and heat sink

S. S. Das¹, S. Parija², R. K. Padhy³, M. Sahu⁴

¹ Department of Physics, K B D A V College, Nirakarpur, Khurda-752 019 (Orissa), India.
² Department of Physics, Nimapara (Autonomous) College, Nimapara, Puri-752 106 (Orissa), India.
³ Department of Physics, D A V Public School, Chandrasekharpur, Bhubaneswar-751 021 (Orissa), India.
⁴ Department of Physics, Jupiter +2 Women’s Science College, IRC Village, Bhubaneswar-751 015 (Orissa), India.

Abstract
This paper investigates the natural convection unsteady magnetohydrodynamic mass transfer flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous flat plate in presence of constant suction and heat sink. Using multi parameter perturbation technique, the governing equations of the flow field are solved and approximate solutions are obtained. The effects of the flow parameters on the velocity, temperature, concentration distribution and also on the skin friction and rate of heat transfer are discussed with the help of figures and table. It is observed that a growing magnetic parameter or Schmidt number or heat sink parameter leads to retard the transient velocity of the flow field at all points, while the Grashof numbers for heat and mass transfer show the reverse effect. It is further found that a growing Prandtl number or heat sink parameter decreases the transient temperature of the flow field at all points while the heat source parameter reverses the effect. The concentration distribution of the flow field suffers a decrease in boundary layer thickness in presence of heavier diffusive species (growing Sc) at all points of the flow field. The effect of increasing Prandtl number Pr is to decrease the magnitude of skin-fraction and to increase the rate of heat transfer at the wall for MHD flow, while the effect of increasing magnetic parameter M is to decrease their values at all points.

Copyright © 2012 International Energy and Environment Foundation - All rights reserved.

Keywords: Natural convection; Magnetohydrodynamic; Mass transfer; Suction; Heat sink.

1. Introduction
The phenomenon of natural convection flow with heat and mass transfer in presence of magnetic field has been given much importance in the recent years in view of its varied applications in science and technology. The study of natural convection flow finds innumerable applications in geothermal and energy related engineering problems. Such phenomena are of great theoretical as well as practical interest in view of their applications in diverse fields such as aerodynamics, extraction of plastic sheets, cooling of infinite metallic plates in a cool bath, liquid film condensation process and in major fields of glass and polymer industries.

In the present problem, we analyze the natural convection unsteady magnetohydrodynamic mass transfer flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous flat plate in presence of constant suction and heat sink. Approximate solutions are obtained for the velocity, temperature, concentration distribution, skin friction and the rate of heat transfer using multi parameter perturbation technique and the effects of the important parameters on the flow field are analyzed with the help of figures and a table.

2. Formulation of the problem
Consider the unsteady natural convection mass transfer flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous plate in presence of constant suction and heat sink and a transverse magnetic field $B_0$. The $x'$-axis is taken in vertically upward direction along the plate and the $y'$-axis is chosen normal to it. Neglecting the induced magnetic field and the Joulean heat dissipation and applying Boussinesq’s approximation the governing equations of the flow field are given by:

Continuity equation:
\[
\frac{\partial v'}{\partial y'} = 0 \quad \Rightarrow \quad v' = -v_0' \quad \text{(constant)},
\]

Momentum equation:
\[
\frac{\partial u'}{\partial t'} + v' \frac{\partial u'}{\partial y'} = \nu \frac{\partial^2 u'}{\partial y'^2} + g \beta (T' - T_{\infty}') + g \beta' (C' - C_{\infty}') - \frac{\sigma B_0^2}{\rho} u',
\]

Energy equation:
\[
\frac{\partial T'}{\partial t'} + v' \frac{\partial T'}{\partial y'} = \kappa \frac{\partial^2 T'}{\partial y'^2} + \rho \frac{C_p}{\rho} \left( \frac{\partial u'}{\partial y'} \right)^2 + S'(T' - T_{\infty}'),
\]

Concentration equation:
\[
\frac{\partial C'}{\partial t'} + v' \frac{\partial C'}{\partial y'} = D \frac{\partial^2 C'}{\partial y'^2}.
\]
The initial and boundary conditions of the problem are:

\[ u' = 0, v' = -v_0', T' = T'_w + \varepsilon(T'_w - T'_\infty)e^{i\alpha}, C' = C'_w + \varepsilon(C'_w - C'_\infty)e^{i\alpha} \] at \( y' = 0 \),

\[ u' \to 0, \quad T' \to T'_\infty, \quad C' \to C'_\infty \] as \( y' \to \infty \). \hspace{1cm} (5)

Introducing the following non-dimensional variables and parameters,

\[ y = \frac{y'v_0}{v}, \quad t = \frac{t'v_0^2}{4v}, \quad \omega = \frac{4\nu v_0^4}{v_0^2}, \quad \rho = \frac{\nu}{\rho}, \quad T = \frac{T' - T'_\infty}{T'_w - T'_\infty}, \quad C = \frac{C'_w - C'_\infty}{C'_w - C'_\infty}, \quad M = \left( \frac{\varepsilon B_0^2}{\rho} \right) \frac{v}{v_0^2}, \quad P_r = \frac{v}{k}, \quad S_c = \frac{\nu G_r}{v_0^3}, \quad G_c = \frac{v \varepsilon \beta (C'_w - C'_\infty)}{v_0^3}, \quad S = \frac{4S'v}{v_0^2}, \quad E_c = \frac{v}{C_p (T'_w - T'_\infty)}. \hspace{1cm} (6)

in Eqs. (2)-(4) under boundary conditions (5), we get

\[ \frac{1}{4} \frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = \frac{\varepsilon^2 u}{\partial y^2} + G_r T + G_c C - M u, \hspace{1cm} (7) \]

\[ \frac{1}{4} \frac{\partial T}{\partial t} - \frac{\partial T}{\partial y} = \frac{1}{P_r} \frac{\varepsilon^2 T}{\partial y^2} + \frac{1}{4} ST + E_c \left( \frac{\partial u}{\partial y} \right)^2, \hspace{1cm} (8) \]

\[ \frac{1}{4} \frac{\partial C}{\partial t} - \frac{\partial C}{\partial y} = \frac{1}{S_c} \frac{\varepsilon^2 C}{\partial y^2}, \hspace{1cm} (9) \]

where \( g \) is the acceleration due to gravity, \( \rho \) is the density, \( \sigma \) is the electrical conductivity, \( \nu \) is the coefficient of kinematic viscosity, \( \beta \) is the volumetric coefficient of expansion for heat transfer, \( \beta^* \) is the volumetric coefficient of expansion for mass transfer, \( \omega \) is the angular frequency, \( \eta_0 \) is the coefficient of viscosity, \( k \) is the thermal diffusivity, \( T \) is the temperature, \( T'_w \) is the temperature at the plate, \( T'_\infty \) is the temperature at infinity, \( C \) is the concentration, \( C'_w \) is the concentration at the plate, \( C'_\infty \) is the concentration at infinity, \( C_p \) is the specific heat at constant pressure, \( D \) is the molecular mass diffusivity, \( G_r \) is the Grashof number for heat transfer, \( G_c \) is the Grashof number for mass transfer, \( M \) is the magnetic parameter, \( P_r \) is the Prandtl number, \( S \) is the heat sink parameter, \( S_c \) is the Schmidt number and \( E_c \) is the Eckert number.

The corresponding boundary conditions are:

\[ u = 0, T = I + \varepsilon e^{i\omega t}, C = I + \varepsilon e^{i\omega t} \] at \( y = 0 \),

\[ u \to 0, T \to 0, \quad C \to 0 \] as \( y \to \infty \). \hspace{1cm} (10)

3. Method of solution

To solve Eqs. (7)-(9), we assume \( \varepsilon \) to be very small and the velocity, temperature and concentration distribution of the flow field in the neighbourhood of the plate as

\[ u(y,t) = u_0(y) + \varepsilon e^{i\omega t} u_1(y), \hspace{1cm} (11) \]

\[ T(y,t) = T_0(y) + \varepsilon e^{i\omega t} T_1(y), \hspace{1cm} (12) \]

\[ C(y,t) = C_0(y) + \varepsilon e^{i\omega t} C_1(y). \hspace{1cm} (13) \]
Substituting Eqs. (11) - (13) in Eqs. (7) - (9) respectively, equating the harmonic and non-harmonic terms and neglecting the coefficients of $\varepsilon^2$, we get

Zeroth order:

$$u_0^* + u_0' - Mu_0 = -G_rT_0 - G_cC_0,$$ (14)

$$T_0^* + P_rT_0' + \frac{P_rS}{4}T_0 = -P_rE_c\left(\frac{\partial u_0}{\partial y}\right)^2,$$ (15)

$$C_0^* + S_cC_0' = 0.$$ (16)

First order:

$$u_0^* + u_0' - \left(\frac{i\omega}{4} + M\right)u_1 = -G_rT_1 - G_cC_1,$$ (17)

$$T_1^* + P_rT_1' - \frac{P_r}{4}(i\omega - S)T_1 = -2P_rE_c\left(\frac{\partial u_0}{\partial y}\right)\left(\frac{\partial u_1}{\partial y}\right),$$ (18)

$$C_1^* + S_cC_1' - \frac{i\omega S_c}{4}C_1 = 0.$$ (19)

The corresponding boundary conditions are

$$y = 0: u_0 = 0, T_0 = 1, C_0 = 1, u_1 = 0, T_1 = 1, C_1 = 1,$$

$$y \to \infty: u_0 = 0, T_0 = 0, C_0 = 0, u_1 = 0, T_1 = 0, C_1 = 0.$$ (20)

Solving Eqs. (16) and (19) under boundary condition (20), we get

$$C_0 = e^{-S_y},$$ (21)

$$C_1 = e^{-m_y}.$$ (22)

Using multi parameter perturbation technique and assuming $E_c << 1$, we assume

$$u_0 = u_{00} + E_cu_{01},$$ (23)

$$T_0 = T_{00} + E_cT_{01},$$ (24)

$$u_1 = u_{10} + E_cu_{11},$$ (25)

$$T_1 = T_{10} + E_cT_{11}.$$ (26)

Now using Eqs. (23)-(26) in Eqs. (14), (15), (17) and (18) and equating the coefficients of like powers of $E_c$ and neglecting those of $E_c^2$, we get the following set of differential equations:

Zeroth order:

$$u_{00}^* + u_{00}' - Mu_{00} = -G_rT_{00} - G_cC_0,$$ (27)
\[ u_{I0}'' + u_{I0}' - \left( M + \frac{i\omega}{4} \right) u_{I0} = -G_s T_{I0} - G_e C_1, \]  
\[ T_{00}'' + P_s T_{00}' + \frac{P_s}{4} T_{00} = 0, \]  
\[ T_{I0}'' + P_s T_{I0}' - \frac{P_s}{4} (i\omega - S) T_{I0} = 0. \]

The corresponding boundary conditions are,
\[ y = 0 : u_{00} = 0, T_{00} = 1, u_{I0} = 0, T_{I0} = 1; \]
\[ y \to \infty : u_{00} = 0, T_{00} = 0, u_{I0} = 0, T_{I0} = 0. \]  
(31)

First order:
\[ u_{0I}'' + u_{0I}' - Mu_{0I} = -G_s T_{0I}, \]  
\[ u_{1I}'' + u_{1I}' - \left( M + \frac{i\omega}{4} \right) u_{1I} = -G_s T_{1I}, \]  
\[ T_{0I}'' + P_s T_{0I}' + \frac{P_s}{4} T_{0I} = -P_s \left( u_{00}' \right)^2, \]  
\[ T_{1I}'' + P_s T_{1I}' - \frac{P_s}{4} (i\omega - S) T_{1I} = -2P_s \left( \frac{\partial u_{00}}{\partial y} \right) \left( \frac{\partial u_{0I}}{\partial y} \right). \]

The corresponding boundary conditions are,
\[ y = 0 : u_{0I} = 0, T_{0I} = 0, u_{1I} = 0, T_{1I} = 0; \]
\[ y \to \infty : u_{0I} = 0, T_{0I} = 0, u_{1I} = 0, T_{1I} = 0. \]  
(36)

Solving Eqs. (27)-(30) subject to boundary condition (31) we get,
\[ u_{00} = A_1 e^{-m_{3y}} + A_2 e^{-S_{3y}} - A_3 e^{-n_{1y}}, \]  
\[ T_{00} = e^{-m_{3y}}, \]  
\[ u_{I0} = A_4 e^{-m_{5y}} + A_5 e^{-m_{1y}} - A_6 e^{-n_{3y}}, \]  
\[ T_{I0} = e^{-m_{3y}}. \]

Solving Eqs. (32)-(35) subject to boundary condition (36) we get,
\[ T_{0I} = a_1 e^{-S_{3y}} + a_2 e^{-2m_{3y}} + a_3 e^{-2m_{5y}} + a_4 e^{-(m_{5}+S_{3})y} + a_5 e^{-(n_{1}+S_{3})y} + a_6 e^{-(m_{3}+n_{1})y} - a_7 e^{-m_{3y}}, \]  
\[ T_{1I} = B_1 e^{-(m_{3}+m_{5})y} + B_2 e^{-(m_{1}+m_{3})y} + B_3 e^{-(m_{5}+S_{3})y} + B_4 e^{-(m_{3}+S_{3})y} + B_5 e^{-(m_{5}+S_{3})y} + B_6 e^{-(n_{3}+S_{3})y} + B_7 e^{-(m_{3}+n_{1})y} + B_8 e^{-(n_{1}+n_{3})y} + B_9 e^{-(m_{3}+n_{5})y} - B_{10} e^{-m_{3y}}, \]
(42)
The heat flux at the wall in terms of Nusselt number is given by

\[ C = e^{-S_y} + \epsilon e^{iot} e^{-m_y}. \]  

### 3.1 Skin friction

The skin friction at the wall is given by

\[ \tau_w = \left( \frac{\partial u}{\partial y} \right)_{y=0} = -m_2 A_1 - S_c A_2 + n_1 A_3 - E_c \left[ b_2 S_e + 2 b_3 m_3 + 2 b_4 n_3 + b_1 (m_3 + S_c) + b_5 (n_1 + S_c) \right] + b_6 (m_3 + n_1) + b_7 (m_3 - b_8 n_1) + \epsilon e^{iot} \left[ -m_3 A_4 - m_1 A_5 + n_3 A_6 - E_c \left[ (m_3 + m_3) D_1 + (m_3 + n_3) D_2 + (m_3 + S_c) D_3 + (n_3 + S_c) D_6 \right] + (m_3 + n_1) D_7 + (m_1 + n_1) D_8 + (n_1 + n_3) D_9 + m_3 D_{10} - n_3 D_{11} \right]. \]

### 3.2 Heat flux

The heat flux at the wall in terms of Nusselt number is given by

\[ N_u = \left( \frac{\partial T}{\partial y} \right)_{y=0} = -m_3 - E_c \left[ 2 a_2 S_e + 2 a_3 m_3 + 2 a_5 n_3 + a_4 (m_3 + S_c) + a_6 (m_1 + S_e) - a_7 m_3 \right] + \epsilon e^{iot} \left[ -m_3 - E_c \left[ (m_3 + m_3) B_1 + (m_1 + m_1) B_2 + (m_3 + n_3) B_3 + (m_3 + S_c) B_4 + B_5 \right] + (n_3 + S_c) B_6 + (m_3 + n_1) B_7 + (m_1 + n_1) B_8 + (n_1 + n_3) B_9 - m_3 B_{10} \right], \]

where

\[ m_1 = \frac{1}{2} \left[ S_c + \sqrt{S_c^2 + i \omega S_c} \right], m_2 = \frac{1}{2} \left[ -S_c + \sqrt{S_c^2 + i \omega S_c} \right], m_3 = \frac{1}{2} \left[ P_r + \sqrt{P_r^2 - S_p} \right], m_4 = \frac{1}{2} \left[ -P_r + \sqrt{P_r^2 - S_p} \right], \]

\[ m_5 = \frac{1}{2} \left[ P_r + P_{r_1} - P_r (S - i \omega) \right], m_6 = \frac{1}{2} \left[ -P_r + \sqrt{P_r^2 - P_r (S - i \omega)} \right], n_1 = \frac{1}{2} \left[ I + \sqrt{+1 + 4M} \right], n_2 = \frac{1}{2} \left[ I - \sqrt{1 + 4M} \right], \]

\[ n_3 = \frac{1}{2} \left[ I + \sqrt{1 + 4 \left( M + i \omega \right)} \right], n_4 = \frac{1}{2} \left[ I - \sqrt{1 + 4 \left( M + i \omega \right)} \right], A_1 = \frac{G_r}{(n_1 - m_1)(n_2 + m_2)}, A_2 = \frac{G_r}{(n_1 - S_e)(n_2 + S_e)}; \]

\[ A_3 = A_1 + A_2, A_4 = \frac{G_r}{(n_1 - m_3)(m_4 + m_5)}, A_5 = \frac{G_r}{(n_1 - m_1)(n_4 + m_7)}, A_6 = A_4 + A_5, A_7 = \frac{1}{2} \left[ P_{r_1} - P_r \left( S - i \omega \right) \right], A_8 = \frac{1}{2} \left[ P_r - \sqrt{P_r^2 - S_p} \right], A_9 = \frac{1}{2} \left[ -P_r + \sqrt{P_r^2 - S_p} \right], \]

\[ a_2 = -m_3 A_1, a_3 = \frac{P_r n_1 A_1}{m_4 + 2m_5}, a_4 = \frac{2}{m_3 + m_4 + S_e}, a_5 = \frac{2}{m_3 + m_4 + S_e}, a_6 = \frac{2}{m_3 + m_4 + S_e}, a_7 = a_3 + a_5 + a_6, B_1 = \frac{2P_r A_4}{m_3 + m_5 + m_6 + m_7}, B_2 = \frac{2P_r A_5}{m_3 - m_3 - m_7}, \]

\[ B_3 = \frac{2P_r A_6}{n_3 + m_5 + m_6 + m_7}, B_4 = \frac{2P_r A_7}{m_5 - m_5 - m_7}, B_5 = \frac{2P_r A_8}{m_5 - m_5 - m_7}, B_6 = \frac{2P_r A_9}{m_5 - m_5 - m_7}. \]
4. Results and discussions

The problem natural convection unsteady magnetohydrodynamic mass transfer flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous flat plate in presence of constant suction and heat sink has been investigated. The governing equations of the flow field are solved employing multi parameter perturbation technique and the effects of the flow parameters on the velocity, temperature, concentration distribution and also on the skin friction and rate of heat transfer in the flow field are analyzed and discussed with the help of velocity profiles 1-5, temperature profiles 6-7, concentration distribution 8 and Table 1 respectively.

4.1 Velocity field

The velocity of the flow field suffers a substantial change in magnitude with the variation of the flow parameters. The important parameters affecting the velocity of the flow field are magnetic parameter $M$, Grashof numbers for heat and mass transfer $Gr$, $Gc$; heat sink parameter $S$ and Schmidt number $Sc$.

Figures 1-5 discuss the effects of these parameters on the velocity of the flow field.

![Figure 1. Velocity profiles against $y$ for different values of $M$ with $Gr=3$, $Gc=3$, $S=-0.1$, $Sc=0.60$, $Pr=0.71$, $Ec=0.002$, $\alpha=5.0$, $\varepsilon=0.2$, $\omega=\pi/2$](image-url)
The effect of magnetic parameter $M$ on the velocity field is discussed in Figure 1. Curve with $M=0$ corresponds to the case of non-MHD flow. Comparing the curves of Figure 1, it is observed that a growing magnetic parameter retards the velocity of the flow field at all points due to the dominant effect of the Lorentz force acting on the flow field. In Figures 2 and 3, we observe the effect of Grashof numbers for heat and mass transfer $G_r, G_c$ respectively on the velocity field. Curves with $G_r < 0$ correspond to heating of the plate, while those with $G_r > 0$ correspond to cooling of the plate. Analyzing the curves of Figures 2 and 3, we come to a conclusion that both the parameters $G_r$ and $G_c$ enhance the velocity of the field at all points. Figure 4 elucidates the effect of heat sink/source parameter $S$ on the velocity of the flow field. Curves with $S<0$ and $S>0$ correspond to the presence of heat sink and heat source respectively in the flow field. The heat source parameter ($S>0$) is found to accelerate the velocity of the flow field at all points while the presence of heat sink ($S<0$) reverses effect. The effect of Schmidt number $S_c$ on the velocity field is discussed in Figure 5. The heavier diffusive species (growing $S_c$) has a decelerating effect on the velocity of the flow field at all points.

![Figure 2](image)

Figure 2. Velocity profiles against $y$ for different values of $G_r$ with $G_r=3, M=1, S=-0.1, S_c=0.60, P_r=0.71, E_c=0.002, \alpha=5.0, \varepsilon=0.2, \omega=\pi/2$
Figure 3. Velocity profiles against $y$ for different values of $G_c$ with $G=3$, $M=1$, $S=-0.1$, $S_r=0.60$, $P_r=0.71$, $E_c=0.002$, $\omega=5.0$, $\varepsilon=0.2$, $\omega t=\pi/2$.

Figure 4. Velocity profiles against $y$ for different values of $S$ with $G=3$, $G_c=3$, $E_c=0.002$, $M=1$, $S_r=0.60$, $P_r=0.71$, $\omega=5.0$, $\varepsilon=0.2$, $\omega t=\pi/2$. 
4.2 Temperature field

The temperature field is found to change appreciably with the variation of Prandtl number $P_r$ and heat sink parameter $S$. These variations have been shown in Figures 6 and 7 respectively. On close observation of the curves of both the figures, we notice that the effect of increasing the magnitude of heat sink parameter and the Prandtl number is to decrease the temperature of the flow field at all points; while the heat source parameter reverses the effect.
4.3 Concentration distribution

Figure 8 depicts the concentration distribution in presence of foreign species such as $H_2$, $He$, $H_2O$ vapour, $NH_3$ and $CO_2$ in the flow field with $S_c=0.22, 0.30, 0.60, 0.78$ and $1.004$ respectively. The concentration distribution of the flow field suffers a decrease in boundary layer thickness in presence of heavier diffusive species (growing $S_c$) at all points of the flow field. It is further observed that heavier the diffusive species, the sharper is the reduction in the concentration boundary layer thickness of the flow field.
4.4 Skin friction and rate of heat transfer
Variations in the values of skin friction $\tau$ and the heat flux i.e. rate of heat transfer $Nu$ against the Prandtl number $Pr$, for different values of magnetic parameter $M$ are entered in Table 1 keeping other parameters of the flow field constant. A growing Prandtl number $Pr$ increases the skin friction for non-MHD flow and decreases it at the wall in case of MHD flow. On the other hand, a growing magnetic parameter $M$ decreases the effect at all points. The effect of increasing Prandtl number $Pr$, is to increase the rate of heat transfer at the wall, while a growing magnetic parameter $M$ leads to decrease its value at all points.

Table 1. Variation in the values of skin friction $\tau$ and the rate of heat transfer $Nu$ against $Pr$ for different values of $M$ with $S$= -0.1, $G_r$=3, $G_c$=3, $S_c$=0.60, $\omega_r$=5.0, $\omega_c$=0.2, $\omega$=\frac{\pi}{2}

<table>
<thead>
<tr>
<th>$Pr$</th>
<th>$M$=0</th>
<th>$M$=0.1</th>
<th>$M$=5.0</th>
<th>$M$=20.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau$</td>
<td>$Nu$</td>
<td>$\tau$</td>
<td>$Nu$</td>
</tr>
<tr>
<td>0.71</td>
<td>11.6271</td>
<td>1.6423</td>
<td>11.3191</td>
<td>1.4287</td>
</tr>
<tr>
<td>2</td>
<td>12.1139</td>
<td>3.2345</td>
<td>8.1317</td>
<td>2.3879</td>
</tr>
<tr>
<td>9</td>
<td>18.1481</td>
<td>-10.812</td>
<td>5.5672</td>
<td>-10.508</td>
</tr>
</tbody>
</table>

8. Conclusion
We present below the following results of physical interest on the velocity, temperature, concentration distribution, skin friction and the rate of heat transfer at the wall of the flow field.
1. A growing magnetic parameter $M$ or Schmidt number $S_c$ or heat sink parameter $S$ leads to retard the transient velocity of the flow field at all points.
2. The effect of increasing Grashof number for heat transfer $G_r$ and mass transfer $G_c$ is to enhance the transient velocity of the flow field at all points.
3. An increase in Prandtl number $Pr$ decreases the transient temperature of the flow field at all points while a growing heat sink parameter $S$ reverses the effect.
4. A heavier diffusive species (growing $S_c$) has a sharper reduction in the concentration boundary layer thickness at all points of the flow field.
5. A growing Prandtl number $Pr$ increases the skin friction for non-MHD flow and decreases it at the wall in case of MHD flow. On the other hand, a growing magnetic parameter $M$ decreases the effect at all points.
6. The effect of increasing Prandtl number $Pr$, is to enhance the magnitude of rate of heat transfer at the wall, while a growing magnetic parameter $M$ leads to decrease its value at all points.

References


S. S. Das did his M. Sc. degree in Physics from Utkal University, Orissa (India) in 1982 and obtained his Ph. D degree in Physics from the same University in 2002. He started his service career as a Faculty of Physics in Nayagarh (Autonomous) College, Orissa (India) from 1982-2004 and presently working as the Head of the faculty of Physics in KBDAV College, Nirakarpur, Orissa (India) since 2004. He has 29 years of teaching experience and 12 years of research experience. He has produced 2 Ph. D scholars and presently guiding 15 Ph. D scholars. Now he is carrying on his Post Doc. Research in MHD flow through porous media. His major fields of study are MHD flow, Heat and Mass Transfer Flow through Porous Media, Polar fluid, Stratified flow etc. He has published 51 papers in the related area, 42 of which are published in Journals of International repute. Also he has reviewed a good number of research papers of some International Journals. Dr. Das is currently acting as the honorary member of editorial board of Indian Journal of Science and Technology and as Referee of AMSE Journal, France; Central European Journal of Physics; International Journal of Medicine and Medical Sciences, Chemical Engineering Communications, International Journal of Energy and Technology, Progress in Computational Fluid Dynamics etc. Dr. Das is the recipient of prestigious honour of being selected for inclusion in Marquis Who’s Who in Science and Engineering of New Jersey, USA for the year 2011-2012 (11th Edition) for his outstanding contribution to research in Science and Engineering.

E-mail address: drssd2@yahoo.com

S. Parija did her M. Sc. degree in Physics from Utkal University, Orissa (India) in 1986 and obtained her M. Phil degree in Physics from the same University in 1988. She served as a Faculty of Physics in A. S. College, Tirtol, Orissa from 1987-1997 and presently working as the Senior faculty of Physics in Nimapara (Autonomous) College, Orissa since 1997. She has 24 years of teaching experience and 3 years of research experience. Presently she is engaged in active research. Her major fields of study are magnetohydrodynamic flow with or without heat transfer and the related problems. She has published 1 paper in the related area.

E-mail address: sephaliparija@yahoo.com

R. K. Padhy obtained his M. Sc. degree in Physics from Berhampur University, Orissa (India) in 2002. He served as a Faculty of Physics in Little Angel Public School, Nizampattam, Andhra Pradesh (India) from 2002-2003 and in Jupiter +2 Science College, Bhubaneswar, Orissa from 2003-2005. Presently he is working as Head of the faculty of Physics in DAV Public School, Chandrasekharpur, Bhubaneswar since 2005. He has 9 years of teaching experience and presently he is engaged in active research. His major field of study is flow and heat transfer in viscous incompressible fluids with or without mass transfer.

E-mail address: rajesh_pip@rediffmail.com
M. Sahu did her M. Sc. degree in Physics from Berhampur University, Orissa (India) in 2002 and won a gold medal as a topper in the subject. She served as a Faculty of Physics in Gandhi Institute of Engineering and Technology, Gunpur, Orissa (India) from 2002-2003 and presently working as the Vice-Principal and Head of the faculty of Physics in Jupiter +2 Women’s Science College, Bhubaneswar since 2003. She has 9 years of teaching experience and presently she is engaged in active research. Her major field of study is hydromagnetic flow with heat transfer.

E-mail address: mira_physics@rediffmail.com