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MHD Free Convection Transient Flow past an Infinite Vertical Porous Flat Plate in Presence of Mass Transfer

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Abstract
The objective of this paper is to analyze mass transfer and free convection effects on unsteady flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous plate in presence of transverse magnetic field. Using multi parameter perturbation technique, the governing equations of the flow field are solved and approximate solutions are obtained for velocity, temperature, concentration distribution, skin friction and the heat flux. The effects of the pertinent parameters such as magnetic parameter, Grashof numbers for heat transfer and mass transfer, Schmidt number, Prandtl number etc. on the flow field are analyzed with the aid of figures and tables. It is observed that a growing magnetic parameter M or Schmidt number S_c is to retard the transient velocity of the flow field at all points while a growing Grashof number for heat and mass transfer G_r, G_c reverses the effect. The effect of increasing Prandtl number P_r decreases the transient temperature of the flow field at all points while a growing frequency parameter ω reverses the effect. An increase in Schmidt number S_c reduces the concentration boundary layer thickness of the flow field at all points. The magnetic parameter or Prandtl number decreases the skin friction at the wall while in case of non-MHD flow (M=0) a growing P_r reverses the effect. The effect of increasing magnetic parameter is to decrease the magnitude of the rate of heat transfer at the wall, while a growing Prandtl number enhances the magnitude of the rate of heat transfer at the wall.

Keywords: MHD, Mass transfer, Free convection, Viscous, Incompressible fluid, Electrically conducting.

1. Introduction
Now-a-days, MHD flow with heat and mass transfer is gathering momentum day by day because of its varied applications in different fields of geophysical and astrophysical studies, engineering sciences and also in industry. In view of its wide interests in several fields of science and technology, Soundalgekar and Ganesan [1] analyzed the transient free convection flow on a semi-infinite vertical plate with mass transfer. Raptis and Tzivanidis [2] estimated the mass transfer effects on the flow past an accelerated infinite vertical plate with variable heat transfer. Bejan and Khair [3] studied the heat and mass transfer by natural convection in a porous medium. Kim and Vafai [4] analyzed the natural convection flow about vertical plate embedded in porous medium. Sattar and Hossain [5] discussed the unsteady hydromagnetic free convection flow with Hall current and mass transfer along an accelerated porous plate with time dependent temperature and concentration. Rao and Pop [6] studied the transient free convection in fluid saturated porous media with temperature dependent viscosity. Attia and Kotb [7] analyzed the MHD flow between two parallel plates with heat transfer.
The effect of applied magnetic field on transient free convective flow in a vertical channel was studied by Jha [8]. Dash and Das [9] estimated the Hall effects on MHD flow along an accelerated porous flat plate with mass transfer and internal heat generation. Chowdhury and Islam [10] reported the MHD free convection flow of visco-elastic fluid past an infinite vertical porous plate. Singh *et al*. [11] analyzed the MHD free convection transient flow through a porous medium in a vertical channel. Das and his associates [12] estimated numerically the mass transfer effects on unsteady flow past an accelerated vertical porous plate with suction. Sharma and Singh [13] discussed the unsteady MHD free convective flow and heat transfer along a vertical porous plate with variable suction and internal heat generation. Das and Mitra [14] explained the unsteady mixed convective MHD flow and mass transfer past an accelerated infinite vertical plate with suction. Das and his team [15] reported the hydromagnetic convective flow past a vertical porous plate through a porous medium with suction and heat source. Das and his co-workers [16] analyzed the unsteady hydromagnetic convective flow past an infinite vertical porous flat plate in a porous medium.
The present study is an extension of the work of Das and his co-workers [16] to mass transfer flow in a non-porous medium and estimates the simultaneous mass transfer and free convection effects on unsteady flow of a viscous

incompressible electrically conducting fluid past an infinite vertical porous plate in presence of transverse magnetic field. Using multi parameter perturbation technique approximate solutions are obtained for velocity, temperature, concentration distribution, skin friction and heat flux. The effects of the various flow parameters affecting the flow field are analyzed with the help of figures and tables.

2. Mathematical formulation of the problem

We consider an unsteady free convective mass transfer flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous flat plate with heat source/sink in presence a transverse magnetic field B_0. The x′-axis is taken along the plate in vertically upward direction and y′-axis 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:

$$\frac{\partial v'}{\partial y'} = 0 \Rightarrow v' = -v_0' \text{ (constant)}, \quad (1)$$

Momentum equation:

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) + \nu\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2}{\rho}u', \quad (2)$$

Energy equation:

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = k\frac{\partial^2 T'}{\partial y'^2} + \frac{\nu}{C_p}\left(\frac{\partial u'}{\partial y'}\right)^2, \quad (3)$$

Concentration equation:

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2}. \quad (4)$$

The boundary conditions of the problem are:

$$u' = 0, v' = -v_0', T' = T'_w + \varepsilon(T'_w - T'_\infty)e^{i\omega' t'}, C' = C'_w + \varepsilon(C'_w - C'_\infty)e^{i\omega' t'}$$

at $y' = 0$,

$$u' \to 0,\ T' \to T'_\infty,\ C' \to C'_\infty \text{ as } y' \to \infty. \quad (5)$$

We introduce the following non-dimensional variables and parameters,

$$y = \frac{y' v_0'}{\nu}, t = \frac{t' v_0'^2}{4\nu}, \omega = \frac{4\nu\omega'}{v_0'^2}, u = \frac{u'}{v_0'}, \nu = \frac{\eta_0}{\rho}, M = \left(\frac{\sigma B_0^2}{\rho}\right)\frac{\nu}{v_0'^2},$$

$$T = \frac{T' - T'_\infty}{T'_w - T'_\infty}, C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, P_r = \frac{\nu}{k}, S_c = \frac{\nu}{D},$$

$$G_r = \frac{\nu g\beta(T'_w - T'_\infty)}{v_0'^3}, \quad G_c = \frac{\nu g\beta^*(C'_w - C'_\infty)}{v_0'^3}, E_c = \frac{v_0'^2}{C_p(T'_w - T'_\infty)}, \quad (6)$$

where, g is the acceleration due to gravity, ρ is the density, σ is the electrical conductivity, ν is the coefficient of kinematic viscosity, β is the volumetric coefficient of expansion for heat transfer, β* is the volumetric coefficient of expansion for mass transfer, ω is the angular frequency, η_0 is the coefficient of viscosity, k is the thermal diffusivity, T is the temperature, T_w is the temperature at the plate, T_∞ is the temperature at infinity, C is the concentration, C_w is the concentration at the plate, C_∞ is the concentration at infinity, C_p is the specific heat at constant pressure, D is the molecular mass diffusivity, P_r is the Prandtl number, S_c is the Schmidt number, G_r is the Grashof number for heat transfer, G_c is the Grashof number for mass transfer, E_c is the Eckert number and M is the magnetic parameter.

Substituting (6) in equations (2)-(4) under boundary conditions (5), we obtain:

$$\frac{1}{4}\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = G_r T + G_c C + \frac{\partial^2 u}{\partial y^2} - Mu, \quad (7)$$

$$\frac{1}{4}\frac{\partial T}{\partial t} - \frac{\partial T}{\partial y} = \frac{1}{P_r}\frac{\partial^2 T}{\partial y^2} + E_c\left(\frac{\partial u}{\partial y}\right)^2, \quad (8)$$

$$\frac{1}{4}\frac{\partial C}{\partial t} - \frac{\partial C}{\partial y} = \frac{1}{S_c}\frac{\partial^2 C}{\partial y^2}. \quad (9)$$

The corresponding boundary conditions are:

$$u = 0, T = 1 + \varepsilon e^{i\omega t}, C = 1 + \varepsilon e^{i\omega t} \text{ at } y = 0,$$

$$u \to 0, T \to 0,\ C \to 0 \text{ as } y \to \infty. \quad (10)$$

3. 3. Method of solution

In order to solve equations (7), (8) and (9), we assume ε to be very small and the velocity and temperature and concentration of the flow field in the neighbourhood of the plate as

$$u(y,t) = u_0(y) + \varepsilon e^{i\omega t}u_1(y), \quad (11)$$

$$T(y,t) = T_0(y) + \varepsilon e^{i\omega t}T_1(y), \quad (12)$$

$$C(y,t) = C_0(y) + \varepsilon e^{i\omega t}C_1(y). \quad (13)$$

Substituting equations (11)-(13) in equations (7)-(9) respectively, equating the harmonic and non-harmonic terms and neglecting the coefficients of ε^2, we get

Zeroth order:

$$u_0'' + u_0' - Mu_0 = -G_r T_0 - G_c C_0, \quad (14)$$

$$T_0'' + P_r T_0' = -P_r E_c\left(\frac{\partial u_0}{\partial y}\right)^2, \quad (15)$$

$$C_0'' + S_c C_0' = 0. \quad (16)$$

First order:

$$u_1'' + u_1' - \frac{i\omega}{4}u_1 - Mu_1 = -G_r T_1 - G_c C_1, \quad (17)$$

$$T_1'' + P_r T_1' - \frac{i\omega P_r}{4}T_1 = -2P_r E_c\left(\frac{\partial u_0}{\partial y}\right)\left(\frac{\partial u_1}{\partial y}\right), \quad (18)$$

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

The corresponding boundary conditions are

$$y=0: u_0=0, T_0=1, C_0=1, u_1=0, T_1=1, C_1=1,$$
$$y\to\infty: u_0=0, T_0=0, C_0=0, u_1=0, T_1=0, C_1=0. \quad (20)$$

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

$$C_0=e^{-S_c y}, \quad (21)$$
$$C_1=e^{-m_1 y}, \quad (22)$$

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

$$u_0=u_{00}+E_c u_{01}, \quad (23)$$
$$T_0=T_{00}+E_c T_{01}, \quad (24)$$
$$u_1=u_{10}+E_c u_{11}, \quad (25)$$
$$T_1=T_{10}+E_c T_{11}. \quad (26)$$

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

Zeroth order:

$$u_{00}''+u_{00}'-M u_{00}=-G_r T_{00}-G_c C_0, \quad (27)$$
$$u_{10}''+u_{10}'-\left(M+\frac{i\omega}{4}\right)u_{10}=-G_r T_{10}-G_c C_1, \quad (28)$$
$$T_{00}''+P_r T_{00}'=0, \quad (29)$$
$$T_{10}''+P_r T_{10}'-\frac{i\omega P_r}{4}T_{10}=0. \quad (30)$$

The corresponding boundary conditions are,

$$y=0: u_{00}=0, T_{00}=1, u_{10}=0, T_{10}=1,$$
$$y\to\infty: u_{00}=0, T_{00}=0, u_{10}=0, T_{10}=0. \quad (31)$$

First order:

$$u_{01}''+u_{01}'-M u_{01}=-G_r T_{01}, \quad (32)$$
$$u_{11}''+u_{11}'-\left(M+\frac{i\omega}{4}\right)u_{11}=-G_r T_{11}, \quad (33)$$
$$T_{01}''+P_r T_{01}'=-P_r\left(u_{00}'\right)^2, \quad (34)$$
$$T_{11}''+P_r T_{11}'-\frac{i\omega P_r}{4}T_{11}=-2P_r\left(\frac{\partial u_{00}}{\partial y}\right)\left(\frac{\partial u_{10}}{\partial y}\right). \quad (35)$$

The corresponding boundary conditions are,

$$y=0: u_{01}=0, T_{01}=0, u_{11}=0, T_{11}=0,$$
$$y\to\infty: u_{01}=0, T_{01}=0, u_{11}=0, T_{11}=0. \quad (36)$$

Solving equations (27)-(30) subject to boundary condition (31), we get

$$u_{00}=A_1 e^{-P_r y}+A_2 e^{-S_c y}-A_3 e^{-m_5 y}, \quad (37)$$
$$T_{00}=e^{-P_r y}, \quad (38)$$
$$u_{10}=A_4 e^{-m_3 y}+A_5 e^{-m_1 y}-A_6 e^{-m_7 y}, \quad (39)$$
$$T_{10}=e^{-m_3 y}. \quad (40)$$

Solving equations (32)-(35) subject to boundary condition (36), we get

$$T_{01}=B_1 e^{-2S_c y}+B_2 e^{-2P_r y}+B_3 e^{-2m_3 y}+B_4 e^{-(P_r+S_c)y}$$
$$+B_5 e^{-(m_5+S_c)y}+B_6 e^{-(P_r+m_5)y}-B_7 e^{-P_r y}, \quad (41)$$
$$T_{11}=D_1 e^{-(P_r+m_3)y}+D_2 e^{-(m_1+P_r)y}+D_3 e^{-(P_r+m_7)y}$$
$$+D_4 e^{-(m_3+S_c)y}+D_5 e^{-(m_1+S_c)y}+D_6 e^{-(m_7+S_c)y}$$
$$+D_7 e^{-(m_3+m_5)y}+D_8 e^{-(m_1+m_5)y}+D_9 e^{-(m_5+m_7)y}-D_{10} e^{-m_3 y}, \quad (42)$$
$$u_{01}=E_1 e^{-2S_c y}+E_2 e^{-2P_r y}+E_3 e^{-2m_5 y}+E_4 e^{-(P_r+S_c)y}+E_5 e^{-(m_5+S_c)y}$$
$$+E_6 e^{-(P_r+m_5)y}+E_7 e^{-P_r y}-E_8 e^{-m_5 y}, \quad (43)$$
$$u_{11}=F_1 e^{-(P_r+m_3)y}+F_2 e^{-(m_1+P_r)y}+F_3 e^{-(P_r+m_7)y}$$
$$+F_4 e^{-(m_3+S_c)y}+F_5 e^{-(m_1+S_c)y}+F_6 e^{-(m_7+S_c)y}$$
$$+F_7 e^{-(m_3+m_5)y}+F_8 e^{-(m_1+m_5)y}+F_9 e^{-(m_5+m_7)y}$$
$$+F_{10} e^{-m_3 y}-F_{11} e^{-m_7 y}. \quad (44)$$

Substituting the values of C_0 and C_1 from equations (21) and (22) in equation (13) the solution for concentration distribution of the flow field is given by

$$C=e^{-S_c y}+\varepsilon e^{i\omega t}e^{-m_1 y}. \quad (45)$$

3. 1. Skin friction

The skin friction at the wall is given by

$$\tau_w=\left(\frac{\partial u}{\partial y}\right)_{y=0}$$
$$=-P_r A_1-S_c A_2+m_5 A_3-E_c\left[2S_c E_1+2P_r E_2+2m_5 E_3+\left(P_r+S_c\right)E_4\right.$$
$$\left.+\left(m_5+S_c\right)E_5+\left(P_r+m_5\right)E_6+P_r E_7-m_5 E_8\right]+\varepsilon e^{i\omega t}\left\{-m_3 A_4\right.$$
$$-m_1 A_5+m_7 A_6-E_c\left[\left(P_r+m_3\right)F_1\right.$$
$$+\left(m_1+P_r\right)F_2+\left(P_r+m_7\right)F_3$$
$$+\left(m_3+S_c\right)F_4+\left(m_1+S_c\right)F_5+\left(m_7+S_c\right)F_6+\left(m_3+m_5\right)F_7$$
$$\left.\left.+\left(m_1+m_5\right)F_8+\left(m_5+m_7\right)F_9+m_3 F_{10}-m_7 D_{11}\right]\right\}. \quad (46)$$

3. 2. Heat flux

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

$$N_u=\left(\frac{\partial T}{\partial y}\right)_{y=0}$$
$$=-P_r-E_c\left[2S_c B_1+2P_r B_2+2m_3 B_3-\right.$$
$$\left.-\left(P_r+S_c\right)B_4+\left(m_5+S_c\right)B_5+\left(P_r+m_5\right)B_6-P_r B_7\right]$$
$$+\varepsilon e^{i\omega t}\left\{-m_3-E_c\left[\left(P_r+m_3\right)D_1+\left(m_1+P_r\right)D_2+\left(P_r+m_7\right)D_3\right.\right.$$
$$+\left(m_3+S_c\right)D_4+\left(m_1+S_c\right)D_5+\left(m_7+S_c\right)D_6+\left(m_3+m_5\right)D_7$$
$$\left.\left.+\left(m_1+m_5\right)D_8+\left(m_5+m_7\right)D_9-m_3 D_{10}\right]\right\}. \quad (47)$$

where,

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

$$m_5 = \frac{1}{2}\left[1+\sqrt{1+4M}\right],\ m_6 = \frac{1}{2}\left[-1+\sqrt{1+4M}\right],$$

$$m_7 = \frac{1}{2}\left[1+\sqrt{1+4\left(M+\frac{i\omega}{4}\right)}\right],$$

$$m_8 = \frac{1}{2}\left[-1+\sqrt{1+4\left(M+\frac{i\omega}{4}\right)}\right],$$

$$A_1 = \frac{G_r}{(m_5-P_r)(m_6+P_r)},\ A_2 = \frac{G_c}{(m_5-S_c)(m_6+S_c)},$$

$$A_3 = A_1 + A_2,\ A_4 = \frac{G_r}{(m_7-m_3)(m_8+m_3)},$$

$$A_5 = \frac{G_c}{(m_7-m_1)(m_8+m_1)},\ A_6 = A_4 + A_5,$$

$$B_1 = \frac{P_r S_c A_2^2}{2(P_r-2S_c)},\ B_2 = \frac{-P_r A_1^2}{2},\ B_3 = \frac{P_r m_5 A_3^2}{2(P_r-2m_5)},$$

$$B_4 = -\frac{2A_1A_2{P_r}^2}{(P_r+S_c)},\ B_5 = -\frac{2P_rS_cA_2A_3m_5}{(P_r-m_5-S_c)(m_5+S_c)},$$

$$B_6 = \frac{2{P_r}^2A_1A_2}{(P_r+m_5)},\ B_7 = B_1+B_2+B_3+B_4+B_5+B_6,$$

$$D_1 = -\frac{2P_rA_1A_6}{(P_r+m_3+m_3)},\ D_2 = \frac{2{P_r}^2A_1A_5m_1}{(m_3-P_r-m_1)(m_4+P_r+m_1)},$$

$$D_3 = \frac{2{P_r}^2A_1A_6m_7}{(m_7-m_3+P_r)(m_7+m_4+P_r)},\ D_4 = -\frac{2P_rA_2A_4m_3}{(m_4+m_3+S_c)},$$

$$D_5 = \frac{2P_rS_cA_2A_5m_1}{(m_3-m_1-S_c)(m_4+m_1+S_c)},$$

$$D_6 = \frac{2P_rS_cA_2A_6m_7}{(m_7-m_3+S_c)(m_7+m_4+S_c)},\ D_7 = \frac{2P_rA_3A_4m_3}{(m_5+m_4+m_3)},$$

$$D_8 = \frac{2P_rA_3A_5m_1m_5}{(m_5-m_3+m_1)(m_5+m_4+m_1)},$$

$$D_9 = \frac{2P_rA_3A_6m_5m_7}{(m_7+m_5+m_3)(m_7+m_5+m_4)},$$

$$D_{10} = D_1+D_2+D_3+D_4+D_5+D_6+D_7+D_8+D_9,$$

$$E_1 = \frac{G_rB_1}{(m_5-2S_c)(m_6+2S_c)},\ E_2 = \frac{G_rB_2}{(m_5-2P_r)(m_6+2P_r)},$$

$$E_3 = \frac{-G_rB_3}{m_5(m_6+2m_5)},\ E_4 = \frac{G_rB_4}{(m_5-P_r-S_c)(m_6+P_r+S_c)},$$

$$E_5 = \frac{-G_rB_5}{S_c(m_6+m_5+S_c)},\ E_6 = \frac{-G_rB_6}{P_r(m_6+m_5+P_r)},$$

$$E_7 = \frac{G_rB_7}{(P_r-m_5)(m_6+P_r)},$$

$$E_8 = E_1+E_2+E_3+E_4+E_5+E_6+E_7,$$

$$F_1 = \frac{G_rD_1}{(m_7-m_3-P_r)(m_8+m_3+P_r)},$$

$$F_2 = \frac{G_rD_2}{(m_7-P_r-m_1)(m_8+P_r+m_1)},$$

$$F_3 = \frac{-G_rD_3}{P_r(m_8+m_7+P_r)},$$

$$F_4 = \frac{G_rD_4}{(m_7-m_3-S_c)(m_8+m_3+S_c)},$$

$$F_5 = \frac{G_rD_5}{(m_7-m_1-S_c)(m_8+m_1+S_c)},$$

$$F_6 = \frac{-G_rD_6}{S_c(m_8+m_7+S_c)},$$

$$F_7 = \frac{G_rD_7}{(m_7-m_5-m_3)(m_8+m_5+m_3)},$$

$$F_8 = \frac{G_rD_8}{(m_7-m_5-m_1)(m_8+m_5+m_1)},$$

$$F_9 = \frac{-G_rD_9}{m_5(m_8+m_7+m_5)},$$

$$F_{10} = \frac{G_rD_{10}}{(m_7-m_3)(m_8+m_3)},$$

$$F_{11} = F_1+F_2+F_3+F_4+F_5+F_6+F_7+F_8+F_9+F_{10}. \quad (48)$$

4. Results and discussions

In the above study, we analyze the simultaneous mass transfer and free convection effects on unsteady flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous flat plate with heat source/sink in presence of a transverse magnetic field. The effects of the pertinent parameters such as magnetic parameter, Grashof numbers for heat transfer and mass transfer, Schmidt number, Prandtl number etc. on the flow field are analyzed with the aid of velocity profiles 1-4, temperature profile 5-6, concentration distribution 7 and Table 1.

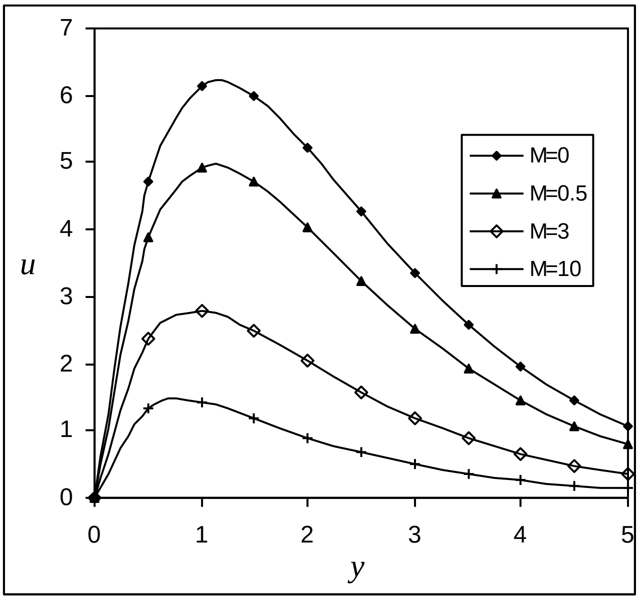

Figure 1. Effect of M on transient velocity profiles against y with G_r=3, G_c =3, S_c=0. 30, P_r=0. 71, E_c=0. 002, ω=5. 0, ε=0. 2, ωt=π/2

4. 1. Velocity field

The velocity of the flow field is affected more or less with the variation of magnetic parameter *M*, Grashof number for heat and mass transfer G_r, G_c, Schmidt number S_c and heat source parameter *S*. The effects of these parameters on the velocity field are presented in Figures 1-4. Figure 1 elucidates the effect of magnetic parameter *M* on the velocity of the flow field. A growing magnetic parameter is found to decelerate the velocity of the flow field at all points of the flow field due to the action of Lorentz force on the flow field. This is in good agreement with the results of Das and his co-workers [16].

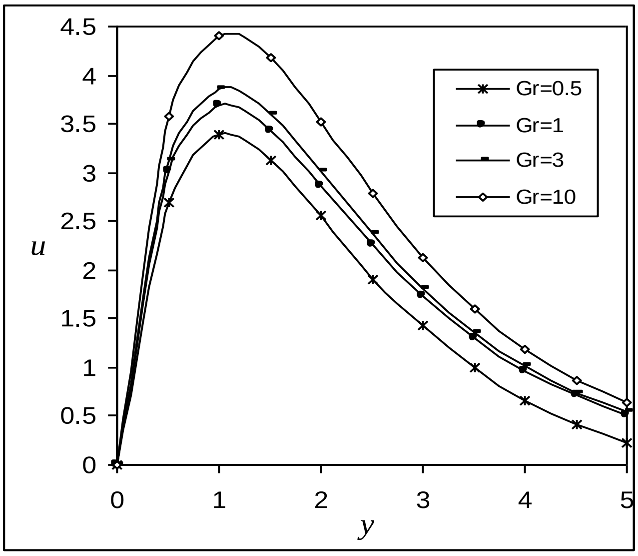

Figure 2. Effect of G_r on transient velocity profiles against *y* with M=1, G_c =3, S_c=0. 30, P_r=0. 71, E_c=0. 002, ω=5. 0, ε=0. 2, ωt=π/2

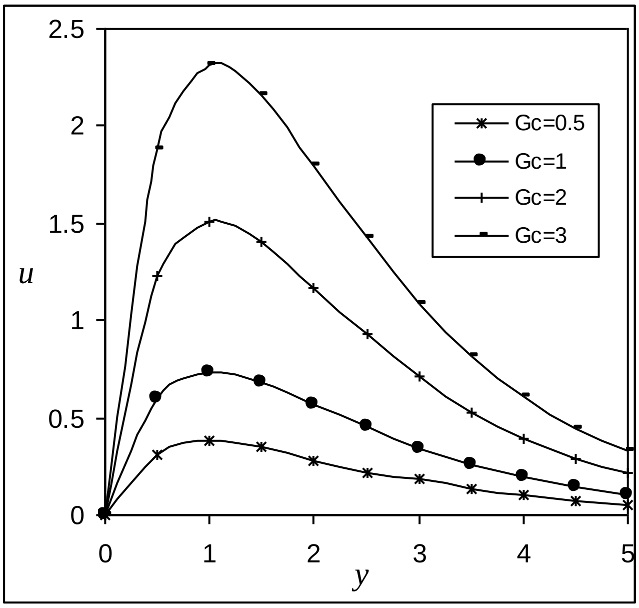

Figure 3. Effect of G_c on transient velocity profiles against *y* with M=1, G_r =3, S_c=0. 30, P_r=0. 71, E_c=0. 002, ω=5. 0, ε=0. 2, ωt=π/2

The effects of Grashof numbers for heat and mass transfer on the velocity field have been presented in Figures 2 and 3 respectively. Comparing the curves of both the figures, one may conclude that a growing Grashof number for heat or mass transfer accelerates the transient velocity of the flow field at all points of the flow field due to the action of free convection current and mass transfer in the flow field. Figure 2 is in good agreement with the results of Das and his co-workers [16]. Figure 4 depicts the effect of Schmidt number S_c on the velocity field. On careful observation of the curves of the curves of the figure, it is seen that a growing S_c (more diffusive species) has a decelerating effect on the transient velocity of the flow field at all points.

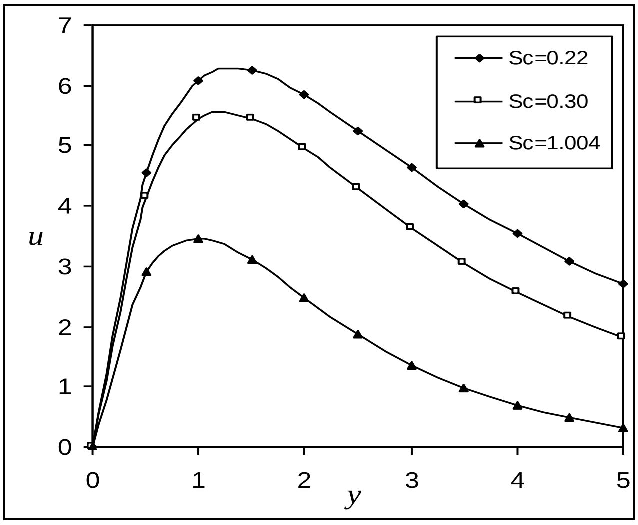

Figure 4. Effect of S_c on transient velocity profiles against *y* with G_r=3, G_c=3, E_c=0. 002, M=1, P_r=0. 71, ω=5. 0, ε=0. 2, ωt=π/2

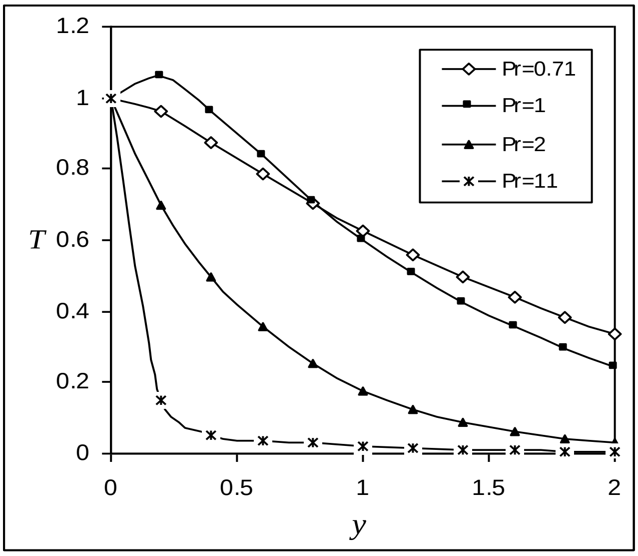

Figure 5. Effect of P_r on transient temperature profiles against *y* with G_r=3, G_c =3, M=1, S_c=0. 30, E_c=0. 002, ω=5. 0, ε=0. 2, ωt=π/2

4. 2. Temperature field

Figures 5 and 6 respectively elucidate the effects of Prandtl number P_r and frequency parameter ω on the temperature field. On close observation of curves of the Figures 5 and 6, it is seen that a growing Prandtl number P_r decreases the transient temperature at all points of the flow field with some discrepancy for P_r=1 while a growing frequency parameter ω reverses the effect. The temperature profiles shown in Figure 5 are in good agreement with the results of Das and his co-workers [16].

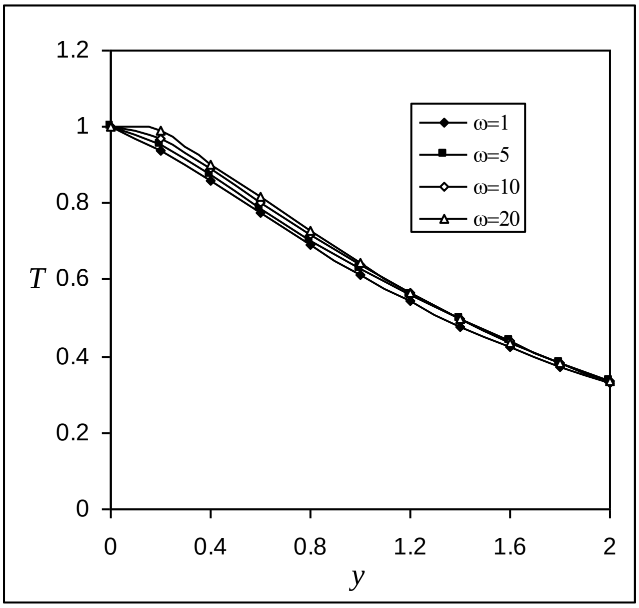

Figure 6. Effect of ω on transient temperature profiles against *y* with P_r =0. 71, G_r=3, G_c =3, *M*=1, S_c=0. 30, E_c=0. 002, ε=0. 2, $\omega t=\pi/2$

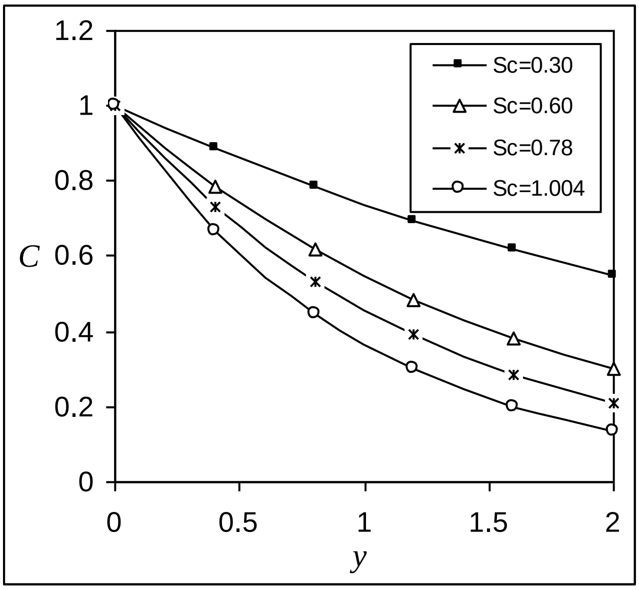

Figure 7. Effect of S_c on transient concentration profiles against *y* with ω=5. 0, ε=0. 2, $\omega t=\pi/2$

4. 3. Concentration distribution

The concentration distribution of the flow field varies vastly with the change of Schmidt number S_c. This has been shown in Figure 7. A growing Schmidt number leads to decrease the concentration distribution of the flow field at all points.

4. 4. Skin friction and Rate of heat transfer

In Tables 1 and 2 respectively, we present the values of skin friction τ and the heat flux in terms of Nusselt number N_u against P_r for different values of *M* keeping other parameters of the flow field constant. The Prandtl number P_r and the magnetic parameter *M* are varied in steps and the variations in skin friction and the heat flux are noted. It is found that a growing magnetic parameter or Prandtl number decreases the skin friction at the wall. On the other hand, in case of non-MHD flow (*M*=0) a growing P_r reverses the effect. Further, it is seen that an increase in magnetic parameter decreases the absolute value of heat flux at the wall, while an increase in Prandtl number reverses the effect. The skin friction and heat flux are in good agreement with the results of Das and his co-workers [16].

Table1. Effect of *M* on skin friction τ against P_r with E_c=0. 002, S_c=0. 30, G_r=3, G_c =3 ω=5. 0, ε=0. 2, $\omega t=\pi/2$

P_r	τ			
	M =0	*M* =0. 2	*M* =3	*M* =10
0. 71	10. 981	10. 816	7. 124	5. 761
2	11. 479	7. 994	6. 012	4. 691
7	15. 632	5. 912	4. 865	3. 743
11	19. 753	5. 503	4. 016	3. 503

Table2. Effect of *M* on heat flux N_u against P_r with E_c=0. 002, S_c=0. 30, G_r=3, G_c =3 ω=5. 0, ε=0. 2, $\omega t=\pi/2$

P_r	N_u			
	M =0	*M* =0. 2	*M* =3	*M* =10
0. 71	1. 647	1. 123	-0. 524	-0. 321
2	3. 255	2. 707	2. 062	0. 534
7	-9. 197	-8. 204	-5. 812	-5. 419
11	-11. 985	-10. 981	-8. 619	-8. 207

5. Conclusion

We present below the following results of physical interest on the velocity, temperature and concentration distribution of the flow field from the above analysis.

1. A growing magnetic parameter *M* or Schmidt number S_c decelerates the transient velocity of the flow field at all points. On the other hand, an increase in Grashof number for heat and mass transfer G_r, G_c reverses the effect.
2. The effect of increasing Prandtl number P_r is to diminish the transient temperature of the flow field at all points with some discrepancy for P_r=1 while a growing frequency parameter ω reverses the effect.
3. An increase in Schmidt number S_c decreases the concentration boundary layer thickness of the flow field at all points.

4. A growing magnetic parameter or Prandtl number decreases the skin friction at the wall, on the other hand a growing P_r reverses the effect in case of non-MHD flow (M=0).
5. The magnetic parameter decreases the magnitude of heat flux at the wall, while a growing Prandtl number increases the magnitude of heat flux at the wall at all points.

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