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Research Article

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Chemical Reaction and Radiation Effects of MHD Free Convective Flow past an Impulsively Moving Vertical Plate with Ramped Wall Temperature and Concentration

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ABSTRACT

An analysis has been carried out to study the effects of thermal radiation and chemical reaction of MHD natural convection flow of a viscous incompressible electrically conducting and heat absorbing fluid past an impulsively moving vertical plate with ramped wall temperature and concentration in a porous medium in the presence of thermal diffusion. The solutions for velocity field, temperature field and concentration distribution are obtained using Laplace transformation technique. The effects of flow parameters such as magnetic parameter (M), Prandtl number (Pr), porosity parameter (Kp), thermal Grashof number (Gr), mass Grashof number (Gc), Schmidt number (Sc), heat absorption parameter (ϕ) and time parameter (t) on the velocity, temperature and concentration distribution of the flow field and the skin friction, heat flux and the rate of mass transfer are studied analytically and presented with the aid of figures and tables. A comparison with earlier study shows that flow separation is caused in case of isothermal plate due to the presence of chemical reacting diffusing species for higher values of Grashof number. Further, the analysis reveals that the Lorentz force opposes the motion of the fluid more effectively in absence of porous matrix and the flow of fluid with higher thermal diffusivity in the presence of porous matrix prevents the back flow.

Key words: Natural convection, ramped wall temperature and concentration, thermal radiation, chemical reaction

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INTRODUCTION

Free convection flows past a vertical plate have been studied extensively in the literature due to applications in engineering and environmental processes. Several investigations were performed using both analytical numerical methods under different thermal conditions which are continuous and well defined at the wall. Practical problems often involve wall conditions that are non-uniform or arbitrary. To understand such problems, it is useful to investigate problems subject to step change in wall temperature. For example in the fabrication of thin-film photovoltaic devices ramped wall temperatures may be employed to achieve a specific finish of the system [1]. Other examples include nuclear heat transfer control, materials processing, turbine blade heat transfer, electronic circuits and sealed gas filled enclosure heat transfer operations [2]. Chandran et al.[3] have presented an analytical solution to the unsteady natural convection flow of an incompressible viscous fluid near a vertical plate with ramped wall temperature. Saha et al.[4] have investigated the natural convection boundary layer adjacent to an inclined semi-infinite flat plate subject to ramp heating. Chaudhary and Jain[5] have developed closed form solutions to unsteady free convection flow past an infinite vertical oscillating plate for the scenario where the bounding plate has a ramped temperature profile using the Laplace transformation technique. Seth and Ansari [6] have studied the MHD natural convection flow past an impulsively moving vertical plate with ramped wall temperature in the presence of thermal diffusion with heat absorption. They [7] have also studied the MHD natural convection flow with radiative heat transfer past an impulsively moving plate with ramped wall temperature. Free convection flows occur not only due to temperature difference but also due to concentration difference or the combination of the two. The study of combined heat and mass transfer play an important role in the design of chemical processing equipment, nuclear reactors, formation and dispersion of fog etc. Both steady-state and transient double-diffusive convection flows are of importance. Muthucumaraswamy et al. [8] have analyzed the heat mass transfer effects on flow past an impulsively started vertical plate. Muthucumaraswamy and Janakiraman [9] have also studied the mass transfer effects on isothermal vertical oscillating plate in the presence of chemical reaction. Beg et al.[10] have discussed the chemically reacting mixed convective heat and mass transfer along inclined and vertical plates with Soret and Dufour effects. The mass transfer effects on MHD flow and heat transfer past a vertical porous plate through a porous medium under oscillatory suction and heat source have studied by Das et al. [11]. Narahari et al. [12] have analyzed the mathematical modeling of mass transfer and free convection current effects on unsteady viscous flow with ramped wall temperature. Rajesh [13] has studied the chemical reaction and radiation effects on the transient MHD free convection flow of dissipative fluid past an infinite vertical porous plate with ramped wall temperature. Recently, the effect of heat and mass transfer on MHD free convection flow past an impulsively moving infinite vertical plate with ramped wall temperature has been studied by Pattnaik et al.[14]. They [15] have also analyzed the radiation and mass transfer effects on MHD free convection flow through porous medium past an exponentially accelerated vertical plate with variable temperature.

The objective of the present paper is to analyze the effects of thermal radiation and chemical reaction of an unsteady MHD free convective flow past an impulsively moving vertical plate with ramped wall temperature and concentration. We have incorporated the thermal radiation as well as mass transfer aspect with chemical reaction to the work of Seth and Ansari [6]. The solutions for velocity field, temperature field and concentration distribution are obtained using Laplace transformation technique.

FORMULATION OF THE PROBLEM AND ITS SOLUTION

Consider an unsteady laminar flow of a viscous incompressible electrically conducting and heat absorbing fluid past an infinite vertical plate embedded in a uniform porous medium. The x^* - axis is taken along the plate in the upward direction and the y^*-axis is normal to the plane of the plate in the fluid. The fluid is permeated by a uniform transverse magnetic field B_0 applied parallel to the y^*-axis. Initially, at time $t^* \le 0$, both the fluid and the plate are at rest and at a constant temperature T_∞^*. At time $t^* > 0$, the plate starts moving in the x^* direction with a uniform velocity U_0 and the temperature of the plate is raised or lowered to $T_\infty^* + (T_w^* - T_\infty^*)\, t^*/t_0$ when $t^* \le t_0$ and thereafter, at $t^* > t_0$, the plate is maintained at the constant temperature T_w^*. Since the plate is infinite along the x^* and z^* directions and are electrically non-conducting all physical quantities, except pressure, will be functions of y^* and t^* only.

It is assumed that no external electric field is applied so the effect of polarization of the fluid is negligible (Cramer and Pai, 1973), and we assumed $E \equiv (0,0,0)$. Also the induced magnetic field is produced by the fluid motion is negligible in comparison to the applied one, so we consider the magnetic field $B \equiv (0, B_0, 0)$. This assumption is justified because the magnetic Reynolds number is very small for metallic liquids and partially ionized fluids. The uncoupling of the momentum equation from Maxwell's relations is a consequence of the small magnetic Reynolds number.

Taking into account the assumptions made above, the governing equations for a laminar natural convection flow of a viscous incompressible electrically conducting and heat absorbing fluid in a uniform porous medium under the Boussinesq approximation in the presence of thermal diffusion are as follows

$$\frac{\partial u^*}{\partial t^*} = \upsilon \frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\sigma B_0^{\,2}}{\rho} u^* - \frac{\upsilon}{K^*} u^* + g\beta (T^* - T_\infty^*) + g\beta^* (C^* - C_\infty^*) \tag{1}$$

$$\frac{\partial T^*}{\partial t^*} = \alpha^* \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{Q_0}{\rho C_p}(T^* - T_\infty^*) - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y^*} \tag{2}$$

$$\frac{\partial C^*}{\partial t^*} = D \frac{\partial^2 C^*}{\partial y^{*2}} - K_l (C^* - C_\infty^*) \tag{3}$$

where $u^*, T^*, g, \beta, \beta^*, \upsilon, \sigma, \rho, K^*, C_p, \alpha^*$ and Q0 are respectively fluid velocity in the x^* direction , temperature of the fluid, acceleration due to gravity, volumetric coefficient of thermal expansion, kinematic coefficient of viscosity, fluid electrical conductivity, fluid density, permeability of the porous medium, specific heat at constant pressure, fluid thermal diffusivity and heat absorption coefficient.

The initial and boundary conditions are

$$\left.\begin{aligned}
&u^* = 0,\ T^* = T_\infty{}^*,\ C^* = C_\infty{}^* \quad for \quad y^* \geq 0\ and\ t^* \leq 0,\\
&u^* = U_0 \quad at \quad y^* = 0 \quad for \quad t^* > 0,\\
&T^* = T_\infty{}^* + (T_w{}^* - T_\infty{}^*)t^*/t_0,\ C^* = C_\infty{}^* + (C_w{}^* - C_\infty{}^*)t^*/t_0 \quad at \quad y^* = 0 \quad for\ 0 < t^* \leq t_0,\\
&T^* = T_w{}^*,\ C^* = C_w{}^* \quad at \quad y^* = 0 \quad for \quad t^* > t_0,\\
&u^* \to 0, T^* \to T_\infty{}^*,\ C^* \to C_\infty{}^* \quad as\ y^* \to \infty \quad for \quad t^* > 0.
\end{aligned}\right\}$$

Introducing the following non-dimensional quantities and parameters

$$y = y^*/U_0 t_0,\ u = u^*/U_0,\ t = t^*/t_0,\ T = (T^* - T_\infty{}^*)/(T_w{}^* - T_\infty{}^*),\ M = \sigma B_0{}^2\upsilon/\rho U_0{}^2,$$

$$C = (C^* - C_\infty{}^*)/(C_w{}^* - C_\infty{}^*),\ K_p = K^* U_0{}^2/\upsilon^2,\ Gr = g\beta\upsilon(T_w{}^* - T_\infty{}^*)/U_0{}^3,\ \Pr = \upsilon/\alpha^*,$$

$$\phi = \upsilon Q_0/\rho C_p U_0{}^2,\ Sc = \upsilon/D,\ Gc = g\beta^*\upsilon(C_w{}^* - C_\infty{}^*)/U_0{}^3 \text{ and } K = K_l\upsilon/U_0{}^2$$

Equations (1), (2) and (3) in non-dimensional form become

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} - \left(M + \frac{1}{K_p}\right)u + GrT + GcC \tag{4}$$

$$\frac{\partial T}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 T}{\partial y^2} - (\phi + Rd)T \tag{5}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - KC \tag{6}$$

where M, Kp, Gr, Gc, Pr, ϕ , Rd and K are magnetic parameter, porosity parameter, Grashof number, Prandtl number, dimensionless heat absorption coefficient, radiation and chemical reaction respectively.

According to the above non-dimensionalisation process, the characteristic time t_0 can be defined as $t_0 = \upsilon/U_0{}^2$. Now the initial and boundary conditions, in a non-dimensional form, reduce to

$u = 0,\ T = 0,\ C = 0$ for $y \geq 0$ and $t \leq 0$, (7a)

$u = 1$ at y = 0 for t > 0, (7b)

T = t , C = t at y = 0 for $0 < t \leq 1$, (7c)

$T = 1,\ C = 1$ at y = 0 for t >1, (7d)

$u \to 0, T \to 0, C \to 0$ as $y \to \infty$ for t > 0. (7e)

It is evident from equations (4), (5) and (6) that the energy equation (5) and mass transfer equation(6) are uncoupled. Therefore, we can obtain first the solution of fluid temperature T(y,t) and concentration C(y,t) by solving equations(5) and (6) then using these in equation(4) the solution for the fluid velocity u(y,t) can be obtained.

Applying the Laplace transforms technique, equations (4), (5) and (6) with the help of equation (7a) reduce to

$$\frac{\partial^2 \overline{u}}{\partial y^2} - \left(s + M + \frac{1}{K_p}\right)\overline{u} = -Gr\overline{T} - Gc\overline{C} \tag{8}$$

$$\frac{\partial^2 \overline{T}}{\partial y^2} - \Pr(s+\phi+Rd)\overline{T} = 0 \tag{9}$$

$$\frac{\partial^2 \overline{C}}{\partial y^2} - Sc(s+K)\overline{C} = 0 \tag{10}$$

where

$$\overline{u}(y,s) = \int_0^\infty u(y,t)e^{-st}dt \qquad \overline{T}(y,s) = \int_0^\infty T(y,t)e^{-st}dt \qquad \overline{C}(y,s) = \int_0^\infty C(y,t)e^{-st}dt$$

(s > 0, s being the Laplace transform parameter).

The boundary conditions (7b) to (7e) become

$$t > 0: \begin{cases} \overline{u} = 1/s, \overline{T} = (1-e^{-s})/s^2, \overline{C} = (1-e^{-s})/s^2 \quad at \;\; y = 0 \\ \overline{u} \to 0, \overline{T} \to 0, \overline{C} \to 0 \quad as \;\; y \to \infty \end{cases} \tag{11}$$

The solution of equations (8), (9) and (10) subject to the boundary conditions (11) are given by

$$\overline{T}(y,s) = \frac{1-e^{-s}}{s^2} e^{-y\sqrt{\Pr(s+\phi+Rd)}} \tag{12}$$

$$\overline{C}(y,s) = \frac{1-e^{-s}}{s^2} e^{-y\sqrt{Sc(s+K)}} \tag{13}$$

$$\overline{u}(y,s) = \frac{1}{s}e^{-y\sqrt{s+\lambda}} - \alpha_1 \frac{1-e^{-s}}{s^2(s-\beta_1)}\left[e^{-y\sqrt{s+\lambda}} - e^{-y\sqrt{\Pr(s+\phi+Rd)}}\right]$$

$$-\alpha_2 \frac{1-e^{-s}}{s^2(s-\beta_2)}\left[e^{-y\sqrt{s+\lambda}} - e^{-y\sqrt{Sc(s+K)}}\right] \tag{14}$$

where

$$\lambda = M + 1/K_p, \; \alpha_1 = Gr/(1-\Pr), \; \beta_1 = (\Pr(\phi+Rd)-\lambda)/(1-\Pr),$$

$$\alpha_2 = Gc/(1-Sc), \; \beta_2 = (ScK-\lambda)/(1-Sc)$$

Taking the inverse Laplace transform of equations (12),(13) and (14), the exact solution for the fluid temperature T(y,t), fluid concentration C(y,t) and fluid velocity u(y,t) is expressed in the following form after simplification.

$$T(y,t) = G(y,t) - H(t-1)G(y,t-1), \tag{15}$$

$$C(y,t) = E(y,t) - H(t-1)E(y,t-1), \tag{16}$$

$$u(y,t) = \frac{1}{2}\left[e^{y\sqrt{\lambda}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{\lambda t}\right) + e^{-y\sqrt{\lambda}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{\lambda t}\right)\right]$$

$$-\alpha_1\left[F(y,t) - H(t-1)F(y,t-1)\right] - \alpha_2\left[R(y,t) - H(t-1)R(y,t-1)\right] \tag{17}$$

where

$$G(y,t) = \frac{1}{2}\left[\left(t + \frac{y}{2}\sqrt{\frac{\Pr}{\phi+Rd}}\right)e^{y\sqrt{(\phi+Rd)\Pr}} erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}} + \sqrt{(\phi+Rd)t}\right)\right.$$

$$\left. + \left(t - \frac{y}{2}\sqrt{\frac{\Pr}{(\phi+Rd)}}\right)e^{-y\sqrt{(\phi+Rd)\Pr}} erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}} - \sqrt{(\phi+Rd)t}\right)\right]$$

$$E(y,t) = \frac{1}{2}\left[\left(t + \frac{y}{2}\sqrt{\frac{Sc}{K}}\right)e^{y\sqrt{KSc}} erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}} + \sqrt{Kt}\right) + \left(t - \frac{y}{2}\sqrt{\frac{Sc}{K}}\right)e^{-y\sqrt{KSc}} erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}} - \sqrt{Kt}\right)\right]$$

$$F(y,t)=\frac{1}{2}\Bigg[\frac{e^{\beta_1 t}}{\beta_1^{\,2}}\Bigg\{e^{y\sqrt{\lambda+\beta_1}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(\lambda+\beta_1)t}\right)+e^{-y\sqrt{\lambda+\beta_1}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{(\lambda+\beta_1)t}\right)$$

$$-e^{y\sqrt{\Pr(\phi+Rd+\beta_1)}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}+\sqrt{(\phi+Rd+\beta_1)t}\right)-e^{-y\sqrt{\Pr(\phi+Rd+\beta_1)}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}-\sqrt{(\phi+Rd+\beta_1)t}\right)\Bigg\}$$

$$-\frac{1}{\beta_1}\left(t+\frac{1}{\beta_1}+\frac{y}{2\sqrt{\lambda}}\right)e^{y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{\lambda t}\right)-\frac{1}{\beta_1}\left(t+\frac{1}{\beta_1}-\frac{y}{2\sqrt{\lambda}}\right)e^{-y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{\lambda t}\right)$$

$$+\frac{1}{\beta_1}\left(t+\frac{1}{\beta_1}+\frac{y}{2}\sqrt{\frac{\Pr}{\phi+Rd}}\right)e^{y\sqrt{(\phi+Rd)\Pr}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}+\sqrt{(\phi+Rd)t}\right)$$

$$+\frac{1}{\beta_1}\left(t+\frac{1}{\beta_1}-\frac{y}{2}\sqrt{\frac{\Pr}{\phi+Rd}}\right)e^{-y\sqrt{(\phi+Rd)\Pr}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}-\sqrt{(\phi+Rd)t}\right)$$

$$R(y,t)=\frac{1}{2}\Bigg[\frac{e^{\beta_2 t}}{\beta_2^{\,2}}\Bigg\{e^{y\sqrt{\lambda+\beta_2}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(\lambda+\beta_2)t}\right)+e^{-y\sqrt{\lambda+\beta_2}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{(\lambda+\beta_2)t}\right)$$

$$-e^{y\sqrt{Sc(K+\beta_2)}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}+\sqrt{(K+\beta_2)t}\right)-e^{-y\sqrt{Sc(K+\beta_2)}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}-\sqrt{(K+\beta_2)t}\right)\Bigg\}$$

$$-\frac{1}{\beta_2}\left(t+\frac{1}{\beta_2}+\frac{y}{2\sqrt{\lambda}}\right)e^{y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{\lambda t}\right)-\frac{1}{\beta_2}\left(t+\frac{1}{\beta_2}-\frac{y}{2\sqrt{\lambda}}\right)e^{-y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{\lambda t}\right)$$

$$+\frac{1}{\beta_2}\left(t+\frac{1}{\beta_2}+\frac{y}{2}\sqrt{\frac{Sc}{K}}\right)e^{y\sqrt{KSc}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}+\sqrt{Kt}\right)+\frac{1}{\beta_2}\left(t+\frac{1}{\beta_2}-\frac{y}{2}\sqrt{\frac{Sc}{K}}\right)e^{-y\sqrt{KSc}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}-\sqrt{Kt}\right)$$

SOLUTION IN CASE OF UNIT PRANDTL AND SCHMIDT NUMBER

The solution (17) for the fluid velocity is not valid for fluids with the Prandtl number equal to one. As the Prandtl number is a measure of the relative strength of the viscosity and thermal conductivity of the fluid, the case Pr=1 corresponds to those fluids for which both viscous and thermal boundary layer thicknesses are of the same order of magnitude. There are several fluids of practical interest that belong to this category. Setting Pr=1 and *Sc*=1 in equations (5) and (6) and following the same procedure as before, the exact solution for the fluid temperature $T(y,t)$, concentration C(y,t) and fluid velocity $u(y,t)$ are obtained and are expressed in the following form

$$T(y,t)=G_1(y,t)-H(t-1)G_1(y,t-1)$$
$$C(y,t)=E_1(y,t)-H(t-1)E_1(y,t-1)$$
$$u(y,t)=\frac{1}{2}\left[e^{y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{\lambda t}\right)+e^{-y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{\lambda t}\right)\right]$$
$$-\alpha_1\left[F_1(y,t)-H(t-1)F_1(y,t-1)\right]-\alpha_2\left[R_1(y,t)-H(t-1)R_1(y,t-1)\right]$$

where

$$G_1(y,t)=\frac{1}{2}\Bigg[\left(t+\frac{y}{2\sqrt{\phi+Rd}}\right)e^{y\sqrt{(\phi+Rd)}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(\phi+Rd)t}\right)$$
$$+\left(t-\frac{y}{2\sqrt{(\phi+Rd)}}\right)e^{-y\sqrt{(\phi+Rd)}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{(\phi+Rd)t}\right)\Bigg]$$

$$E_1(y,t)=\frac{1}{2}\left[\left(t+\frac{y}{2\sqrt{K}}\right)e^{y\sqrt{K}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{Kt}\right)+\left(t-\frac{y}{2\sqrt{K}}\right)e^{-y\sqrt{K}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{Kt}\right)\right]$$

$$F_1(y,t)=\frac{1}{2}\left[\left(t+\frac{y}{2\sqrt{(\phi+Rd)}}\right)e^{y\sqrt{\phi+Rd}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(\phi+Rd)t}\right)\right.$$
$$+\left(t-\frac{y}{2\sqrt{(\phi+Rd)}}\right)e^{-y\sqrt{\phi+Rd}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{(\phi+Rd)t}\right)$$
$$\left.-\left(t+\frac{y}{2\sqrt{\lambda}}\right)e^{y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{\lambda t}\right)-\left(t-\frac{y}{2\sqrt{\lambda}}\right)e^{-y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{\lambda t}\right)\right]$$

$$R_1(y,t)=\frac{1}{2}\left[\left(t+\frac{y}{2\sqrt{K}}\right)e^{y\sqrt{K}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{Kt}\right)+\left(t-\frac{y}{2\sqrt{K}}\right)e^{-y\sqrt{K}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{Kt}\right)\right.$$
$$\left.-\left(t+\frac{y}{2\sqrt{\lambda}}\right)e^{y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{\lambda t}\right)-\left(t-\frac{y}{2\sqrt{\lambda}}\right)e^{-y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{\lambda t}\right)\right]$$

SOLUTION IN CASE OF ISOTHERMAL PLATE

Equations (15), (16) and (17) present an analytical solution for the fluid temperature, concentration and velocity for the flow of a viscous incompressible electrically conducting fluid near an impulsively moving vertical plate with ramped temperature and concentration. In order to highlight the effects of the ramped temperature distribution within the flow near an impulsively moving vertical plate with uniform temperature. Taking into consideration the assumptions made in this paper, the solution for the fluid temperature and velocity for the flow near an isothermal impulsively moving vertical plate are obtained and are expressed in the form

$$T(y,t)=\frac{1}{2}\left[e^{y\sqrt{(\phi+Rd)\Pr}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}+\sqrt{(\phi+Rd)t}\right)+e^{-y\sqrt{(\phi+Rd)\Pr}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}-\sqrt{(\phi+Rd)t}\right)\right]$$

$$C(y,t)=\frac{1}{2}\left[e^{y\sqrt{KSc}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}+\sqrt{Kt}\right)+e^{-y\sqrt{KSc}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}-\sqrt{Kt}\right)\right]$$

$$u(y,t)=\frac{1+\delta_1+\delta_2}{2}\left[e^{y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{\lambda t}\right)+e^{-y\sqrt{\lambda}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{\lambda t}\right)\right]$$
$$-\frac{\delta_1}{2}e^{\beta_1 t}\left[\left\{e^{y\sqrt{\lambda+\beta_1}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(\lambda+\beta_1)t}\right)+e^{-y\sqrt{\lambda+\beta_1}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{(\lambda+\beta_1)t}\right)\right\}\right.$$
$$\left.-\left\{e^{y\sqrt{\Pr(\phi+Rd+\beta_1)}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}+\sqrt{(\phi+Rd+\beta_1)t}\right)+e^{-y\sqrt{\Pr(\phi+Rd+\beta_1)}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}-\sqrt{(\phi+Rd+\beta_1)t}\right)\right\}\right]$$
$$-\frac{\delta_1}{2}\left[e^{y\sqrt{(\phi+Rd)\Pr}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}+\sqrt{(\phi+Rd)t}\right)+e^{-y\sqrt{(\phi+Rd)\Pr}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}-\sqrt{(\phi+Rd)t}\right)\right]$$
$$-\frac{\delta_2}{2}e^{\beta_2 t}\left[\left\{e^{y\sqrt{\lambda+\beta_2}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{(\lambda+\beta_2)t}\right)+e^{-y\sqrt{\lambda+\beta_2}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{(\lambda+\beta_2)t}\right)\right\}\right.$$
$$\left.-\left\{e^{y\sqrt{Sc(K+\beta_2)}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}+\sqrt{(K+\beta_2)t}\right)+e^{-y\sqrt{Sc(K+\beta_2)}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}-\sqrt{(K+\beta_2)t}\right)\right\}\right]$$
$$-\frac{\delta_2}{2}\left[e^{y\sqrt{KSc}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}+\sqrt{Kt}\right)+e^{-y\sqrt{KSc}}erfc\left(\frac{y}{2}\sqrt{\frac{Sc}{t}}-\sqrt{Kt}\right)\right]$$

NUSSELT NUMBER, SHERWOOD NUMBER AND SKIN-FRICTION

The expressions for Nusselt number (*Nu*), Sherwood number (*Sh*) and skin-friction(τ), which are measures of the rate of heat transfer, rate of mass transfer and shear stress at the plate respectively, are presented in the following form for the ramped temperature and isothermal plates.

For the ramped temperature plate

$$Nu = -\left.\frac{\partial T}{\partial y}\right]_{y=0} = \frac{1}{2}\sqrt{\frac{\Pr}{\phi + Rd}}\left[1 - erfc\left(\sqrt{(\phi+Rd)t}\right)\right] + t\sqrt{(\phi+Rd)\Pr}$$

$$+ t\left\{\sqrt{\frac{\Pr}{\pi t}}e^{-(\phi+Rd)t} - \sqrt{(\phi+Rd)\Pr}\, erfc\left(\sqrt{(\phi+Rd)t}\right)\right\}$$

$$Sh = -\left.\frac{\partial C}{\partial y}\right]_{y=0} = \frac{1}{2}\sqrt{\frac{Sc}{K}}\left[1 - erfc\left(\sqrt{Kt}\right)\right] + t\sqrt{KSc} + t\left\{\sqrt{\frac{Sc}{\pi t}}e^{-Kt} - \sqrt{KSc}\, erfc\left(\sqrt{Kt}\right)\right\}$$

$$\tau = \left.\frac{\partial u}{\partial y}\right]_{y=0} = \sqrt{\lambda}\left[erfc(\sqrt{\lambda t}) - 1\right] - \frac{1}{\sqrt{\pi t}}e^{-\lambda t} - \alpha_1\left[F_2(y,t) - H(t-1)F_2(y,t-1)\right]$$

$$-\alpha_2\left[R_2(y,t) - H(t-1)R_2(y,t-1)\right]$$

where

$$F_2(y,t) = \frac{e^{\beta_1 t}}{\beta_1^{\,2}}\left\{\sqrt{\lambda+\beta_1}\left[erfc(\sqrt{(\lambda+\beta_1)t}) - 1\right] - \frac{1}{\sqrt{\pi t}}e^{-(\lambda+\beta_1)t}\right\} - \frac{1}{2\beta_1\sqrt{\lambda}}\left[1 - erfc(\sqrt{\lambda t})\right]$$

$$+\frac{1}{\beta_1}\left(t + \frac{1}{\beta_1}\right)\left\{\sqrt{\lambda}\left[1 - erfc(\sqrt{\lambda t})\right] + \frac{1}{\sqrt{\pi t}}e^{-\lambda t}\right\} - \frac{e^{\beta_1 t}}{\beta_1^{\,2}}\left\{\sqrt{\Pr(\phi+Rd+\beta_1)}\left[erfc(\sqrt{(\phi+Rd+\beta_1)t}) - 1\right]\right.$$

$$\left. - \sqrt{\frac{\Pr}{\pi t}}e^{-(\phi+Rd+\beta_1)t} - \frac{1}{2\beta_1}\sqrt{\frac{\Pr}{\phi+Rd}}\left[1 - erfc(\sqrt{(\phi+Rd)t})\right]\right\}$$

$$-\frac{1}{\beta_1}\left(t + \frac{1}{\beta_1}\right)\left\{\sqrt{\phi\Pr}\left[1 - erfc(\sqrt{\phi t})\right] + \sqrt{\frac{\Pr}{\pi t}}e^{-\phi t}\right\}$$

$$R_2(y,t) = \frac{e^{\beta_2 t}}{\beta_2^{\,2}}\left\{\sqrt{\lambda+\beta_2}\left[erfc(\sqrt{(\lambda+\beta_2)t}) - 1\right] - \frac{1}{\sqrt{\pi t}}e^{-(\lambda+\beta_2)t}\right\} - \frac{1}{2\beta_2\sqrt{\lambda}}\left[1 - erfc(\sqrt{\lambda t})\right]$$

$$+\frac{1}{\beta_2}\left(t + \frac{1}{\beta_2}\right)\left\{\sqrt{\lambda}\left[1 - erfc(\sqrt{\lambda t})\right] + \frac{1}{\sqrt{\pi t}}e^{-\lambda t}\right\} - \frac{e^{\beta_2 t}}{\beta_2^{\,2}}\left\{\sqrt{Sc(K+\beta_2)}\left[erfc(\sqrt{(K+\beta_2)t}) - 1\right]\right.$$

$$\left. - \sqrt{\frac{Sc}{\pi t}}e^{-(K+\beta_2)t} - \frac{1}{2\beta_2}\sqrt{\frac{Sc}{K}}\left[1 - erfc(\sqrt{Kt})\right]\right\} - \frac{1}{\beta_2}\left(t + \frac{1}{\beta_2}\right)\left\{\sqrt{KSc}\left[1 - erfc(\sqrt{Kt})\right] + \sqrt{\frac{Sc}{\pi t}}e^{-Kt}\right\}$$

For the isothermal plate

$$Nu = -\left.\frac{\partial T}{\partial y}\right]_{y=0} = \sqrt{\Pr(\phi+Rd)}\left[1 - erfc(\sqrt{(\phi+Rd)t})\right] + \sqrt{\frac{\Pr}{\pi t}}e^{-(\phi+Rd)t}$$

$$Sh = -\left.\frac{\partial C}{\partial y}\right]_{y=0} = \sqrt{KSc}\left[1 - erfc(\sqrt{Kt})\right] + \sqrt{\frac{Sc}{\pi t}}e^{-\phi t}$$

$$\tau = \left.\frac{\partial u}{\partial y}\right]_{y=0} = (1+\delta_1+\delta_2)\left\{\sqrt{\lambda}\,\left[erfc(\sqrt{\lambda t})-1\right] - \frac{1}{\sqrt{\pi t}}e^{-\lambda t}\right\}$$

$$-\delta_1 e^{\beta_1 t}\left\{\sqrt{\lambda+\beta_1}\,\left[erfc(\sqrt{(\lambda+\beta_1)t})-1\right] - \frac{1}{\sqrt{\pi t}}e^{-(\lambda+\beta_1)t}\right\}$$

$$-\delta_1\left\{\sqrt{\Pr(\phi+Rd)}\,\left[erfc(\sqrt{(\phi+Rd)t})-1\right] - \sqrt{\frac{\Pr}{\pi t}}e^{-(\phi+Rd)t}\right\}$$

$$-\delta_1 e^{\beta_1 t}\left\{\sqrt{\Pr(\phi+Rd+\beta_1)}\,\left[erfc(\sqrt{(\phi+Rd+\beta_1)t})-1\right] - \sqrt{\frac{\Pr}{\pi t}}e^{-(\phi+Rd+\beta_1)t}\right\}$$

$$-\delta_2 e^{\beta_2 t}\left\{\sqrt{\lambda+\beta_2}\,\left[erfc(\sqrt{(\lambda+\beta_2)t})-1\right] - \frac{1}{\sqrt{\pi t}}e^{-(\lambda+\beta_2)t}\right\} - \delta_2\left\{\sqrt{KSc}\,\left[erfc(\sqrt{Kt})-1\right] - \sqrt{\frac{Sc}{\pi t}}e^{-Kt}\right\}$$

$$-\delta_2 e^{\beta_2 t}\left\{\sqrt{(Sc+\beta_2)}\,\left[erfc(\sqrt{(Sc+\beta_2)t})-1\right] - \sqrt{\frac{Sc}{\pi t}}e^{-(K+\beta_2)t}\right\}$$

RESULTS AND DISCUSSION

The problem of unsteady MHD free convective flow past an impulsively moving vertical plate with ramped wall temperature and concentration has been considered. The solutions for velocity field, temperature field and concentration distribution are obtained using Laplace transformation technique. The effects of flow parameters such as Prandtl number (Pr), permeability parameter (Kp), magnetic parameter (M), thermal radiation parameter (Rd), chemical reaction parameter(K), thermal Grashof number (*Gr*) and mass Grashof number (*Gc*) on the velocity field have been studied analytically and presented with the aid of figs.1-7. The effects of flow parameters such as Prandtl number (Pr), thermal radiation parameter (Rd) and heat absorption parameter (ϕ) have been presented in figs.8, 9 and 10 respectively. The effects of flow parameters such as Schmidt number (*Sc*) and chemical reaction parameter (K) have been presented in figs.11 and 12 respectively. We have discussed the result for for two cases i.e. for ramped as well as for isothermal. The solid lines stand for ramped and dotted lines stand for isothermal.

Fig.1 shows the effect of Prandtl number on velocity profile. It is observed that the fluid velocity u decreases with the increase in Prandtl number for both ramped temperature as well as isothermal plates. The Prandtl number is the ratio of the kinematic viscosity to the thermal diffusivity of the fluid. Therefore, the thermal diffusivity has a retarding influence where as the kinematic viscosity has an accelerating influence on the velocity profile. For highly viscous fluids the velocity decreases.

Fig.2 shows the effect of permeability parameter (Kp) on velocity profile. It is observed that the fluid velocity increases with the increase in permeability parameter for both ramped temperature as well as isothermal plates i.e. in absence of porous matrix the velocity increases.

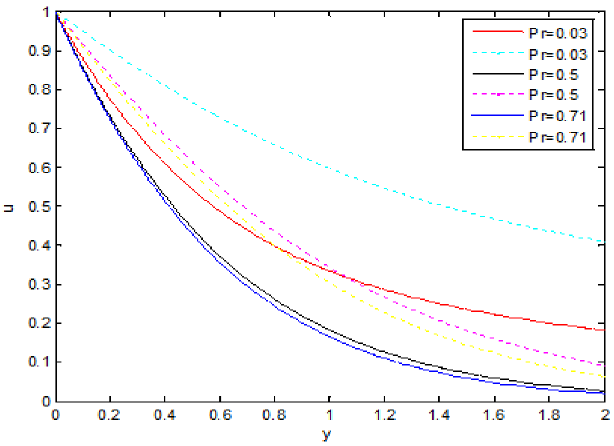

Fig. 1 Effect of Prandtl number (Pr) on velocity profile

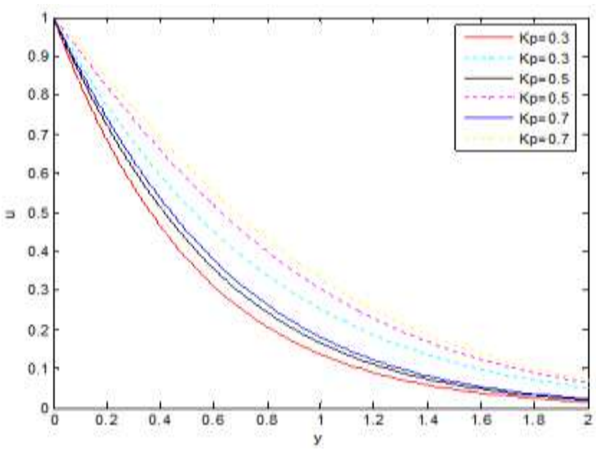

Fig. 2 Effect of porosity parameter (Kp) on velocity of profile

Fig.3 depicts the effect of magnetic parameter (*M*) on velocity profile. It is observed that the fluid velocity decreases with an increase in magnetic parameter for both ramped temperature as well as isothermal plates. So, the magnetic field has a retarding influence on the velocity field. Fig.4 and Fig.5 depict the effect of thermal radiation parameter (*Rd*) and chemical reaction parameter (*K*) on velocity profile respectively. From both the figures it is observed that the velocity of the fluid decreases with the increase in thermal radiation and chemical reaction parameter. But no such appreciable change has marked. Chemical reaction parameter has a very negligible effect on the flow field. Further, it is seen that chemical reaction parameter decreases the velocity significantly. The decrease may be attributed to the absorption of heat energy due to endothermic reaction (K>0). Also, it is interesting to note that presence of heavier diffusing species causes a decrease in velocity leading to thinning of the boundary layer thickness. Fig.6 and Fig.7 show the effect of thermal Grashof number (*Gr*) and mass Grashof number (*Gc*) on velocity profile respectively. In the flow phenomenon the Grashof number characterizes the free convection. From fig.6 it is observed that the effect of *Gr* is to enhance the velocity of the flow field at all points for both ramped temperature as well as isothermal plate. From fig.7 it is also observed that the Grashof number (*Gc*) for mass transfer accelerates the flow field at all points for both ramped temperature as well as isothermal plate.

It is concluded that the velocity increases with an increasing in the value of porosity parameter, thermal Grashof number, mass Grashof number but reverse effect is observed in case of magnetic parameter, heat absorption co-efficient, thermal radiation parameter, Schmidt number, chemical reaction parameter and Prandtl number.

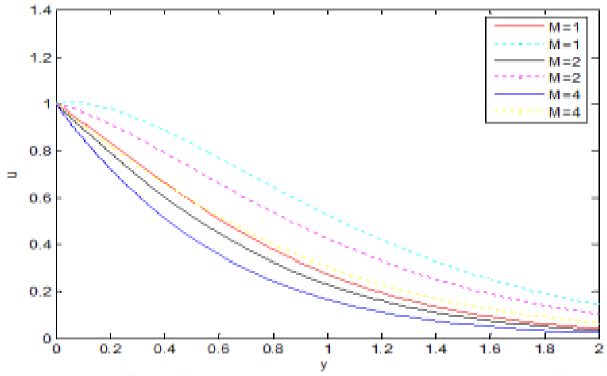

Fig. 3 Effect of magnetic parameter (M) on velocity profile

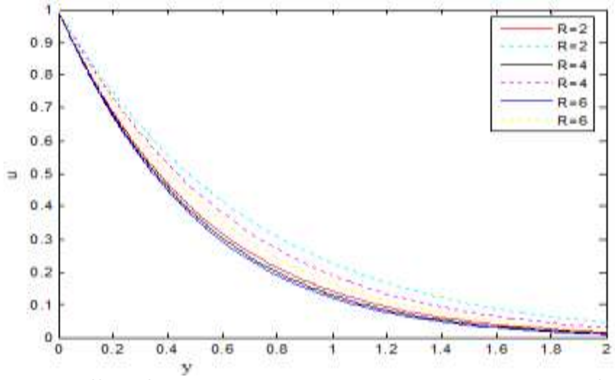

Fig.4 Effect of thermal radiation parameter (R) on velocity profile

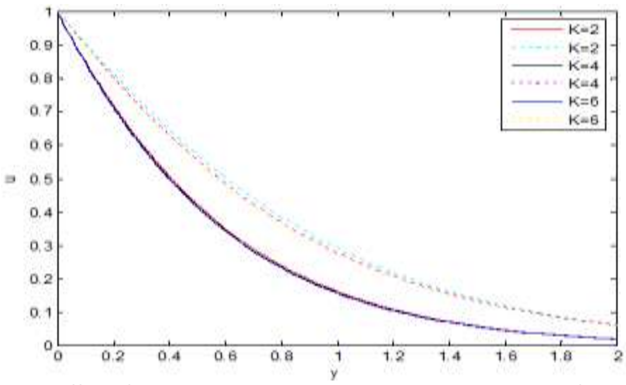

Fig. 5 Effect of chemical reaction parameter (K) on velocity profile

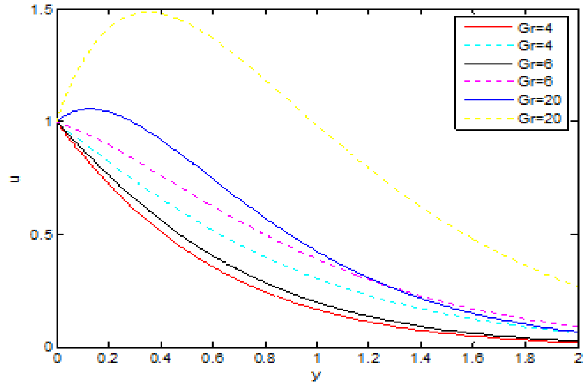

Fig. 6 Effect of thermal Grashoff number (Gr) on velocity profile

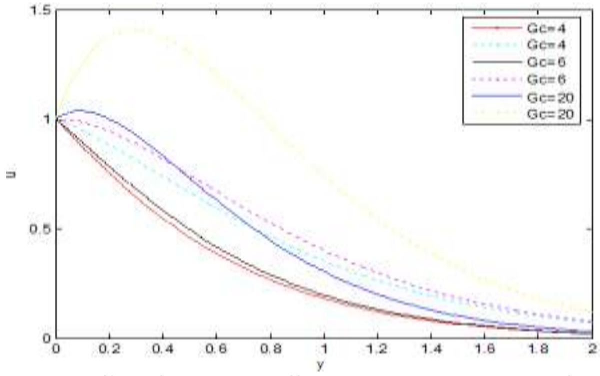

Fig. 7 Effect of mass Grashoff number (Gc) on velocity profile

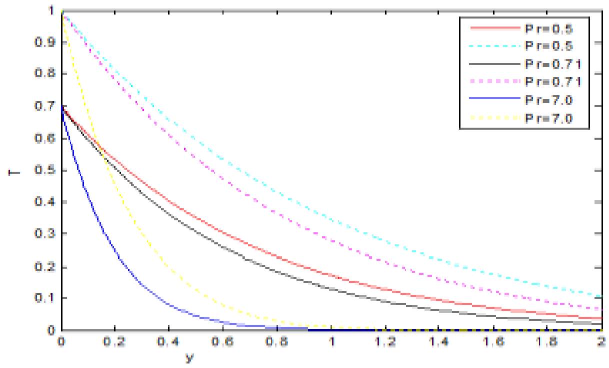

Fig. 8 Effect of Prandtl number (Pr) on temperature profile

Fig.8 shows the effect of Prandtl number (Pr) on temperature profile. It is observed that the temperature of the flow field diminishes as the Prandtl number increases for both ramped temperature and isothermal plates. In case of highly viscous fluid, the temperature of the fluid decreases very sharply but in case of less viscous fluid, the temperature of the fluid decreases very slowly. This implies that when thermal conductivity of the fluid is very large in comparison to the viscosity of the fluid, then there is a slow variation in the fluid temperature in the boundary region. Fig.9 and 10 show the effect of radiation parameter (Rd) and heat absorption parameter (ϕ) on temperature profile. It is observed from both the figures that the thermal radiation and heat absorption (thermal sink) have the tendency to reduce the temperature of the fluid for both ramped temperature and isothermal plates. It is concluded that the fluid temperature decreases with an increase in Prandtl number, heat absorption parameter and thermal radiation parameter. Temperature at the wall remains maximum and decreases slowly at the layer away from the plate. Thermal boundary layer thickness is significantly large near the plate in case of ramped wall temperature whereas in case of isothermal plate the thickness is minimum. Fig.11 and 12 show the effect of Schmidt number (Sc) and chemical reaction parameter (K) on concentration profile. From fig.11 it is observed that the concentration distribution decreases at all points of the flow field with the increase of the Schmidt number. This shows that the heavier diffusing species have a greater retarding effect on the concentration distribution of the flow field in case of both ramped temperature and isothermal plates. From fig.12 it is also marked that the chemical reaction parameter has a retarding influence on the concentration distribution of the flow field.

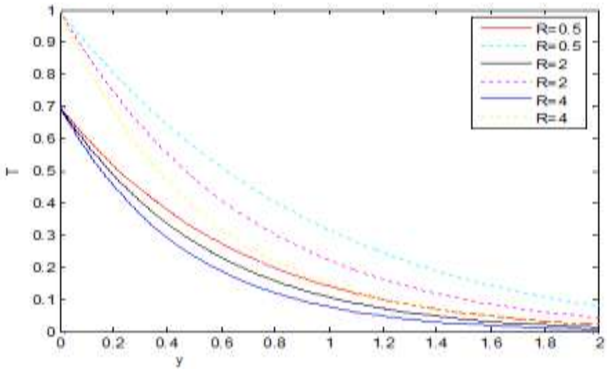

Fig. 9 Effect of radiation parameter (R) on temperature profile

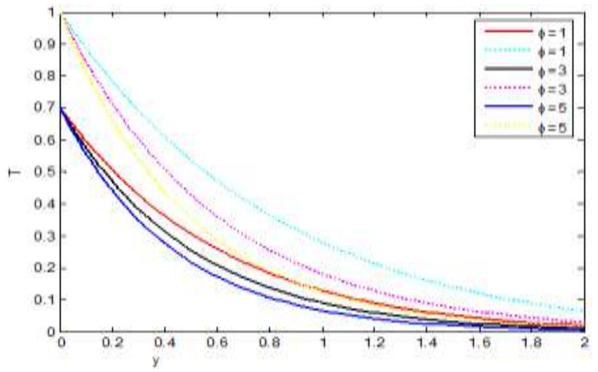

Fig. 10 Effect of heat absorption parameter (ϕ) on temperature profile

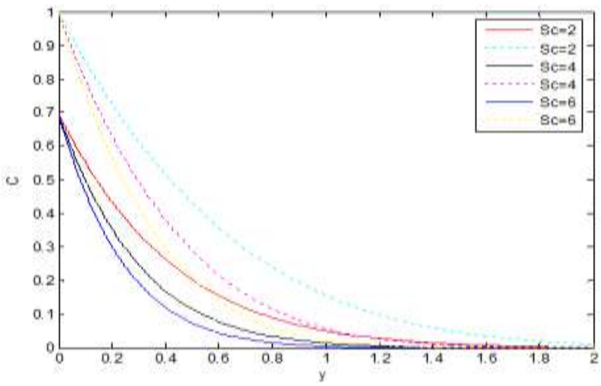

Fig. 11 Effect of Schmidt number (Sc) on concentration profile

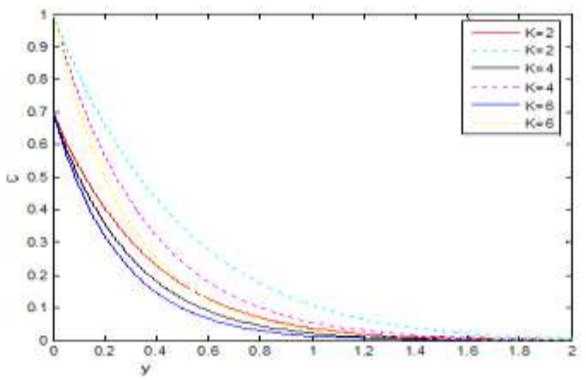

Fig. 12 Effect of chemical reaction parameter (K) on concentration profile

The numerical values of non-dimensional skin-friction are entered in table 1. It is observed that for both ramped temperature and isothermal plate, skin friction increases with an increase in $K, \phi, \Pr, Sc, Rd$ and M whereas it decreases with time t, Gc and K_p. An important finding from the present study is that flow separation occurs for higher values of buoyancy parameter due to presence of diffusing species and chemical reaction in case of isothermal plate. As pointed out by Seth and Ansari [6] for $Gr = 6.0$, the skin friction was negative, but in the present study, the skin-friction becomes negative when $Gr = 10.0$.

From table 2, it is seen that Nusselt number increases with increase in $\Pr, t, Rd$ and decreases with an increase in ϕ for ramped wall temperature, whereas in case of isothermal plate, the Nusselt number increases with increase in $\Pr, \phi, Rd$ and decreases for large span of time. The rate of heat transfer falls rapidly for large span of time in case of isothermal plate but reverse effect is experienced for ramped wall temperature.

From table 3, it is observed that Sherwood number which determines the rate of mass transfer at the surface of the wall decreases with an increase in chemical reaction parameter (K) but the reverse effect is observed in case of Schmidt number and time parameter. Sherwood number attains its maximum value for larger span of time.

Table -1 Skin Friction

S. No.	K	ϕ	t	Pr	Sc	Gc	K_p	Gr	M	R_d	Ramped temp(τ)	Isothermal plate(τ)
1	0.2	1	0.2	0.71	2.7	0.4	0.5	2	2	4	2.0855	1.609
2	0.2	1	0.2	0.71	2.7	0.4	0.5	2	2	4	2.0859	1.6094
3	0.2	3	0.2	0.71	2.7	0.4	0.5	2	2	4	2.0926	1.6317
4	0.2	1	0.5	0.71	2.7	0.4	0.5	2	2	4	1.753	1.3535
5	0.2	1	0.2	7	2.7	0.4	0.5	2	2	4	2.1111	1.8985
6	0.2	1	0.2	0.71	0.6	0.4	0.5	2	2	4	2.083	1.6065
7	2	1	0.2	0.71	2.7	3	0.5	2	2	4	2.0262	1.5497
8	2	1	0.2	0.71	2.7	0.4	4	2	2	4	1.7391	1.147
9	2	1	0.2	0.71	2.7	0.4	0.5	4	2	4	2.0259	1.0729
10	0.2	1	0.2	0.71	2.7	0.4	0.5	2	4	4	2.4611	2.0454
11	0.2	1	0.2	0.71	2.7	0.4	0.5	6	4	4	1.9655	0.536
12	0.2	1	0.2	0.71	2.7	0.4	0.5	10	4	4	1.8454	-0.5371
13	0.2	1	0.2	0.71	2.7	0.4	0.5	2	2	10	2.0916	1.6315

Table -2 Nusselt Number

S. No.	Pr	ϕ	t	Rd	Ramped wall(Nu)	Isothermal plate(Nu)
1	2	1	0.2	4	1.3859	2.1297
2	0.71	1	0.2	4	0.8257	1.2689
3	2	3	0.2	4	1.2678	2.7592
4	2	1	0.5	4	2.0404	1.6499
5	2	1	0.2	10	2.1516	2.2785

Table - 3 Sherwood Number

Sc	K	t	$(Sh)_{ramp}$	$(Sh)_{iso}$
2	2	0.5	1.4716	2.1005
2	2	0.7	1.8855	2.0467
4	2	0.7	2.6665	2.8944
4	4	0.7	2.3321	2.8356

CONCLUSION

- The magnetic field, thermal diffusion, thermal radiation and chemical reaction have a retarding influence on the fluid velocity, whereas natural convection, porosity of the medium and mass Grashof number have an accelerating influence on the fluid velocity for both ramped temperature and isothermal plates.
- The fluid velocity is smaller for the ramped temperature plate than for the isothermal plate.
- The thermal diffusion, thermal radiation and heat absorption coefficient have a retarding influence on the fluid temperature for both ramped temperature and isothermal plates.
- The fluid temperature is also lower for the ramped temperature plate than for the isothermal plate.
- The Schmidt number and chemical reaction parameter have a decelerating influence on the concentration profile.
- Lorentz force opposes the motion of the fluid more effectively in the absence of porous matrix.
- The decrease of temperature may be attributed to the loss of heat energy due to radiation as well as low diffusion.
- The flow separation is controlled due to the presence of chemically reacting species which is an important finding of the present study.

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