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Research Article

HEAT AND MASS TRANSFER CHARACTERISTICS ON NEWTONIAN FLUID OVER A VERTICAL POROUS PLATE IN CONDUCTING FIELD WITH RAMPED BOUNDARY CONDITION

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A B S T R A C T

An exact solution for an unsteady MHD free convection flow of a viscous incompressible, electrically conducting, optically thick radiating and heat absorbing fluid past an accelerated moving vertical plate with variable ramped wall temperature and as well as ramped wall concentration in the presence of Hall current is investigated. The dimensionless governing equations are solved in the closed form using Laplace transform technique. The expressions for the fluid velocity, fluid concentration and fluid temperature are obtained. The effects of various physical parameters on fluid velocities, fluid temperature and fluid concentration are displayed graphically where as those of shear stress and rate of heat transfer at the plate are presented in the tabular form.

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INTRODUCTION

Effect of thermal radiation on hydro magnetic free convection flow plays an important role in several scientific and industrial processes such as high temperature casting and levitation, thermo-nuclear fusion, furnace design, glass production, solar power technology etc.Hossain *et al*. [1] investigated the effect of radiation on free convective from a porous a vertical plate. Muthucumaraswamy and Kumar [2] examined thermal radiation effects on moving infinite vertical plate in the presence of variable temperature and mass diffusion. Magyari *et al*. [3] produced analytical solution for an unsteady free convection flow through a porous medium. Chamka and Khaled [4] focused on hydromagnetic combined heat and mass transfer by natural convection from a permeable surface embedded in a fluid saturated porous medium. Raju and Varma [5] presented an unsteady MHD free convection oscillatory Couette flow through a porous medium with periodic wall temperature. Pal and Mondal [6] studied radiation effects on combined convection over a vertical flat plate embedded in a porous medium of variable porosity. Singh [7] Analyzed heat source and radiation effects on magneto-convection flow of a viscoelastic fluid past a stretching sheet with Kummer's functions. Rashad *et al*. [8] investigated thermophoresis effect on heat and mass transfer radiation. Makind, and Mhone [9] examined heat transfer to MHD oscillatory flow in a channel filled with porous medium. Makinde and Aziz [10] focused on MHD mixed convection from a vertical plate embedded in porous medium with a convective boundary condition. Kandasamy *et al*. [11] studied on the effects of chemical reaction, heat and mass transfer along a wedge with heat source and concentration in the presence of suction or injection. Bhattacharyya *et al*. [12] investigated MHD boundary layer stagnation-point flow and mass transfer over a permeable shrinking sheet with suction/blowing and chemical reaction. Rashidi and Erfani [13] presented an analytical study of MHD stagnation point flow in a porous media with heat transfer. Umamaheswar *et al*. [14] examined MHD convective heat and mass transfer flow of a Newtonian fluid past a vertical porous plate with chemical reaction, radiation absorption and thermal diffusion. Chandram *et al*. [15] investigated natural convection near a vertical plate with ramped wall temperature. Seth *et al*. [16] examined the effects of thermal radiation and rotation on unsteady hydromagnetic free convection flow past an impulsively moving vertical plate with ramped temperature in a porous medium. Seth *et al*. [17] investigated the effect of rotation on unsteady hydro magnetic natural convection flow past an impulsively moving vertical plate with ramped temperature in a porous medium with thermal diffusion and heat absorption. Seddeek and Aboeldahab [18] studied the radiation effects on unsteady MHD free convection with Hall current near an infinite vertical porous plate. Das *et al*. [19]

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examined the unsteady hydromagnetic flow of a heat absorbing dusty fluid past a permeable vertical plate with ramped temperature. Palani and Abbas [20] studied free convection MHD flow with thermal radiation from an impulsively started vertical plate. Rajesh [21] focused on 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. Mohamed and Abo-Dahab [22] studied the influence of chemical reaction and thermal radiation on the heat and mass transfer in a porous medium with heat transfer in MHD micro polar flow over a vertical moving porous plate in a porous medium with heat generation. Rani *et al.* [23] investigated heat and mass transfer effects on MHD free convection flow over an inclined plateembedded in a porous medium. Veeresh *et al.*[24] studiedheat and mass transfer in MHD mixed convection flow on a movinginclined porous plate. Khan *et al*. [25] examined the effects of Wall Shear Stress on Unsteady MHD Conjugate Flow in a Porous Medium with Ramped WallTemperature. Sinha *et al.* [26] focused in MHD Free Convective Flow through a Porous Medium Past a Vertical Plate with Ramped Wall Temperature. Ibrahim *et.al* [27] examined thermal radiation the effecton a porous media under optically thick approximation. Das *et al.* [28] studied the unsteady MHD flow and heat transfer past a porous plate in a rotating system.

The aim of the present study is to investigate an unsteady MHD free convection flow of a viscous incompressible, electrically conducting, optically thick radiating and heat absorbing fluid past an accelerated moving vertical plate with variable ramped wall temperature and as well as ramped wall concentration in the presence of Hall current.

Formulation of the problem and its solution

Consider unsteady hydro magnetic free convection flow of a viscous, incompressible, electrically conducting, optically thick radiating and heat absorbing fluid past a moving infinite vertical plate with variable ramped temperature. We choose the Cartesian coordinate system (x^1,y^1,z^1) in such a way that x^*-axis is along the vertical plate upward direction, y^*-axis is normal to x^1y^1-plane. A uniform transverse magnetic field of strength $B_0$is applied in a direction parallel to y^1-axis. Initially, i.e. at time $t_1<0$, both the plate and surrounding fluid are at rest and maintained at uniform temperature$T_\infty{}^1$. At time t*>0, the plate starts moving along x^1direction with a velocity $U(t^1)=a^1t^1$ (a^1 being arbitrary constant) and at the same time temperature of the plate is raised to $T_\infty{}^1+(T_\omega{}^1-T_\infty{}^1)(t^1/t_0)$ when $0<t^1\le t_0$ and it is maintained at uniform temperature $T_\omega{}^1$when $t^1>t_0$ (t_0 being critical time for rampedness).

Since plate is of infinite extent along x^1 and z^1directions, all physical quantities except pressure depend on y^1 and t^1only. Induced magnetic field produced by fluid motion in neglected in comparison to applied one. This is justified because magnetic Reynolds number is very small for liquid metals and partially ionized fluids which are commonly used in various industrial processes. Since no external electric field is applied into the flow-field so the effect of polarization of fluid is negligible which corresponds to the case where no energy is added or extracted from the fluid by electrical means.

With the assumptions made above, the governing equations for the fluid flow problem taking Hall current into account, under Boussinesq approximation, are given by

$$\frac{\partial u^1}{\partial t^1}=\nu\frac{\partial^2u^1}{\partial y^{1^2}}-\frac{\sigma B_0{}^2}{\rho(1+m^2)}(u^1+mw^1)+g\beta(T^1-T_\infty{}^1)+g\beta^1(C^1-C_\infty{}^1)-\frac{\nu}{k^1}u^1 \tag{1}$$

$$\frac{\partial w^1}{\partial t^1}=\nu\frac{\partial^2w^1}{\partial y^{1^2}}+\frac{\sigma B_0{}^2}{\rho(1+m^2)}(mu^1-w^1)-\frac{\nu}{k^1}w^1 \tag{2}$$

$$\frac{\partial T^1}{\partial t^1}=\frac{k}{pc_p}\frac{\partial^2T^1}{\partial y^{1^2}}-\frac{Q_0}{\rho c_p}(T^1-T_\infty{}^1)-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y^1} \tag{3}$$

$$\frac{\partial C^1}{\partial t^1}=D\frac{\partial^2C^1}{\partial y^{1^2}}-k^1(C^1-C_\infty{}^1) \tag{4}$$

Initial and boundary conditions to be satisfied are

$$t^1\le 0: u^1=0, w^1=0, T^1=T_\infty{}^1, C^1=C_\infty{}^1,\ \text{for all } y^1\ge 0 \tag{5}$$

$$t^1>0: u^1=a^1t^1, w^1=0,$$

$$T^1=\left\{T_\infty{}^1+(T_w{}^1-T_\infty{}^1)\frac{t^1}{t_0}\right.\quad \text{at } y^1=0 \text{ when } 0<t^1\le t_0,\ \text{ and } T^1=T_w{}^1 \text{ at } y^1=0 \text{ when } t^1>t_0. \tag{6}$$

$$C^1 = \left\{ C_\infty{}^1 + (C_w{}^1 - C_\infty{}^1)\frac{t^1}{t_0} \quad \text{at } y^1 = 0 \text{ when } 0<t^1 \le t_0, \quad \text{and } C^1 = C_w{}^1 \quad \text{at } y^1 = 0 \text{ when } t^1 > t_0. \right.$$

$$t^1 > 0 : u^1 \to 0, w^1 \to 0, T^1 \to T_\infty{}^1, C^1 \to C_\infty{}^1, \text{ as } y^1 \to \infty \tag{7}$$

For an optically thick gray fluid, the radiative heat flux q_r is approximated by Rosseland approximation which is given

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T^{1^4}}{\partial y^1} \tag{8}$$

It is assumed that the temperature difference between fluid in the boundary layer region and free-stream is very small so that t^{1^4} may be expressed as a linear function of temperature T^1. Expanding t^{1^4} in Taylor series about $T_\infty{}^1$ and neglecting second and higher order terms, we get

$$T^{1^4} = 4T_\infty{}^{1^3}T^1 - 3T_\infty{}^{1^4} \tag{9}$$

Using equations (9) and (8) in (3) we get

$$\frac{\partial T^1}{\partial t^1} = \frac{k}{pc_p}\left(1 + \frac{16\sigma^* T_\infty{}^{1^3}}{3kk^*}\right)\frac{\partial^2 T^1}{\partial y^{1^2}} - \frac{Q_0}{\rho c_p}(T^1 - T_\infty{}^1) \tag{10}$$

We introduce following non dimensional quantities and flow parameters to present (1),(2) and (10) along with initial and boundary conditions (5)-(7) in non-dimensional form

$$y = \frac{U_0 y^1}{v}, t = \frac{U_0{}^2 t^1}{v}, u = \frac{u^1}{U_0}, w = \frac{w^1}{U_0}, T = \frac{(T^1 - T^1{}_\infty)}{(T_w{}^1 - T^1{}_\infty)}, G_r = \frac{vg\beta(T^1{}_w - T^1{}_\infty)}{U_0{}^3},$$

$$C = \frac{(C^1 - C^1{}_\infty)}{(C_w{}^1 - C^1{}_\infty)}, G_m = \frac{vg\beta^1(C^1{}_w - C^1{}_\infty)}{U_0{}^3}, M^2 = \frac{\sigma B^2{}_0 v}{\rho U^2{}_0}, N_r = \frac{16\sigma^* T^{1^3}{}_\infty}{3kk^*}, \tag{11}$$

$$t_1 = \frac{U_0{}^2 t_0}{v}, P_r = \frac{\sigma v c_p}{k}, Q = \frac{Q_0 v}{\sigma c_p U_0{}^2}.$$

Making use of equation (11), equations (1), (2), (4) and (10), in non-dimensional form, reduce to

$$\frac{\partial F}{\partial t} + \frac{M^2(1-im)}{(1+m^2)}F = \frac{\partial^2 F}{\partial y^2} + G_r T + G_m C \tag{12}$$

$$\frac{\partial T}{\partial t} = \frac{(1+N_r)}{P_r}\frac{\partial^2 T}{\partial y^2} - QT \tag{13}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial y^2} - k_r C \tag{14}$$

Where $F(y,t) = u(y,t) + iw(y,t).$

Initial and boundary conditions (5) to (7), in non-dimensional form, are given by

$$t \le 0 : F = 0, T = 0, C = 0, \text{ for all } y \ge 0 \tag{15}$$

$$t > 0 : F = at, T = \left\{ \frac{t}{t_1} \text{ at y=0 for } 0<t \le t_1, T = 1 \quad \text{at y=0 for } t>t_1, \right.$$

$$C = \begin{cases} \frac{t}{t_1} 0 < t < t_1, C = 1, t > t_1 \; at \; y = 0 \end{cases} \tag{16}$$

$$t > 0 : F \to 0, T \to 0, C \to 0, \text{ as y} \to \infty \tag{17}$$

Where $a = \frac{a^1 v}{U_0^{\ 3}}$ is non-dimensional constant.

It is evident from equation (12),(13) and (14) that energy equation (13) is uncoupled from momentum equation (13). Using Laplace transform technique, first the solution for fluid temperature T(y, t) is obtained by solving equation (13) and second the solution fluid concentrate C(y, t) is obtained by solving equation (14) subject to the initial and boundary conditions (15) to (17) and then using this solution in equation (12), solution for fluid velocity F(y, t) is obtained. The exact solutions for fluid temperature T(y, t), the exact solutions for fluid concentrate C(y,t) and fluid velocity F(y,t) are obtained and expressed in the following simplified form (equations18,19and 20 are solutions)

$$T(y,t) = T_1 - H(t-t_1) * T_2 \tag{18}$$

$$T_1 = \frac{1}{t_1}\left\{\left(\frac{t}{2} - \frac{y}{4\sqrt{\lambda_2 Q}}\right) e^{-\frac{y\sqrt{Q}}{\sqrt{\lambda_2}}} erfc\left(\frac{y}{2\sqrt{\lambda_2 t}} - \sqrt{Qt}\right) + \left(\frac{t}{2} + \frac{y}{4\sqrt{\lambda_2 Q}}\right) e^{-\frac{y\sqrt{Q}}{\sqrt{\lambda_2}}} erfc\left(\frac{y}{2\sqrt{\lambda_2 t}} - \sqrt{Qt}\right)\right\}$$

$$T_2 = \frac{1}{t_1}\left(\begin{array}{l} \left(\frac{t-t_1}{2} - \frac{y}{4\sqrt{\lambda_2 Q}}\right) e^{\left(\frac{-y\sqrt{Q}}{\sqrt{\lambda_2}}\right)} erfc\left(\frac{y}{2\sqrt{\lambda_2 (t-t_1)}} - \sqrt{Q(t-t_1)}\right) + \\ \left(\frac{t-t_1}{2} + \frac{y}{4\sqrt{\lambda_2 Q}}\right) e^{\left(\frac{-y\sqrt{Q}}{\sqrt{\lambda_2}}\right)} erfc\left(\frac{y}{2\sqrt{\lambda_2 (t-t_1)}} + \sqrt{Q(t-t_1)}\right) \end{array}\right)$$

$$C(y,t) = C_1 - H(t-t_1) * C_2 \tag{19}$$

$$C_1 = \frac{1}{t_1}\left\{\left(\frac{t}{2} - \frac{y\sqrt{S_c}}{4\sqrt{K_r}}\right) e^{-y\sqrt{S_c}\sqrt{K_r}} erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} - \sqrt{K_r t}\right)\right\} +$$

$$\frac{1}{t_1}\left\{\left(\frac{t}{2} + \frac{y\sqrt{S_c}}{4\sqrt{K_r}}\right) e^{y\sqrt{S_c}\sqrt{K_r}} erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}} + \sqrt{K_r t}\right)\right\}$$

$$C_2 = \frac{1}{t_1}\left\{\left(\frac{(t-t_1)}{2} - \frac{y\sqrt{S_c}}{4\sqrt{K_r}}\right) e^{-y\sqrt{S_c}\sqrt{K_r}} erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{(t-t_1)}} - \sqrt{K_r (t-t_1)}\right)\right\} +$$

$$\frac{1}{t_1}\left\{\left(\frac{(t-t_1)}{2} + \frac{y\sqrt{S_c}}{4\sqrt{K_r}}\right) e^{y\sqrt{S_c}\sqrt{K_r}} erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{(t-t_1)}} + \sqrt{K_r (t-t_1)}\right)\right\}$$

$$F(y,t) = -a_1 F_1 + a_2 F_2 + a_1 F_3 - a_2 F_4 + a_1 F_5 \tag{20}$$

where

$$F_1 = (f_1 + f_2 + f_3) - H(t-t_1) * (f_4 + f_5 + f_6)$$

$$F_2 = (g_1 + g_3 + g_5) - H(t-t_1) * (g_2 + g_4 + g_6)$$

$$F_3 = (h_1 + h_3 + h_5) - H(t-t_1) * (h_2 + h_4 + h_6)$$

$$F_4 = (l_1 + l_3 + l_5) - H(t-t_1) * (l_2 + l_4 + l_6)$$

$$F_5 = d_1 - H(t-t_1) * d_2$$

$$f_1 = \frac{-1}{\lambda_7^{\,2}}\left\{ e^{-y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{\lambda_3 t} \right) + e^{y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{\lambda_3 t} \right) \right\}$$

$$f_2 = \frac{-1}{\lambda_7}\left\{ \left(\frac{t}{2} - \frac{y}{4\sqrt{\lambda_3}} \right) e^{-y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{\lambda_3 t} \right) + \left(\frac{t}{2} + \frac{y}{4\sqrt{\lambda_3}} \right) e^{y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{\lambda_3 t} \right) \right\}$$

$$f_3 = \frac{-e^{\lambda_7 t}}{2\lambda_7^{\,2}}\left\{ e^{-y\sqrt{\lambda_3+\lambda_7}}\, erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{(\lambda_3+\lambda_7)t} \right) + e^{y\sqrt{\lambda_3+\lambda_7}}\, erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{(\lambda_3+\lambda_7)t} \right) \right\}$$

$$f_4 = \frac{-1}{\lambda_7^{\,2}}\left\{ e^{-y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} - \sqrt{\lambda_3 (t-t_1)} \right) + e^{y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} + \sqrt{\lambda_3 (t-t_1)} \right) \right\}$$

$$f_5 = \frac{-1}{\lambda_7}\left\{ \begin{array}{l} \left(\frac{(t-t_1)}{2} - \frac{y}{4\sqrt{\lambda_3}} \right) e^{-y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} - \sqrt{\lambda_3 (t-t_1)} \right) + \\ \left(\frac{(t-t_1)}{2} + \frac{y}{4\sqrt{\lambda_3}} \right) e^{y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} + \sqrt{\lambda_3 (t-t_1)} \right) \end{array} \right\}$$

$$f_6 = \frac{-e^{\lambda_7 (t-t_1)}}{2\lambda_7^{\,2}}\left\{ \begin{array}{l} e^{-y\sqrt{\lambda_3+\lambda_7}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} - \sqrt{(\lambda_3+\lambda_7)(t-t_1)} \right) + \\ e^{y\sqrt{\lambda_3+\lambda_7}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} + \sqrt{(\lambda_3+\lambda_7)(t-t_1)} \right) \end{array} \right\}$$

$$g_1 = -\frac{1}{2a_3^{\,2}}\left(e^{-y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{\lambda_3 t} \right) + e^{y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{\lambda_3 t} \right) \right)$$

$$g_2 = -\frac{1}{2a_3^{\,2}}\left(e^{-y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} - \sqrt{\lambda_3 (t-t_1)} \right) + e^{y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} + \sqrt{\lambda_3 (t-t_1)} \right) \right)$$

$$g_3 = \frac{1}{a_3}\left(\left(\frac{t}{2} - \frac{y}{4\sqrt{\lambda_3}} \right) e^{-y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{\lambda_3 t} \right) + \left(\frac{t}{2} + \frac{y}{4\sqrt{\lambda_3}} \right) e^{y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{\lambda_3 t} \right) \right)$$

$$g_4 = \frac{1}{a_3}\left(\begin{array}{l} \left(\frac{(t-t_1)}{2} - \frac{y}{4\sqrt{\lambda_3}} \right) e^{-y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} - \sqrt{\lambda_3 (t-t_1)} \right) + \\ \left(\frac{(t-t_1)}{2} + \frac{y}{4\sqrt{\lambda_3}} \right) e^{y\sqrt{\lambda_3}}\, erfc\left(\frac{y}{2\sqrt{(t-t_1)}} + \sqrt{\lambda_3 (t-t_1)} \right) \end{array} \right)$$

$$g_5 = \frac{e^{-a_3 t}}{2a_3^{\,2}}\left\{ e^{-y\sqrt{\lambda_3-a_3}}\, erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{(\lambda_3-a_3)t} \right) + e^{y\sqrt{\lambda_3-a_3}}\, erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{(\lambda_3-a_3)t} \right) \right\}$$

$$g_6 = \frac{e^{-a_3(t-t_1)}}{2{a_3}^2}\left\{e^{-y\sqrt{\lambda_3-a_3}}erfc\left(\frac{y}{2\sqrt{(t-t_1)}}-\sqrt{(\lambda_3-a_3)(t-t_1)}\right)+e^{y\sqrt{\lambda_3-a_3}}erfc\left(\frac{y}{2\sqrt{(t-t_1)}}+\sqrt{(\lambda_3-a_3)(t-t_1)}\right)\right\}$$

$$h_1 = \frac{-1}{2\lambda_7^2}\left\{e^{-y\sqrt{\frac{Q}{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2 t}}-\sqrt{Qt}\right)+e^{y\sqrt{\frac{Q}{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2 t}}+\sqrt{Qt}\right)\right\}$$

$$h_2 = \frac{-1}{2\lambda_7^2}\left\{e^{-y\sqrt{\frac{Q}{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2(t-t_1)}}-\sqrt{Q(t-t_1)}\right)+e^{y\sqrt{\frac{Q}{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2(t-t_1)}}+\sqrt{Q(t-t_1)}\right)\right\}$$

$$h_3 = \frac{1}{\lambda_7}\left\{\left(\frac{t}{2}-\frac{y}{4\sqrt{\lambda_2 Q}}\right)e^{-\frac{y\sqrt{Q}}{\sqrt{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2 t}}-\sqrt{Qt}\right)+\left(\frac{t}{2}+\frac{y}{4\sqrt{\lambda_2 Q}}\right)e^{\frac{y\sqrt{Q}}{\sqrt{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2 t}}+\sqrt{Qt}\right)\right\}$$

$$h_4 = \frac{1}{\lambda_7}\left(\begin{array}{l}\left(\frac{t-t_1}{2}-\frac{y}{4\sqrt{\lambda_2 Q}}\right)e^{\left(\frac{-y\sqrt{Q}}{\sqrt{\lambda_2}}\right)}erfc\left(\frac{y}{2\sqrt{\lambda_2\left(t-t_1\right)}}-\sqrt{Q(t-t_1)}\right)+\\ \left(\frac{t-t_1}{2}+\frac{y}{4\sqrt{\lambda_2 Q}}\right)e^{\left(\frac{y\sqrt{Q}}{\sqrt{\lambda_2}}\right)}erfc\left(\frac{y}{2\sqrt{\lambda_2\left(t-t_1\right)}}+\sqrt{Q(t-t_1)}\right)\end{array}\right)$$

$$h_5 = \frac{e^{\lambda_7 t}}{2\lambda_7^2}\left\{e^{-y\sqrt{\frac{Q+\lambda_7}{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2 t}}-\sqrt{(Q+\lambda_7)t}\right)+e^{y\sqrt{\frac{Q+\lambda_7}{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2 t}}+\sqrt{(Q+\lambda_7)t}\right)\right\}$$

$$h_6 = \frac{e^{\lambda_7(t-t_1)}}{2\lambda_7^2}\left\{\begin{array}{l}e^{-y\sqrt{\frac{Q+\lambda_7}{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2(t-t_1)}}-\sqrt{(Q+\lambda_7)(t-t_1)}\right)+\\ e^{y\sqrt{\frac{Q+\lambda_7}{\lambda_2}}}erfc\left(\frac{y}{2\sqrt{\lambda_2(t-t_1)}}+\sqrt{(Q+\lambda_7)(t-t_1)}\right)\end{array}\right\}$$

$$l_1 = -\frac{1}{2{a_3}^2}\left(e^{-y\sqrt{S_c K_r}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}-\sqrt{K_r t}\right)+e^{y\sqrt{S_c K_r}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}+\sqrt{K_r t}\right)\right)$$

$$l_2 = -\frac{1}{2{a_3}^2}\left(e^{-y\sqrt{S_c K_r}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{(t-t_1)}}-\sqrt{K_r(t-t_1)}\right)+e^{y\sqrt{S_c K_r}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{(t-t_1)}}+\sqrt{K_r(t-t_1)}\right)\right)$$

$$l_3 = \frac{1}{a_3}\left(\left(\frac{t}{2}-\frac{y\sqrt{S_c}}{4\sqrt{K_r}}\right)e^{-y\sqrt{S_c K_r}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}-\sqrt{K_r t}\right)+\left(\frac{t}{2}+\frac{y\sqrt{S_c}}{4\sqrt{K_r}}\right)e^{y\sqrt{S_c K_r}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}+\sqrt{K_r t}\right)\right)$$

$$l_4 = \frac{1}{a_3}\left(\begin{array}{l}\left(\frac{(t-t_1)}{2}-\frac{y\sqrt{S_c}}{4\sqrt{K_r}}\right)e^{-y\sqrt{S_c K_r}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{(t-t_1)}}-\sqrt{K_r(t-t_1)}\right)\\ +\left(\frac{(t-t_1)}{2}+\frac{y\sqrt{S_c}}{4\sqrt{K_r}}\right)e^{y\sqrt{S_c K_r}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{(t-t_1)}}+\sqrt{K_r(t-t_1)}\right)\end{array}\right)$$

$$l_5 = \frac{e^{-a_3 t}}{2{a_3}^2}\left\{e^{-y\sqrt{(K_r-a_3)S_c}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}-\sqrt{(K_r-a_3)t}\right)+e^{y\sqrt{(K_r-a_3)S_c}}erfc\left(\frac{y\sqrt{S_c}}{2\sqrt{t}}+\sqrt{(K_r-a_3)t}\right)\right\}$$

$$l_6 = \frac{e^{-a_3(t-t_1)}}{2a_3{}^2}\left\{\begin{array}{l} e^{-y\sqrt{(K_r-a_3)S_c}}\, erfc\left(\dfrac{y\sqrt{S_c}}{2\sqrt{(t-t_1)}} - \sqrt{(K_r-a_3)(t-t_1)}\right) \\ + e^{y\sqrt{(K_r-a_3)S_c}}\, erfc\left(\dfrac{y\sqrt{S_c}}{2\sqrt{(t-t_1)}} + \sqrt{(K_r-a_3)(t-t_1)}\right) \end{array}\right\}$$

$$d_1 = \left(\frac{t}{2} - \frac{y}{4\sqrt{\lambda_3}}\right) \mathrm{e}^{-y\sqrt{\lambda_3}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{\lambda_3 t}\right) + \left(\frac{t}{2} + \frac{y}{4\sqrt{\lambda_3}}\right) \mathrm{e}^{y\sqrt{\lambda_3}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{\lambda_3 t}\right)$$

$$d_2 = \left(\frac{(t-t_1)}{2} - \frac{y}{4\sqrt{\lambda_3}}\right) \mathrm{e}^{-y\sqrt{\lambda_3}} erfc\left(\frac{y}{2\sqrt{(t-t_1)}} - \sqrt{\lambda_3 (t-t_1)}\right) + \left(\frac{(t-t_1)}{2} + \frac{y}{4\sqrt{\lambda_3}}\right) \mathrm{e}^{y\sqrt{\lambda_3}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{\lambda_3 (t-t_1)}\right)$$

$$a_1 = \frac{G_r}{t_1\lambda_5}, a_2 = \frac{G_m}{t_1(S_c-1)}, a_3 = \frac{S_c K_r - \lambda_3}{(S_c-1)},$$

$$\lambda_2 = \frac{1+N_r}{P_r}; \lambda_3 = \frac{M^2(1-im)}{1+m^2}; \lambda_4 = \frac{Q}{\lambda_2}; \lambda_5 = \frac{1}{\lambda_2} - 1; \lambda_6 = \lambda_4 - \lambda_3; \lambda_7 = \frac{\lambda_6}{\lambda_5}$$

Expression for rate of heat transfer at the plate i.e.the rate of heat transfer in terms of Nusselt number is given by

$$Nu = -\left(\frac{\partial T}{\partial y}\right)_{y=0} = -[b1 - H(t-t_1)*(b2)] . \tag{21}$$

Another important physical quantity is the mass transfer coefficient, i.e. the Sherwood number which is in non-dimensional form is given by

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = -[b3 - (b4)*H(t-t_1)] \tag{22}$$

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

$$\tau = -\left(\frac{\partial F}{\partial y}\right)_{y=0} = -[a_1*(b11) + a_2*(b18) + a_1*(b25) - a_2*(b32) + a*(b35)] \tag{23}$$

Where b_1, b_2 … are the constants.

RESULTS AND DISCUSSION

To gain a perspective of the physics of the flow regime, we have studied numerically the effects of Magnetic field (M), Grashoff number (Gr), modified Grashof number (Gm), Prandtl number (Pr), heat absorption parameter (Qor ϕ), radiation parameter (Nr), Schmidt number (Sc), chemical reaction parameter (Kr), Hall current (m_1) and various values of critical time for rampedness (t_1) on the velocity, temperature, concentration, shear stress function, Nusselt number and Sherwood number.

Figures 1-3 demonstrate the variations of the fluid temperature under the effects of different parameters. The effects of radiation parameter on temperature are presented in figure 1and it is seen that the surface temperature decreases with the increasing values of radiation parameter for both the cases of t=1.8 and t=0.6. The effects of heat absorption parameter on temperature are exhibited in figure 2. It shows that the temperature decreases with the increasing values of heat absorption parameter for the values of t=1.5 and t=0.5. The effects of critical time for rampedness on temperature are exhibited in figure 3. It is observed that the temperature decreases with the increasing values of critical time for rampedness for the values of t=1.8 and t=0.6.

Figures 4-6 indicates the variations of the fluid concentration under the efects of different parameters. Figure 4 illustrates the influence of chemical reaction on the concentration. It is noticed that concentration decreases with the increasing values of chemical reaction for the values of t=1.6 and t=0.6. Figure 5 exhibits the influence of critical time for rampedness on the concentration. It is seen that concentration decreases with the increasing values of critical time for rampedness for the values of t=1.5 and t=0.5. Figure 6 presents the influence of Schmidt number on the concentration. It is perceived that concentration decreases with the increasing values of Schmidt number for the values of t=1.6 and t=0.6.

Figures 7-15 demonstrate the variations of the fluid velocity under the effects of different parameters. Figure 7 shows the effect of Grashf numer on velocity distribution. It is noticed that the velocity increases with the increasing values of Grashf number for the values of t=1.5 and t=0.5.Figure 8 depicts the effect modified Grashf numer on velocity distribution. It is shows that the velocity increases with the increasing values of modified Grashf number for the values of t=1.5 and t=0.5. Figure 9 exhibites the effect of Magnetic field on velocity distribution. It is observed that the velocity increases with the increasing values of Magnetic field number for the value of t=1.5 but decreses for the value of t=0.5. Figure 10 displays the effect of Schmidt number on velocity distribution. It is noticed that the velocity decreases with the increasing values of Schmidt number for the values of t=1.5 and t=0.5. Figure 11 demanstrates the effect of chemical reaction on velocity distribution. It is seen that the velocity decreases with the increasing values of chemical reaction parameter for the values of t=1.5 and t=0.5. Figure 12 displays the effect heat absorption on velocity distribution. It can be seen that the velocity decreases with increasing the values of heat absorption parameter for the value of t=1.5 but velocity increses with decreasing values(negative values) of heat absorption parameter for the value of t=0.5. Figure 13 presents the effect of radiation parameter on velocity distribution. It is perceived that the velocity decreases with the increasing values of radiation parameter for the values of t=1.5 and t=0.5.. Figure 14 dispicts the effect of critical time for rampedness on velocity distribution. It is shows that the velocity decreases with the increasing values of critical time for rampedness for the values of t=1.5 and t=0.5. Figure 15 depicts the effect of Hall current on velocity distribution. It is noticed that the velocity increases with the increasing values of Hall current for the values of t=1.5 and t=0.5.

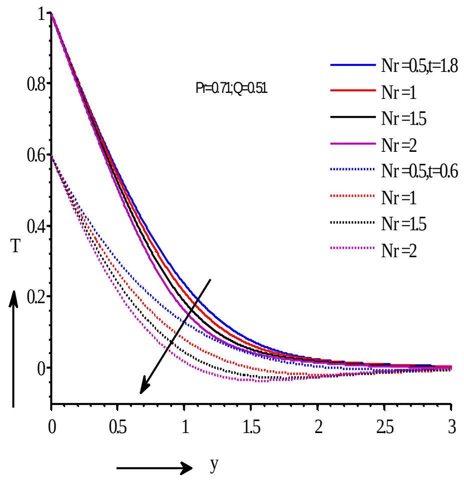

Figure 1 Effect of radiation parameter Nr on temperature

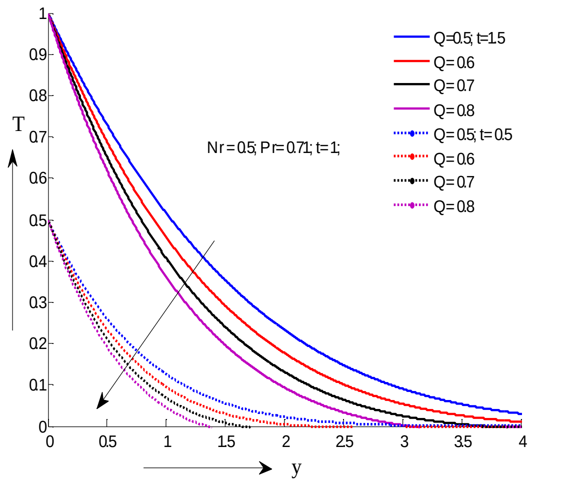

Figure 2 Effect of heat absorption parameter Q on temperature

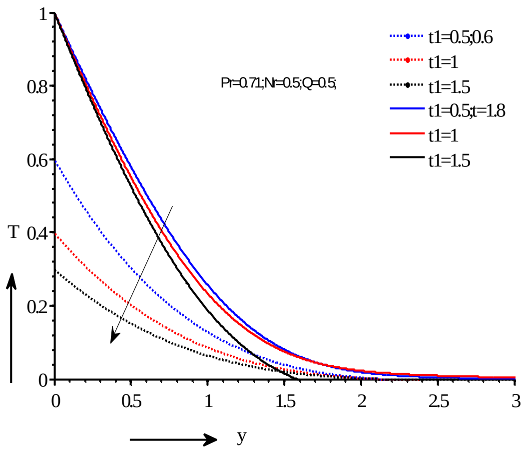

Figure 3 Effect of rampedness t_1 on temperature

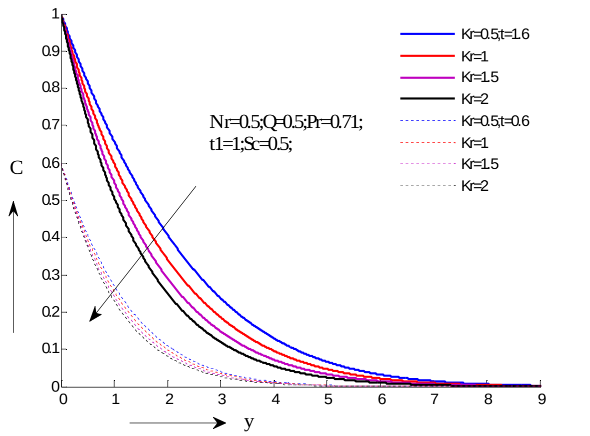

Figure 4 Effect of chemical reaction Kr on concentration

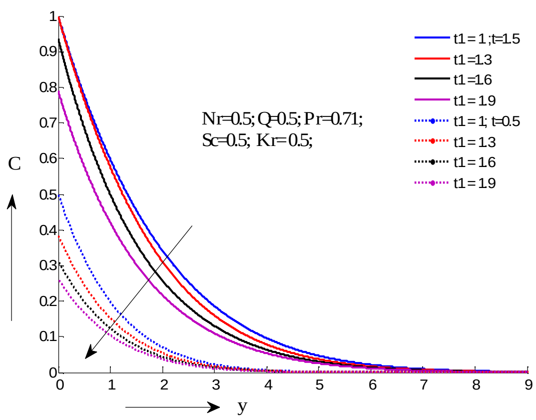

Figure 5 Effect of critical time for rampedness t_1 on concentration

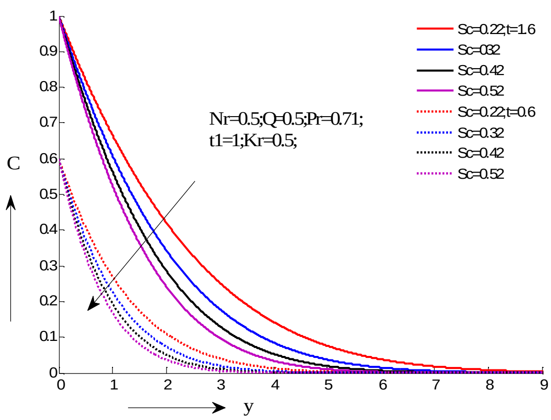

Figure 6 Effect of Schmidt number Sc on concentration

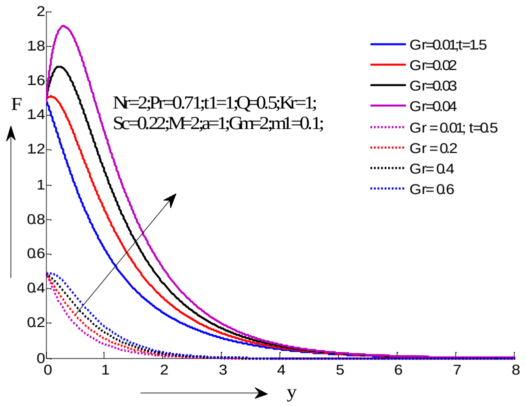

Figure 7 Effect of Grashof number Gr on velocity

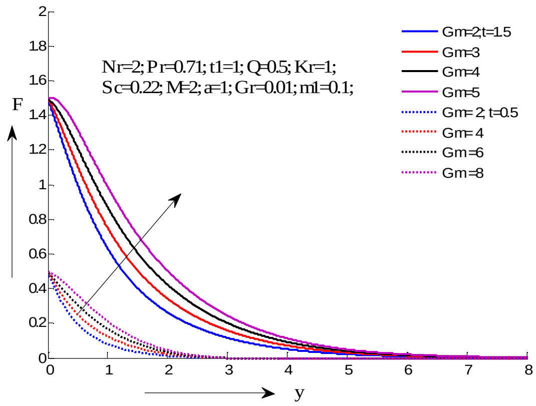

Figure 8 Effect of modified Grashof number Gm on velocity

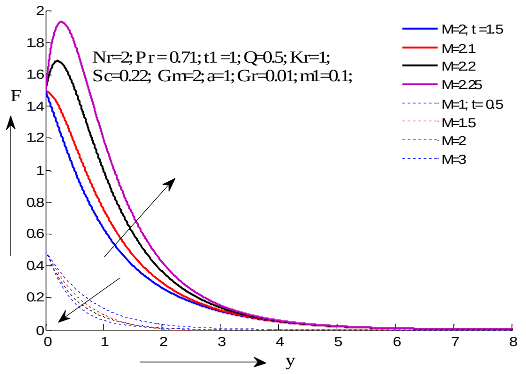

Figure 9 Effect of Magnetic field M on velocity

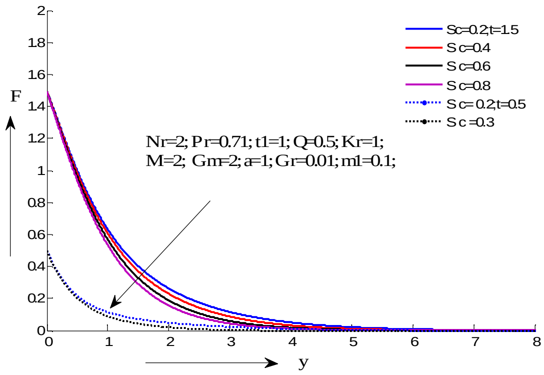

Figure 10 Effect of Schmidt number Sc on velocity

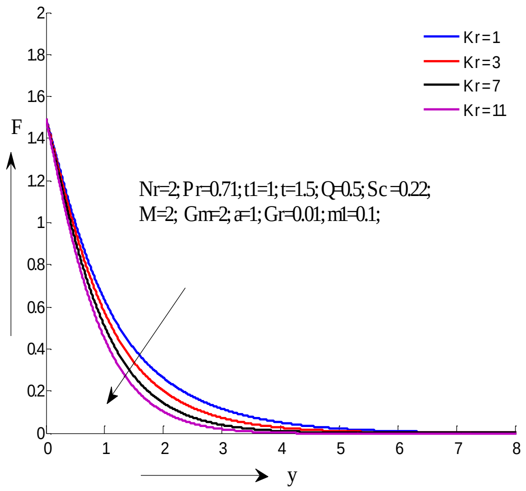

Figure 11 Effect of chemical reaction parameter Kr on velocity

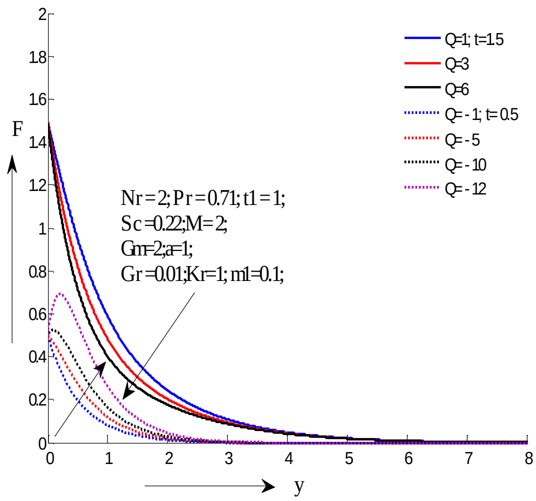

Figure 12 Effect of heat absorption Q on velocity

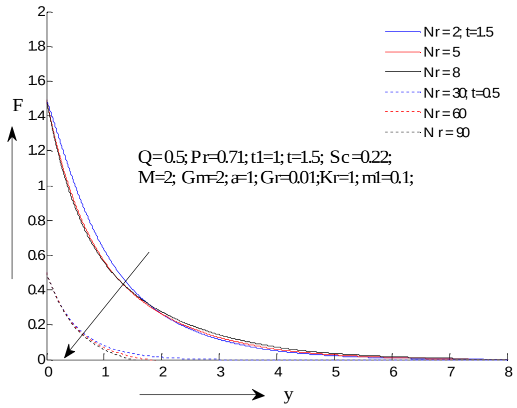

Figure 13 Effect radiation parameter Nr on velocity

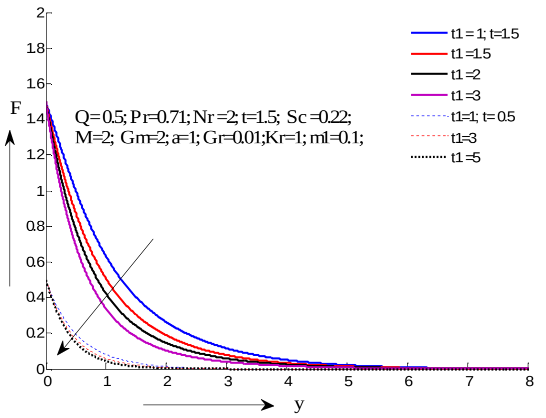

Figure 14 Effect of critical time for rampedness t1 on velocity

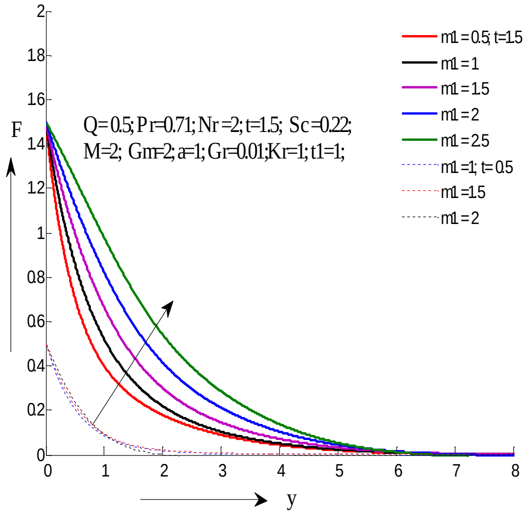

Figure 15 Effect of Hall current m1 on velocity

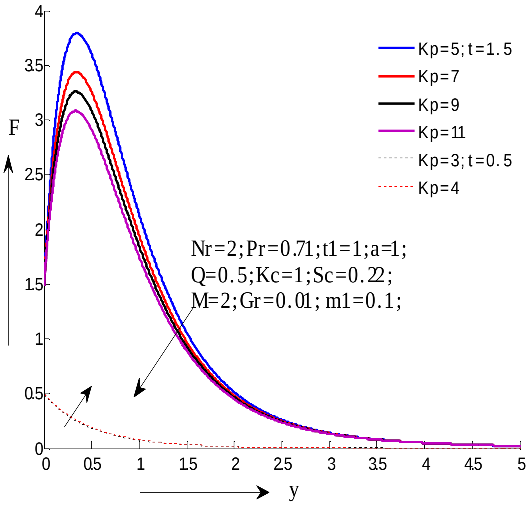

Figure 16 Effect of porosity parameter (Kp) on velocit

Table 1 Influence of Gr, Gm, m1 and M on skin friction coefficient

Gr	Gm	m_1	M	τ at t=1.5	τ at t=0.5
0.01	2	0.11	1.1	12.9488	0.1530
0.02	2	0.11	1.1	25.1820	0.1382
0.03	2	0.11	1.1	37.4152	0.1235
0.04	2	0.11	1.1	49.6484	0.1088
0.01	2	0.11	1.1	12.9488	0.1530
0.01	3	0.11	1.1	12.2898	0.5886
0.01	4	0.11	1.1	11.6308	1.0242
0.01	5	0.11	1.1	10.9718	1.4598
0.01	2	0.11	1.1	12.9488	0.1540
0.01	2	0.12	1.1	10.9715	0.1550
0.01	2	0.13	1.1	8.9805	0.1562
0.01	2	0.14	1.1	7.0080	0.1575
0.01	2	0.11	1.1	2.3497	1.9972
0.01	2	0.11	1.2	1.6780	1.6224
0.01	2	0.11	1.3	1.1263	1.6224
0.01	2	0.11	1.4	0.6335	1.3165

Table 2 Influence of Nr and Q on Nussult number and skin friction coefficient

Nr	Q	Nu	τ at t=1.5	τ at t=0.5
0.5	0.5	0.6939	12.9691	0.1530
1	0.5	0.6009	4.1934	0.1569
1.5	0.5	0.5375	2.7115	0.1579
2	0.5	0.4906	2.1841	0.1582
1	0.5	0.6939	12.9691	0.1530
1	1	0.9308	7.5404	0.1556
1	1.5	1.1226	4.5406	0.1579
1	2	1.2857	2.8746	0.1599

Table 3 Effect of Kc and Sc on Sherwood number and skin friction coefficient

Kr	Sc	Sh	τ at t=1.5	τ at t=0.5
1	0.22	0.4986	12.948	0.1530
2	0.22	0.6723	12.7890	0.2045
3	0.22	0.9394	12.4151	0.3570
4	0.22	1.1492	11.9682	0.5873
1	0.22	0.4986	12.9488	0.1530
1	0.42	0.6889	12.7812	0.5992
1	0.62	0.8370	12.6031	0.7281
1	0.82	0.9626	12.4050	0.8373

Table 4 Effect of t_1 on Nusselt number, Sherwood number and skin friction

t_1	Nu	Sh	τ at t=1.5	Nu	Sh	τ at t=0.5
1	0.6939	0.4986	12.9488	0.8073	0.4337	0.1530
2	0.5488	0.4661	7.7797	0.5382	0.2891	0.1325
2.5	0.4390	0.3729	6.7712	0.4037	0.2169	0.2753
3	0.3658	0.3108	6.0989	0.3229	0.1735	0.3610

The influence of Grashof number modified Grashof number, Hall parameter, magnetic parameter is presented in table 1. From this table it is noticed thatas Grashof number increases skin friction increases at t=1.5 and decreases at t=0.5. As modified Grashof number increases skin friction decreases at t=1.5 whereas it increases at t=0.5. As Hall parameter increases skin friction decreases at t= 1.5 but it increases at t=0.5. Similarly as magnetic parameter increases skin friction decreases at t=1.5 and increases at t=0.5.Influence of radiation parameter and heat absorption parameter on Nussult number and skin friction coefficient is presented in table 2. From this table, it is noticed thatas radiation parameter increases Nusselt number decreases where as skin friction decreases at t=1.5but increasesat t=0.5. As heat absorption parameter increases Nusselt number increases and skin friction decreases at t=1.5 where as it increases at t=0.5. Effect of chemical reaction parameter and Schmidt number on Sherwood number and skin friction coefficient is presented in table 3. From this table it is noticed that, as the values of chemical reaction parameter increases, Sherwood number increases but skin friction decreases at t=1.5 and increases at t=0.5. As Schmidt number increases Sherwood number increases and skin friction decreases at t=1.5butincreases t=0.5. Effect of t_1 on Nusselt number, Sherwood number and skin friction at t=1.5 is presented in table 4 from this it is noticed that, as the presence of rampedness increases

Nussult number, Sherwood number, skin friction decreases at t=1.5 where as Nussult number, Sherwood number increases at t=0.5 however skin friction decreases at t=0.5

CONCLUSION

The non-dimensional governing equations of the problem are solved by using Laplace transform method. The variations in the velocity, temperature and concentration with the effects of various parameters encountered in the problem are studied through graphs. Also the effects some of the above parameters on skin friction, Nusselt number and Sherwood number are observed.

- The fluid velocity increases with the increasing values of Grashof number, modified Grashof number, heat absorption parameter and Hall effect but a reverse trend is found in the case of Magnetic field, reaction parameter, Schmidt number, radiation parameter.
- The fluid temperature decreases with the increasing values of radiation parameter, heat absorption parameter, and critical time for rampedness.
- The fluid concentration decreases with the increasing values of chemical reaction, Schmidt number and critical time for rampedness.
- Skin friction decreases for increasing values of critical time for rampedness and Hall Effect.

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