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Convective Ramped Wall Temperature and Concentration Boundary Layer Flow of a Chemically Reactive Heat Absorbing and Radiating Fluid over a Vertical Plate in Conducting Field with Hall Current

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Abstract

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.

Keywords: MHD; Hall effect; Radiation; Heat absorption; Ramped wall temperature; Ramped wall concentration

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. Chandrakala [1] analyzed radiation effects on flow past an impulsively started vertical oscillating plate with uniform heat flux. Chandram et al. [2] investigated natural convection near a vertical plate with ramped wall temperature. Prasad and Reddy [3] observed radiation effects on an unsteady MHD convective heat and mass transfer flow past a semi-infinite vertical permeable moving plate embedded in a porous medium. Chandrakala and Bhaskar [4] considered thermal radiation effects on MHD flow past a vertical oscillating plate. Israel-Cookey et al. [5] examined MHD oscillatory couette flow of a radiating viscous fluid in a porous medium with periodic wall temperature. Jain and Singh [6] noticed that Hall and thermal radiation effects on an unsteady rotating free convection slip flow along a porous vertical moving plate. Aurangzaib and Sharidan [7] obtained effects of Soret and Dufour on unsteady MHD flow by mixed convection over a vertical surface in porous media with internal heat generation, chemical reaction and Hall current. Chaudhary et al. [8] presented effects of Hall current and thermal radiation on an unsteady free convection slip flow along a vertical plate embedded in a porous medium with constant heat and mass flux. Shateyi et al. [9] analyzed the effects of thermal radiation, Hall currents, Soret and Dufour on MHD flow by mixed convection over a vertical surface in porous media. Seth et al. [10] discussed 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. Shit and Haldar [11] have investigated combined effects of thermal radiation and Hall current on MHD free-convective flow and mass transfer over a stretching sheet with variable viscosity. Singh and Pathak [12] studied effect of rotation and Hall current on mixed convection MHD flow through a porous medium in a vertical channel in presence of thermal radiation. Takhar and Ram [13] assumed free convection in hydromagnetic flows of a viscous heat-generating fluid with wall temperature oscillation and Hall currents. Ahmed and Sharma [14] have considered the radiation effect on a transient MHD flow with mass transfer past an impulsively fixed infinite vertical plate. Rajesh and Varma [15] solved radiation effects on MHD flow through a porous medium with variable temperature or variable mass diffusion. Vijayalakshmi and Kamalam [16] established effects of radiation on an accelerated vertical plate with uniform mass diffusion. Ahmad et al. [17] examined unsteady MHD free convective flow past a vertical porous plate immersed in a porous medium with Hall current, thermal diffusion and heat transfer. Ahmed and Sarmah [18] MHD transient flow past an impulsively started horizontal porous plate in a rotating system with Hall current. Seth et al. [19] obtained effect of rotation on unsteady hydromagnetic natural convection flow past an impulsively moving vertical plate with ramped temperature in a porous medium with thermal diffusion and heat absorption. Malique and Sattar [20] presented the effects of variable properties and Hall current on steady MHD laminar convective fluid flow due to a porous rotating disk. Seth and Ansari [21] analyzed MHD natural convection flow past an impulsively moving vertical plate with ramped wall temperature in the presence of thermal diffusion with heat absorption. Seth et al. [22] discussed hartmann flow in a rotating system in the presence of inclined magnetic field with Hall effects. Kumar et al. [23] has investigated hydromagnetic couette flow in a rotating system with Hall effects. Seth et al. [24] studied Hall effects on oscillatory hydromagnetic couette flow in a rotating system. Kinyanjui et al. [25] assumed magneto hydrodynamic free convection heat and mass transfer of a heat generating fluid past an impulsively started infinite vertical porous plate with Hall current and radiation absorption.

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Cookey et al. [26] have considered influence of viscous dissipation and radiation on unsteady MHD free convection flow past an infinite heated vertical plate in a porous medium with time dependent suction. Aboeldahab and Aziz [27] solved viscous dissipation and Joule heating effects on MHD free convection from a vertical plate with power-law variation in surface temperature in the presence of Hall and ion-slip currents. Seth et al. [28] established effect of rotation on heat transfer characteristics of hydromagnetic channel flow in the presence of inclined magnetic field. Seth [29] examined effects of Hall current on unsteady hydro magnetic couette flow in a rotating system. Muthucumaraswamy and Ganesan [30] obtained radiation effects on the flow past an impulsively started infinite vertical plate with variable temperature. Seth et al. [31] presented effect of hall current on hydromagnetic free and forced convection flow in a rotating channel. Seddeek et al. [32] analyzed radiation effects on unsteady MHD free convection with hall current near an infinite vertical porous plate. Aboedahab and Elbarbary [33] have investigated hall current effect on magneto hydrodynamic free-convection flow past a semi-infinite vertical plate with mass transfer. Kumar et al. [34] studied effect of inclination of applied magnetic field and hall current on generalized oscillatory MHD Couette flow. Das et al. [35] has considered unsteady hydromagnetic flow of a heat absorbing dusty fluid past a permeable vertical plate with ramped temperature. Thermal and solutal buoyancy effect [36,37] on MHD boundary layer flow of a visco-elastic fluid past a porous plate with varying suction and heat source in the presence of thermal diffusion was investigated by Chandra et al. [38] recently. Unsteady MHD free convection flow of a viscous dissipative Kuvshinski fluid past an infinite vertical porous plate in the presence of radiation, thermal diffusion and chemical effects were considered by Vidyasagar et al. [39]. Heat and mass transfer in MHD mixed convection flow on a moving inclined porous plate was investigated by Raju et al. [40].

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^1-axis is along the vertical plate upward direction, y^1-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 t1 < 0, both the plate and surrounding fluid are at rest and maintained at uniform temperature $T_\infty{}^1$. At time $t^1 > 0$, 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^1 directions, all physical quantities except pressure depend on y^1 and t^1 only. 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 considering Hall current, under Boussinesq approximation, are given by

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

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

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

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

Initial and boundary conditions to be satisfied are

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

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

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

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

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

For an optically thick gray fluid, the radiative heat flux q_r is approximated by Ross eland approximation that 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_∞^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

$$\begin{gathered} y = \frac{U_0 y^1}{v}, t = \frac{U_0^2 t^1}{v}, u = \frac{u^1}{U_0}, w = \frac{w^1}{U_0}, T = \frac{(T^1 - T^1{}_\infty)}{(T_w^1 - T^1{}_\infty)}, G_r = \frac{vg\beta(T^1{}_w - T^1{}_\infty)}{U_0^3}, \\ C = \frac{(C^1 - C^1{}_\infty)}{(C_w^1 - C^1{}_\infty)}, G_m = \frac{vg\beta^1(C^1{}_w - C^1{}_\infty)}{U_0^3}, M^2 = \frac{\sigma B^2{}_0 v}{\rho U^2{}_0}, N_r = \frac{16\sigma^* T^{1^3}{}_\infty}{3kk^*}, \\ t_1 = \frac{U_0^2 t_0}{v}, P_r = \frac{\sigma v c_p}{k}, \varphi = \frac{Q_0 v}{\sigma c_p U_0^2}. \end{gathered} \tag{11}$$

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

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

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

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

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

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

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

$$t > 0 : F = at, T = \begin{cases} \frac{t}{t_1} \text{ at y=0 for } 0<t \le t_1, T = 1 \quad \text{at y=0 for } t>t_1, \end{cases} \tag{16}$$

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

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, 19 and 20 are solutions).

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

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

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

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

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

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

$$F(y,t) = -a_1F_1 + a_2F_2 + a_1F_3 - a_2F_4 + a_1F_5 \tag{20}$$

where

$$F_1 = (f_1 + f_2 + f_3) - H(t-t_1)*(f_4 + f_5 + f_6)$$
$$F_2 = (g_1 + g_3 + g_5) - H(t-t_1)*(g_2 + g_4 + g_6)$$
$$F_3 = (h_1 + h_3 + h_5) - H(t-t_1)*(h_2 + h_4 + h_6)$$
$$F_4 = (l_1 + l_3 + l_5) - H(t-t_1)*(l_2 + l_4 + l_6)$$
$$F_5 = d_1 - H(t-t_1)*d_2$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$b1 = \frac{1}{t_1}\left\{ \begin{array}{l} \frac{-t}{\sqrt{\pi\lambda_2 t}} e^{-\phi(t)} + erfc\left(-\sqrt{\phi(t)}\right)\left(\frac{(t)}{2}\right)\left(-\sqrt{\frac{\phi}{\lambda_2}}\right) + erfc\left(-\sqrt{\phi(t)}\right)\left(\frac{-1}{4\sqrt{\lambda_2\phi}}\right) \\ + erfc\left(\sqrt{\phi(t)}\right)\left(\frac{(t)}{2}\right)\left(\sqrt{\frac{\phi}{\lambda_2}}\right) + erfc\left(\sqrt{\phi(t)}\right)\left(\frac{1}{4\sqrt{\lambda_2\phi}}\right) \end{array}\right\}$$

$$b2 = \frac{1}{t_1}\left\{ \begin{array}{l} \frac{-(t-t_1)}{\sqrt{\pi\lambda_2(t-t_1)}} e^{-\phi(t-t_1)} + erfc\left(-\sqrt{\phi(t-t_1)}\right)\left(\frac{(t-t_1)}{2}\right)\left(-\sqrt{\frac{\phi}{\lambda_2}}\right) + erfc\left(-\sqrt{\phi(t-t_1)}\right)\left(\frac{-1}{4\sqrt{\lambda_2\phi}}\right) \\ + erfc\left(\sqrt{\phi(t-t_1)}\right)\left(\frac{(t-t_1)}{2}\right)\left(\sqrt{\frac{\phi}{\lambda_2}}\right) + erfc\left(\sqrt{\phi(t-t_1)}\right)\left(\frac{1}{4\sqrt{\lambda_2\phi}}\right) \end{array}\right\}$$

$$b3=\frac{1}{t_1}\left\{\begin{array}{l}\left(-\sqrt{\frac{S_c t}{\pi}}\right)e^{-K_r t}+erfc\left(-\sqrt{K_r t}\right)\left(\frac{-t\sqrt{S_c K_r}}{2}\right)+erfc\left(-\sqrt{K_r t}\right)\left(\frac{-\sqrt{S_c}}{4\sqrt{K_r}}\right)\\+erfc\left(\sqrt{K_r t}\right)\left(\frac{t\sqrt{S_c K_r}}{2}\right)+erfc\left(\sqrt{K_r t}\right)\left(\frac{\sqrt{S_c}}{4\sqrt{K_r}}\right)\end{array}\right\}$$

$$b4=\frac{1}{t_1}\left\{\begin{array}{l}\left(-\sqrt{\frac{S_c (t-t_1)}{\pi}}\right)e^{-K_r (t-t_1)}+erfc\left(-\sqrt{K_r (t-t_1)}\right)\left(\frac{-t\sqrt{S_c K_r}}{2}\right)+erfc\left(-\sqrt{K_r (t-t_1)}\right)\left(\frac{-\sqrt{S_c}}{4\sqrt{K_r}}\right)\\+erfc\left(\sqrt{K_r (t-t_1)}\right)\left(\frac{(t-t_1)\sqrt{S_c K_r}}{2}\right)+erfc\left(\sqrt{K_r (t-t_1)}\right)\left(\frac{\sqrt{S_c}}{4\sqrt{K_r}}\right)\end{array}\right\}$$

$$b5=\frac{-1}{\lambda_7^{\,2}}\left\{\left(\frac{-2}{\sqrt{\pi t}}\right)e^{-\lambda_3 t}+erfc\left(-\sqrt{\lambda_3 t}\right)\left(-\sqrt{\lambda_3}\right)+erfc\left(\sqrt{\lambda_3 t}\right)\left(\sqrt{\lambda_3}\right)\right\}$$

$$b6=\frac{-1}{\lambda_7^{\,2}}\left\{\left(\frac{-2}{\sqrt{\pi(t-t_1)}}\right)e^{-\lambda_3 (t-t_1)}+erfc\left(-\sqrt{\lambda_3 (t-t_1)}\right)\left(-\sqrt{\lambda_3}\right)+erfc\left(\sqrt{\lambda_3 (t-t_1)}\right)\left(\sqrt{\lambda_3}\right)\right\}$$

$$b7=\frac{-1}{\lambda_7}\left\{\begin{array}{l}\frac{-t}{\sqrt{\pi t}}e^{-\lambda_3 (t)}+erfc\left(-\sqrt{\lambda_3 (t)}\right)\left(\frac{(t)}{2}\right)\left(-\sqrt{\lambda_3}\right)+erfc\left(-\sqrt{\lambda_3 (t)}\right)\left(\frac{-1}{4\sqrt{\lambda_3}}\right)\\+erfc\left(\sqrt{\lambda_3 (t)}\right)\left(\frac{(t)}{2}\right)\left(\sqrt{\lambda_3}\right)+erfc\left(\sqrt{\lambda_3 (t)}\right)\left(\frac{1}{4\sqrt{\lambda_3}}\right)\end{array}\right\}$$

$$b8=\frac{-1}{\lambda_7}\left\{\begin{array}{l}\frac{-(t-t_1)}{\sqrt{\pi (t-t_1)}}e^{-\lambda_3 (t-t_1)}+erfc\left(-\sqrt{\lambda_3 (t-t_1)}\right)\left(\frac{(t-t_1)}{2}\right)\left(-\sqrt{\lambda_3}\right)+erfc\left(-\sqrt{\lambda_3 (t-t_1)}\right)\left(\frac{-1}{4\sqrt{\lambda_3}}\right)\\+erfc\left(\sqrt{\lambda_3 (t-t_1)}\right)\left(\frac{(t-t_1)}{2}\right)\left(\sqrt{\lambda_3}\right)+erfc\left(\sqrt{\lambda_3 (t-t_1)}\right)\left(\frac{1}{4\sqrt{\lambda_3}}\right)\end{array}\right\}$$

$$b9=\frac{-1e^{\lambda_7 t}}{2\lambda_7^{\,2}}\left\{\left(\frac{-2}{\sqrt{\pi t}}\right)e^{-(\lambda_3+\lambda_7)t}+erfc\left(-\sqrt{(\lambda_3+\lambda_7)t}\right)\left(-\sqrt{\lambda_3+\lambda_7}\right)+erfc\left(\sqrt{(\lambda_3+\lambda_7)t}\right)\left(\sqrt{\lambda_3+\lambda_7}\right)\right\}$$

$$b10=\frac{-1e^{\lambda_7 (t-t_1)}}{2\lambda_7^{\,2}}\left\{\begin{array}{l}\left(\frac{-2}{\sqrt{\pi (t-t_1)}}\right)e^{-(\lambda_3+\lambda_7)(t-t_1)}+erfc\left(-\sqrt{(\lambda_3+\lambda_7)(t-t_1)}\right)\left(-\sqrt{\lambda_3+\lambda_7}\right)\\+erfc\left(\sqrt{(\lambda_3+\lambda_7)(t-t_1)}\right)\left(\sqrt{\lambda_3+\lambda_7}\right)\end{array}\right\}$$

$$b11=(b5+b7+b9)-H(t-t_1)*(b6+b8+b10)$$

$$b12=\frac{-1}{2a_3^{\,2}}\left\{\left(\frac{-2}{\sqrt{\pi t}}\right)e^{-\lambda_3 t}+erfc\left(-\sqrt{\lambda_3 t}\right)\left(-\sqrt{\lambda_3}\right)+erfc\left(\sqrt{\lambda_3 t}\right)\left(\sqrt{\lambda_3}\right)\right\}$$

$$b13=\frac{-1}{2a_3^{\,2}}\left\{\left(\frac{-2}{\sqrt{\pi (t-t_1)}}\right)e^{-\lambda_3 (t-t_1)}+erfc\left(-\sqrt{\lambda_3 (t-t_1)}\right)\left(-\sqrt{\lambda_3}\right)+erfc\left(\sqrt{\lambda_3 (t-t_1)}\right)\left(\sqrt{\lambda_3}\right)\right\}$$

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$$b14=\frac{1}{a_3}\left\{\begin{array}{l}\frac{-t}{\sqrt{\pi t}}e^{-\lambda_3(t)}+erfc\left(-\sqrt{\lambda_3(t)}\right)\left(\frac{(t)}{2}\right)\left(-\sqrt{\lambda_3}\right)+erfc\left(-\sqrt{\lambda_3(t)}\right)\left(\frac{-1}{4\sqrt{\lambda_3}}\right)\\+erfc\left(\sqrt{\lambda_3(t)}\right)\left(\frac{(t)}{2}\right)\left(\sqrt{\lambda_3}\right)+erfc\left(\sqrt{\lambda_3(t)}\right)\left(\frac{1}{4\sqrt{\lambda_3}}\right)\end{array}\right\}$$

$$b15=\frac{1}{a_3}\left\{\begin{array}{l}\frac{-(t-t_1)}{\sqrt{\pi t}}e^{-\lambda_3((t-t_1))}+erfc\left(-\sqrt{\lambda_3((t-t_1))}\right)\left(\frac{((t-t_1))}{2}\right)\left(-\sqrt{\lambda_3}\right)+erfc\left(-\sqrt{\lambda_3((t-t_1))}\right)\left(\frac{-1}{4\sqrt{\lambda_3}}\right)\\+erfc\left(\sqrt{\lambda_3((t-t_1))}\right)\left(\frac{((t-t_1))}{2}\right)\left(\sqrt{\lambda_3}\right)+erfc\left(\sqrt{\lambda_3((t-t_1))}\right)\left(\frac{1}{4\sqrt{\lambda_3}}\right)\end{array}\right\}$$

$$b16=\frac{1e^{a_3 t}}{2a_3^{\,2}}\left\{\left(\frac{-2}{\sqrt{\pi t}}\right)e^{-(\lambda_3-a_3)t}+erfc\left(-\sqrt{(\lambda_3-a_3)t}\right)\left(-\sqrt{\lambda_3-a_3}\right)+erfc\left(\sqrt{(\lambda_3-a_3)t}\right)\left(\sqrt{\lambda_3-a_3}\right)\right\}$$

$$b17=\frac{1e^{a_3(t-t_1)}}{2a_3^{\,2}}\left\{\begin{array}{l}\left(\frac{-2}{\sqrt{\pi(t-t_1)}}\right)e^{-(\lambda_3-a_3)(t-t_1)}+erfc\left(-\sqrt{(\lambda_3-a_3)(t-t_1)}\right)\left(-\sqrt{\lambda_3-a_3}\right)\\+erfc\left(\sqrt{(\lambda_3-a_3)(t-t_1)}\right)\left(\sqrt{\lambda_3-a_3}\right)\end{array}\right\}$$

$$b18=(b12+b14+b16)-H(t-t_1)*(b13+b15+b17)$$

$$b19=\frac{-1}{2\lambda_7^{\,2}}\left\{\frac{-2}{\sqrt{\pi\lambda_2 t}}e^{-\phi(t)}+erfc\left(-\sqrt{\phi(t)}\right)\left(-\sqrt{\frac{\phi}{\lambda_2}}\right)+erfc\left(\sqrt{\phi(t)}\right)\left(\sqrt{\frac{\phi}{\lambda_2}}\right)\right\}$$

$$b20=\frac{-1}{2\lambda_7^{\,2}}\left\{\frac{-2}{\sqrt{\pi\lambda_2(t-t_1)}}e^{-\phi(t-t_1)}+erfc\left(-\sqrt{\phi((t-t_1))}\right)\left(-\sqrt{\frac{\phi}{\lambda_2}}\right)+erfc\left(\sqrt{\phi((t-t_1))}\right)\left(\sqrt{\frac{\phi}{\lambda_2}}\right)\right\}$$

$$b21=\frac{1}{\lambda_7}\left\{\begin{array}{l}\frac{-t}{\sqrt{\pi\lambda_2 t}}e^{-\phi(t)}+erfc\left(-\sqrt{\phi(t)}\right)\left(\frac{(t)}{2}\right)\left(-\sqrt{\frac{\phi}{\lambda_2}}\right)+erfc\left(-\sqrt{\phi(t)}\right)\left(\frac{-1}{4\sqrt{\lambda_2\phi}}\right)\\+erfc\left(\sqrt{\phi(t)}\right)\left(\frac{(t)}{2}\right)\left(\sqrt{\frac{\phi}{\lambda_2}}\right)+erfc\left(\sqrt{\phi(t)}\right)\left(\frac{1}{4\sqrt{\lambda_2\phi}}\right)\end{array}\right\}$$

$$b22=\frac{1}{\lambda_7}\left\{\begin{array}{l}\frac{-(t-t_1)}{\sqrt{\pi\lambda_2(t-t_1)}}e^{-\phi(t-t_1)}+erfc\left(-\sqrt{\phi(t-t_1)}\right)\left(\frac{(t-t_1)}{2}\right)\left(-\sqrt{\frac{\phi}{\lambda_2}}\right)+erfc\left(-\sqrt{\phi(t-t_1)}\right)\left(\frac{-1}{4\sqrt{\lambda_2\phi}}\right)\\+erfc\left(\sqrt{\phi(t-t_1)}\right)\left(\frac{(t-t_1)}{2}\right)\left(\sqrt{\frac{\phi}{\lambda_2}}\right)+erfc\left(\sqrt{\phi(t-t_1)}\right)\left(\frac{1}{4\sqrt{\lambda_2\phi}}\right)\end{array}\right\}$$

$$b23=\frac{1e^{\lambda_7 t}}{2\lambda_7^{\,2}}\left\{\left(\frac{-2}{\sqrt{\pi\lambda_2 t}}\right)e^{-(\lambda_7+\phi)t}+erfc\left(-\sqrt{(\lambda_7+\phi)t}\right)\left(-\sqrt{\frac{\lambda_7+\phi}{\lambda_2}}\right)+erfc\left(\sqrt{(\lambda_7+\phi)t}\right)\left(\sqrt{\frac{\lambda_7+\phi}{\lambda_2}}\right)\right\}$$

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$$b24=\frac{1e^{\lambda_7(t-t_1)}}{2\lambda_7^{\,2}}\left\{\begin{array}{l}\left(\frac{-2}{\sqrt{\pi\lambda_2(t-t_1)}}\right)e^{-(\lambda_7+\phi)(t-t_1)}+erfc\left(-\sqrt{(\lambda_7+\phi)(t-t_1)}\right)\left(-\sqrt{\frac{\lambda_7+\phi}{\lambda_2}}\right)\\+erfc\left(\sqrt{(\lambda_7+\phi)(t-t_1)}\right)\left(\sqrt{\frac{\lambda_7+\phi}{\lambda_2}}\right)\end{array}\right\}$$

$$b25=(b19+b21+b23)-H(t-t_1)*(b20+b22+b24)$$

$$b26=\frac{-1}{2a_3^{\,2}}\left\{\left(-2\sqrt{\frac{S_c}{\pi t}}\right)e^{-K_rt}+erfc\left(-\sqrt{K_rt}\right)\left(-\sqrt{S_cK_r}\right)+erfc\left(\sqrt{K_rt}\right)\left(\sqrt{S_cK_r}\right)\right\}$$

$$b27=\frac{-1}{2a_3^{\,2}}\left\{\left(-2\sqrt{\frac{S_c}{\pi t}}\right)e^{-K_r(t-t_1)}+erfc\left(-\sqrt{K_r(t-t_1)}\right)\left(-\sqrt{S_cK_r}\right)+erfc\left(\sqrt{K_r(t-t_1)}\right)\left(\sqrt{S_cK_r}\right)\right\}$$

$$b28=\frac{1}{a_3}\left\{\begin{array}{l}\left(-\sqrt{\frac{S_ct}{\pi}}\right)e^{-K_rt}+erfc\left(-\sqrt{K_rt}\right)\left(\frac{-t\sqrt{S_cK_r}}{2}\right)+erfc\left(-\sqrt{K_rt}\right)\left(\frac{-\sqrt{S_c}}{4\sqrt{K_r}}\right)\\+erfc\left(\sqrt{K_rt}\right)\left(\frac{t\sqrt{S_cK_r}}{2}\right)+erfc\left(\sqrt{K_rt}\right)\left(\frac{\sqrt{S_c}}{4\sqrt{K_r}}\right)\end{array}\right\}$$

$$b29=\frac{1}{a_3}\left\{\begin{array}{l}\left(-\sqrt{\frac{S_c(t-t_1)}{\pi}}\right)e^{-K_r(t-t_1)}+erfc\left(-\sqrt{K_r(t-t_1)}\right)\left(\frac{-t\sqrt{S_cK_r}}{2}\right)+erfc\left(-\sqrt{K_r(t-t_1)}\right)\left(\frac{-\sqrt{S_c}}{4\sqrt{K_r}}\right)\\+erfc\left(\sqrt{K_r(t-t_1)}\right)\left(\frac{(t-t_1)\sqrt{S_cK_r}}{2}\right)+erfc\left(\sqrt{K_r(t-t_1)}\right)\left(\frac{\sqrt{S_c}}{4\sqrt{K_r}}\right)\end{array}\right\}$$

$$b30=\frac{1e^{-a_3t}}{2a_3^{\,2}}\left\{\left(\frac{-2\sqrt{S_c}}{\sqrt{\pi t}}\right)e^{-(K_r-a_3)t}+erfc\left(-\sqrt{((K_r-a_3)t}\right)\left(-\sqrt{(K_r-a_3)}\right)+erfc\left(\sqrt{(K_r-a_3)t}\right)\left(\sqrt{(K_r-a_3)}\right)\right\}$$

$$b31=\frac{1e^{-a_3(t-t_1)}}{2a_3^{\,2}}\left\{\begin{array}{l}\left(\frac{-2\sqrt{S_c}}{\sqrt{\pi(t-t_1)}}\right)e^{-(K_r-a_3)(t-t_1)}+erfc\left(-\sqrt{((K_r-a_3)(t-t_1)}\right)\left(-\sqrt{(K_r-a_3)}\right)\\+erfc\left(\sqrt{(K_r-a_3)(t-t_1)}\right)\left(\sqrt{(K_r-a_3)}\right)\end{array}\right\}$$

$$b32=(b26+b28+b30)-H(t-t_1)*(b27+b29+b31)$$

$$b33=\left\{\begin{array}{l}\frac{-t}{\sqrt{\pi t}}e^{-\lambda_3(t)}+erfc\left(-\sqrt{\lambda_3(t)}\right)\left(\frac{(t)}{2}\right)\left(-\sqrt{\lambda_3}\right)+erfc\left(-\sqrt{\lambda_3(t)}\right)\left(\frac{-1}{4\sqrt{\lambda_3}}\right)\\+erfc\left(\sqrt{\lambda_3(t)}\right)\left(\frac{(t)}{2}\right)\left(\sqrt{\lambda_3}\right)+erfc\left(\sqrt{\lambda_3(t)}\right)\left(\frac{1}{4\sqrt{\lambda_3}}\right)\end{array}\right\}$$

$$b34 = \left\{ \begin{array}{l} \frac{-(t-t_1)}{\sqrt{\pi t}} e^{-\lambda_3((t-t_1))} + erfc\left(-\sqrt{\lambda_3((t-t_1))}\right)\left(\frac{((t-t_1))}{2}\right)\left(-\sqrt{\lambda_3}\right) + erfc\left(-\sqrt{\lambda_3((t-t_1))}\right)\left(\frac{-1}{4\sqrt{\lambda_3}}\right) \\ + erfc\left(\sqrt{\lambda_3((t-t_1))}\right)\left(\frac{((t-t_1))}{2}\right)\left(\sqrt{\lambda_3}\right) + erfc\left(\sqrt{\lambda_3((t-t_1))}\right)\left(\frac{1}{4\sqrt{\lambda_3}}\right) \end{array} \right\}$$

$$b35 = b33 - H(t-t_1) * b34; \text{ Where } H(t-t_1) = \text{Heaviside}(t-t_1).$$

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 (Q or ϕ), radiation parameter (Nr), Schmidt number (Sc), chemical reaction parameter (Kr), Hall current (m1) and various values of critical time for rampedness (t1) 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 1 and 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 effect of heat absorption parameter on temperature is 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 demonstrates 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 depicts the effect of critical time for rampedness on velocity distribution. It is shows that the velocity decreases

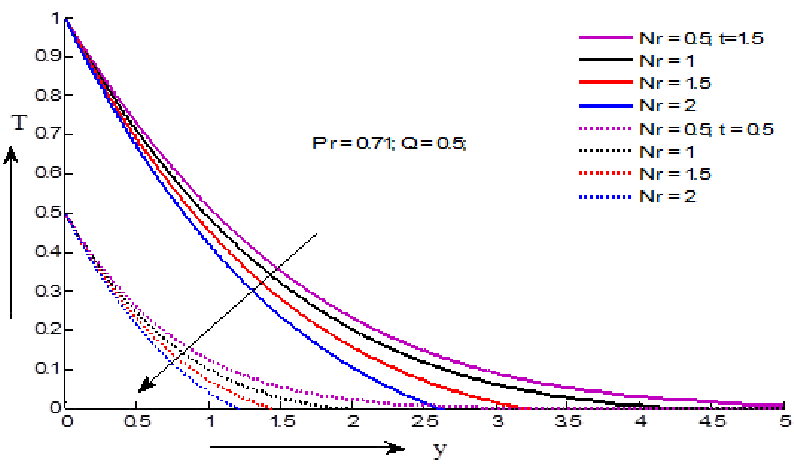

Figure 1: Effect of radiation parameter Nr on temperature.

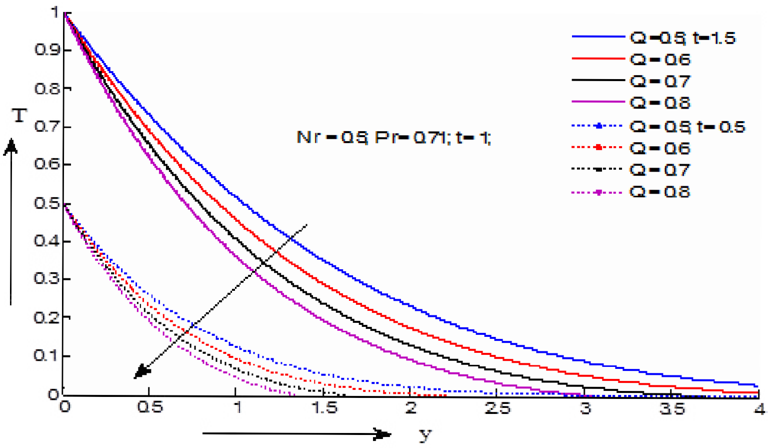

Figure 2: Effect of heat absorption parameter Q on temperature.

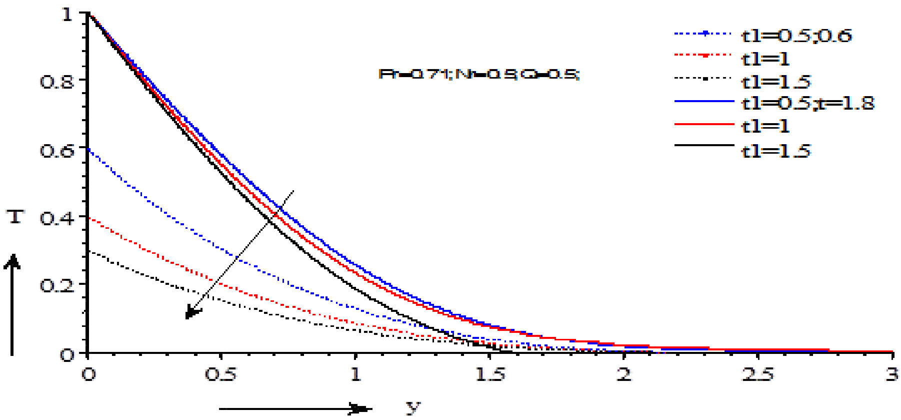

Figure 3: Effect of rampedness t1 on temperature.

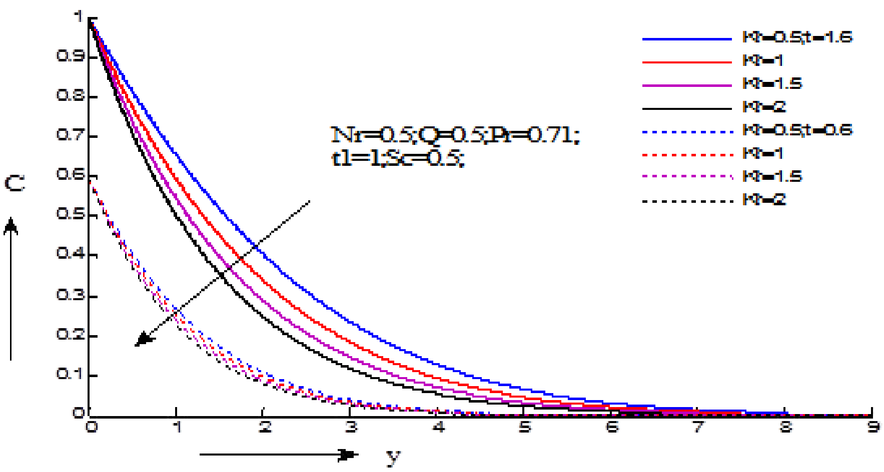

Figure 4: Effect of chemical reaction Kr on concentration.

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.

We also recorded numerical values of the surface skin friction (τ), Nusselt number (Nu) and Sherwood number (Sh) in tabular form. From

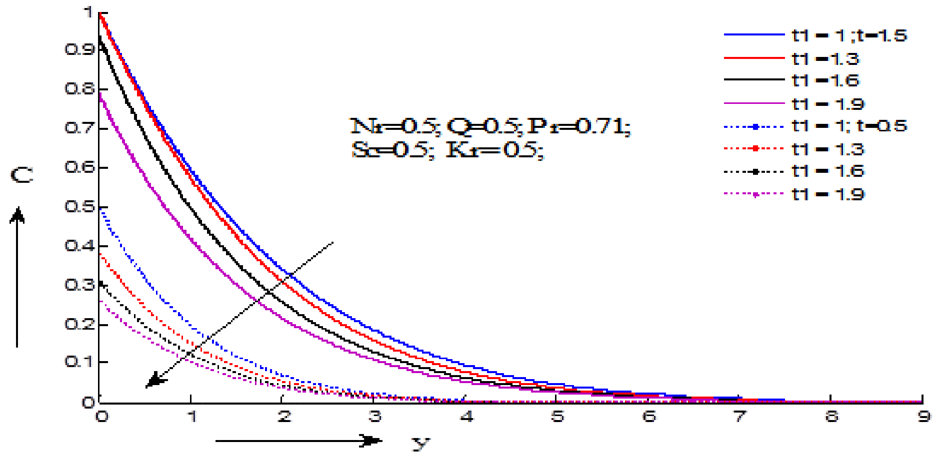

Figure 5: Effect of critical time for rampedness t1 on concentration.

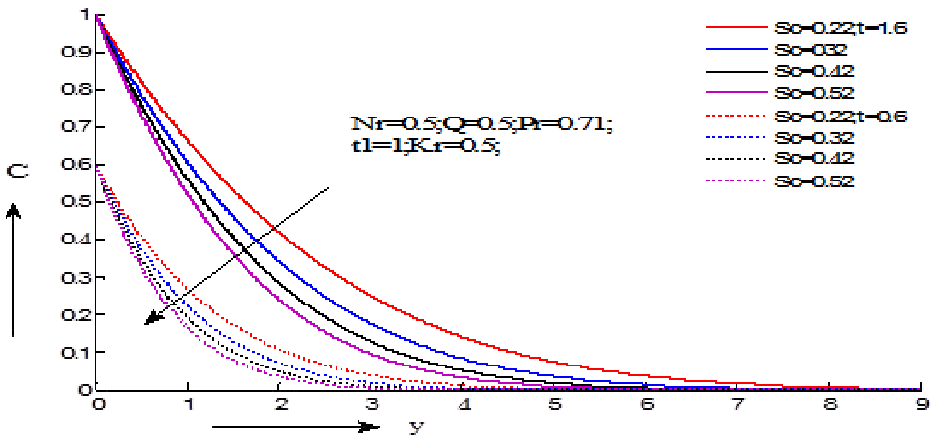

Figure 6: Effect of Schmidt number Sc on concentration.

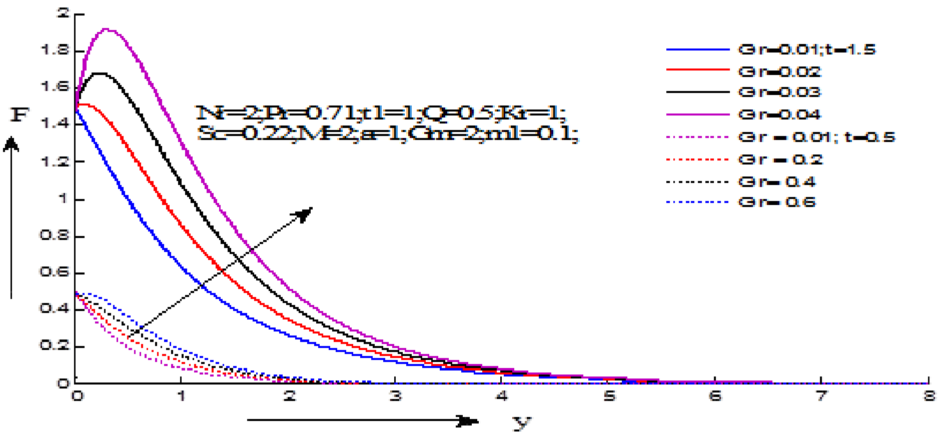

Figure 7: Effect of Grash of number Gr on velocity.

Table 1 it is observed that Nusselt number and skin fraction decreases for increasing values of Nr. From Table 2 it is noticed that Nusselt number decreases for the increasing values of Nr. whereas skin friction increases for increasing values of Nr. From Table 3 it is noted that Nusselt number increase due to an increase in heat absorption parameter Q or ϕ and skin friction decrease due to an increase in heat absorption parameter. From Table 4 it is cleared that both Nusselt number and skin friction increase due to an increase in heat absorption parameter. From Table 5 it is shows

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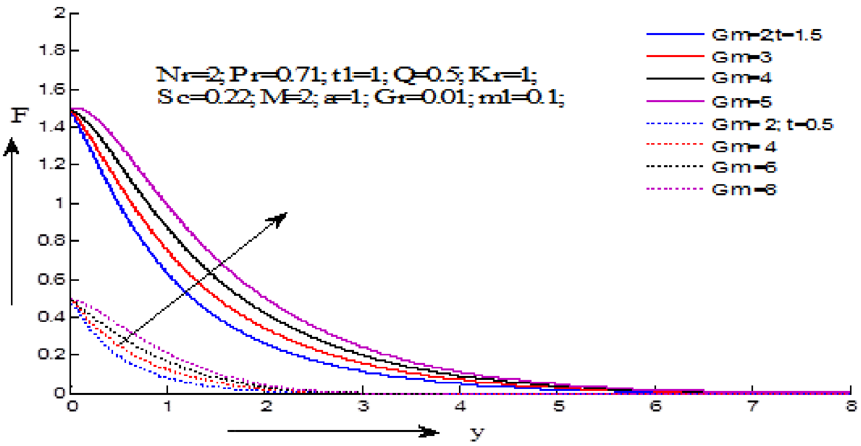

Figure 8: Effect of modified Grash of number Gm on velocity.

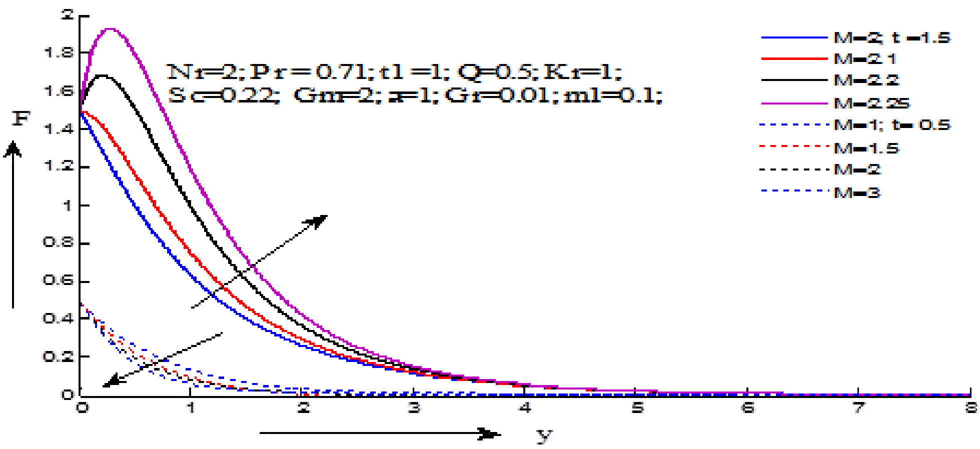

Figure 9: Effect of magnetic field M on velocity.

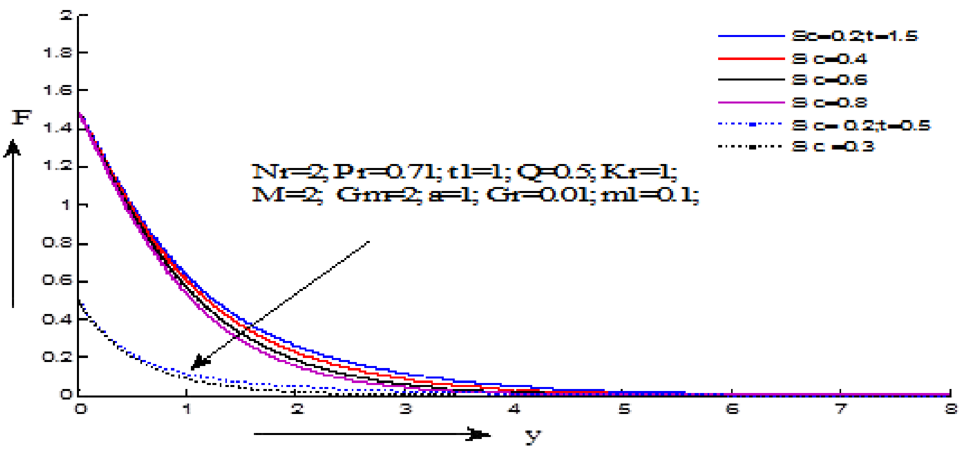

Figure 10: Effect of Schmidt number Sc on velocity.

that both Nusselt number and skin friction decrease due to an increase in rampedness t1. From Table 6 it is noticed that Nusselt number decrease due to an increase in rampedness and skin friction increase due to an increase in rampedness. From Table 7 it is observed that Sherwood number increase due to an increase in reaction parameter Kr (but reverse skin friction) and skin friction increase due to a decrease in chemical reaction.

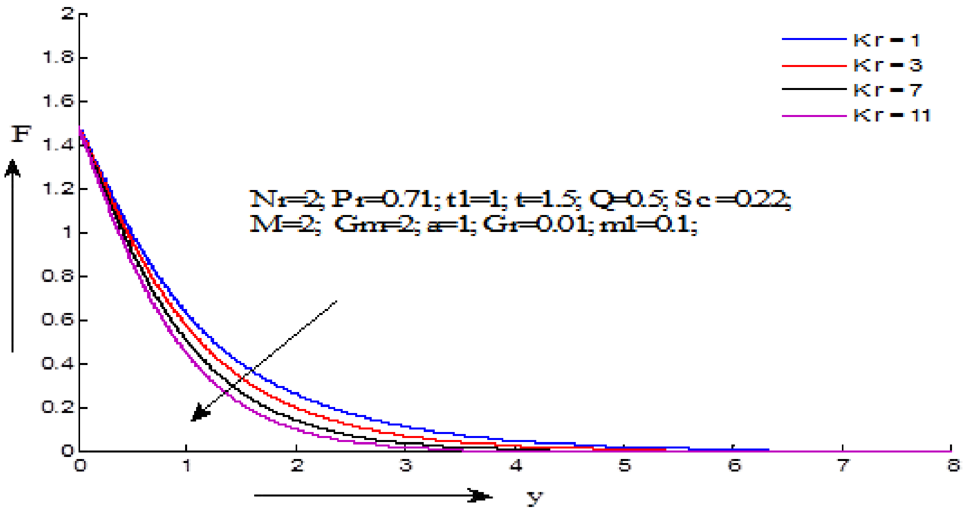

Figure 11: Effect of chemical reaction parameter Kr on velocity.

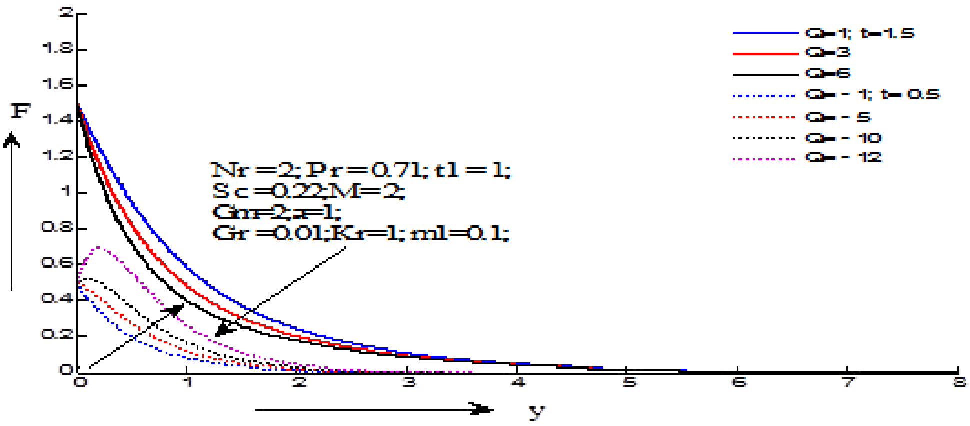

Figure 12: Effect of heat absorption Q on velocity.

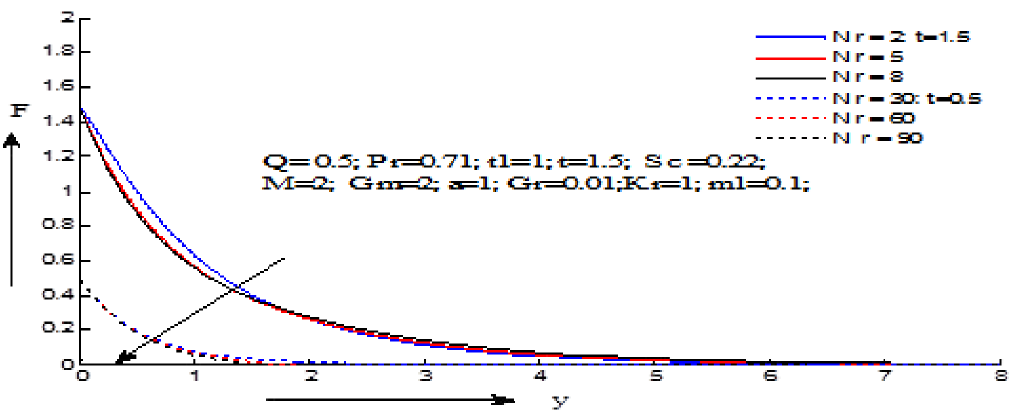

Figure 13: Effect radiation parameter Nr on velocity.

From Table 8 it is cleared that both Sherwood number and skin friction increase due to an increase in chemical reaction parameter. From Table 9 it is noted that Sherwood number increase due to an increase in Schmidt number (but reverse skin friction) and skin friction increase due to a decrease in Schmidt number. From Table 10 it is shows that both Sherwood number and skin friction increase due to an increase in Schmidt

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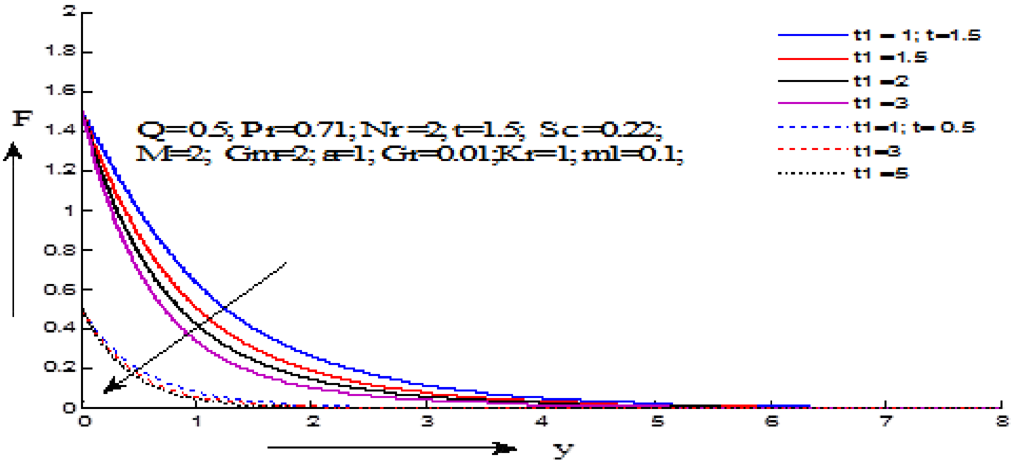

Figure 14: Effect of critical time for rampedness t1 on velocity.

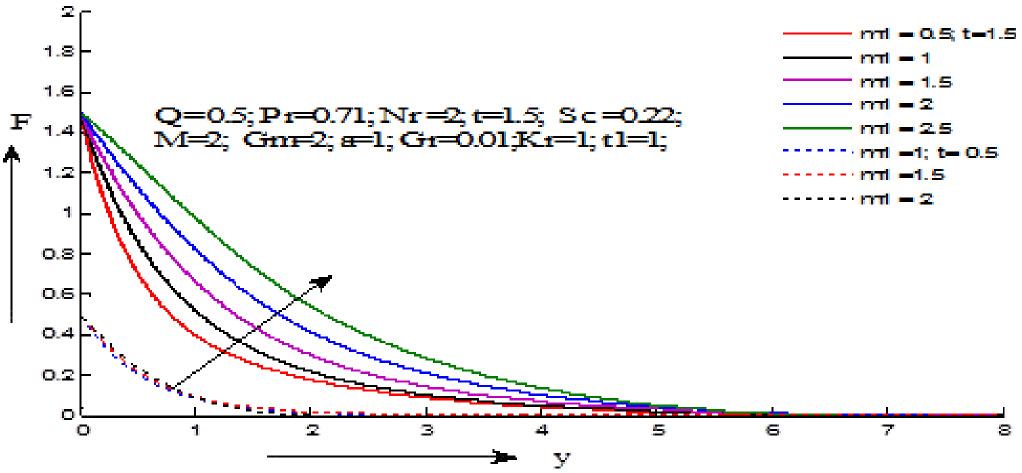

Figure 15: Effect of hall current m1 on velocity.

Nr at t = 1.5	Nu	Sh	τ
0.5	0.6939	0.4986	12.9691
1	0.6009	0.4986	4.1934
1.5	0.5375	0.4986	2.7115
2	0.4906	0.4986	2.1841

Table 1: Variations in skin friction, Nusselt number and Sherwood number with Nr and t.

Nr at t = 0.5	Nu	Sh	τ
0.5	0.8073	0.4337	0.1530
1	0.6992	0.4337	0.1569
1.5	0.6254	0.4337	0.1579
2	0.5709	0.4337	0.1582

Table 2: Variations in skin friction, Nusselt number and Sherwood number with Nr and t.

number. From Table 11 it is observed that skin friction increase due to an increase in Grashof number. From Table 12 it is show that skin friction decrease due to an increase in Grashof number. From Table 13 it is noticed that skin friction decrease due to an increase in modified Grashof number. From Table 14 it is cleared that skin friction increase due to an increase in modified Grashof number. From Table 15 it is examined that skin friction decrease due to an increase in Hall current (m1). From Table 16 it is noticed that skin friction increase due to an increase in Hall current (m1). From Tables 17 and 18 it is observed that skin friction decrease due to an increase in Magnetic field.

Q (= ϕ) at t = 1.5	Nu	Sh	τ
0.5	0.6939	0.4986	12.9691
1	0.9308	0.4986	7.5404
1.5	1.1226	0.4986	4.5406
2	1.2857	0.4986	2.8746

Table 3: Variations in skin friction, Nusselt number and Sherwood number with Q and t.

Q (= ϕ) at t = 0.5	Nu	Sh	τ
0.5	0.8073	0.4377	0.1530
1	0.8026	0.4377	0.1556
1.5	0.8065	0.4377	0.1579
2	0.8169	0.4377	0.1599

Table 4: Variations in skin friction, Nusselt number and Sherwood number with Q and t.

T_1 (= t1) at t = 1.5	Nu	Sh	τ
1	0.6939	0.4986	12.9488
2	0.5488	0.4661	7.7797
2.5	0.4390	0.3729	6.7712
3	0.3658	0.3108	6.0989

Table 5: Variations in skin friction, Nusselt number and Sherwood number with T_1 and t.

T_1 (= t1) at t = 0.5	Nu	Sh	τ
1	0.8073	0.4337	0.1530
1.5	0.5382	0.2891	0.1325
2	0.4037	0.2169	0.2753
2.5	0.3229	0.1735	0.3610

Table 6: Variations in skin friction, Nusselt number and Sherwood number with T_1 and t.

Kr at t = 1.5	Nu	Sh	τ
1	0.6939	0.4986	12.948
2	0.6939	0.6723	12.7890
3	0.6939	0.9394	12.4151
4	0.6939	1.1492	11.9682

Table 7: Variations in skin friction, Nusselt number and Sherwood number with Kr and t.

Kr at t = 0.5	Nu	Sh	τ
1	0.8073	0.4337	0.1530
2	0.8073	0.4881	0.2045
3	0.8073	0.5849	0.3570
4	0.8073	0.6699	0.5873

Table 8: Variations in skin friction, Nusselt number and Sherwood number with Kr and t.

Conclusion

The non-dimensional governing equations of the problems 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 and 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, Magnetic field (t = 1.5), heat absorption parameter (Qor) (t = 0.5) and Hall effect (m1), but a reverse trend is found in the case of Magnetic field (t = 0.5), reaction parameter, Schmidt number, heat absorption parameter (Qor) (at t = 1.5), radiation parameter Nr and various values of critical time for rampedness (t1).
- The velocity increases with decreasing values of (negative values) heat absorption parameter (Qor) (at t = 0.5). The velocity decreases with increasing values of heat absorption parameter (Qor) (at t = 1.5).
- The fluid temperature decreases with the increasing values of radiation parameter Nr, heat absorption parameter (Qor) and various values of critical time for rampedness (t1).

Sc at t = 1.5	Nu	Sh	τ
0.22	0.6939	0.4986	12.9488
0.42	0.6939	0.6889	12.7812
0.62	0.6939	0.8370	12.6031
0.82	0.6939	0.9626	12.4050

Table 9: Variations in skin friction, Nusselt number and Sherwood number with Sc and t.

Sc at t = 0.5	Nu	Sh	τ
0.22	0.8073	0.4337	0.1530
0.42	0.8073	0.5992	0.5992
0.62	0.8073	0.7281	0.7281
0.82	0.8073	0.8373	0.8373

Table 10: Variations in skin friction, Nusselt number and Sherwood number with Sc and t.

Gr at t = 1.5	Nu	Sh	τ
0.01	0.6939	0.4986	12.9488
0.02	0.6939	0.4986	25.1820
0.03	0.6939	0.4986	37.4152
0.04	0.6939	0.4986	49.6484

Table 11: Variations in skin friction, Nusselt number and Sherwood number with Gr and t.

Gr at t = 0.5	Nu	Sh	τ
0.01	0.8073	0.4337	0.1530
0.02	0.8073	0.4337	0.1382
0.03	0.8073	0.4337	0.1235
0.04	0.8073	0.4337	0.1088

Table 12: Variations in skin friction, Nusselt number and Sherwood number with Gr and t.

Gm at t = 1.5	Nu	Sh	τ
2	0.6939	0.4986	12.9488
3	0.6939	0.4986	12.2898
4	0.6939	0.4986	11.6308
5	0.6939	0.4986	10.9718

Table 13: Variations in skin friction, Nusselt number and Sherwood number with Gm and t.

Gm at t = 0.5	Nu	Sh	τ
2	0.8073	0.4337	0.1530
3	0.8073	0.4337	0.5886
4	0.8073	0.4337	1.0242
5	0.8073	0.4337	1.4598

Table 14: Variations in skin friction, Nusselt number and Sherwood number with Gm and t.

M_1 (= m1) at t = 1.5	Nu	Sh	τ
0.11	0.6939	0.4986	12.9488
0.12	0.6939	0.4986	10.9715
0.13	0.6939	0.4986	8.9805
0.14	0.6939	0.4986	7.0080

Table 15: Variations in skin friction, Nusselt number and Sherwood number with M_1 and t.

M1 (= m1) at t = 0.5	Nu	Sh	τ
0.11	0.8073	0.4337	0.1540
0.12	0.8073	0.4337	0.1550
0.13	0.8073	0.4337	0.1562
0.14	0.8073	0.4337	0.1575

Table 16: Variations in skin friction, Nusselt number and Sherwood number with M_1 and t.

M at t = 1.5	Nu	Sh	τ
1.1	0.6939	0.4986	2.3497
1.2	0.6939	0.4986	1.6780
1.3	0.6939	0.4986	1.1263
1.4	0.6939	0.4986	0.6335

Table 17: Variations in skin friction, Nusselt number and Sherwood number with M and t.

M at t = 0.5	Nu	Sh	τ
1.1	0.8073	0.4337	1.9972
1.2	0.8073	0.4337	1.6224
1.3	0.8073	0.4337	1.6224
1.4	0.8073	0.4337	1.3165

Table 18: Variations in skin friction, Nusselt number and Sherwood number with M and t.

- The fluid concentration decreases with the increasing values of chemical reaction Kr, Schmidt number various values of critical time for rampedness (t1).
- Skin friction decreases for increasing values of critical time for rampedness (t1) (at t = 1.5) but reverse (at t = 0.5).
- Skin friction decreases for increasing values of Hall Effect (t = 1.5) but reverse (t = 0.5).

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