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Research Paper

Effects of Thermal Diffusion and Radiation on Magnetohydrodynamic (MHD) Chemically Reacting Fluid Flow Past a Vertical Plate in a Slip Flow Regime

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Abstract. An analysis has been conceded to study the effects of Soret and thermal radiation effects on the magnetohydrodynamic convective flow of a viscous, incompressible, electrically conducting fluid with heat and mass transfer over a plate with time-dependent suction velocity in a slip flow regime in the presence of first-order chemical reaction. The slip conditions at the boundaries for the governing flow are taken for the velocity and temperature distributions and a uniform magnetic field of strength is applied normal to the flow direction. The free stream velocity is assumed to be subject to follow an exponentially small perturbation law. Analytical solutions are obtained for velocity, temperature and concentration fields for the governing partial differential equations depending on slip flow boundary circumstances by using the traditional perturbation method.

Keywords: Thermal diffusion, Porous medium, Heat and mass transfer, Chemical reaction, Slip flow regime.

1. Introduction

In nature, so many flows exist which are caused not only by the temperature differences but also by concentration differences. These mass transfer differences do affect the rate of heat transfer. The phenomenon of heat and mass transfer often occurs in chemically processing industries such as polymer production, food processing etc. The chemical reaction effects depend whether the reaction is homogeneous or heterogeneous. In the majority of cases, a chemical reaction depends on the concentration of the species itself. The MHD viscous flow containing heat and mass transfer has attracted many researchers for its applications in various areas like power and cooling systems, cooling of nuclear reactors, Magnetohydrodynamic power generation systems. Seddeek [1] studied thermal radiation and buoyancy effects on MHD free convective heat generating flow over an accelerating permeable surface with temperature dependent viscosity. The hydromagnetic mixed convective flow of a viscous incompressible electrically conducting fluid and mass transfer over a vertical porous plate with constant heat flux embedded in a porous medium was investigated by Makinde [2]. Mbeledogu [3] analyzed MHD free convection flow of a Boussinesq fluid past a moving vertical plate under the simultaneous action of buoyancy and transverse magnetic field. Chamkha [4] analyzed MHD heat and mass transfer flow past a semi-infinite vertical permeable plate with heat absorption. Chambre and Young [5] studied the effects of diffusion on chemically reactive species in a laminar boundary layer flow. Das et al. [6] investigated the effects of mass transfer on flow past an impulsively started infinite vertical plate in the presence of first-order chemical reaction. Muthucumaraswamy and Ganesan [7] performed a theoretical investigation on flow past an impulsively started infinite vertical

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plate with uniform heat flux and variable mass diffusion taking into account a first order chemical reaction. Ibrahim and Makinde [8] presented for two-dimensional MHD boundary layer flow of a continuously moving vertical porous plate in a chemically reacting medium. The influence of first-order chemical reaction on unsteady MHD mixed convection flow over a moving vertical plate was studied by Prakash et al. [9]. A study of vorticity of fluctuating flow past an inclined plate with variable suction with slip flow regime by Mittal and Bijalwan [10]. Rajput et al. [11] carried out a study on free convection flow with mass transfer of a magnetic polar fluid through a porous medium in a slip flow regime. Pal and Talukdar [12] presented the effects of Joule heating and thermal radiation on unsteady MHD radiative mixed convection over a vertical plate through porous medium in the presence of viscous dissipation. Anjalidevi and Samuel Raj [13] studied the effects of thermal diffusion and MHD free convection flow with heat and mass transfer past a moving vertical porous plate with time-dependent suction in the presence of heat source in a slip flow regime. Raju et al. [14] performed a theoretical investigation on thermal diffusion effects on free convection between heated inclined plates through a porous medium.

In this problem, an investigation is done on the chemical reaction and thermal diffusion effects on unsteady magnetohydrodynamic free convection flow with heat and mass transfer past a moving vertical plate in the presence of heat source and radiation with time-dependent suction in a slip flow regime. The governing coupled partial differential equations were solved subject to the slip flow conditions analytically by regular perturbation technique. The stream of the flow is considered to consist of a mean velocity over where the velocity is varying exponentially with time.

2. Formulation of the Problem

An unsteady MHD viscous, incompressible and electrically conducting fluid with heat and mass transfer past a moving vertical infinite plate with time-dependent suction in a slip flow regime is considered taking into account thermal diffusion effects in the presence of first-order chemical reaction (see Fig. 1).

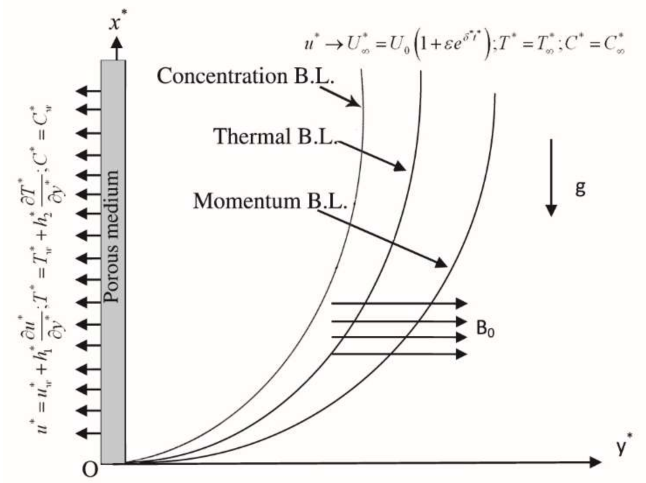

Fig. 1. Physical Configuration of the Problem

The symbol x^* is taken along the plate in the vertical upward direction against the gravitational field and y^* is considered normal to it. A transverse uniform magnetic field of strength B_0 is applied in the direction normal to the flow. The magnetic Reynolds number is assumed to be small enough so that the induced magnetic field can be neglected. It is assumed that there is a slip in velocity and jump in temperature near the surface of the fluid. It is also assumed that viscous and Joule dissipations are neglected in the energy equation and since the plate is long in length infinitely all the physical coordinates are functions of y^* and t^* only. Then under the usual Boussinesq approximation, the governing boundary layer equations of the flow transport are given by:

$$\frac{\partial v^*}{\partial y^*} = 0 \tag{1}$$

$$\frac{\partial u^*}{\partial t^*} + v^*\frac{\partial u^*}{\partial y^*} = \frac{dU_\infty^*}{dt^*} - \frac{\sigma B_0^2}{\rho}\left(u^* - U_\infty^*\right) + \nu\frac{\partial^2 u^*}{\partial y^{*2}} + g\,\beta_T\left(T^* - T_\infty^*\right) + g\,\beta_c\left(C^* - C_\infty^*\right) \tag{2}$$

$$\rho C_p\left(\frac{\partial T^*}{\partial t^*} + v^*\frac{\partial T^*}{\partial y^*}\right) = \kappa\frac{\partial^2 T^*}{\partial y^{*2}} + S^*\left(T^* - T_\infty^*\right) - \frac{\partial q_r^*}{\partial y^*} \tag{3}$$

$$\frac{\partial C^*}{\partial t^*} + v^*\frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} + D_1\frac{\partial^2 T^*}{\partial y^{*2}} - K\left(C^* - C_\infty\right) \tag{4}$$

where u^* and v^* are components of velocities along and perpendicular to the plate, x^* and y^* are distances along and perpendicular to the plate respectively, ρ is the density of the fluid, g is the acceleration due to gravity , σ is the electrical conductivity, B_0 is the Magnetic flux density, β_T is the coefficient of volume expansion of the working fluid, β_c is the coefficient of volumetric expansion with concentration , U_∞^* is the velocity of the fluid in the free stream, ν is kinematic viscocity , κ is thermal conductivity , S^* is coefficient of heat source , C^* is the concentration of the fluid, C_∞^* is concentration at infinity, D is chemical molecular diffusivity, D_1 is thermal diffusivity, K is the coefficient of chemical reaction, C_p is specific heat at constant pressure. The radiative heat flux is given by:

$$\frac{\partial q_r^*}{\partial y^*} = 4\left(T^* - T_\infty\right) I' \tag{5}$$

where $I' = \int_0^\infty K_{\lambda w} \frac{\partial e_{b\lambda}}{\partial T^*} d\lambda, K_{\lambda w}$ is the absorption coefficient at the wall and $e_{b\lambda}$ is Planck's constant. The slip flow boundary conditions are given by:

$$u^* = u_w^* + h_1^* \frac{\partial u^*}{\partial y^*} \quad , \quad T^* = T_w^* + h_2^* \frac{\partial T^*}{\partial y^*} \quad , \quad C^* = C_w^* \qquad \text{at} \quad y^* = 0 \tag{6}$$

$$u^* \to U_\infty^* = U_0\left(1 + \varepsilon e^{\delta^* t^*}\right), \; T^* = T_\infty^*, \; C^* = C_\infty^* \qquad \text{as} \quad y^* \to \infty \tag{7}$$

where u_w^* is the velocity at the wall, T_w^* is the temperature at the wall, C_w^* is the concentration at the wall, ε and δ^* are scalar constants which are less than unity ($\varepsilon < 1$) and U_0 is the scale of stream velocity. The plate is subjected to variable suction and from the equation (1), it can be written as:

$$v^* = -V_0\left(1 + \varepsilon\alpha e^{\delta^* t^*}\right) \tag{8-a}$$

$$h_1^* = \left(\frac{2 - f_1}{f_1}\right)\xi_1 \;,\; \xi_1 = \left(\frac{\pi}{2p\rho}\right)^{\frac{1}{2}} \qquad h_2^* = \left(\frac{2-a}{a}\right)\xi_2 \;,\xi_2 = \left(\frac{2\gamma}{\gamma+1}\right)\frac{\xi_1}{\Pr} \tag{8-b}$$

where α is a real positive constant and $\varepsilon\alpha$is less than unity, V_0 is the scale of the suction velocity which has a non-zero positive constant, ξ_1 is the mean free path and constant, f_1 is Maxwell's reflection coefficient, γ is the ratio of specific heats, and 'a' is the thermal accommodation coefficient. Introducing the following non dimensional scheme as:

$$\begin{gathered} u = \frac{u^*}{U_0}, v = \frac{v^*}{V_0}, t = \frac{t^* V_0^2}{\nu}, y = \frac{V_0 y^*}{\nu}, \delta = \frac{\delta^* \nu}{V_0^2}, u_w = \frac{u_w^*}{U_0} \\ U = \frac{U_\infty^*}{U_0}, \theta = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*}, C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*}, K = \frac{K^* \nu}{V_0^2} \end{gathered} \tag{9}$$

The governing equations of the problem in non-dimensional form are given by:

$$\frac{\partial u}{\partial t} - \left(1 + \varepsilon\alpha e^{\delta t}\right)\frac{\partial u}{\partial y} = \frac{dU}{dt} + \frac{\partial^2 u}{\partial y^2} + Gr\theta + GcC - M\left(u - U\right) \tag{10}$$

$$\frac{\partial \theta}{\partial t} - \left(1 + \varepsilon\alpha e^{\delta t}\right)\frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} + \frac{S}{\Pr}\theta - F\theta \tag{11}$$

$$\frac{\partial C}{\partial t} - \left(1 + \varepsilon\alpha e^{\delta t}\right)\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} + A\frac{\partial^2 \theta}{\partial y^2} - KrC \tag{12}$$

The corresponding boundary conditions in non-dimensional form are:

$$u = u_w + h_1\frac{\partial u}{\partial y} \;,\; \theta = 1 + h_2\frac{\partial \theta}{\partial y}, C = 1 \qquad \text{at} \quad y = 0 \tag{13}$$

$$u = U(t), \theta \to 0, \quad C \to 0 \qquad \text{as} \quad y \to \infty \tag{14}$$

where $U(t) = 1 + \varepsilon e^{\delta t}$ and

$u_w = \frac{u_w^*}{U_0}$, Velocity ratio parameter; $h_1 = \frac{h_1^* V_0}{\nu}$, Slip parameter due to velocity

$h_2 = \frac{h_2^* V_0}{\nu}$, Slip parameter due to jump in temperature

3. Solution of the Problem

A set of partial differential equations (10)–(12) cannot be solved in closed form. However, it can be solved analytically after reducing to a system of ordinary differential equations (19)-(21) and (24)-(26) in dimensionless forms which are done by representing the velocity, temperature and concentration are assumed in the following forms which are given below:

$$u(y) = u_0(y) + \varepsilon e^{\delta t} u_1(y) + o(\varepsilon^2) \tag{15}$$

$$\theta(y) = \theta_0(y) + \varepsilon e^{\delta t} \theta_1(y) + o(\varepsilon^2) \tag{16}$$

$$C(y) = C_0(y) + \varepsilon e^{\delta t} C_1(y) + o(\varepsilon^2) \tag{17}$$

$$U(t) = 1 + \varepsilon e^{\delta t} \tag{18}$$

By substituting these in the equations (10) to (12), the following zeroth order and first order equations are obtained. The corresponding boundary conditions are also calculated by substituting in equation (13) and (14).

Zeroth order equations

The zeroth order equations are obtained as

$$u_0'' + u_0' - M u_0 = -Gr\theta_0 - GcC_0 - M \tag{19}$$

$$\theta_0'' + \Pr\theta_0' + (S - \Pr F)\theta_0 = 0 \tag{20}$$

$$C_0'' + ScC_0' - KrScC_0 = -AS c\theta_0'' \tag{21}$$

with the corresponding boundary conditions

$$u_0 = u_w + h_1 \frac{\partial u_0}{\partial y},\ \theta_0 = 1 + h_2 \frac{\partial \theta_0}{\partial y},\ C_0 = 1 \quad at \quad y = 0 \tag{22}$$

$$u_0 \to 1,\ \theta_0 \to 0,\ C_0 \to 0 \quad as \quad y \to \infty \tag{23}$$

First order equations:

$$u_1'' + u_1' - (M + \delta)u_1 = -Gr\theta_1 - GcC_1 - \alpha u_0' - (M + \delta) \tag{24}$$

$$\theta_1'' + \Pr\theta_1' + (S - \Pr F - \Pr\delta)\theta_1 = -\alpha \Pr\theta_0' \tag{25}$$

$$C_1'' + ScC_1' - (KrSc + Sc\delta)C_1 = -\alpha ScC_0' - ASc\theta_1'' \tag{26}$$

with the corresponding boundary conditions

$$u_1 = h_1 \frac{\partial u_1}{\partial y},\ \theta_1 = h_2 \frac{\partial \theta_1}{\partial y}, C_1 = 0 \quad \text{at} \quad y = 0 \tag{27}$$

$$u_1 \to 1,\ \theta_1 \to 0,\ C_1 \to 0 \quad \text{as} \quad y \to \infty \tag{28}$$

Here the prime denotes differentiation with respect to y.

Zeroth order solutions

On solving equations (19) to (21) subject to the boundary conditions in (22) and (23) the zeroth order solutions are given by:

$$u_0(y) = 1 + B_3 e^{-m_8 y} + (W_6 - W_3)e^{-m_2 y} - (W_4 + W_5)e^{-m_6 y} \tag{29}$$

$$\theta_0(y) = B_1 e^{-m_2 y} \tag{30}$$

$$C_0(y) = e^{-m_6 y} + W_2\left(e^{-m_6 y} - e^{-m_2 y}\right) \tag{31}$$

First order solutions

On solving equations (24) to (26) subject to the boundary conditions (27) and (28) the first order solutions are given by:

$$u_1(y) = 1 + B_5 e^{-m_{12} y} + (w_{16} + w_{19} - w_{12})e^{-m_2 y} + (w_{13} - w_{17})e^{-m_4 y} - (w_{15} + w_{20})e^{-m_6 y} + w_{18} e^{-m_8 y} - w_{14} e^{-m_{10} y} \tag{32}$$

$$\theta_1(y) = W_1 e^{-m_2 y} - B_2 e^{-m_4 y} \tag{33}$$

$$C_1(y) = B_4 e^{-m_{10} y} + (W_7 + W_8)e^{-m_6 y} - (W_9 + W_{10})e^{-m_2 y} + W_{11} e^{-m_4 y} \tag{34}$$

where all the constants involved in the equations (29) to (34) are given in the appendix.

Solutions up to first Order

On Substituting the values of $u_0(y)$ and $u_1(y)$ in (15), we have

$$u(y) = \left[1 + B_3 e^{-m_8 y} + (W_6 - W_3)e^{-m_2 y} - (W_4 + W_5)e^{-m_6 y}\right] + \varepsilon e^{\delta t}\begin{bmatrix} 1 + B_5 e^{-m_{12} y} + (W_{16} + W_{19} - W_{12})e^{-m_2 y} + (W_{13} - W_{17})e^{-m_4 y} \\ -(W_{15} + W_{20})e^{-m_6 y} + W_{18} e^{-m_8 y} - W_{14} e^{-m_{10} y} \end{bmatrix} \tag{35}$$

On substituting the values $\theta_0(y)$ and $\theta_1(y)$ in (16), we have

$$\theta(y) = B_1 e^{-m_2 y} + \varepsilon e^{\delta t}\left[W_1 e^{-m_2 y} - B_2 e^{-m_4 y}\right] \tag{36}$$

On substituting the values of $C_0(y)$ and $C_1(y)$ in (17), we have

$$\begin{aligned} C(y) &= [e^{-m_6 y} + W_2\left(e^{-m_6 y} - e^{-m_2 y}\right) \\ &+ \varepsilon e^{\delta t}\begin{bmatrix} B_4 e^{-m_{10} y} + (W_7 + W_8)e^{-m_6 y} \\ -(W_9 + W_{10})e^{-m_2 y} + W_{11} e^{-m_4 y} \end{bmatrix} \end{aligned} \tag{37}$$

Skin friction:

The skin friction coefficient at the plate is given by $C_{fx} = \tau / \rho U_0 V_0 = \partial u / \partial y|_{y=0}$, then one can obtain:

$$\begin{aligned} C_{fx} &= \left[-m_8 B_3 - m_2 (W_6 - W_3) + m_6 (W_4 + W_5)\right] + \\ \varepsilon e^{\delta t} &\begin{bmatrix} -m_{12} B_5 - m_2 (W_{16} + W_{19} - W_{12}) - m_4 (W_{13} - W_{17}) \\ + m_6 (W_{15} + W_{20}) - m_8 W_{18} + m_{10} W_{14} \end{bmatrix} \end{aligned} \tag{38}$$

Nusselt Number:

The rate of heat transfer in terms of the Nusselt number Nu_x is given in a non-dimensional form by

$$Nu_x = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0}, \quad Nu_x = m_2 B_1 - \varepsilon e^{\delta t}\left(-m_2 w_1 + m_4 B_2\right) \tag{39}$$

Sherwood Number:

The rate of mass transfer in non-dimensional form is given by:

$$Sh_x = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = \left[m_6 + m_6 w_2 - m_2 w_2\right] + \varepsilon e^{\delta t}\left[m_{10} B_4 + m_6 (w_7 + w_8) - m_2 (w_9 + w_{10}) + m_4 w_{11}\right] \tag{40}$$

4. Results and Discussion

To get more physical insight into the problem, the numerical computations have been carried out to discuss various physical parameters like Magnetic parameter M, chemical reaction parameter K, Radiation parameter F, Grashof number Gr, Mass Grashof number Gc, Thermal diffusion parameter A, Velocity ratio parameter u_w and the slip parameters h_1 (velocity slip) and h_2 (Jump in temperature) on velocity, temperature and concentration fields. Fig. 2 demonstrates the effects of velocity ratio parameter on the flow transport. It is observed that an increase in velocity ratio parameter increases the velocity and it influences more rapidly near the plate and it remains the same moving far away from the plate. The effect of the radiation parameter on the velocity field is presented through Fig. 3. It is observed that the velocity decreases with increasing values of the radiation parameter. Fig. 4 reveals that the dimensionless velocity profiles for different values of the magnetic parameter. It is seen that with increasing values of magnetic field parameter the velocity of the flow field gets reduced. Physically this is true because the transversely applied magnetic field acts as a drag force those results in a decrease in velocity which is known as Lorentz force. Fig. 5 encloses the effect of slip parameter due to velocity. The slip parameter due to velocity enhances the velocity near the plate and is uniform away from the plate.

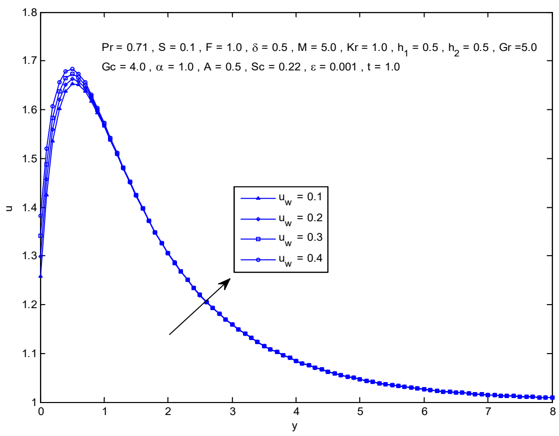

Fig. 2. Velocity profiles for different values of velocity ratio parameter 'u_w'

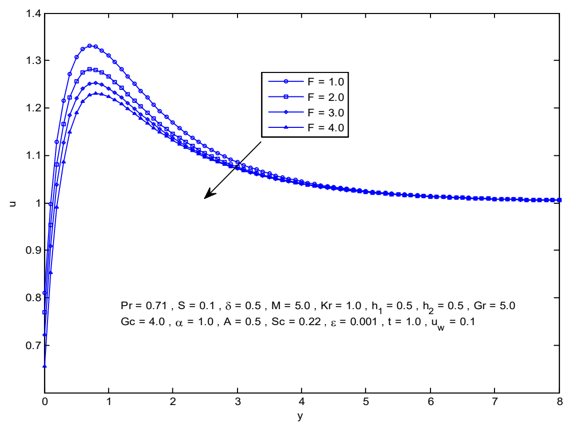

Fig. 3. Velocity profiles for different values of radiation parameter 'F'

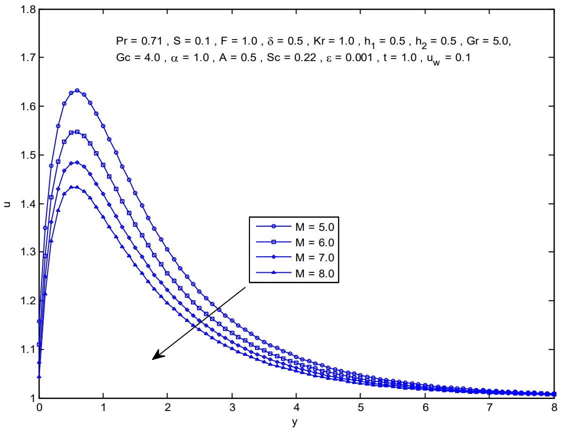

Fig. 4. Velocity profiles for different values of magnetic parameter 'M'

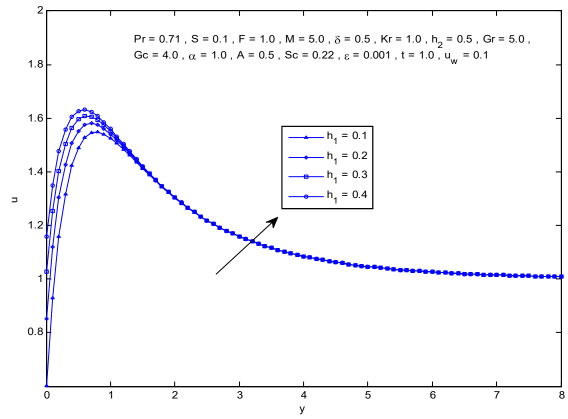

Fig. 5. Velocity profiles for different values of slip parameter due velocity 'h_1'

Fig. 6 discloses the influence of slip parameter due to the jump in temperature over the dimensionless velocity. It is noticed that the slip parameter due to jump in temperature decelerates the velocity distribution. The temperature profiles for different values of Prandtl number, heat source parameter, radiation parameter and the slip parameter due to jump in temperature are illustrated through Fig. 7 to Fig. 9 respectively. From Fig. 7 and Fig. 8, it is observed that as Prandtl number increases the temperature distribution decreases. And it is very interesting to note that the thickness of the thermal boundary layer is reduced due to an increment in Prandtl number while it enhances with increasing values of the heat source parameter.

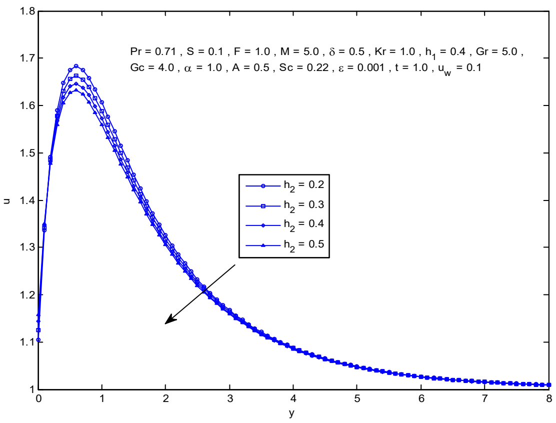

Fig. 6. Velocity profiles for different values of slip parameter due to jump in temperature 'h_2'

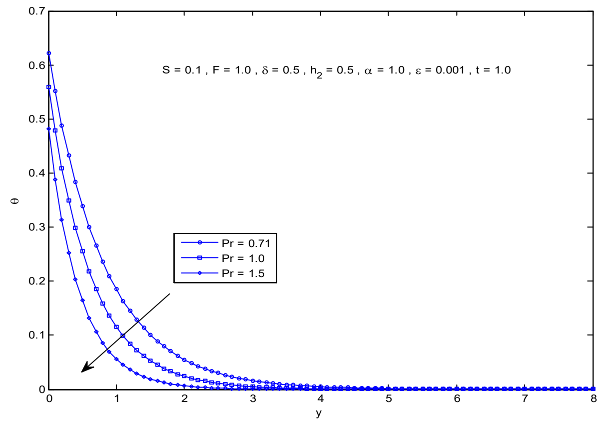

Fig. 7. Temperature profiles for different values of Prandtl number 'Pr'

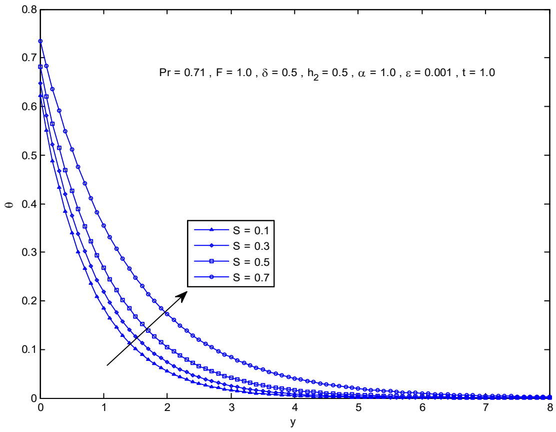

Fig. 8. Temperature profiles for different values of heat source parameter 'S'

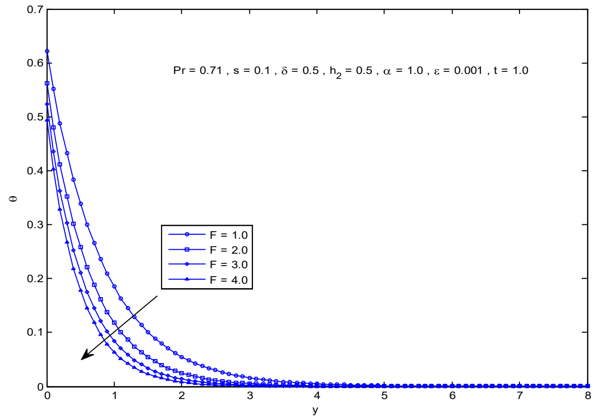

Fig. 9. Temperature profiles for different values of radiation parameter 'F'

From Fig. 9 and Fig. 10 it is found that the temperature distribution reduces either an increase in radiation parameter or an increase in slip parameter due to jump in temperature. The concentration distribution is prominently affected by thermal diffusion parameter, chemical reaction parameter and Schmidt number which are visualized through Fig. 11 to Fig. 13. From these figures, it is noted that concentration increases with increasing values of thermal diffusion parameter while it decreases with increasing values of Schmidt number and chemical reaction parameter. Finally, from the Table 1, it is seen that with an increase in Prandtl number or magnetic parameter or slip parameters skin-friction decreases whereas Nusselt number decreases in magnitude with increasing values of slip parameters and Sherwood number increases with an increase in slip velocity or jump in temperature.

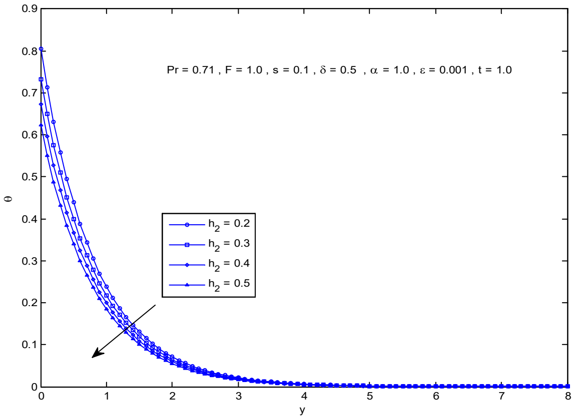

Fig. 10. Temperature profiles for different values of slip parameter due to jump in temperature ‘h2’

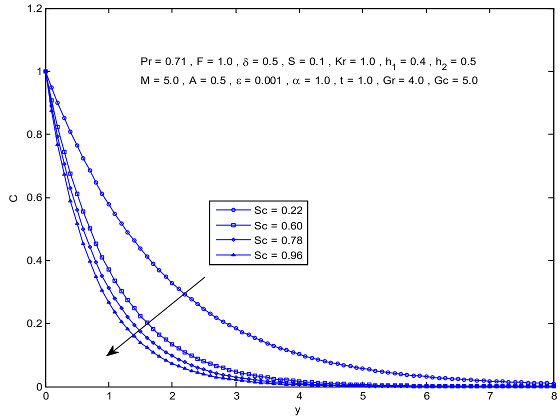

Fig. 11. Concentration profiles for different values of Schmidt number ‘Sc’

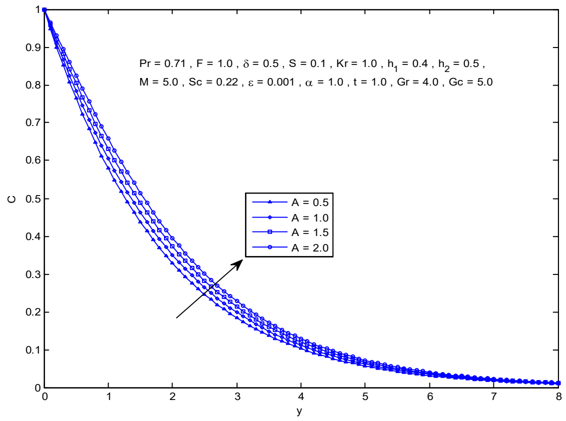

Fig. 12. Concentration profiles for different values of Soret number ‘A’

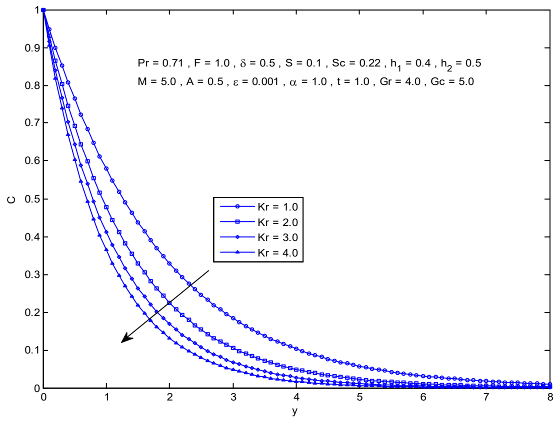

Fig. 13. Concentration profiles for different values of chemical reaction parameter ‘Kr’

Table 1. Skin-friction, Nusselt number and Sherwood number for various physical parameters

Pr	F	M	Kr	h_1	h_2	Gr	Gc	Sc	A	Cf_x	Nu_x	Sh_x
0.71	1.0	5.0	1.0	0.4	0.5	4.0	5.0	0.22	0.5	1.8932	-0.7548	0.5284
1.0	1.0	5.0	1.0	0.4	0.5	4.0	5.0	0.22	0.5	1.8523	-0.8800	0.5136
1.5	1.0	5.0	1.0	0.4	0.5	4.0	5.0	0.22	0.5	0.6543	-1.5946	0.4244
0.71	2.0	5.0	1.0	0.4	0.5	4.0	5.0	0.22	0.5	1.8519	-0.8754	0.5142
0.71	3.0	5.0	1.0	0.4	0.5	4.0	5.0	0.22	0.5	1.8961	-0.9536	0.5048
0.71	4.0	5.0	1.0	0.4	0.5	4.0	5.0	0.22	0.5	2.0193	-1.0117	0.4977
0.71	1.0	6.0	1.0	0.4	0.5	4.0	5.0	0.22	0.5	1.8561	-0.7548	0.5284
0.71	1.0	7.0	1.0	0.4	0.5	4.0	5.0	0.22	0.5	1.8316	-0.7548	0.5284
0.71	1.0	8.0	1.0	0.4	0.5	4.0	5.0	0.22	0.5	1.8148	-0.7548	0.5284
0.71	1.0	5.0	2.0	0.4	0.5	4.0	5.0	0.22	0.5	1.7503	-0.7548	0.7258
0.71	1.0	5.0	3.0	0.4	0.5	4.0	5.0	0.22	0.5	1.6277	-0.7548	0.8776
0.71	1.0	5.0	4.0	0.4	0.5	4.0	5.0	0.22	0.5	1.5119	-0.7548	1.0055
0.71	1.0	5.0	1.0	0.5	0.5	4.0	5.0	0.22	0.5	1.6430	-0.7548	0.5284
0.71	1.0	5.0	1.0	0.6	0.5	4.0	5.0	0.22	0.5	1.4450	-0.7548	0.5284
0.71	1.0	5.0	1.0	0.7	0.5	4.0	5.0	0.22	0.5	1.2844	-0.7548	0.5284
0.71	1.0	5.0	1.0	0.4	0.6	4.0	5.0	0.22	0.5	1.8042	-0.7018	0.5328
0.71	1.0	5.0	1.0	0.4	0.7	4.0	5.0	0.22	0.5	1.7268	-0.6558	0.5367
0.71	1.0	5.0	1.0	0.4	0.8	4.0	5.0	0.22	0.5	1.6589	-0.6154	0.5401
0.71	1.0	5.0	1.0	0.4	0.5	5.0	5.0	0.22	0.5	2.2051	-0.7548	0.5284
0.71	1.0	5.0	1.0	0.4	0.5	6.0	5.0	0.22	0.5	2.5170	-0.7548	0.5284
0.71	1.0	5.0	1.0	0.4	0.5	7.0	5.0	0.22	0.5	2.8289	-0.7548	0.5284
0.71	1.0	5.0	1.0	0.4	0.5	4.0	6.0	0.22	0.5	1.7845	-0.7548	0.5284
0.71	1.0	5.0	1.0	0.4	0.5	4.0	7.0	0.22	0.5	1.6758	-0.7548	0.5284
0.71	1.0	5.0	1.0	0.4	0.5	4.0	8.0	0.22	0.5	1.5670	-0.7548	0.5284
0.71	1.0	5.0	1.0	0.4	0.5	4.0	5.0	0.60	0.5	1.4650	-0.7548	0.9735

Table 1. Continued

Pr	F	M	Kr	h_1	h_2	Gr	Gc	Sc	A	Cf_x	Nu_x	Sh_x
0.71	1.0	5.0	1.0	0.4	0.5	4.0	5.0	0.78	0.5	1.1965	-0.7548	1.1564
0.71	1.0	5.0	1.0	0.4	0.5	4.0	5.0	0.96	0.5	0.8487	-0.7548	1.3309
0.71	1.0	5.0	1.0	0.4	0.5	4.0	5.0	0.22	0.6	1.9143	-0.7548	0.4648
0.71	1.0	5.0	1.0	0.4	0.5	4.0	5.0	0.22	0.7	1.9354	-0.7548	0.4012
0.71	1.0	5.0	1.0	0.4	0.5	4.0	5.0	0.22	0.8	1.9565	-0.7548	0.3375

5. Conclusion

The unsteady MHD heat and mass transfer chemically reacting fluid flow past a moving vertical plate in a slip flow regime with time-dependent suction taking into account thermal diffusion effects with the heat source is investigated. The solutions are obtained for velocity, temperature, concentration, the rate of heat transfer, the rate of mass transfer and the skin-friction coefficient. From the solutions cited in the previous section and then from results and discussion, the following conclusions are made.

1. An increase in velocity ratio parameter of the fluid flow increases while it decreases with increasing values of the magnetic field parameter.
2. The velocity accelerates with an increase in the thermal diffusion parameter as well as with thermal Grashof number.
3. The thickness of the thermal boundary layer is reduced due to an increment in Prandtl number while it enhances with increasing values of the heat source parameter.
4. The temperature distribution reduces either an increase in radiation parameter or an increase in slip parameter due to jump in temperature.
5. Concentration increases with increasing values of thermal diffusion parameter while it decreases with increasing values of Schmidt number.

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Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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Nomenclature

a	Thermal accommodation coefficient	Kr	Chemical reaction parameter
A	Soret effect	$K_{\lambda w}$	Absorption coefficient
B_0	Magnetic flux density	N_x	Local Nusselt Number
C	Species concentration	Pr	Prandtl number
C_{fx}	Local skin friction coefficient	Q_0	Volumetric rate of heat generation or absorption
C_p	Specific heat at constant pressure	q_w	Heat flux per unit area at the plate
C_w	Wall dimensional concentration	S	Heat source parameter
C_∞	Ambient temperature	Sc	Schmidt number
C^*	Dimensional concentration	Sh_x	Sherwood number
D	Chemical Molecular diffusivity	t	Dimensionless time
D_1	Thermal diffusivity	T	Temperature in the boundary layer
$e_{b\lambda}$	Planck's constant	T_w	Wall dimensional temperature
f_1	Maxwell's reflection co-efficient	T_∞	Ambient temperature
F	Radiation parameter	U_0	Scale of stream velocity
g	Gravitational acceleration	U_w^*	Velocity of the wall
Gr	Grashof number	U_∞^*	Velocity of the fluid in free stream
Gc	Modified Grashof number	u_w	Velocity ratio parameter
h_1	Slip parameter due to velocity	u, v	Components of the velocities

h_2	Slip parameter due to jump in temperature	x, y	Co-ordinate system

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Appendix

$$m_2 = \frac{\Pr + \sqrt{\Pr^2 - 4(S - \Pr F)}}{2} \qquad m_4 = \frac{\Pr + \sqrt{\Pr^2 - 4(S - \Pr F - \Pr\delta)}}{2} \qquad m_6 = \frac{Sc + \sqrt{Sc^2 + 4KrSc}}{2}$$

$$m_8 = \frac{1 + \sqrt{1 + 4M}}{2} \qquad m_{10} = \frac{Sc + \sqrt{Sc^2 + 4(KrSc + \delta Sc)}}{2} \qquad m_{12} = \frac{1 + \sqrt{1 + 4(M + \delta)}}{2}$$

$$B_1 = \frac{1}{1 + h_2 m_2} \qquad B_2 = \frac{w_1(1 + h_2 m_2)}{1 + h_2 m_4} \qquad B_3 = \frac{u_w - 1 + (1 + h_1 m_2)w_3 + (1 + h_1 m_6)(w_3 + w_5) - (h_1 m_2 - 1)w_6}{1 + h_1 m_8}$$

$$B_4 = -w_7 - w_8 + w_9 + w_{10} - w_{11} \qquad B_5 = \frac{\left[-1 + (w_{12} - w_{16} - w_{19})(1 + h_1 m_2) + (w_{17} - w_{13})(1 + h_1 m_4) + (w_{15} + w_{20})(1 + h_1 m_6) - (1 + h_1 m_8)w_{18} + (1 + h_1 m_{10})w_{14}\right]}{1 + h_1 m_{12}}$$

$$w_1 = \frac{\alpha \Pr m_2 B_1}{m_2^2 - \Pr m_2 + (S - \Pr F - \Pr\delta)} \qquad w_2 = \frac{A\, Scm_2^2 B_1}{m_2^2 - Scm_2 - KrSc} \qquad w_3 = \frac{GrB_1}{m_2^2 - m_2 - M}$$

$$w_4 = \frac{Gc}{m_6^2 - m_6 - M} \qquad w_5 = \frac{Gcw_2}{m_6^2 - m_6 - M} \qquad w_6 = \frac{Gcw_2}{m_2^2 - m_2 - M}$$

$$w_7 = \frac{\alpha Scm_6}{m_6^2 - Scm_6 - (KrSc + \delta Sc)} \qquad w_8 = \frac{\alpha Scm_6 w_2}{m_6^2 - Scm_6 - (KrSc + \delta Sc)} \qquad w_9 = \frac{\alpha Scm_2 w_2}{m_2^2 - Scm_2 - (KrSc + \delta Sc)}$$

$$w_{10} = \frac{AScm_2^2 w_1}{m_2^2 - Scm_2 - (KrSc + \delta Sc)} \quad w_{11} = \frac{AScm_4^2 B_2}{m_4^2 - Scm_4 - (KrSc + \delta Sc)} \quad w_{12} = \frac{Grw_1}{m_2^2 - m_2 - (M + \delta)}$$

$$w_{13} = \frac{GrB_2}{m_4^2 - m_4 - (M + \delta)} \quad w_{14} = \frac{GcB_4}{m_{10}^2 - m_{10} - (M + \delta)} \quad w_{15} = \frac{Gc(w_7 + w_8)}{m_6^2 - m_6 - (M + \delta)}$$

$$w_{16} = \frac{Gc(w_9 + w_{10})}{m_2^2 - m_2 - (M + \delta)} \quad w_{17} = \frac{Gcw_{11}}{m_4^2 - m_4 - (M + \delta)} \quad w_{18} = \frac{\alpha m_8 B_3}{m_8^2 - m_8 - (M + \delta)}$$

$$w_{19} = \frac{\alpha m_2(w_6 - w_3)}{m_2^2 - m_2 - (M + \delta)} \quad w_{20} = \frac{\alpha m_6(w_4 + w_5)}{m_6^2 - m_6 - (M + \delta)}$$