Influence of Radiation Absorption, Chemical Reaction on MHD Mixed Convective Heat and Mass Transfer Flow Past a Stretching Sheet in Slip Flow Regime

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Abstract
The aim of the problem is to analyze the combined influence of Radiation absorption and thermal radiation under the influence of chemical reaction on MHD mixed convective heat and mass transfer flow of a viscous electrically conducting fluid past a stretching sheet in the presence of non-uniform heat source with Hall currents in slip-flow regime. The governing equations of the heat and mass transfer flow have been solved by Galerkin finite element analysis with three nodded line segments. The velocity, temperature and concentration have been analyzed. The rate of heat and mass transfer on the plate has been discussed numerically for different parametric values.
Keywords: Radiation absorption; Thermal Radiation; Non-Uniform Heat Source; Slip Regime; Hall Currents; Heat & Mass Transfer; Soret and Dufour effects; Stretching sheet; Chemical reaction.

1.   Introduction

In flows through porous medium with combined buoyancy effects owing to heat and mass transfer, the coupling of heat and mass transfer takes place owing to the density variatios with temperature and concentration. The direct coupling between temperature and concentration is possible when the cross diffusion (Soret and Dufour) effect is small. When mass flux is produced due to temperature gradients it is known as Soret effect and Dufour effect refers to the heat flux by concentration gradients. Knobloch [1980] and Taslim and Narusawa [1986] explained the relation between Dufour and Soret numbers. Dulal Pal and Monda [2012] studied the combined effect of Soret and Dufour on unsteady MHD non-Darcy mixed convection over a stretching sheet embedded in a saturated porous medium in the presence of thermal radiation, viscous dissipation and chemical reaction. Anwar [2009] made a numerical study of MHD heat and mass transfer from a stretching surface in a porous medium with Soret and Dufour effects. Sallam [2010] investigated the thermo-diffusion and diffusion-thermo effects on mixed convection heat and mass transfer in a porous medium. Kuznetsov and Neild [2011] analysed the double fiffision natural convective boundary layer flow of a nanofluid past a vertical plate. Stanford Sateyi et.,al [2010] investigated the effect of Hall currents with Soret and Dufour effects on the flow past a vertical surface. Sarojamma et al [2015] have studied the influence of Hall currents on cross diffusive convection in a MHD boundary layer flow on stretching sheet in porous medium with heat generation.

In 1961, Sakiadis [1961] who developed a numerical solution for the boundary layer flow field over a continuous solid surface moving with constant speed. Due to entertainment of ambient fluid, this boundary layer flow situation is quite different from the classical Blassius problem over a semi-infinite flat plate. Suction or injection of a stretched surface was studied by Erickson et.al. [1966], and Fox et.al. [1968] for uniform velocity and temperature and investigates its effects on the heat and mass transfer in the boundary layer. Chen and Char [1988] have studied the suction and injection on a linearly moving plate subject to uniform wall temperature and heat flux and the more general case using a power law velocity and temperature distribution at the surface was studied by Ali [1995]. Magyari et.al. [2001] have reported analytical and computational solution when the surface moves with rapidly decreasing velocities using the self-similar method. In all the papers mentioned above the effect of buoyancy force was relaxed. The above investigations having a definite bearing on the problem of a Polymer sheet extruded continuously from a dye. It is usually assumed that the sheet is in extensible, but situations may arise in the polymer industry in which it is necessary to deal with a stretching plastic sheet, as noted by Crane [1970]. The study of heat generation or absorption in moving fluids is important in the problems dealing with chemical reactions and these concerned with dissociating distribution. Consequently, the practice deposition rate in nuclear reactors, electronic chips and semiconductor waves. Vajravelu and Hadjinicolaou [1997] have studied the heat characteristics in the laminar boundary layer of a viscous fluid over a stretching sheet with viscous dissipation or frictional heating and internal heat generation. Mohebujjaman et.al. [2007] have studied the MHD heat transfer mixed convection flow along a vertical stretching sheet in presence of magnetic field with heat generation. Sajid et.al. [2007, 20] have discussed the non-similar analytic solution for MHD flow and heat transfer in a third-order fluid over a stretching sheet. Biliana et.al. [2009] have analyzed the numerical solution of the boundary layer flow over an exponentially stretching sheet with thermal radiation. Jat et.al. [2009] have studied the MHD flow and heat transfer over a

stretching sheet.

The The behavior of laminar boundary layer past a moving continuous and linearly stretching surface is a significant type of flow has considerable practical applications in engineering, electrochemistry (Chin [1975], Gorla [1978]) and polymer processing, (Griffith [1964, 3], Erickson et. al. [1966]). For example, materials manufactured by extrusion process and heat treated materials traveling between a feed roll and a windup roll or on a conveyor belt possesses the characteristics of a moving continuous surface. The hydromagnetic flow and heat transfer problems have become important industrially. To be more specific, it may be pointed out that many metallurgical processes involve the cooling of continuous strips or filaments by drawing them through a quiescent fluid and that in the process of drawing, these strips are sometimes stretched. Mention may be made of drawing, annealing and tinning of copper wires. In all the cases the properties of the final product depend to a great extent on the rate of cooling. By drawing such strips in an electrically conducting fluid subjected to magnetic fluid, the rate of cooling can be controlled and a final product of desired characteristics can be achieved. Another interesting application of hydro magnetics to metallurgy lies in the purification of molten metals from nonmetallic inclusions by the application of a magnetic field. The study of heat and mass transfer is necessary for the determining the quantity of the final product. However, there are fluids, which react chemically with some other ingredients present in them. The effect of a chemical reaction on the flow past an impulsively started infinite vertical plate with uniform heat flux was studied by Das et.al. [1994], Anderson et. al. [1994], have studied the diffusion of a chemical reactive species from a linearly stretching sheet. Anjalidevi and Kandaswamy [1999] have investigated the effect of a chemical reaction on the flow along a semi infinite horizontal plate in the presence of heat transfer. Anjalidevi and Kandaswamy [2000] have studied the effect of a chemical reaction on the flow in the presence of heat transfer and magnetic field. Muthukumaraswamy and Ganesan [2000] have analyzed the effect of a chemical reaction on the unsteady flow past on impulsively started semi-infinite vertical plate, which is subject to uniform heat flux. McLeod and Rajagopal [1987] have investigated the uniqueness of the flow of a Navier Stoke's fluid due to a linear stretching boundary. Raptis et. al. [2006], have studied the viscous flow over a non-linearly stretched sheet in the presence of a chemical reaction and magnetic field.

The effect of chemical reaction on free convective flow and mass transfer of a viscous, incompressible and electrically conducting fluid over a stretching sheet was investigated by Afify [2004] in the presence of a transverse magnetic field. In all these investigations the electrical conductivity of the fluid was assumed to be uniform. However, in an ionized fluid where the density is low and/or magnetic field is very strong, the conductivity normal to the magnetic field is reduced due to the spiraling of electrons and ions about the magnetic lines of force before collisions take place and a current induced in a direction normal to both the electric and magnetic fields. This phenomenon available in the literature is known as Hall Effect. Thus the study of MHD viscous flows, heat and mass transfer with Hall currents has important bearing in the engineering applications.

Samad and Mohebujjaman [2009] have studied MHD heat and mass transfer free convection flow along a vertical stretching sheet in the presence of magnetic field with heat generation. Seddeek [2007] have studied the heat and mass transfer on a stretching sheet with a magnetic field in a visco-elastic fluid flow through a porous medium with heat source or sink. Veena et.al. [2007] have discussed the non-similar solutions for heat and mass transfer flow in an electrically conducting visco-elastic fluid over a stretching sheet embedded in a porous medium. Hsiao [2008] has analysed the heat and mass transfer for electrical conducting mixed convection with radiation effect for visco-elastic fluid past a stretching sheet. Shit [2009] has studied Hall effects on MHD free convective flow on mass transfer over a stretching sheet. Raghavendra Rao [2012] has discussed the effect of chemical reaction, Hall effects on the convective heat and mass transfer flow past a stretching sheet.

Hall effect on MHD boundary layer flow over a continues semi-infinite flat plate moving with a uniform velocity in its own plane in an incompressible viscous and electrically conducting fluid in the presence of a uniform transverse magnetic field were investigated by Watanabe and Pop [1995]. Abo-Eldahab and Elbarbary [2001] have investigated free convective flows past a semi-infinite vertical plate with mass transfer. The effect of Hall current on the study MHD flow of an electrically conducting, incompressible Burger's fluid between two parallel electrically insulating infinite plane was studied by Rana et. al. [2008].

It is well known that the boundary condition for a viscous fluid at a solid wall obeys no-slip condition; i.e the fluid velocity matches the velocity of the solid boundary. However, in many practical applications, the particle adjacent to a permeable surface no longer takes the velocity of the surface but the particle at the surface has a finite tangential velocity which slips along the surface. The flow regime is called a slip-flow regime, and this effect can not be neglected. Sharma and Chowdary [2003] studied the effect of variable suction on transient free convective viscous incompressible flow past a vertical plate in a slip-flow regime. Hayat et al [2002] investigated the flow of an elastico-viscous fluid past an infinite wall time-dependent suction. Hayat et al [2003] examined the non-newtonian flows over an oscillating plate with variable suction. Sahin [2010] have studied the influence of chemical reaction on transient MHD free convection flow over a vertical plate in slip-flow regime.

Hayat et al [2003] studied fluctuating flow of a third–order fluid past an infinite plate with variable suction. Sharma [2005] investigated the effects of periodic temperature and concentration on the unsteady free stream consisting of a mean velocity which vary exponentially with time. DulalPal Babulal Talukdar [2014] have studied the influence of fluctuating thermal and mass diffusion on unsteady MHD buoyancy-driven convection past a vertical surface with chemical reaction, Soret effect and slip-flow condition. Reddy [2014] studied the influence of MHD thermal radiation boundary layer flow of a Nanofluid past a stretching sheet.

In this paper, we study the combined influence of chemical reaction, Hall currents and thermal radiation on convective heat and mass transfer flow of a viscous electrically conducting fluid past a stretching sheet in the presence of non-uniform heat source with slip-flow regime. The equations governing the flow of heat and mass transfer have been solved by Galerkin finite element analysis with three nodded line segments. The velocity, temperature and concentration have been analyzed for different values of G, M, m, R, N, N_1, Rd, Sc, A_1, B_1, A and γ.The rate of heat and mass transfer on the plate has been evaluated numerically for different variations.

2. Problem Formulation

We considered a steady convective flow of an incompressible, viscous and electrically conducting fluid past a plate through a porous medium in the vertical direction stretching with a velocity proportional to the distance from the origin 'O', of a stationary frame of reference O (x,y,z).The positive x-coordinate is measured along the stretching sheet in the direction of motion and the positive y coordinate is measured normal to the sheet in the outward direction towards the fluid, the x-axis coincides with the leading edge of the stretching sheet.
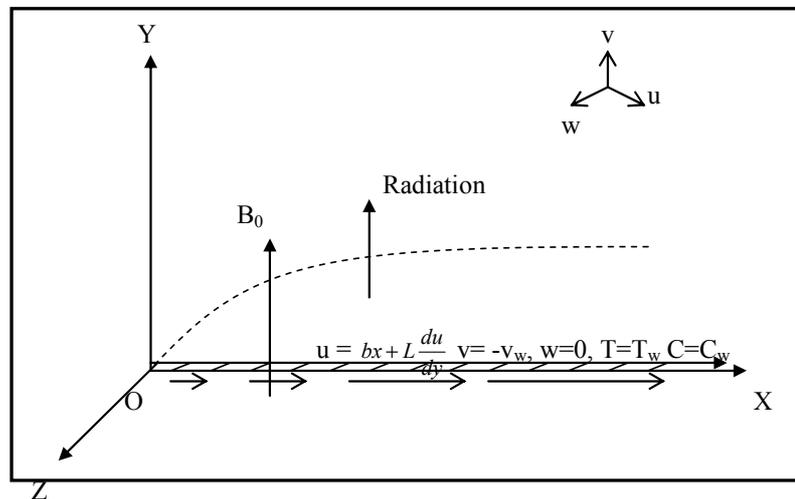

Figure 1. Schematic Diagram of the Problem

The Rosseland approximation is used to describe the radiative heat flux in the energy equation. The flow is subjected to a strong transverse magnetic field with a constant intensity Bo along the positive y-direction. The magnetic Reynolds number is assumed to be small enough (Re<<1),so that the induces magnetic field can be neglected. The governing equations for the magnetic field $\nabla.\overline{H} = 0$,where $\overline{H} = (Hx, Hy, Hz)$ gives Hy = Ho(constant) everywhere in the flow field, which gives $\overline{H} = (0,0, Ho)$ .If (Jx, Jy, Jz) are the component of current density $\overline{J}$,then the equation of conservation of electric charge $\nabla.\overline{J} = 0$ gives Jy =0 everywhere in the flow since the plate is electrically non-conducting. The generalized Ohm's law, in the absence of electric field[22] ,is of the form

$$\overline{J} + \frac{\omega_e \tau_e}{H_0}(\overline{J} + \overline{H}) = \sigma(\mu_e \overline{V} x \overline{H}) + \frac{1}{en_e}\nabla p_e \tag{1}$$

Where $\overline{V}, \sigma, \mu_e, \tau_e, e, n_e$ and p_e are the velocity, the electrical conductivity, the magnetic permeability, the cyclotron frequency, the electron collision time, the electric charge, the number density of the electron and the electron pressure respectively. Under the usual assumption, the electron pressure (for a weakly ionized gas), the thermoelectric pressure and ion slip are negligible, so we have from the Ohm's law

$$j_x + \omega_e \tau_e j_y = (\sigma \mu_e H_o)v$$

$$j_y - \omega_e \tau_e jx = -(\sigma \mu_e H_o)w$$

From these equations ,we obtain that

$$j_x = (\sigma\mu_e H_o)(uu + w)$$
$$j_y = (\sigma\mu_e H_o)(mw + u)` \tag{2}$$

The flow has significant thermal radiation, chemical reaction, heat source and Hall, Soret and Dufour effects .By using Boussinesq approximation the basic boundary layer equations of flow, heat and mass transfer are

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0 \tag{3}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = v\frac{\partial^2 u}{\partial y^2} + \beta_T g(T - T_\infty) + \beta_c g(C - C_\infty) - \frac{\sigma\mu_e^2 H_0^2}{\rho(1+m^2)}(u+mw) - (\frac{\mu}{\rho k})u \tag{4}$$

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} = v\frac{\partial^2 w}{\partial y^2} + \frac{\sigma\mu_e^2 H_0^2}{\rho(1+m^2)}(mu-w) - (\frac{\mu}{\rho k})w \tag{5}$$

$$\rho C_p(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}) = k_f\frac{\partial^2 T}{\partial y^2} + \frac{Dk_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} + \frac{\sigma\mu_e^2 H_0^2}{\rho(1+m^2)}(u^2+w^2) - \frac{\partial q_R}{\partial y} + q''' \tag{6}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y}) = D\frac{\partial^2 C}{\partial y^2} + \frac{Dk_T}{T_m}\frac{\partial^2 T}{\partial y^2} - k_r'(C - C_\infty) \tag{7}$$

Where u and v are velocity components in the x-direction and y-direction respectively, w is the velocity component in the z-direction,v is the kinematic coefficient of viscosity, g is the Acceleration due to gravity, β_T is the coefficient of thermal expansion, T is the temperature of the fluid inside the thermal boundary layer, Tw is the plate temperature, T_∞ is the temperature of the fluid in the free stream with $T_w > T_\infty$, β_c is the volume coefficient of expansion with concentration, C is the concentration,σ is the electrical conductivity of the fluid,μe is the magnetic permeability of the fluid, e is the electron charge, ne is the electron number density, te is the electron collision time, me is the mass of electron, Bo is the Magnetic field of constant strength,ρ is the density of the fluid, m($\omega_e\tau_e$) is the Hall parameter, μ is the dynamic viscosity, k is permeability of the porous medium, Cp is the specific heat constant pressure, kf is the thermal conductivity, Cs is the concentration susceptibility, D is the mass diffusivity, K_T is the thermal–diffusivity rate, qR is the radiative heat flux in the y-direction. Tm is the mean fluid temperature, Cw is the uniform concentration, C∞ is the free stream concentration with Cw>C∞, and k_r' is the chemical reaction parameter.

The boundary conditions are

$$u = U_s + L\frac{\partial u}{\partial y} = bx + L\frac{\partial u}{\partial y}, v = -v_w w = 0, \quad T = T_w, \quad C = C_w \quad at \quad y = o \tag{7}$$

$$u \to 0, \quad w \to 0, \quad T \to T_\infty, C \to C_\infty \qquad as \quad y \to \infty$$

Where Us is the velocity of the surface, b is a constant with dimension (time)$^{-1}$ and v_w is the suction (>0) or injection (<0) of the velocity at the plate. L is the velocity slip factor.

Employing Rosseland diffusion approximation (Raptis [2006]), the radiative heat flux is given by

$$q_R = -\frac{4\sigma^\bullet}{3\beta_R}\frac{\partial T'^4}{\partial y} \tag{8}$$

Where $\sigma^\bullet$ is the Stefan-Boltzmann constant and β_R is the mean absorption coefficient, temperature difference within the flow are assumed to be sufficiently small so that T'^4 may be expressed as a linear function of temperature T using a truncated Taylor series about the free stream temperature T∞, i.e

$$T'^4 = 4T_\infty^3 T - 3T_\infty^4 \tag{9}$$

From equations (8) & (9), we obtain

$$T'^4\frac{\partial q_R}{\partial y} = -\frac{16\sigma^\bullet T_\infty^3}{3\beta_R}\frac{\partial^2 T}{\partial y^2} \tag{10}$$

The coefficient q''' is the rate of internal heat generation (>0) or absorption (<0).

The internal heat generation/absorption q''' is modeled (Dulal pal [2012]) as

$$q''' = (\frac{ku_s}{xv})[A^\bullet(T_w - T_\infty)f''(\eta) + B^\bullet(T - T_\infty)] \tag{11}$$

Where $A^{\bullet}$ and $B^{\bullet}$ are coefficients of space-dependent and temperature-dependent heat generation or absorption respectively. It is noted that the case $A^{\bullet} > 0$, and $B^{\bullet} > 0$, corresponds to internal heat generation and that $A^{\bullet} < 0$, and $B^{\bullet} < 0$,the case corresponds to the internal heat absorption.

Introducing the similarity variables as

$$\eta = \sqrt{(b/\nu)}\, y \qquad , \quad u = bxf'(\eta), \qquad v = -\sqrt{b\nu}\, f(\eta) \qquad \theta = \frac{T - T_{\infty}}{T_w - = T_{\infty}} \quad , \phi = \frac{C - C_{\infty}}{C_w - C_{\infty}} \tag{12}$$

Substituting (12) in equations(4)-(7) results in to the non-linear ordinary differential equations of the form

$$f''' + f f'' - (f')^2 + G(\theta + N\phi) - \frac{M^2}{1 + m^2}(f' + mg) - D^{-1} f' = 0, \tag{13}$$

$$g'' + fg' - f'g + \frac{M^2}{1 + m^2}(mf' - g) + D^{-1}g = 0 \tag{14}$$

$$\frac{1}{Pr}(1 + \frac{4}{3}Rd)\theta'' + f\,\theta' + Du\phi'' + \frac{M^2 Ec}{1 + m^2}(f'^2 + g^2) + \frac{1}{Pr}(A^{\bullet} f' + B^{\bullet}\theta) = 0 \tag{15}$$

$$\phi'' + Sc(f\phi' + Sr\theta'' - \gamma\phi) = 0 \tag{16}$$

The transformed boundary conditions are

$$\begin{aligned}
f'(\eta) &= 1 + A f''(0),,\ f(\eta) = f_w,\ g(\eta) = 0, \theta(\eta) = 1,\ \phi(\eta) = 1 \qquad & at\ \eta = 0 \\
f'(\eta) &= 0, g(\eta) = 0, \theta(\eta) = 0, \phi(\eta) = 0 \qquad & as\ \eta \to \infty
\end{aligned} \tag{17}$$

Where $f_w = \dfrac{v_w}{\sqrt{b\nu}}$ is the mass transfer coefficient such that fw>o represents suction and fw<0 represents injection at the surface.

The local Skin friction coefficient C_{fx} along the z-direction is defined by

$$C_{fx} = \frac{2\tau_{wx}}{\rho(ax)^2} \tag{18}$$

Where τ_{wx} is the wall shearing stress given by $\tau_{wx} = \mu(\dfrac{\partial u}{\partial y})_{y=0}$ \hfill (19)

Bu using the relation (12),equations (17)-(19) take the form

$$C_{fx}\, Re_x^{-1/2} = 2f''(0)$$

$$and \tag{20}$$

$$C_{fz}\, Re_x^{-1/2} = 2g'(0)$$

The heat flux is given by

$$q_w = -k_f(\frac{\partial T}{\partial y})_{y=0} \tag{21}$$

The local Nusselt number is given by

$$Nu_x = \frac{xq_w}{k_f} \tag{22}$$

By using the non-dimensional variables equations (12) in equations (21)&(22),we get

$$Nu_x\, Re_x^{-1/2} = -\theta'(0) \tag{23}$$

The mass transfer coefficient may be written as follows:

$$q_m = -D(\frac{\partial C}{\partial y})_{y=0} \tag{24}$$

Where D is is the molecular diffusivity.

The local Sherwood number is given by

$$Sh_x = \frac{xq_m}{D} \tag{25}$$

By using the equations (12) in equations (24)&(25),we get

$$Sh_x\, Re_x^{-1/2} = -\phi'(0) \tag{26}$$

3. Numerical procedure

An exact solution for f from equations(13)-(16) together with the boundary conditions(17) in the absence of Hall currents, thermal buoyancy and solutal buoyancy can be obtained as

$$f(\eta) = f_w + \frac{1}{a}(1 - \exp(-a\eta))$$

$$a = \frac{f_w + \sqrt{f_w^2 + 4(M^2 + D^{-1} + 1)}}{2}$$

The set of non-linear differential equations (13)-(16) with the boundary conditions (17) are solved numerically employing Runge_Kutta fourth order technique together with the shooting technique. The boundary conditions as $\eta \to \infty$ enable us to use value of f', g, θ, ϕ. So that the velocity, temperature and concentration fields can be obtained for different variations in the physical parameters such as Grashof number (G), Buoyancy ratio(N), Radiation parameter (Rd),chemical reaction parameter(γ), Hall parameter(m), Magnetic parameter (M), Inverse Darcy parameter(D^{-1}), Eckert Number(Ec), Non-uniform Heat source parameters($A^\bullet$, $B^\bullet$).

4. Results and Discussion

To get a physical insight of the problem, the profiles of velocity, temperature and concentration are graphically presented. The values of the parameters are fixed throughout the computations as M=m=1, G=1, N=1, D^{-1}=1, Pr=0.71, Rd=0.5, Ec=0.01, Sr=2.0, Du=0.03, Sc=1.3, γ=0.5, fw=0.1, A=0.01=B, A=0.1.

The influence of Grashof number G on the flow variables is exhibited in Figs.2-5.From Figs. 2&3 it is found that increasing values of G has an enhancing effect on the primary and cross flow velocity components. We may conclude that the thermal buoyancy enhances the thickness of the boundary layer. The velocity components increase rapidly near the stretching surface with maximum attaining at η=1 and falls to in the flow region eventually attaining the zero value at far infinity. It can be seen from Figs. 4&5 that the effect of increasing the thermal buoyancy parameter (G) is to reduce the temperature and concentration throughout the thermal and solutal boundary layers. This can be attributed to the fact that an increase in G leads to a reduction in the thickness of the thermal and solutal boundary layer.

Figs.6-9 represent the effect of the magnetic parameter (M) on the velocity, temperature and concentration. From Fig. 6 we find that the influence of the magnetic parameter (M) is to reduce the primary and secondary velocity components near the plate (0≤η≤4) and outside this range the influence is negligible. This reduction is due to the fact the magnetic field provides a resisting type of force known as the Lorentz force. This force tends to lesser the motion of the fluid and as a result the velocity components reduce in the boundary layer. It is found that the velocity along the sheet deceases with increase in M accompanied by a reduction in the thickness of the boundary layer. From Fig.7, it is interesting to note that the magnetic parameter on the cross velocity has an opposite effect to that of the other velocity components. It is seen from the profiles that the cross flow velocity rapidly increases attaining its maximum value at η=1 and then decreases in the remaining flow region. From the Fig.8 we find that the temperature enhances with increase in the magnetic parameter, the frictional resistance on account of the magnetic field results in the reduction in the velocity and thereby enhances the temperature in the thermal boundary layer. Hence, there is an increase in the thickness of the thermal boundary layer .Similar reduction in concentration can be notices with increase in the magnetic parameter (Fig.9).

Figs.10-13 show the effect of Hall current on the velocity, temperature and concentration. It can be seen from the velocity profiles that an increase in the Hall parameter (m) enhances both the primary velocity and cross flow velocity. The temperature and concentration distributions depreciate in the boundary layer with increase in the Hall parameter (m) (Figs. 12&13). Figs.14-17 represent the effect of buoyancy ratio (N) on the velocity, temperature and concentration.It is observed from the profiles that when the molecular buoyancy force dominates over the thermal buoyancy force the primary velocity and Cross flow velocity components enhances when the buoyancy forces are in the same direction and for the forces acting in opposite directions the components reduce in the boundary layer. The temperature and concentration reduces with increase in N>0 and enhances with N<0 in the boundary layer. (Figs. 16&17). Figs. 18-21 show the variation of velocity, temperature and concentration with thermal radiation parameter (Rd). It is found that there is a significant rise in the primary velocity in the presence of thermal radiation throughout the boundary layer. A similar behavior for the cross flow velocity is also noticed with Rd. It can be seen from the profiles of the cross flow velocity(g) that the rise in the cross flow velocity g is relatively lesser than that of the primary velocity(f') in the boundary layer. The radiation parameter is found to enhance the hydrodynamic boundary layer along the x and z-directions. The presence of the thermal radiation is very significant on the variation of temperature. It is seen from the profiles the temperature increases rapidly in the presence of the thermal radiation parameter in the entire thermal boundary layer. This may be attributed to the fact that as the Rosseland radiative absorption parameter Rd diminishes the

corresponding heat flux divergence and thus raising the rate of radiative heat transfer to the fluid causing a rise in the temperature of the fluid. The thickness of the boundary layer increases in the presence of Rd (Fig. 20).The effect of Rd on mass concentration is not significant as compared to the velocity and temperature. However, the concentration reduces in the solutal boundary layer with increase in Rd (Fig. 21)

Figs. 22-25 show the variation of chemical reaction effect on the velocity, temperature and concentration. From Figs. (22&23) we observe that the primary velocity (f') and cross flow velocity (g) reduces with increase in the chemical reaction parameter (γ) in both degenerating and generating chemical reaction cases. The variation of temperature with γ shows that the temperature reduces in the degenerating chemical reaction case and enhances in the generating chemical reaction case (Fig. 24) while the concentration decreases with increasing values of the chemical reaction parameter inn both degenerating and generating chemical reaction cases. In fact the concentration of the species steadily falls from its higher value on the surface to lower value eventually attaining the free stream concentration as $\eta \to \infty$ (Fig. 25).

The effect of non-uniform heat source on the velocity, temperature and concentration is exhibited in Figs. 26-29. From Figs. 26&27 we find that the presence of the heat source generates energy in the thermal boundary layer and as a consequence the temperature rises. Near the plate an overshoot in the temperature is also noticed. Increasing the value of $A_1>0,B_1>0$(heat generating source) produce further rise in the temperature. In the case of $A_1<0,B_1<0$,the temperature falls with deceasing values of $A_1<0$, $B_1<0$ due to the absorption of energy in the boundary layer. The primary and cross flow velocity enhances marginally with increase in heat generation ($A_1>0$, $B_1>0$) while we notice a depreciation in them in the case of heat absorption ($A_1<0,B_1<0$). The temperature enhances with heat generation and reduces with heat absorption (Fig. 28). The effect of heat generation/absorption parameter is to enhance the mass concentration marginally (Fig. 29).

Figs. 30-33 represent the variation of radiation Absorption (Q_1) on the velocity, temperature and concentration.It is found that from Figs. 30&31 that higher the radiation absorption larger the primary and cross flow velocity components in the boundary layer. Also an increase in Q_1 results in an increase in the temperature and reduces the species concentration in the boundary layer (Figs. 32&33). Figs. 34-37 depict the influence of the Eckert number (Ec) on velocities, temperature and concentration. It is pointed out that the presence of Eckert number increases the temperature. This is due to the fact the thermal energy is reserved in the fluid on account of friction heating. Hence, the temperature distribution rises in the entire thermal boundary layer (Fig. 36).The primary and the cross flow velocity components are also found to enhance for increasing the values of Ec due to the energy release which increases the momentum. However, the mass concentration reduces with increase in Ec (Fig.37). Figs.38-41 exhibits the influence of Soret and Dufour effects on the velocity, temperature and concentration .It is found that increasing the Soret parameter So(or decreasing Dufour parameter Du) results in an increase in the primary and cross flow velocity components (Figs. 38&39). Increasing So (or decreasing du) leads to a depreciation in the temperature and enhancement in the mass concentration in the boundary layer (Fig. 40&41).

Figs. 42-45 represents the influence of slip velocity parameter A on the velocity components,temperature and concentration.it can be seen from the profiles the primary and cross flow velocities decreases in the boundary layer with increase in slip velocity parameter A. This is due to the fact that in increase in A leads to a decrease in the thickness of the momentum boundary layer. From Figs. 44&45, we find that the temperature and mass concentration enhances with increase in A. This can be attributed to the fact that thermal boundary layer and the solutal boundary layer increases with increase in the velocity slip parameter A.
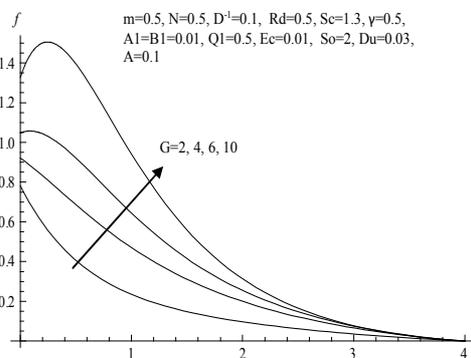

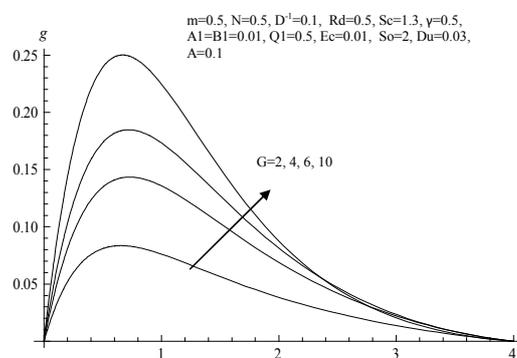Figure 2. Effect of Grashof Number G on axial velocity f'

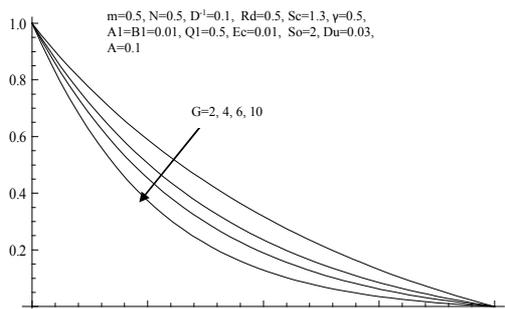Figure 3. Effect of Grashof Number G on cross velocity g

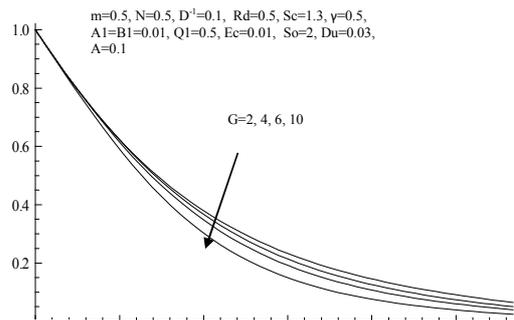Figure 4. Effect of Grashof Number G on Temperature θ

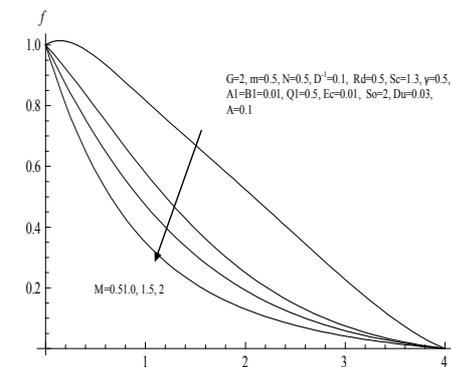Figure 5. Effect of Grashof Number G on Concentration φ

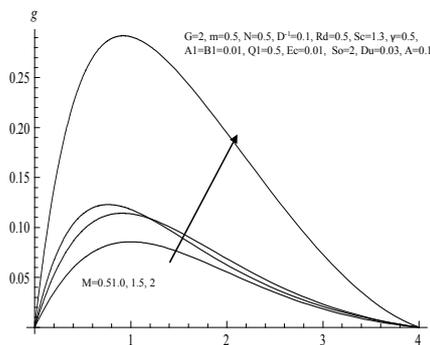Figure 6. Effect of Hartmann Number M on axial velocity f'

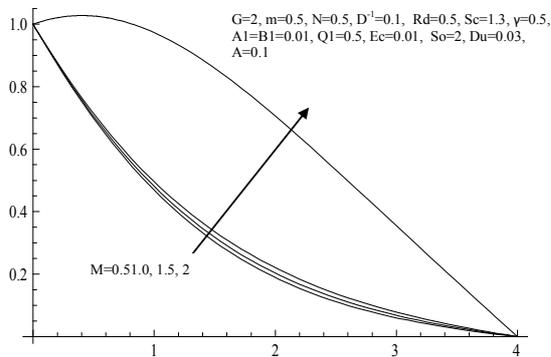Figure 7. Effect of Hartmann Number M on cross flow velocity g

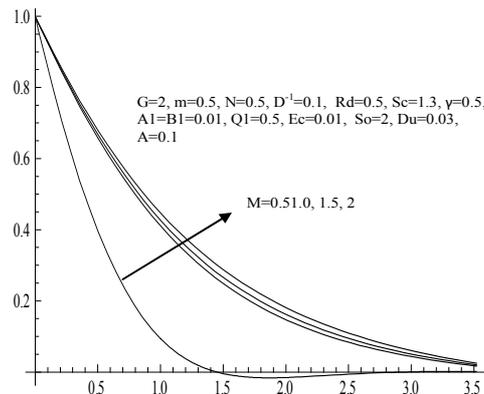Figure 8. Effect of Hartmann Number M on Temperature θ

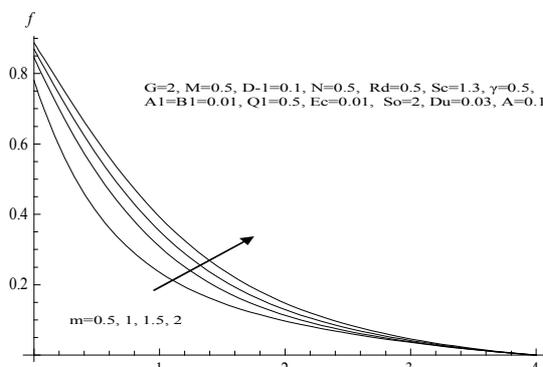Figure 9. Effect of Hartmann Number M on Concentration φ

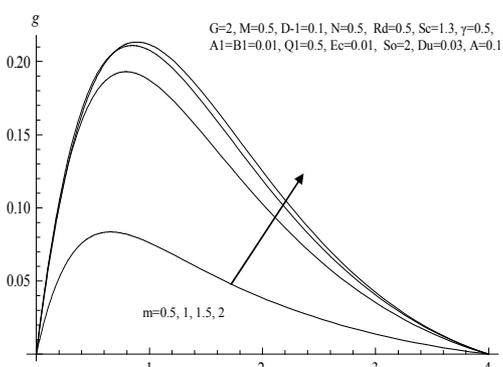Figure 10. Effect of Hall current m on axial velocity f'

Figure 11. Effect of Hall current m on cross flow velocity g
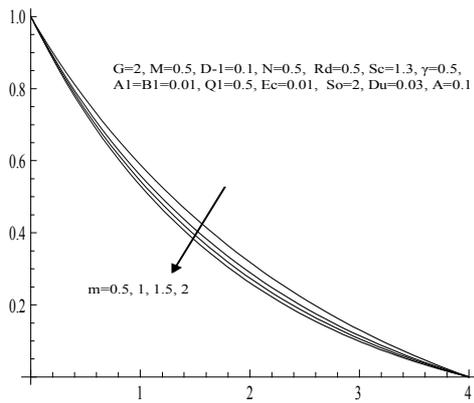
Figure 12. Effect of Hall current m on Temperature θ
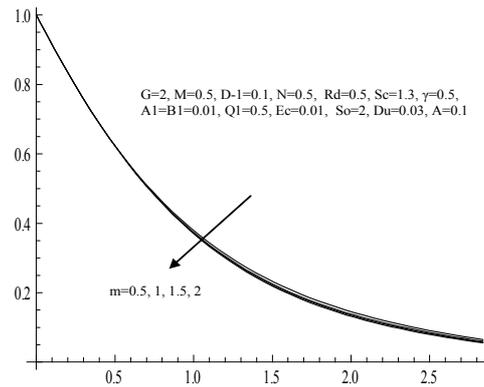
Figure 13. Effect of Hall current m on Concentration ϕ
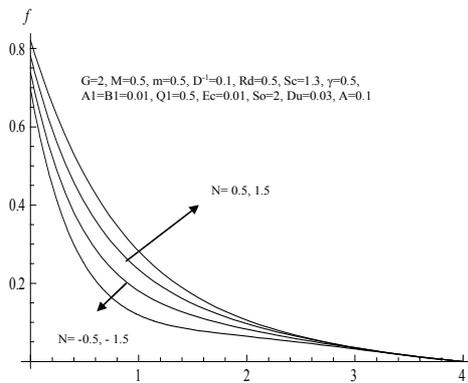
Figure 14. Effect of Buoyancy Ratio N on axial velocity f'
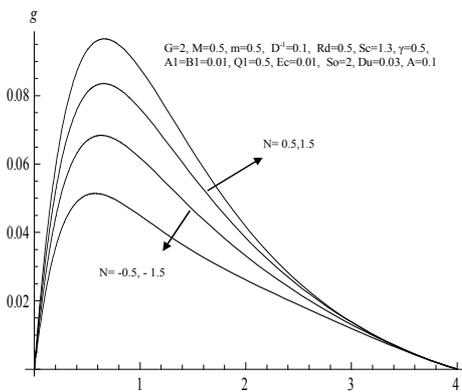
Figure 15. Effect of Buoyancy Ratio N on cross velocity g
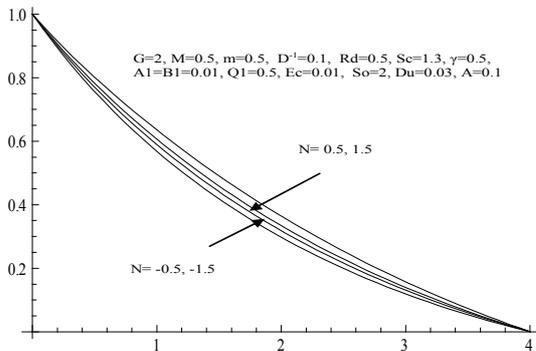
Figure 16. Effect of Buoyancy Ratio N on Temperature θ
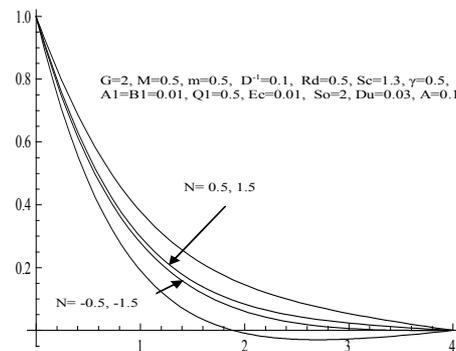
Figure 17. Effect of Buoyancy Ratio N on Concentration ϕ

Rd-var
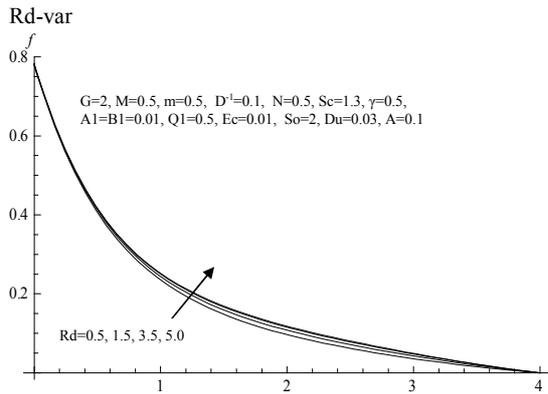
Figure 18. Effect of Radiation Rd on axial velocity f'
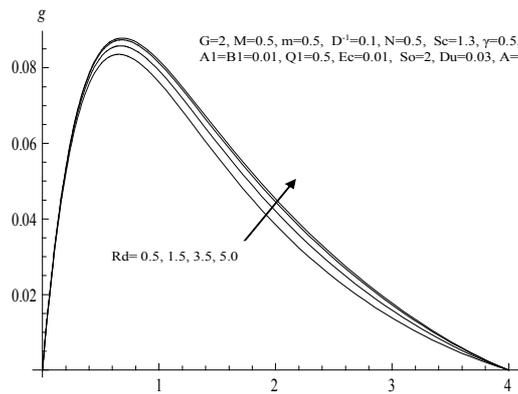
Figure 19. Effect of Radiation Rd on cross flow velocity g
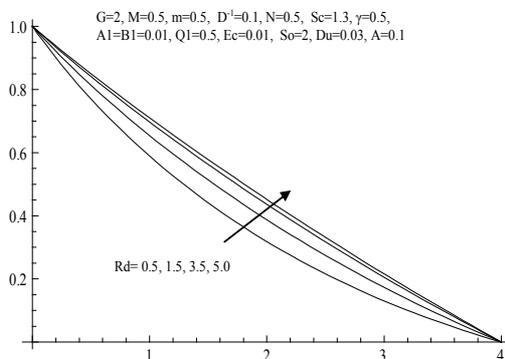
Figure 20. Effect of Radiation Rd on Temperature θ
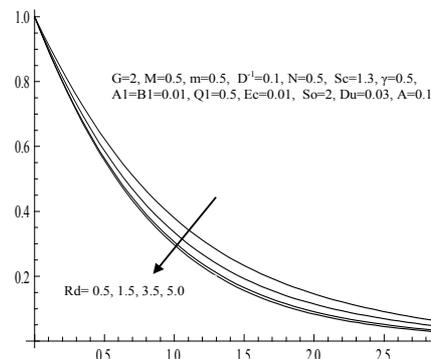
Figure 21. Effect of Radiation Rd on Concentration ϕ
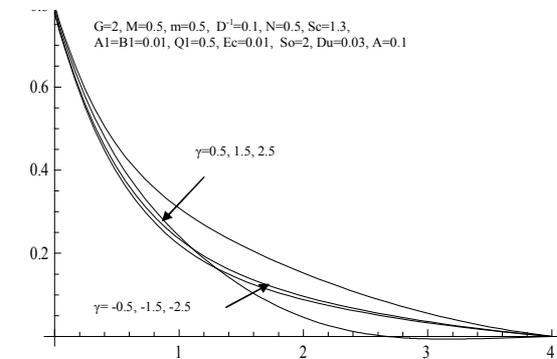
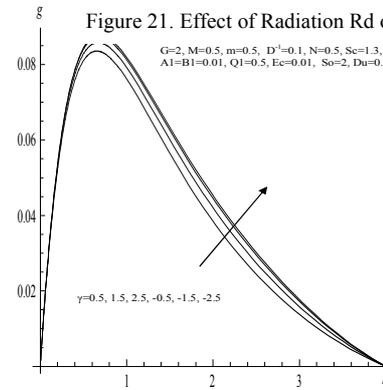Figure 22. Effect of chemical reaction γ on axial velocity f'

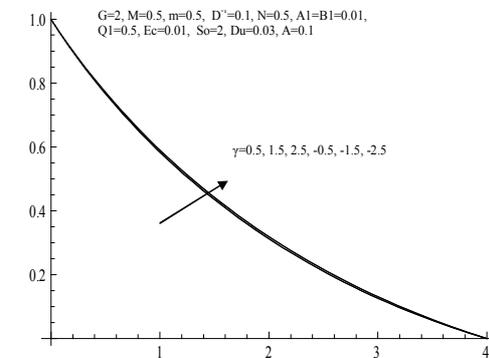Figure 23. Effect of chemical reaction γ on cross flow velocity g

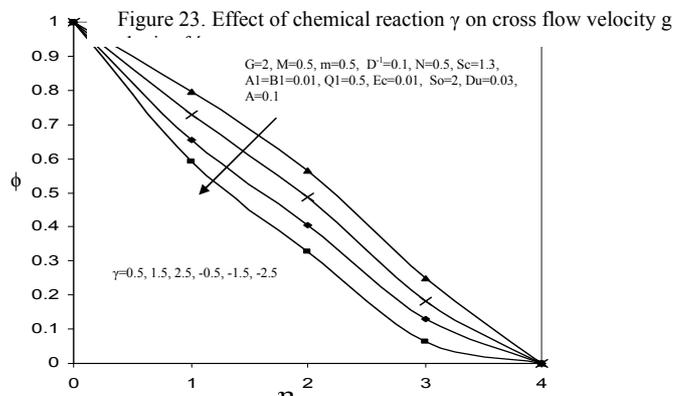Figure 24. Effect of chemical reaction γ on Temperature θ

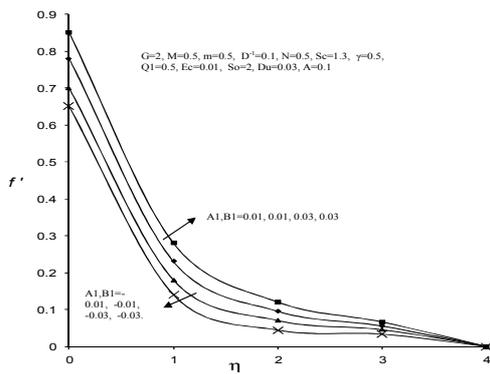Figure 25. Effect of chemical reaction γ on Concentration ϕ

Figure 26. Effect of Non-uniform heat source A_1, B_1 on axial velocity f'
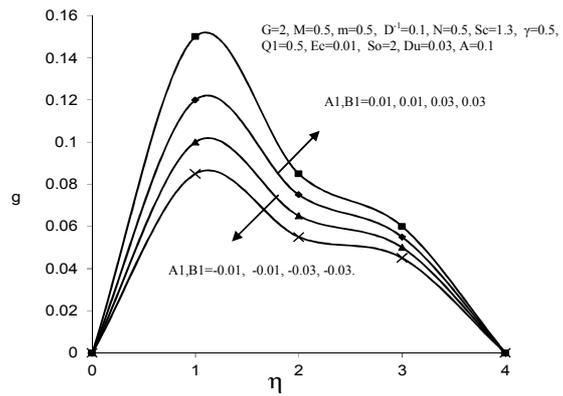

Figure 27. Effect of Non-uniform heat source A_1, B_1 on Cross flow velocity g
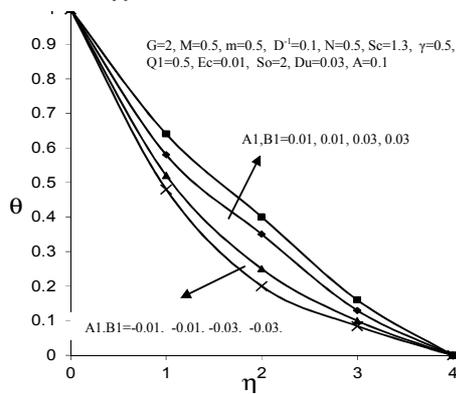

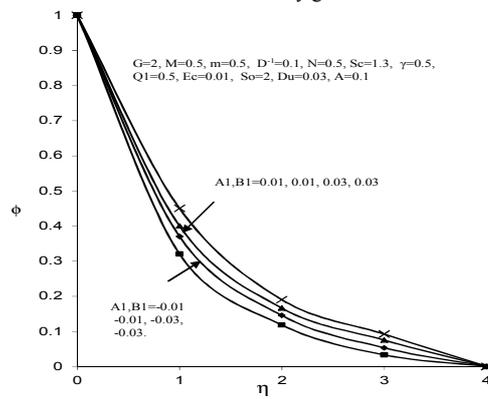Figure 28. Effect of Non-uniform heat source A_1, B_1 on Temperature θ

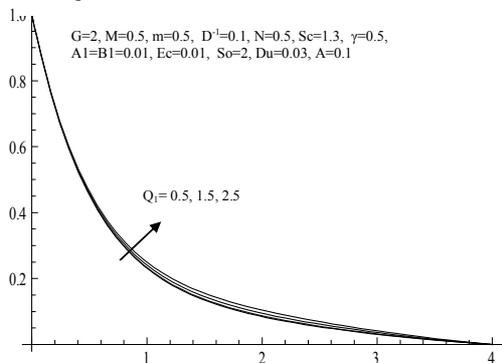Figure 29. Effect of Non-uniform heat source A_1, B_1 on Concentration φ

Figure 30. Effect of on Radiation absorption Q_1 axial velocity f'
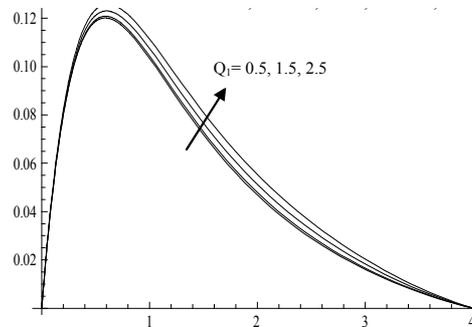

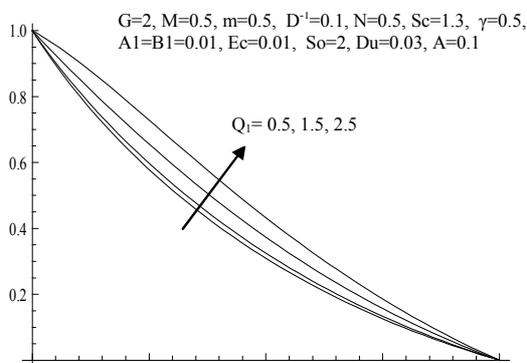Figure 31. Effect of on Radiation absorption Q_1 cross flow velocity g

Figure 32. Effect of on Radiation absorption Q_1 Temperature θ
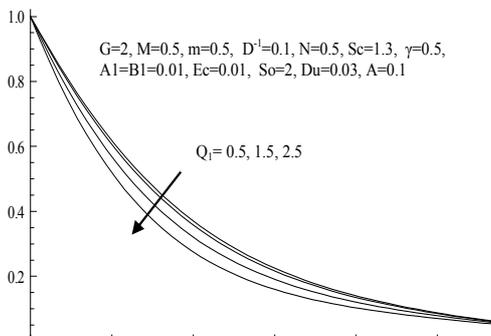
Figure 33. Effect of on Radiation absorption $Q_{1Concentration}$ φ
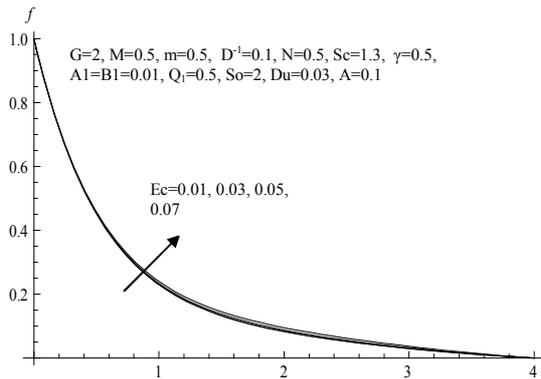
Figure 34. Effect of on Dissipation parameter Ec on axial velocity f'
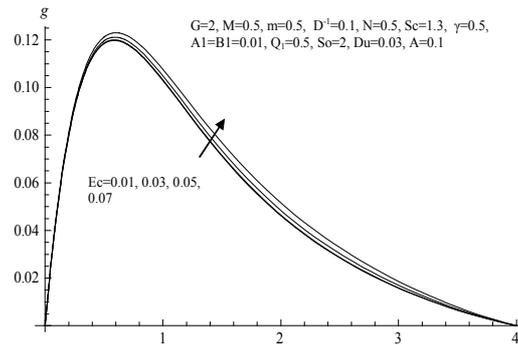
Figure 35. Effect of on Dissipation parameter Ec on cross flow velocity g
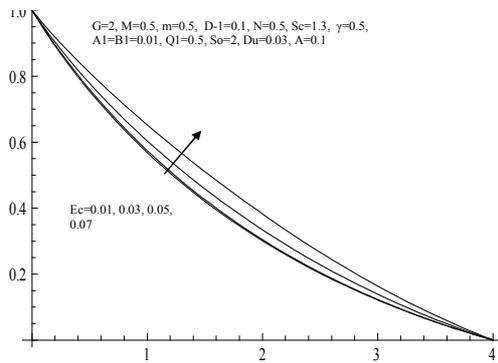
Figure 36. Effect of on Dissipation parameter Ec on Temperature θ

Figure 37. Effect of on Dissipation parameter Ec on Concentration φ

Figure 38. Effect of on Soret So and Dufour Du effects on axial velocity f'

Figure 39. Effect of on Soret So and Dufour Du effects on cross flow velocity f'

Figure 40. Effect of on Soret So and Dufour Du effects on Temperature θ

Figure 41. Effect of on Soret So and Dufour Du effects on Concentration φ

Figure 42. Effect of Slip velocity parameter A on axial velocity f'

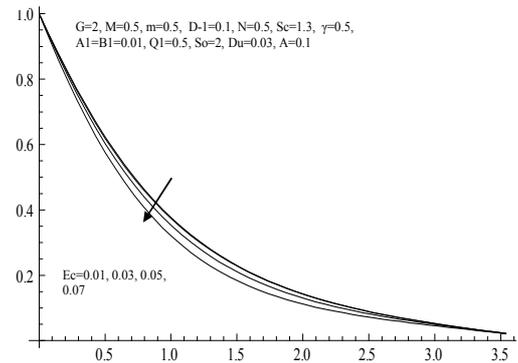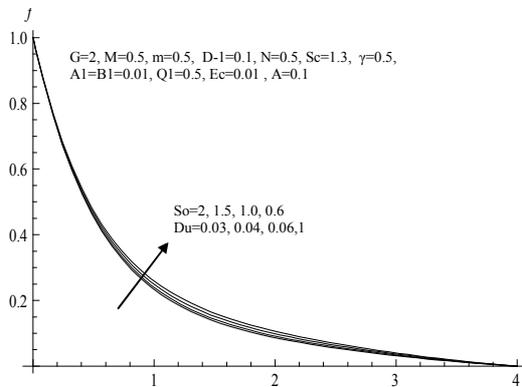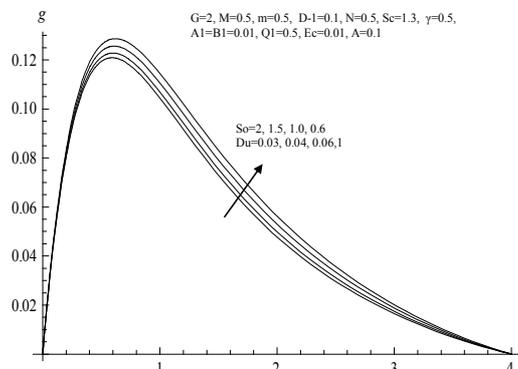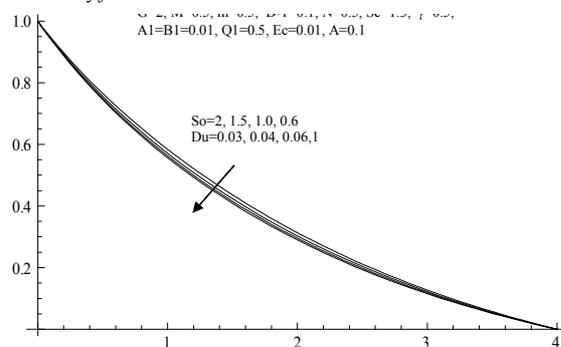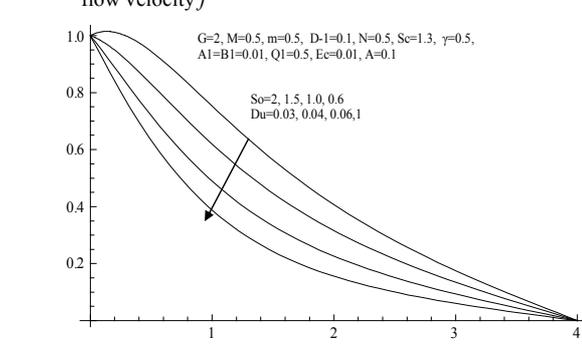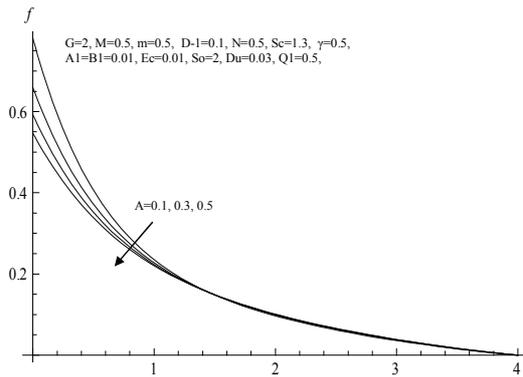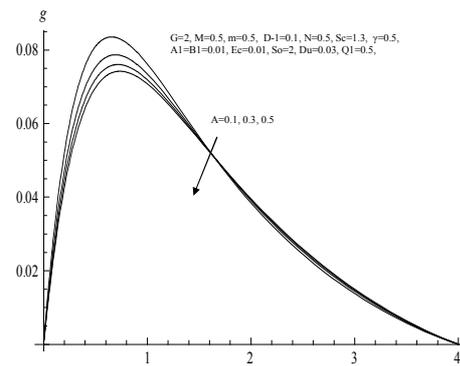Figure 43. Effect of Slip velocity parameter A on cross flow velocity g
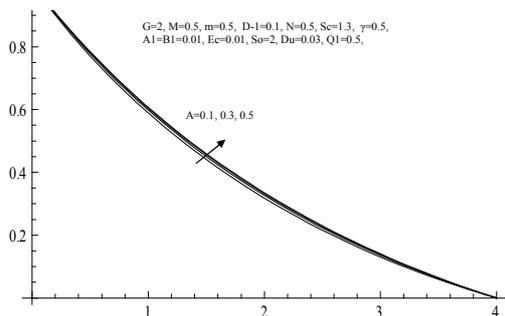

Figure 44. Effect of Slip velocity parameter A on Temperature θ
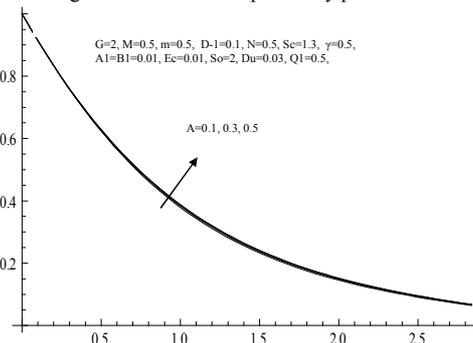
Figure 45. Effect of Slip velocity parameter A on Concentration ϕ

From Table. 2 it is observed that an increase in the thermal buoyancy parameter (G) reduces the skin friction coefficient and enhances the rate of heat and mass transfer at the wall. The skin friction coefficient enhances with increase in the magnetic parameter(M) in view of the larger momentum exerted on the wall with increasing values of M. The magnetic parameter reduces the wall heat transfer rate. The Sherwood number at the wall reduces with increase in M. An increase in the Hall parameter (m) enhances the skin friction coefficient and enhances the rate of heat and mass transfer at the wall. The variation with respect to the buoyancy ratio (N) shows that when the molecular buoyancy force dominates over the thermal buoyancy force the skin friction coefficient reduces and the rate heat and mass transfer at the wall increases when the buoyancy forces are in the same direction and for the forces acting in opposite directions, an opposite effect is noticed in the behavior of C_{fx}, Nu and Sh. An increase in the strength of the heat generation ($A_1>0,B_1>0$) reduces the skin friction coefficient, Nusselt number and enhances the Sherwood number at the wall while in case of heat absorption ($A_1<0,B_1<0$) case, we find a reduction in C_{fx} and enhancement in Nu and Sh .with respect to radiation parameter Rd, we notice an increment in C_{fx} and Sh and reduction in Nu at the wall. Increasing the Soret parameter So (or decreasing Dufour parameter) leads to a reduction in C_{fx} and Sh and enhancement in Nu. Higher the dissipative heat larger C_{fx} and Sh and lesser Nu. An increase n the slip velocity parameter (A) reduces C_{fx} and Nu and enhances Sh at the wall. The skin friction enhances and Nusselt number reduces in both the degenerating and generating chemical reaction cases. The Sherwood number enhances in the degenerating chemical reaction case and reduces in the generating chemical reaction case.an increase in the suction parameter fw increases the skin friction coefficient C_{fx}, Nusselt number and Sherwood number and a reversed effect is noticed in the case of fw<0. With reference to Pr, we find that lesser the thermal diffusion smaller C_{fx} and larger Nu and Sh .

		τx	τz	Nu	Sh
G	2	-1.06575	0.373644	0.53571	-0.1416671
	4	-0.660661	0.480958	0.625921	-0.212989
	6	-0.273973	0.574884	0.698544	-0.405039
	10	-0.451548	0.73311	0.811032	-0.681518
M	0.5	-0.212487	-0.0727461	0.726708	-0.479081
	1.0	-0.314993	0.0161793	0.70408	-0.421914
	1.5	-0.756737	0.269906	0.604185	-0.156414
	2.5	-1.06575	0.373644	0.53571	-0.101667
m	0.5	-1.06575	0.373644	0.53571	0.1041667
	1.0	-0.723902	0.682746	0.593247	-0.130219
	1.5	-0.594201	0.685923	0.621219	-0.208006
	2.5	-0.494957	0.652992	0.644729	-0.270559
Sc	0.24	-1.06498	0.375356	0.532728	0.217523
	0.66	-1.06558	0.374427	0.533816	0.153206
	1.3	-1.06575	0.373644	0.53571	0.091667
	2.01	-1.06546	0.373198	0.538091	0.047228
N	0.5	-1.06575	0.373644	0.53571	0.1041667
	1.5	-0.863159	0.416433	0.567315	0.779123
	-0.5	-1.27632	0.327071	0.498739	2.09272
	-1.5	-1.4982	0.274631	0.454261	1.37095
A_1,B_1	0.01,0.01	-1.06575	0.373644	0.53571	0.0416671
	0.03.0.03	-1.06637	0.373509	0.52197	0.0969671
	-0.01,-0.01	-1.06514	0.373776	0.549286	-0.013054
	-0.03,-0.03	-1.06455	0.373906	0.562702	-0.067213
Rd	0.5	-1.06575	0.373644	0.53571	0.1041667
	1.5	-1.07161	0.372126	0.409532	0.544668
	3.5	-1.07527	0.371071	0.334705	0.836618
	5	-1.07637	0.370735	0.312657	0.921793
So/Du	2.0/0.03	-1.06575	0.373644	0.53571	0.1041667
	1.5/0.04	-1.07658	0.368827	0.529849	0.336632
	1.0/0.06	-1.08698	0.364181	0.518605	0.631516
	0.6/1.0	-1.09421	0.360956	0.496734	0.867529
Fw	0.2	-1.06575	0.373644	0.53571	0.0416671
	0.4	-1.11337	0.375062	0.585866	0.0560947
	-0.2	-0.983313	0.368022	0.455448	0.15761
	-0.4	-0.94007	0.363604	0.417237	0.189177
Ec	0.01	-1.06575	0.373644	0.53571	0.1041667
	0.03	-1.06619	0.373571	0.523712	0.0946876
	0.5	-1.06662	0.373498	0.511721	0.14767
	0.7	-1.06727	0.373388	0.493748	0.227074
A	0.1	-1.06575	0.373644	0.53571	0.1041667
	0.2	-0.789175	0.335588	0.511819	0.12434
	0.3	-0.639654	0.31433	0.498429	0.170779
	0.5	-0.538163	0.299609	0.489138	0.203044
Gm	0.5	-1.06575	0.373644	0.53571	0.1041667
	1.5	-1.09668	0.360421	0.519457	0.918138
	-0.5	-0.931626	0.433374	0.587967	-2.89758
	-1.5	-1.09474	0.34473	0.54307	-0.54721
Pr	0.71	-1.06575	0.373644	0.53571	0.1041667
	1.71	-1.04752	0.377431	0.959163	-1.7041
	3.71	-1.02101	0.381418	1.67114	-4.84043
	7.0	-0.993328	0.384657	2.61371	-9.27178

Table 2. Variations of Skin friction, Nusselt number and Sherwood number for various parameter

5. Conclusions

The problem relating to the influence of thermal radiation, radiation absorption, non-linear density temperature relation, mixed convective flow and heat and mass transfer in a circular annulus in the presence of heat generation/absorption has been analyzed. The linearity of the fluid is assumed to vary as an inverse linear function of temperature. The numerical results were obtained and compared with previously reported cases available in the literature and they were found to be in good agreement. Graphical results for various parametric conditions were presented and discussed for different values. The main findings are summarized below:

- An increase in the Hall parameter (m) enhances both the primary velocity and cross flow velocities, temperature and concentration distributions depreciate in the boundary layer. Increase in the Hall parameter (m) enhances the skin friction coefficient and enhances the rate of heat and mass transfer at the wall.

- An increase in Buoyancy ratio (N) enhances both the velocities when the buoyancy forces are acting in the same direction and the opposite effect is observed when the buoyancy forces are acting in the opposite direction. Temperature and concentration reduces with increase in N>0 and enhances with N<0.

- The primary velocity (f´) and cross flow velocity (g) reduces with increase in the chemical reaction parameter (γ) in both degenerating and generating chemical reaction cases. The temperature reduces in the degenerating chemical reaction case and enhances in the generating chemical reaction case. Whereas the concentration decreases with increasing values of the chemical reaction parameter inn both degenerating and generating chemical reaction cases.

- The skin friction enhances and Nusselt number reduces in both the degenerating and generating chemical reaction cases. The Sherwood number enhances in the degenerating chemical reaction case and reduces in the generating chemical reaction case.

- Higher the Thermal radiation parameter Rd larger the cross flow velocity and lesser the primary velocity. The presence of the thermal radiation, temperature increase rapidly in the boundary layer. The concentration reduces in the solutal boundary layer with increase in Rd.

- The presence of Eckert number Ec increases the temperature, both velocity components and reduces the concentration.

- The influence of increasing Soret parameter (So) (or decreasing Dufour parameter Du) results in an increase in both velocity components, concentration and leads a depreciation in temperature in the boundary layer.

- Higher the radiation absorption larger the primary, cross flow velocity components and temperature profiles in the boundary layer and reduces the species concentration in the boundary layer.

- The effect of heat generation/absorption parameter is to enhance the mass concentration marginally. The temperature enhances with heat generation and reduces with heat absorption. The primary and cross flow velocity enhances marginally with increase in heat generation ($A_1>0, B_1>0$), while both the velocities depreciates in the case of heat absorption ($A_1<0, B_1<0$).

- The primary and cross flow velocities decreases in the boundary layer with increase in slip velocity parameter A. The temperature and mass concentration enhances with increase in A. This can be attributed to the fact that thermal boundary layer and the solutal boundary layer increases with increase in the velocity slip parameter A.

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