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Radiation and Mass Transfer Effects on MHD Free Convective Flow along a Stretching Surface with Heat Generation and Chemical Reaction

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Abstract: The present paper analyzes the radiation effects on the heat and mass transfer characteristics of a viscous incompressible electrically conducting fluid near an isothermal vertical stretching sheet, in the presence of heat generation and chemical reaction. The governing equations are transformed by using similarity transformation and the resultant dimensionless equations are solved numerically using the Runge-Kutta fourth order method with shooting technique. The effects of various governing parameters on the velocity, temperature, concentration, skin-friction coefficient, Nusselt number, Sherwood number and chemical reaction are computed and discussed in detail.

I. INTRODUCTION

The incompressible flow of viscous fluids due to a stretching surface has become increasingly important in the last years due to the extensive engineering applications. Such applications include the aerodynamic extrusion of plastic sheets, the boundary layer along a liquid film condensation process, the cooling bath and the glass and polymer industries. There exists also a lot of work done on stretching surface with the speed proportional to the distance from the origin and less attention is given to the flow over an exponentially stretching sheet.

Crane [3] was the first to study the steady two-dimensional boundary layer flow due to a stretching surface in a viscous and incompressible quiescent fluid, and presented an exact analytical solution. Subsequently, many authors have considered various aspects of this problem and obtained similarity solutions. The paper by Magyari and keller [13,14,15], and Liao and Pop [10] contain a good amount of references on this problem. Chiam [5] have investigated the steady two dimensional stagnation point flow of an incompressible viscous fluid over a flat deformable sheet when the sheet is stretched in its own plane with a velocity potential to the distance from the stagnation point. It is shown that a boundary layer depends on the ratio of the velocity of the stretching surface to that of the frictionless potential flow in the neighborhood of the stagnation point. This problem was then extended by Nazar et al [16] to the boundary layer flow past a stretching sheet in an incompressible micro polar fluid.

over a flat The study of the boundary layer behavior on continuous surfaces is important because the analysis of such flows finds applications in different areas such as the aerodynamic extrusion of plastic sheet, the cooling of a metallic plate in a cooling bath, the boundary layer along material handling conveyers, and the boundary layer along a liquid film in condensation processes. As examples on stretched sheets, 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, when these strips are stretched.

The flow near a stagnation point has attracted many investigations during the past several decades of its wide applications such as cooling of electronic devices by fans, cooling of nuclear reactors, and many hydrodynamic processes. Ramachandran et al. [17] studied the laminar mixed convection in two dimensional stagnation flows around heated surfaces by considering both cases of an arbitrary surface heat flux variations. The found that a reverse flow developed in the buoyancy opposing flow region, and dual solutions are found to exist for a certain rang of the buoyancy parameter. This work was the extended by Devi et al.[6] to unsteady case, and by Lok et al. [12] to a vertical surface immersed in a micropolar fluid. Dual solutions were found to exist by these authors for certain range of buoyancy parameter. The existence of dual solutions in the opposing flow case was also reported recently by Chin et al. [4], Ling et al. [11] and Ishak et al. [8,9].

At high operating temperatures, radiation effect can be quite significant. Many processes in engineering areas occur at high temperatures and knowledge of radiation heat transfer becomes very important for the design of the pertinent equipment. Nuclear power plants, gas turbines and various propulsion devices for aircraft, missiles, satellites and space vehicles are example of such engineering areas. Takhar *et al.*[18] studied the radiation effects on MHD free convection flow for nongray-gas past semi-infinite vertical plate. Anki Reddy and Bhaskar Reddy [2] analyzed the thermal radiation effects on hydromagnetic flow due to an

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exponentially stretching sheet. Aliakbar et al. [1] investigated the influence of thermal radiation on MHD flow of Maxwellian fluids above stretching sheets. Ghaly and Elbarbary [7] reported the effect of radiation on free convection flow on MHD along a stretching surface with uniform free stream.

However the interaction of radiation with mass transfer of an electrically conducting and diffusing fluid past a stretching surface has received little attention. Hence an attempt is made to investigate the radiation effects on a steady free convection flow near an isothermal vertical stretching sheet in the presence of a magnetic field and heat generation and chemical reaction.

II. MATHEMATICAL ANALYSIS

A steady two-dimensional free convection flow of a viscous incompressible, electrically conducting and radiating fluid adjacent to a vertical stretching sheet with mass transfer and heat generation is considered. The flow is assumed to be in the direction of x' -axis, taken along the vertical plate and the y' - axis normal to the plate. Two equal and opposite forces are introduced along the x' -axis, so that the sheet is stretched keeping the origin fixed. The plate is maintained at a constant temperature T_w', which is higher than the constant temperature T_∞' of the surrounding fluid and a constant concentration C_w', which is greater than the constant concentration C_∞' of the surrounding fluid. A uniform magnetic field is applied in the direction perpendicular to the plate. The fluid is assumed to be slightly conducting, and hence the induced magnetic field is negligible in comparison with the applied magnetic field. It is further assumed that there is no applied voltage, so that electric field is absent. The fluid is considered to be a gray, absorbing emitting radiation but non-scattering medium and the Rossel and approximation is used to describe the radiative heat flux in the energy equation. It is also assumed that all the fluid properties are constant except that of the influence of the density variation with temperature and concentration in the body force term (Boussinesq’s approximation).

Then, under the above assumptions, the governing boundary layer equations are

$$\frac{\partial u'}{\partial x'}+\frac{\partial v'}{\partial y'}=0 \qquad (1)$$

$$u'\frac{\partial u'}{\partial x'}+v'\frac{\partial u'}{\partial y'}=\nu\frac{\partial^2 u'}{\partial y'^2}-\frac{\sigma_0 B_0^2}{\rho}u'+g\beta(T'-T_\infty')+g\beta^*(C'-C_\infty') \qquad (2)$$

$$u'\frac{\partial T'}{\partial x'}+v'\frac{\partial T'}{\partial y'}=\frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y'}+Q_0(T'-T_\infty') \qquad (3)$$

$$u'\frac{\partial C'}{\partial x'}+v'\frac{\partial C'}{\partial y'}=D\frac{\partial^2 C'}{\partial y'^2}+kr^2(C'-C_\infty') \qquad (4)$$

where u' and v' are the velocity components in the x' and y' directions respectively, T' - the temperature of the fluid in the boundary layer, C' - the species concentration in the boundary layer, g - the acceleration due to gravity, ν is the fluid kinematics viscosity, ρ - the density, σ_0 - the electric conductivity of the fluid, β and $\beta*$ - the coefficients of thermal and concentration expansions respectively, k - the thermal conductivity, C_p- the specific heat at constant pressure, μ - the viscosity, B_0 - the magnetic induction, , Q_0 - the heat generation/absorption , D- the mass diffusivity and q_r is the radiative heat flux.

The boundary conditions for the velocity, temperature and concentration fields are

$$u'=cx,\ v'=0,\ T'=T_w',\ C'=C_w' \ \text{at}\ y=0$$

$$u'\to u_\infty',\ T'\to T_\infty',\ C'\to C_\infty' \ \text{as}\ y\to\infty \qquad (5)$$

where $c>0$, and u_∞ is the free stream velocity.

By using the Rosseland approximation [19], we have

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T'^4}{\partial y'} \quad (6)$$

where σ^* is the Stefan-Boltzmann constant and k^* is the mean absorption coefficient. By using (6), the energy equation (3) becomes

$$u'\frac{\partial T'}{\partial x'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2} + \frac{4\sigma^*}{3k^*\rho c_p}\frac{\partial^2 T'^4}{\partial y'^2} + Q_0(T' - T'_\infty) \quad (7)$$

In order to write the governing equations and the boundary conditions in dimensionless form, the following non-dimensional quantities are introduced.

$$x = \frac{cx'}{u'_\infty}, \quad y = \frac{cy'}{u'_\infty}R, \quad u = \frac{u'}{u'_\infty}, \quad v = \frac{v'}{u'_\infty}R, \quad R = \frac{u_\infty}{\sqrt{cv}} \quad \theta = \frac{T' - T''_\infty}{T'_w - T'_\infty},$$

$$\phi = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \; M = \frac{\sigma_0 B_0^2}{\rho c}, \; Gr = \frac{g\beta(T'_w - T'_\infty)}{cu'_\infty}, \; Gc = \frac{g\beta^*(C'_w - C'_\infty)}{cu'_\infty}, \quad (8)$$

$$\Pr = \frac{\mu c_p}{k}, \quad Q = \frac{Q_0}{c\rho c_p}, \quad Sc = \frac{v}{D}, \quad F = \frac{kk^*}{4\sigma^* T_\infty^3}, \quad r = \frac{T'_w - T'_\infty}{T'_\infty}, \quad kr^2 = \frac{kr^2}{C'_\infty}$$

In view of the equation (8), the equations (1), (2), (4) and (7) reduce to the following non-dimensional form.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (9)$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} - Mu + Gr\theta + Gc\phi \quad (10)$$

$$u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} + \frac{4}{3F\Pr}\left((1+r\theta)^3\frac{\partial^2\theta}{\partial y^2} + 3r(1+r\theta)^2\left(\frac{\partial\theta}{\partial y}\right)^2\right) + Q\theta \quad (11)$$

$$u\frac{\partial \phi}{\partial x} + v\frac{\partial \phi}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} - kr^2\phi \quad (12)$$

The corresponding boundary conditions are

$$u = x, \quad v = 0, \quad \theta = 1, \quad \phi = 1 \quad \text{at} \quad y = 0$$

$$u = 1, \quad \theta = 0, \quad \phi = 0 \quad \text{as} \quad y \to \infty \quad (13)$$

where R, Gr, Gc, Pr, Q, F, r, kr and Sc are the Reynolds number , thermal Grashof number, solutal Grashof number, Prandlt number ,heat generation parameter, radiation parameter, the relative difference between the temperature of the sheet and the temperature far away from the sheet and Schmidt number respectively.

Introducing a dimensionless stream function ψ defined in the usual way

$$u = \frac{\partial\psi}{\partial y}, v = -\frac{\partial\psi}{\partial x} \quad (14)$$

the continuity equation (9) is identically satisfied and the momentum equation (10), energy equation (11) and concentration equation (12) becomes

$$\frac{\partial\psi}{\partial y}\frac{\partial^2\psi}{\partial x\partial y} - \frac{\partial\psi}{\partial x}\frac{\partial^2\psi}{\partial y^2} = \frac{\partial^3\psi}{\partial y^3} - M\frac{\partial\psi}{\partial y} + Gr\theta + Gc\phi \quad (15)$$

$$\frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x} - \frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2\theta}{\partial y^2} + \frac{4}{3F\Pr}\left((1+r\theta)^3\frac{\partial^2\theta}{\partial y^2} + 3r(1+r\theta)^2\left(\frac{\partial\theta}{\partial y}\right)^2\right) + Q\theta \quad (16)$$

$$\frac{\partial\psi}{\partial y}\frac{\partial\phi}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\phi}{\partial y}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2}-kr^2\phi \tag{17}$$

and the boundary conditions (13) become

$$\frac{\partial\psi}{\partial y}=x\,,\quad \frac{\partial\psi}{\partial x}=0\,,\quad \theta=1\,,\quad \phi=1 \quad \text{at}\quad y=0,$$

$$\frac{\partial\psi}{\partial y}\to 1\,,\ \theta\to 0\,,\ \phi\to 0 \qquad \text{as}\ y\to\infty \tag{18}$$

Introducing

$$\psi(x,y)=f(y)+xg(y)\,, \tag{19}$$

in equations (15), (16) and (17) and equating the coefficient of x^0 and x^1, we obtain the coupled non-linear ordinary differential equations

$$f'''=f'g'-gf''+Mf'-Gr\theta-Gc\phi \tag{20}$$

$$g'''=(g')^2-gg''+Mg' \tag{21}$$

$$(3F+4(1+r\theta)^3)\theta''+3\Pr Fg\theta'+12r(1+r\theta)^2\theta'^2+3F\Pr Q\theta=0 \tag{22}$$

$$\phi''+Scg\phi'-kr^2Sc\phi=0 \tag{23}$$

Where a prime denotes differentiation with respect to y.

In view of (19), the boundary conditions (18) reduce to

$$f=0\,,\ f'=0\,,\ g=0\,,\ g'=1\,,\ \theta=1\,,\ \phi=1 \quad \text{at}\quad y=0$$

$$f'\to 1\,,\ g'\to 0\,,\ \theta\to 0\,,\ \phi\to 0 \quad \text{as}\ y\to\infty \tag{24}$$

The physical quantities which are of importance for this type problem are the skin friction coefficient, the Nusselt number and Sherwood number, which are defined by

$$\tau_w=\mu\left(\frac{\partial u'}{\partial y'}\right)_{y'=0},\qquad Nu=\frac{q_w}{k(T'_w-T'_\infty)}\,,\ Sh=\frac{M_w}{D(C'_w-C'_\infty)} \tag{25}$$

where

$$q_w=-k\left(\frac{\partial T'}{\partial y'}\right)_{y'=0},\ M_w=-D\left(\frac{\partial C'}{\partial y'}\right)_{y'=0} \tag{26}$$

Using (19), the quantities in (26) can be expressed as

$$\tau_w=\mu cR\left(\frac{\partial u}{\partial y}\right)_{y=0}=\mu cR[f''(0)+xg''(0)]\ ,$$

$$Nu=\frac{cR}{u_\infty}\theta'(0)\,,\ Sh=\frac{cR}{u_\infty}\phi'(0)\,. \tag{27}$$

III. SOLUTION OF THE PROBLEM

The equations (20) - (23) are coupled and non-linear partial differential equations and hence analytical solution is not possible. Hence the dimensionless governing equations are solved numerically using the fourth-order Runge-Kutta method with shooting technique. The shooting method for linear equations is based on replacing the boundary value problem by two initial value problems, and solution of the boundary value problem is a linear combination between the solutions of the two initial value problems. The shooting method for the nonlinear boundary value problem is similar to the linear case, except that the solution of the nonlinear problem can not be simply expressed as a linear combination between the solutions of the two initial value problems. The numerical computations have been done by the symbolic computation software Mathematica. The fourth-order Runge-Kutta method is used to solve the initial value problems. The equation (2.23)being linear, solving it analytically, we directly get ϕ. The numerical approach is carried out in two stages. Solving the equation (21) by the nonlinear shooting method we obtain g. Hence, equations (20) and (22) reduce to a system of linear equations with variable coefficients which could be solved by the linear shooting method to obtain f and θ. The functions f', g', θ and ϕ are shown in figures.

IV. RESULTS AND DISCUSSION

As a result of the numerical calculations, the dimensionless velocity, temperature and concentration distributions for the flow under consideration are obtained and their behavior have been discussed for variations in the governing parameters viz., the thermal Grashof number *Gr*, solutal Grashof number *Gc*, magnetic filed parameter *M*, Radiation parameter *F*, the parameter of relative difference between the temperature of the sheet and temperature far away from the sheet *r*, Prandtl number *Pr*, heat generation parameter *Q* , Schmidt number *Sc* and Chemical reaction parameter kr. In the present study, the following default parametric values are adopted. *Gr* = 2.0, *Gc* = 2.0, *M* = 0.5, *Pr* = 0.71, *F* = 1.0, *r* = 0.05, *Q* = 0.1, *Sc* = 0.6, kr=0.5. All graphs therefore correspond to these unless specifically indicated on the appropriate graph.

Fig.1. shows the variation of the dimensionless velocity component f' for several sets of values of thermal Grashof number *Gr*. As expected, it is observed that there is a rise in the velocity due to enhancement of thermal buoyancy force. Here, the positive values of *Gr* correspond to cooling of the plate. Also, as *Gr* increases, the peak values of the velocity increases rapidly near the plate and then decays smoothly to the free stream velocity.

The variation of the dimensionless velocity component f' for several sets of values of solutal Grashof number *Gc* is depicted in Fig.2. As expected, the fluid velocity increases and the peak value is more distinctive due to increase in the species buoyancy force. The velocity distribution attains a distinctive maximum value in the vicinity of the plate and then decreases properly to approach the free stream value.

For various values of the magnetic parameter *M*, the dimensionless velocity component f' is plotted in Fig.3(a). It can be seen that as *M* increases, the velocity decreases. As M increases, the Lorentz force, which opposes the flow, also increases and leads to enhanced deceleration of the flow. This result qualitatively agrees with the expectations, since the magnetic filed exerts a retarding force on the free convection flow. Fig.3(b). shows that the dimensionless temperature profiles for different values of magnetic parameter *M*. It is observed that the temperature increases with an increase in the magnetic parameter *M*.

Fig.4 (a). illustrates the dimensionless velocity component f' for different values of the Prandtl number *Pr*. The numerical results show that the effect of increasing values of Prandtl number results in a decreasing velocity. From Fig.4(b), it is observed that an increase in the Prandtl number results a decrease of the thermal boundary layer thickness and in general lower average temperature with in the boundary layer. The reason is that smaller values of *Pr* are equivalent to increasing the thermal conductivities, and therefore heat is able to diffuse away from the heated plate more rapidly than for higher values of *Pr*. Hence in the case of smaller Prandtl numbers as the boundary layer is thicker and the rate of heat transfer is reduced.

The effect of the Radiation parameter *F* on the dimensionless velocity component f' and dimensionless temperature are shown in Figs. 5(a) and 5(b) respectively. Fig.5 (a) shows that velocity component f' decreases with an increase in the radiation parameter *F*. From Fig.5(b) it is seen that the temperature decreases as the radiation parameter *F* increases. This result qualitatively agrees with expectations, since the effect of radiation is to decrease the rate of energy transport to the fluid, thereby decreasing the temperature of the fluid.

The influence of the parameter of relative difference between the temperature of the sheet and the temperature far away from the sheet *r* on dimensionless velocity f' and temperature profiles are plotted in Figs. 6(a) and 6(b) respectively. Fig.6(a) shows that dimensionless velocity f' increases with an increase in *r*. It is observed that the temperature increases with an increase in *r* (Fig.6 (b)).

Figs. 7(a) and 7(b) depict the dimensionless velocity f' and temperature profiles for different values of the heat generation parameter *Q*. It is noticed that an increase in the heat generation parameter *Q* results in an increase in the dimensionless velocity f' and temperature with in the boundary layer.

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The influence of the Schmidt number *Sc* on the dimensionless velocity f' and concentration profiles are plotted in Figs. 8(a) and 8(b) respectively. As the Schmidt number increases the concentration decreases. This causes the concentration buoyancy effects to decrease yielding a reduction in the fluid velocity. The reductions in the velocity and concentration profiles are accompanied by simultaneous reductions in the velocity and concentration boundary layers. These behaviors are clear from Figs. 8(a) and 8(b).The effect of various parameters on the functions f'', g'', θ' and ϕ' at the plate surface is tabulated in Tables 1 and 2 for $r = 0.05$. It is observed that the magnitude of the wall temperature gradient increases as Prandtl number *Pr* or radiation parameter *F* increases, while it decreases as the magnetic parameter *M* or the heat source/sink parameter *Q* increases. The magnitude of the wall concentration gradient decreases as the magnetic field parameter *M* increases, while it increases with an increase in the Schmidt number *Sc*. Further more, the negative values of the wall temperature and concentration gradients, for all values of the dimensionless parameters, are indicative of the physical fact that the heat flows from the sheet surface to the ambient fluid.

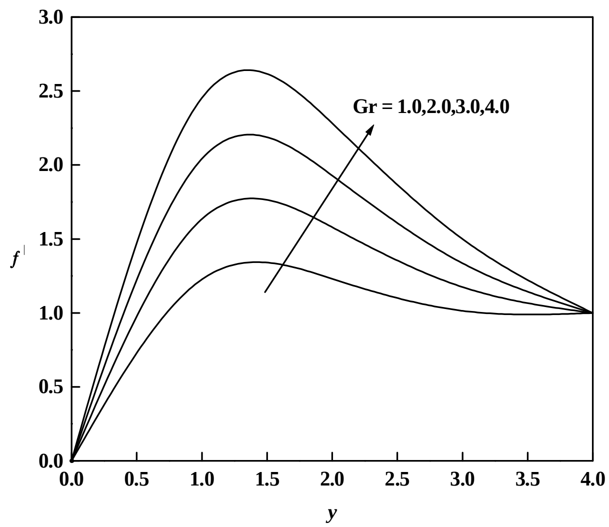

Fig.1 Variation of the velocity component f' with *Gr*

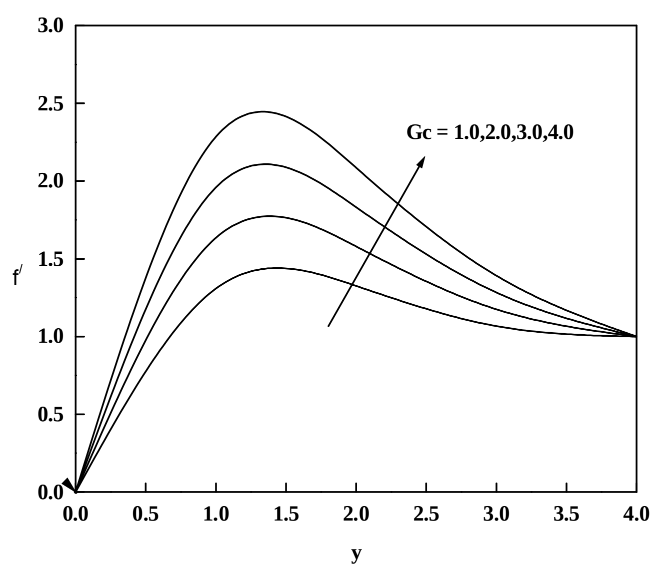

Fig.2 Variation of the velocity component f' with *Gc*

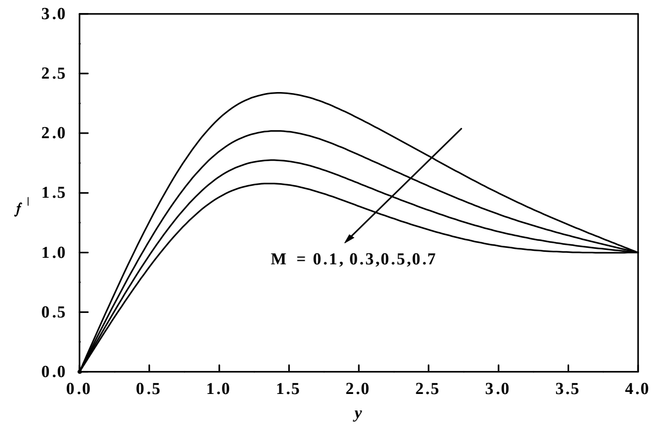

Fig.3 (a) Variation of the velocity component f' with M

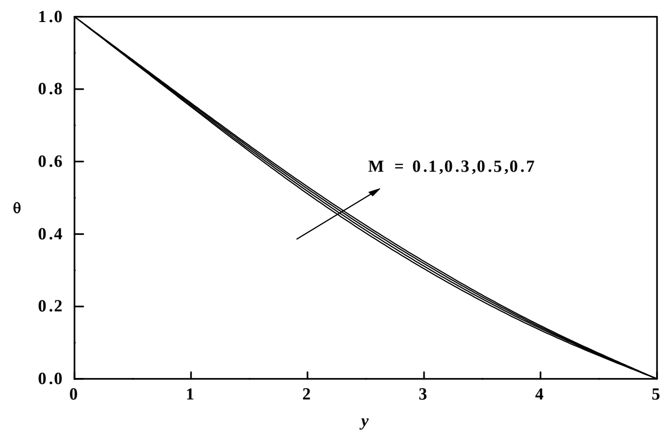

Fig.3 (b) Variation of the temperature with M

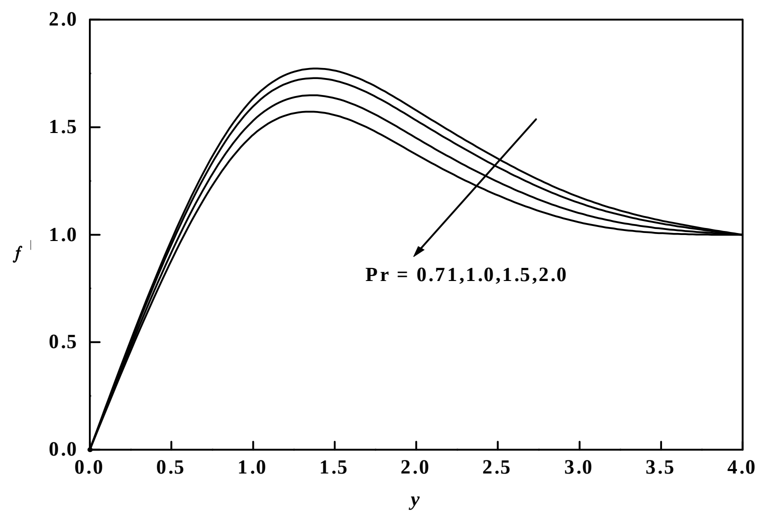

Fig.4(a) Variation of the velocity component f' with Pr

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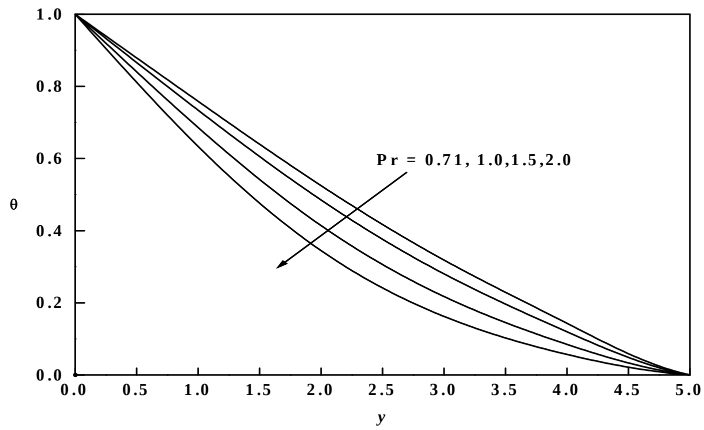

Fig.4(b) Variation of the temperature with *Pr*

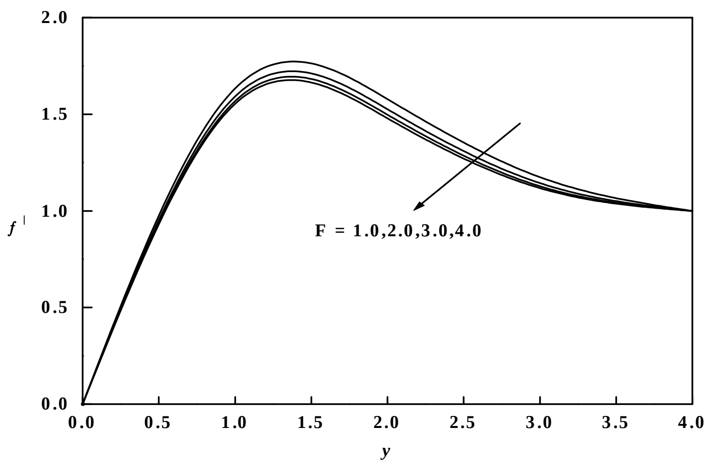

Fig .5(a) Variation of the velocity component f' with *F*

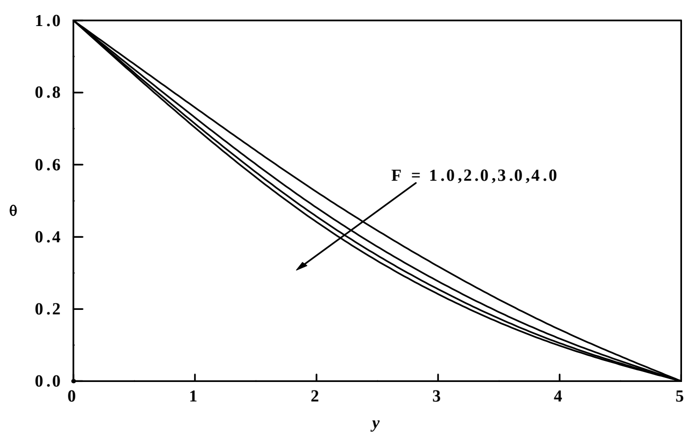

Fig.5 (b) Variation of the temperature with *F*

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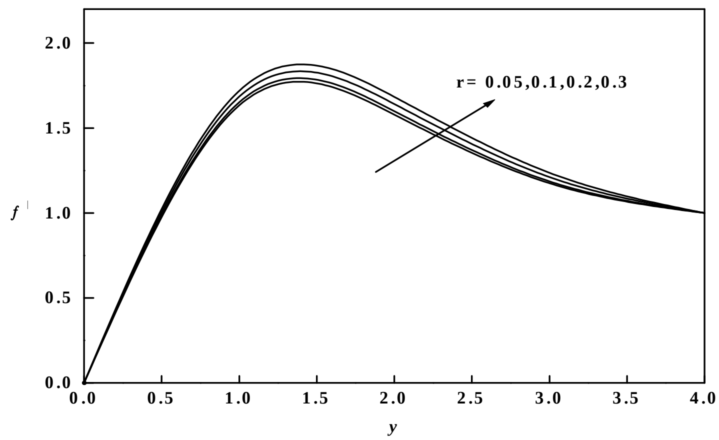

Fig.6 (a) Variation of the velocity component f' with r

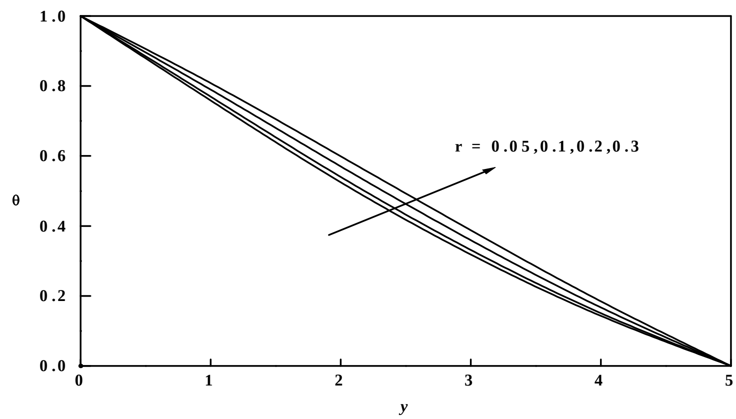

Fig.6(b) Variation of the temperature with r

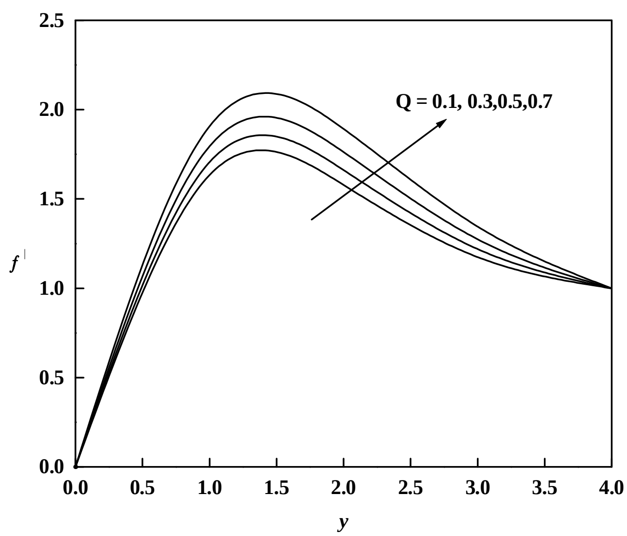

Fig.7(a)Variation of the velocity component f' with Q

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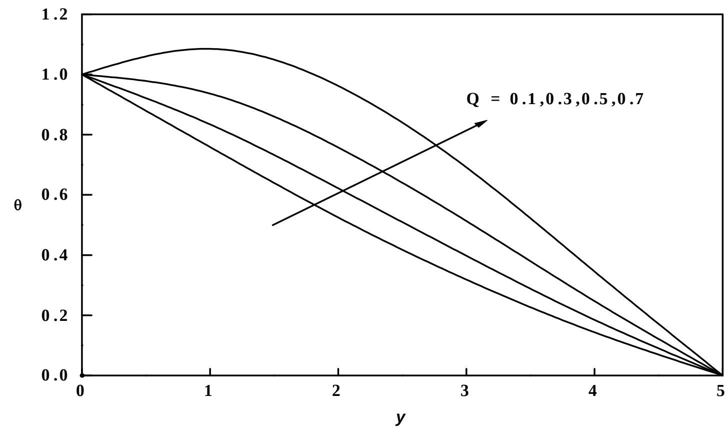

Fig.7(b) Variation of the temperature with Q

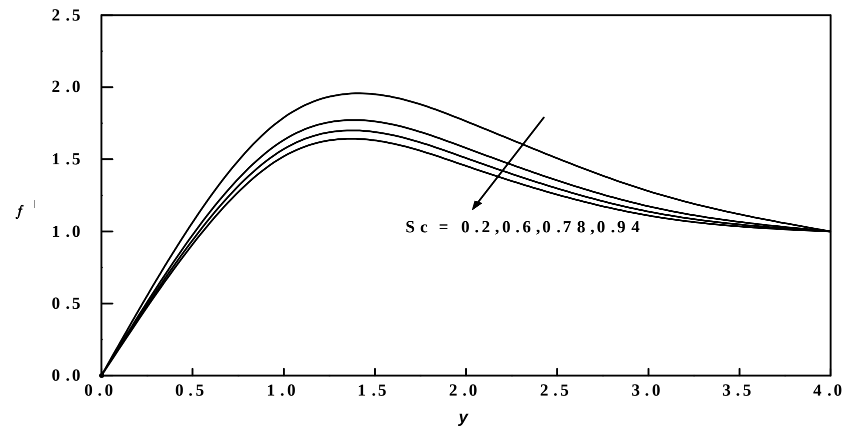

Fig.8 (a) Variation of the velocity component f' with *Sc*

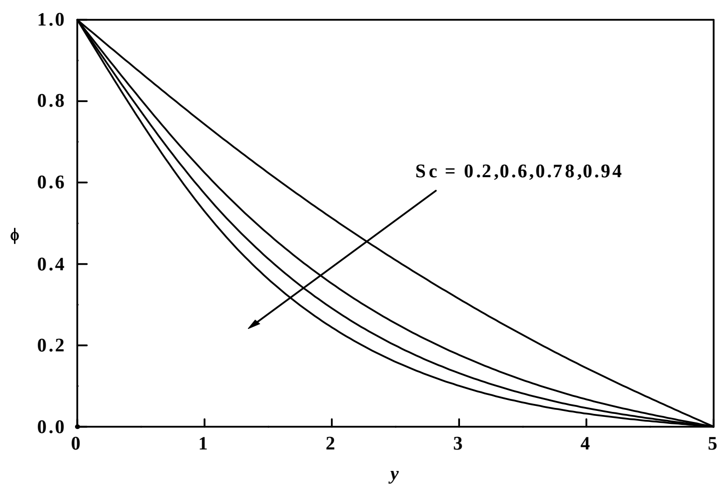

Fig.8(b) Variation of the concentration with *Sc*

Table 1 Variation of f'', g'', θ', ϕ' at the plate with *Gr, Gc, M* for *Pr* = 0.71, *F* = 1.0, *r* = 0.05, *Q* = 0.1, *Sc* = 0.6, kr=0.5.

Gr	***Gc***	***M***	$f''(0)$	$g''(0)$	$\theta'(0)$	$\phi'(0)$
2.0	2.0	0.5	5.5646	-1.2256	-0.285343	-0.697237
3.0	2.0	0.5	7.1043	-1.2256	-0.285343	-0.697237
2.0	3.0	0.5	6.60829	-1.2256	-0.285343	-0.697237
2.0	2.0	1.0	3.99946	-1.41442	-0.277459	-0.687319

Table 2 Variation of f'', g'', θ', ϕ' at the plate with *Pr, F, Q, Ec, Sc* for *Gr = 2.0 , Gc = 2.0,*

Pr	*F*	*Q*	*Sc*	*kr*	$f''(0)$	$g''(0)$	$\theta'(0)$	$\phi'(0)$
0.71	1.0	0.1	0.6	0.5	5.5646	-1.2256	-0.285343	-0.697237
1.0	1.0	0.1	0.6	0.5	5.49202	-1.2256	-0.24783	-0.697237
0.71	2.0	0.1	0.6	0.5	5.47976	-1.2256	-0.312753	-0.697237
0.71	1.0	0.15	0.6	0.5	5.61013	-1.2256	-0.266714	-0.697237
0.71	1.0	0.1	0.78	0.5	5.36079	-1.2256	-0.285343	-0.800796
0.71	1.0	0.1	0.6	1.0	5.27293	-1.2256	-0.285343	-0.891036

V. CONCLUSIONS

A. The dimensionless velocity component f' increases with an increase of Grashof number *Gr,* solutal Grashof number Gc, the parameter of relative difference between the temperature of the sheet and the temperature far away from the sheet *r*, heat generation parameter Q and chemical reaction rate constant kr .

B. The dimensionless velocity component f' decreases with an increase of Magnetic field parameter M, Prandtl number Pr, radiation parameter F and Schmidt number Sc.

C. The dimensionless temperature component θ increases with an increase of Magnetic field parameter M, the parameter of relative difference between the temperature of the sheet and the temperature far away from the sheet *r* and heat generation parameter Q.

D. The dimensionless temperature component θ decreases with an increase of Prandtl number Pr and radiation parameter F.

E. The dimensionless concentration component ϕ decreases with an increase Schmidt number Sc and chemical reaction rate constant kr.

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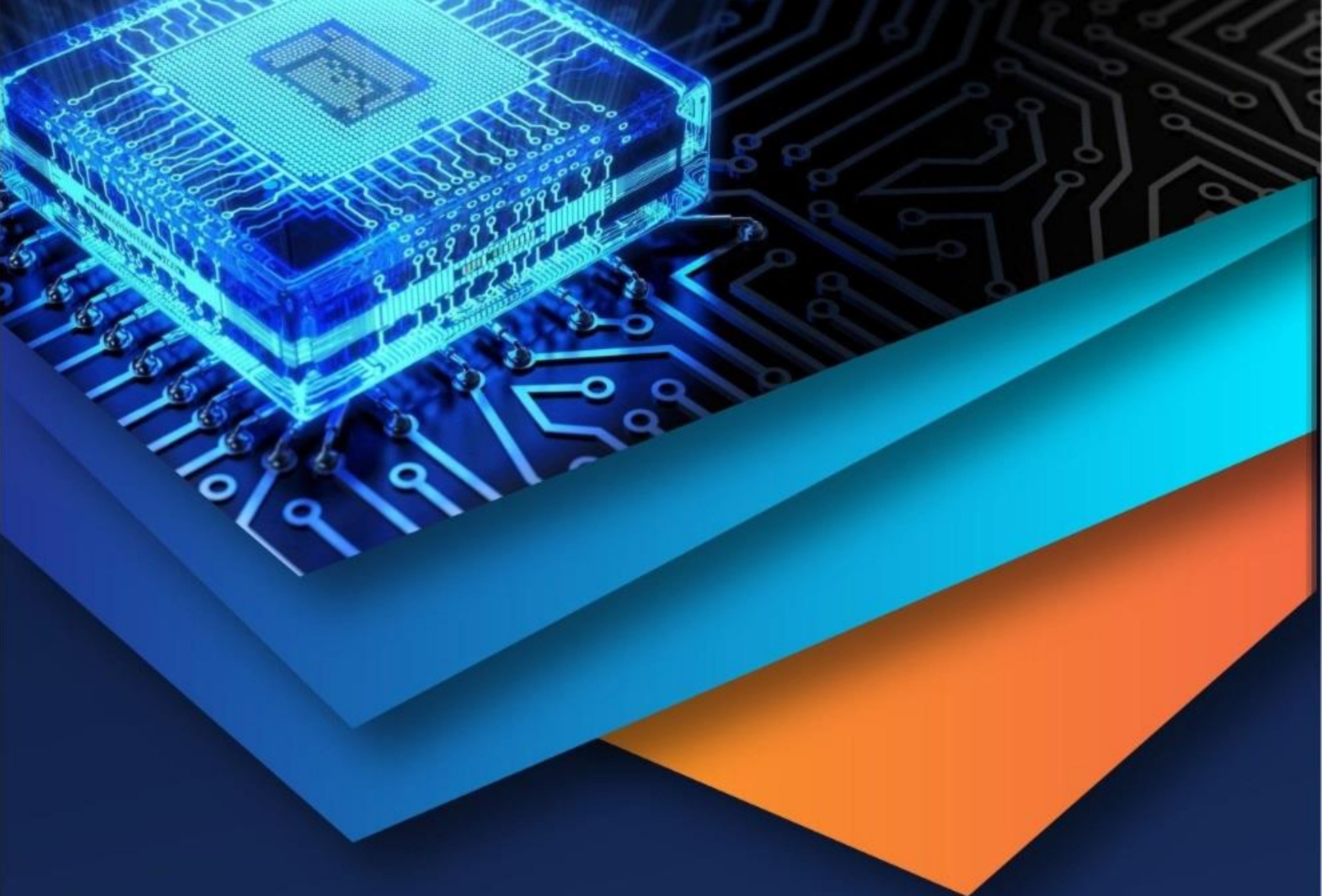

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