CHEMICAL REACTION AND HALL EFFECTS ON UNSTEADY FLOW PAST AN ISOTHERMAL VERTICAL PLATE IN A ROTATING FLUID WITH VARIABLE MASS DIFFUSION

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Abstract

This present paper investigates the effects of radiation, chemical reaction and porosity of the medium on unsteady flow of a viscous, incompressible and electrically conducting fluid past an exponentially accelerated vertical plate with variable wall temperature and mass diffusion in the presence of transversely applied uniform magnetic field. The plate temperature and the concentration level near the plate increase linearly with time. The fluid model under consideration has been solved by perturbation technique. The model contains equations of motion, diffusion equation and equation of energy. To analyze the solution of the model, reasonable sets of the values of the parameters have been considered. The numerical data obtained is discussed with the help of graphs.

Keywords*:* Hall Current, Radiation, Chemical reaction, MHD, Mass Diffusion

Introduction

The Magnetohydrodynamic (MHD) flow problems play important role in different areas of science and technology. These have many applications in industry, for instance, magnetic material processing, glass manufacturing control processes and purification of crude oil. Investigation of hydromagnetic natural convection flow with heat and mass transfer in porous and non-porous media has drawn considerable attentions of several researchers owing to its applications in geophysics, astrophysics, aeronautics, meteorology, electronics, chemical, and metallurgy and petroleum industries. Magnetohydrodynamic (MHD) natural convection flow of an electrically conducting fluid with porous medium has also been successfully exploited in crystal formation.[1-11]

However, thermal radiation effects on hydromagnetic natural convection flow with heat and mass transfer play a vital role in manufacturing processes viz. glass production, design of fins, steel rolling, furnace design, casting and levitation, etc. Moreover, several engineering processes occur at very high temperatures where the knowledge of radiative heat transfer becomes indispensible for the design of pertinent equipment. Nuclear power plants, gas turbines and various propulsion devices for missiles, aircraft, satellites and space vehicles are examples of such engineering areas.[12-22]

The study of natural convection flow induced by the simultaneous action of thermal and solutal buoyancy forces acting over bodies with different geometries in a fluid with porous medium is prevalent in many natural phenomena and has varied a wide range of industrial applications. For example, the presence of pure air or water is impossible because some foreign mass may be present either naturally or mixed with air or water due to industrial emissions, in atmospheric flows. Natural processes such as attenuation of toxic waste in water bodies, vaporization of mist and fog, photosynthesis, transpiration, sea-wind formation, drying of porous solids, and formation of ocean currents occur due to thermal and solutal buoyancy forces developed as a result of difference in temperature or concentration or a combination of these two. Such configuration is also encountered in several practical systems for industry based applications viz. cooling of molten metals, heat exchanger devices, petroleum reservoirs, insulation systems, filtration, nuclear waste repositories, chemical catalytic reactors and processes, desert coolers, frost formation in vertical channels, wet bulb thermometers, etc. Considering the importance of such fluid flow problems.[23-33]

Mathematical Formulation

An unsteady hydromagnetic flow of fluid past an infinite isothermal vertical plate with varying mass diffusion exists. The fluid and the plate rotate in unison with a uniform angular velocity Ω' about the $z'-$ axis normal to the plate. Initially the fluid is assumed to be at rest and surrounds an infinite vertical plate with temperature T'_∞ and concentration C'_∞. A magnetic field of uniform strength B_0 is transversely applied to the plate. The $x'-$axis is taken along the plate in the vertically upward direction and the $z'-$axis is taken normal to the plate. The physical model of the problem shown in **fig. (1)**. At time $t' > 0$, the plate and the fluid are at the same temperature T'_∞ in the stationary condition with concentration level C'_∞ at all the points. At time $t' > 0$, the plate is subjected to a uniform velocity $u = u_0$ in its own plane against the gravitational force. The plate temperature and concentration level near the plate are raised uniformly and are maintained constantly thereafter. All the physical properties of the fluid are considered to be constant except the influence of the body force term. Then under the usual Boussinesq's approximation the unsteady flow equations are momentum equation, energy equation, and mass equation respectively.

Equation of Momentum:

$$\frac{\partial u'}{\partial t'} - 2\Omega' v = v\frac{\partial^2 u}{\partial z^2} - \frac{1}{\rho}\frac{\partial \rho}{\partial x} + g + \frac{B_0}{\rho} j_y \tag{1}$$

$$\frac{\partial v}{\partial t} - 2\,\Omega'\,u = v\,\frac{\partial^2 v}{\partial z^2} - \frac{B_0}{\rho} j_x \tag{2}$$

Equation of Energy

$$\rho c_p \frac{\partial T'}{\partial t'} = k\frac{\partial^2 T'}{\partial z^2} - \frac{\partial q}{\partial z} \tag{3}$$

Equation of diffusion

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C}{\partial z^2} - Kr'\left(C - C'_\infty\right) \tag{4}$$

As, no large velocity gradient here, the viscous term in equation (1) vanishes for small and hence for the outer flow, beside there is no magnetic field along $x-$direction gradient, so this results in,

$$0 = D\frac{\partial \rho}{\partial x} - p_{\infty} g \tag{5}$$

By eliminating the pressure term from equation (1) and (5), we obtain

$$\frac{\partial u'}{\partial t'} - 2\Omega' v = v\frac{\partial^2 u}{\partial z^2} - \frac{1}{\rho}\frac{\partial \rho}{\partial x} + \left(\rho_{\infty} - \rho\right) g + \frac{B_0}{\rho} j_y \tag{6}$$

The Boussinesq approximation gives

$$\rho_{\infty} - \rho = \rho_{\infty}\beta\left(T' - T'_{\infty}\right) + \rho_{\infty}\beta\left(C' - C'_{\infty}\right) \tag{7}$$

On using (2.7) in the equation (2.6) and noting that ρ_{∞} is approximately equal to 1, the momentum equation reduces to

$$\frac{\partial u'}{\partial t'} - 2\Omega' v = v\frac{\partial^2 u}{\partial z^2} + \frac{B_0}{\rho} j_y + g\ \beta\left(T' - T'_{\infty}\right) + g\ \beta^{*}\left(C' - C'_{\infty}\right) \tag{8}$$

The generalized Ohm’s law with Hall currents is taken into account and ion – slip and thermo-electric

$$j + \frac{\omega \mathrm{T}_e}{B_0}\left(j \times B\right) = \sigma\left[E + q \times B\right] \tag{9}$$

The equation (9) gives

$$j_x - m j_y = \sigma v B_0 \tag{10}$$

$$j_y - m j_x = \sigma u B_0 \tag{11}$$

where $m = \omega_e \mathrm{T}_e$ is Hall parameter.
Solving (10) and (11) for j_x and j_y, we have

$$j_x = \frac{\sigma B_0}{\left(1 + m^2\right)}\left(v - mu\right) \tag{12}$$

$$j_y = \frac{\sigma B_0}{\left(1 + m^2\right)}\left(u - mv\right) \tag{13}$$

where B_0 – Imposed magnetic field, m – Hall parameter, ν – Kinematic viscosity, Ω_z – Component of angular viscosity, Ω – Non-dimensional angular velocity, J_z – component of current density j, ρ – Fluid density, σ – Electrical conductivity, t' – Time, μ – Coefficient of viscosity, T – Temperature of the fluid near the plate, T_w – Temperature of the plate, θ – Dimensionless temperature, T_{∞} – Temperature of the fluid far away from the plate, C –

Dimensionless concentration, $\kappa-$Thermal conductivity, $\beta-$Volumetric coefficient of thermal expansion, $\beta^{*}-$Volumetric coefficient of expansion with concentration, $C'-$Species concentration in the fluid, C_w- Wall concentration, $C_\infty-$Concentration for away from the plate, $t-$ Non-dimensional time $(u,v,w)-$Components of velocity field F, $(U,V,W)-$Non dimensional velocity components, $(x,y,z)-$Cartesian co-ordinates.

On the use of (12) and (13), the momentum equations (8) and (2) become

$$\frac{\partial u'}{\partial t'}=v\frac{\partial^2 u}{\partial z^2}+2\Omega' v-\frac{\sigma\mu_e^2H_0^2}{\rho\left(1+m^2\right)}(u+mv)+g\ \beta\left(T'-T'_\infty\right)+g\ \beta^{*}\left(C'-C'_\infty\right) \quad (14)$$

$$\frac{\partial v}{\partial t'}=v\frac{\partial^2 u}{\partial z^2}+2\Omega v-\frac{\sigma\mu_e^2H_0^2}{\rho\left(1+m^2\right)}(v-mu) \quad (15)$$

$$\rho C_p\frac{\partial T}{\partial t'}=k\frac{\partial^2 T}{\partial z^2}-\frac{\partial q}{\partial z} \quad (16)$$

$$\frac{\partial C'}{\partial t'}=D\frac{\partial^2 C'}{\partial z^2}-Kr'\left(C-C'_\infty\right) \quad (17)$$

Due to small Coriolis force, the second term on the right side of the equation (14) and (15) comes into existence.

The boundary conditions are given by:

$$\begin{aligned}&u=0,\quad T=T_\infty^{*},\ \ C=C_\infty^{*}, && \forall\ \ y,t'\le 0\\ t'>0:\ &u=u_0,T\to T_w,C'=C'_\infty+\left(C'_w-C'_\infty\right) && at\quad y=0\\ &u\to 0,T\to T_\infty,C'\to C'_\infty && at\quad y\to\infty\end{aligned}$$

$$u=0,\quad T=T,\ \ C=C_\infty,\ v=0 \qquad \forall\ \ y,t'\le 0 \quad (18)$$

$$u\to u,T\to T_w,C'=C'_w,v=0\quad at\quad z=0\ \ for\ \ all\ t'\le 0 \quad (19)$$

The dimensionless quantities are introduced as follows:

$$\begin{aligned}&U=\frac{u}{u_0},V=\frac{v}{u_0},t=\frac{t'u_0^2}{v},Z=\frac{zu_0^2}{v^2},\Omega=\Omega\frac{v}{u_0^2},M^2=\frac{\sigma\mu_e^2H_0{}^2v}{2\rho u_0{}^2},\Pr=\frac{\mu c_p}{\kappa}\\ &Gr=\frac{g\beta v\left(T_\omega-T_\infty\right)}{u_0{}^3},Gc=\frac{g\beta^{*}v\left(C'_\omega-C'_\infty\right)}{u_0{}^3},R=\frac{16a^{*}\sigma v^2T_\infty^3}{k\,u_0^2},Kr=\frac{Kr'v}{u_0^2}\end{aligned} \quad (20)$$

where $Sc-$ Schmidt number, $Gr-$Thermal Grashof number, $Gc-$Mass Grashof number, $\Pr-$Prandtl number, $M-$Hartman number, $Kr-$Chemical reaction parameter, $R-$Radiation parameter.

Together with the equation (1), (2), (3) and (4), boundary conditions (18), (19), using (20), we have

$$\frac{\partial U}{\partial t}=\frac{\partial^2 U}{\partial Z^2}+2V\left(\Omega-\frac{2m^2}{1+m^2}\right)+\frac{2m^2}{1+m^2}U+Gr\ \theta+Gc\ C \tag{21}$$

$$\frac{\partial V}{\partial t}=\frac{\partial^2 V}{\partial Z^2}-2U\left(\Omega+\frac{2m^2}{1+m^2}\right)+\frac{2m^2}{1+m^2}\ V \tag{22}$$

The boundary conditions

$$\begin{array}{lll} U=0,\ \ \theta=0,\ \ C=0,\ \ V=0 & \forall & Z,t\le 0 \\ U\to 1,\ \ \theta\to 1,\ \ C\to t,\ \ V\to 0 & \forall & t>0 \end{array} \tag{23}$$

$$U\to 0,\ \ \theta\to 0,\ \ C\to 0,\ \ V\to 0 \quad \forall \quad t>0 \tag{24}$$

Now equations (21), (22) and the boundary conditions (23), (24) can be combined to give:

$$\frac{\partial F}{\partial t}=\frac{\partial^2 F}{\partial Z^2}-F\ a+Gr\ \theta+Gc\ C \tag{25}$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{\Pr}\frac{\partial^2 \theta}{\partial Z^2}-\frac{R}{\Pr}\ \theta \tag{26}$$

$$\frac{\partial C}{\partial t}=\frac{1}{Sc}\frac{\partial^2 C}{\partial Z^2}-Kr\ C \tag{27}$$

where $F=U+iV$ and $a=2\left[\frac{M^2}{\left(1+m^2\right)}+i\left(\Omega-\frac{M^2 m}{\left(1+m^2\right)}\right)\right]$

In this study the value of (rotation parameter) is taken to be $\Omega-\frac{M^2 m}{\left(1+m^2\right)}$, as a result of this the transverse velocity vanishes

with the boundary conditions

$$\begin{array}{llll} F=0,\ \ \theta=0,\ \ C=0 & & \forall & Z,t\le 0 \\ F\to 1,\ \ \theta\to 1,\ \ C\to t, & at\ Z=0 & \forall & t>0 \\ F\to 0,\ \ \theta\to 0,\ \ C\to 0, & at\ Z\to\infty & \forall & t>0 \end{array} \tag{28}$$

Method of Solution

Equation (25) – (27) are coupled, non – linear partial differential equations and these cannot be solved in closed – form using the initial and boundary conditions (28). However, these equations can be reduced to a set of ordinary differential equations, which can be solved analytically. This can be done by representing the velocity, temperature and concentration of the fluid in the neighborhood of the fluid in the neighborhood of the plate as

$$\begin{aligned} F(z,t) &= F_0(z)e^{i\omega t} \\ \theta(z,t) &= \theta_0(z)e^{i\omega t} \\ C(z,t) &= C_0(z)e^{i\omega t} \end{aligned} \qquad (29)$$

Substituting (29) in Equation (25) – (27) and equating the harmonic and non – harmonic terms, we obtain

$$F_0'' - \beta_3^2 F_0 = -Gr\,\theta_0 - GmC_0 \qquad (30)$$

$$\theta_0'' - \beta_2^2\theta_0 = 0 \qquad (31)$$

$$C_0'' - \beta_1^2 Sc\,C_0 = 0 \qquad (32)$$

The corresponding boundary conditions can be written as

$$\begin{aligned} &F_0 = 1,\ \theta_0 = 1,\ \ C_0 = t, && at\ Z = 0 \\ &F_0 = 0,\ \ \theta_0 = 0, C_0 = 0, && as\ Z \to \infty \end{aligned} \qquad (33)$$

Solving the equations (30) – (32) under the boundary condition (33), we get the solution for fluid velocity; temperature; concentration is expressed below using perturbation method:

$$F_0 = A_1 e^{-\beta_2 y} + A_2 e^{-\beta_1 y} + A_3 e^{\beta_3 y}$$

$$\theta_0 = e^{-\beta_2 y}$$

$$C_0 = t\ e^{-\beta_1 y}$$

In view of the above equation (29) becomes

$$\begin{aligned} F(z,t) &= \left\{A_1 e^{-\beta_2 y} + A_2 e^{-\beta_1 y} + A_3 e^{\beta_3 y}\right\} e^{i\omega t} \\ \theta(z,t) &= \left\{e^{-\beta_2 y}\right\} e^{i\omega t} \\ C(z,t) &= \left\{t\ e^{-\beta_1 y}\right\} e^{i\omega t} \end{aligned}$$

Coefficient of Skin-Friction

The coefficient of skin-friction at the vertical porous surface is given by

$$C_f = \left(\frac{\partial F}{\partial Z}\right)_{z=0} = -\left(\beta_2 A_1 + \beta_1 A_2 + \beta_3 A_3\right)$$

Coefficient of Heat Transfer

The rate of heat transfer in terms of Nusselt number at the vertical porous surface is given by

$$Nu = \left(\frac{\partial T}{\partial Z}\right)_{z=0} = -\beta_2$$

Sherwood number

$$Sh = \left(\frac{\partial C}{\partial Z}\right)_{Z=0} = t\ \beta_1$$

RESULTS AND DISSCUSSIONS

The problem has been formulated, analyzed and solved analytically using perturbation technique. The effect of parameters like thermal Grashof number (Gr), mass Grashof number (Gc), Schmidt number (Sc), Reaction parameter (K), Chemical reaction parameter (Kr), Radiation Parameter (R), Prandtl number $(\Pr)$, Hartmann number (M), Hall parameter (m) on Axial Velocity (F), Temperature (θ) and Concentration (C) are computed and intercepted through graphs.

The effects of Grashof numbers for heat and mass transfer (Gr, Gc) are illustrated in **Fig. (2)** respectively. The Grashof number for heat transfer signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. As expected, it is observed that there was a rise in the axial velocity due to the enhancement of thermal buoyancy force. Also, as (Gr) increases, the peak values of the velocity increases rapidly near the porous plate and then decays smoothly to the free stream velocity. The Grashof number for mass transfer (Gc) defines the ratio of the species buoyancy force to the viscous hydrodynamic force. 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. It is noticed that the velocity increases with increasing values of the Grashof number for mass transfer. The influences of the Schmidt number (Sc) on the axial velocity profiles are plotted in **Fig. (3)** respectively. It is noticed from this figure that, the axial velocity decrease on increasing Sc. The Schmidt number embodies the ratio of the momentum to the mass diffusivity. The Schmidt number therefore quantifies the relative effectiveness of momentum and mass transport by diffusion in the hydrodynamic (velocity) boundary layer. **Fig. (4)** display the effect of magnetic field parameter or Hartmann number (M) on axial velocity. It is seen from these figures that the axial velocity increases when M increases. That is the axial velocity fluid motion is retarded due to application of transverse magnetic field. This phenomenon clearly agrees with the fact that Lorentz force that appears due to interaction of the magnetic field and fluid axial velocity resists the fluid motion. The influence of the hall parameter (m) on axial velocity profiles is as shown in **Figs. (5)** respectively. It is observed from these figures that the axial velocity profiles increase with an increase in the hall parameter m. This is because, in general, the Hall currents reduce the resistance offered by the Lorentz force. This means that Hall currents have a tendency to increase the fluid velocity components. **Fig. (6)** illustrates the behaviour of axial velocity profiles for different values of the chemical reaction parameter(Kr). It is pertinent to mention that $(Kr > 0)$ corresponds to a destructive chemical reaction. It can be seen from the profiles that the axial velocity increases in the degenerating chemical reaction in the boundary layer. This is due to the fact that the increase in the rate of chemical reaction rate leads to thinning of a momentum in a boundary layer in degenerating chemical reaction. It can be seen from the profiles that the cross flow axial velocity reduces in the degenerating chemical reaction. It is evident from **Fig. (7)** that, the thermal radiation parameter (R)leads to increases in the axial velocity with increasing values of thermal radiation parameter. Thus, the **Fig. (7)** are in excellent agreement with the laws of Physics. Thus as R increases, the axial velocity increases. Now, from this figure, it may be inferred that radiation has a more significant effect on temperature than on velocity. Thus, the thermal radiation does not have a significant effect on the velocities but produces a comparatively more pronounced effect on the temperature of the mixture. It is noticed form **Fig. (8)** that the effects of rotation on the axial respectively. It is evident from **Fig. (8)** that, axial velocity increases on increasing in reaction parameter (K). This implies that rotation retards fluid flow in the axial velocity flow direction and accelerates fluid flow in the axial velocity flow direction in the boundary layer region. This may be attributed to the fact that when the frictional layer at the moving plate is suddenly set into the motion then the Coriolis force acts as a constraint in the main fluid flow. **Fig. (9)** Shows the temperature profile for different values of Prandtl number$(\Pr)$. It is observed that temperature increases with decrease in values of Prandtl number and also heat transfer is predominant in air when compared to water. **Fig. (10)** indicates that effect of radiation parameter (R) on the temperature profiles. It is deduced that temperature profiles decrease of the fluid near the plate decrease when radiation parameter are increased. Physically, thermal radiation causes a fall in temperature of the fluid medium and thereby causes a fall in kinetic energy of the fluid particles. This results in a corresponding decrease in fluid velocities. **Fig. (11)** shows a destructive type of chemical reaction because the concentration decreases for increasing chemical reaction parameter which indicates that the diffusion rates can be tremendously changed by a chemical reaction. This is due to the fact that an increase in the chemical reaction Kr causes the concentration at the boundary layer to become thinner, which decreases the concentration of the diffusing species. This decrease in the concentration of the diffusing species diminishes the mass diffusion. **Fig. (12)** represents the concentration profile for various values of Schmidt number(Sc). It is noticed that the concentration field decreases with increase in values of Schmidt number.

Appendix

$$\beta_1^2=(i\omega+Kr)Sc,\beta_2^2=(R+i\omega\Pr),\beta_3^2=(i\omega+a),A_1=-\frac{Gr}{\beta_2^2-\beta_3^2},A_2=-\frac{Gr\ t}{\beta_1^2-\beta_3^2}$$

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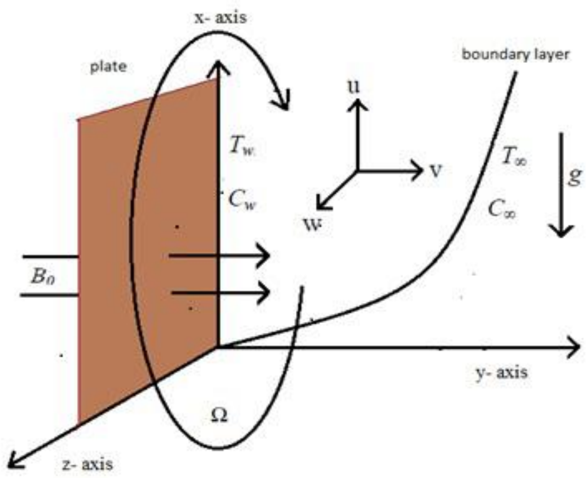

Fig. (1): The geometrical model of the problem

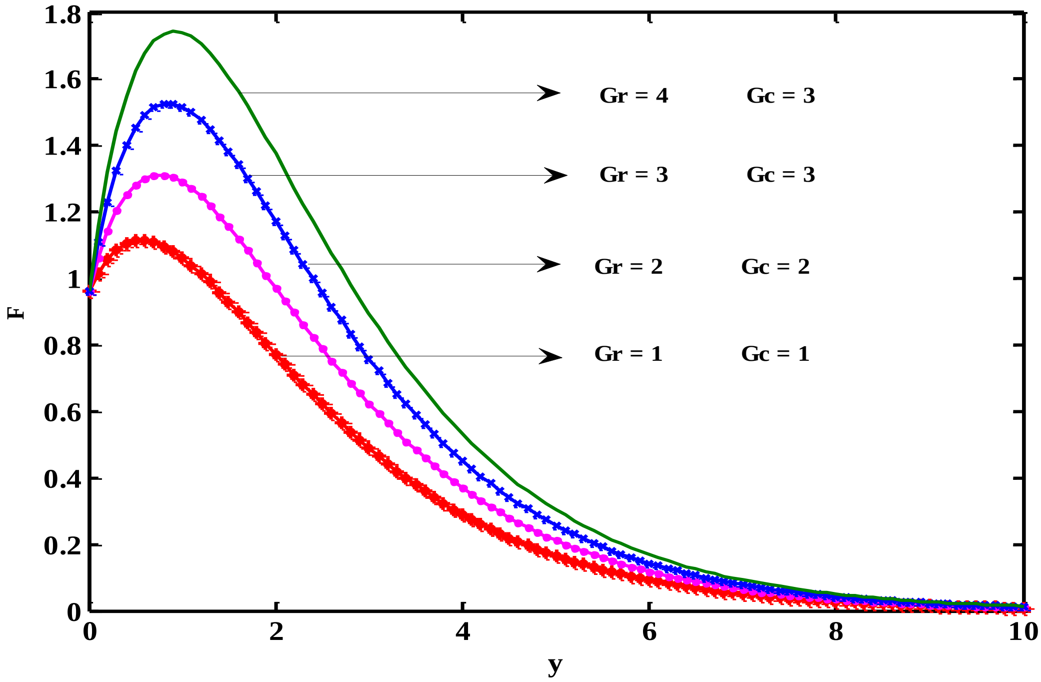

Fig. (2): Axial velocity profiles for different values of Gr, Gc

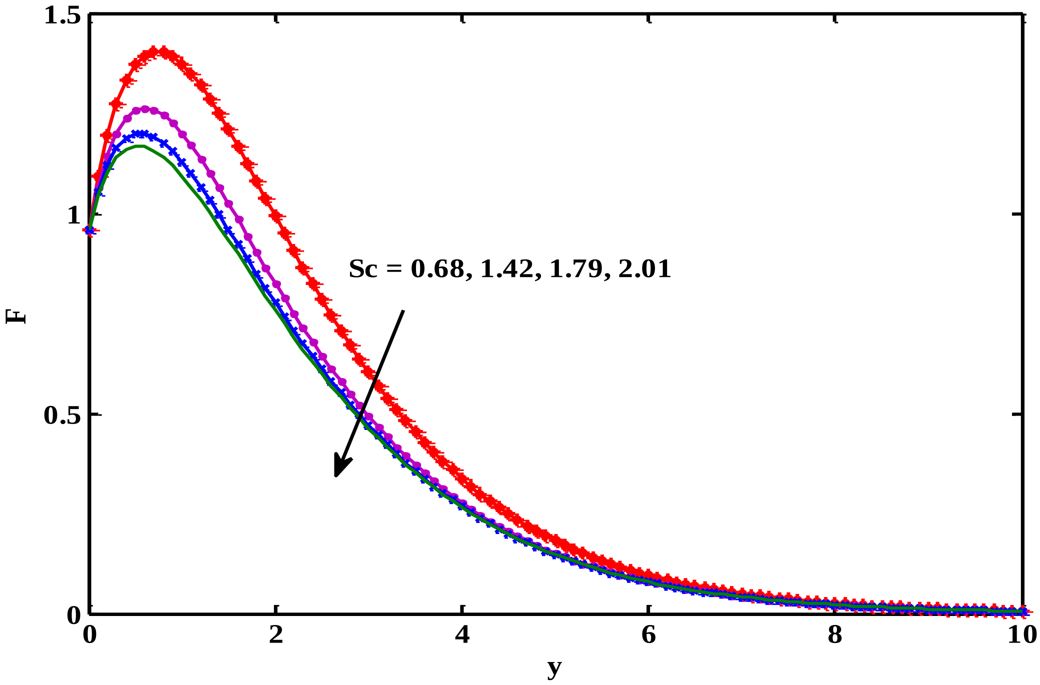

Fig. (3): Axial velocity profiles for different values of Sc

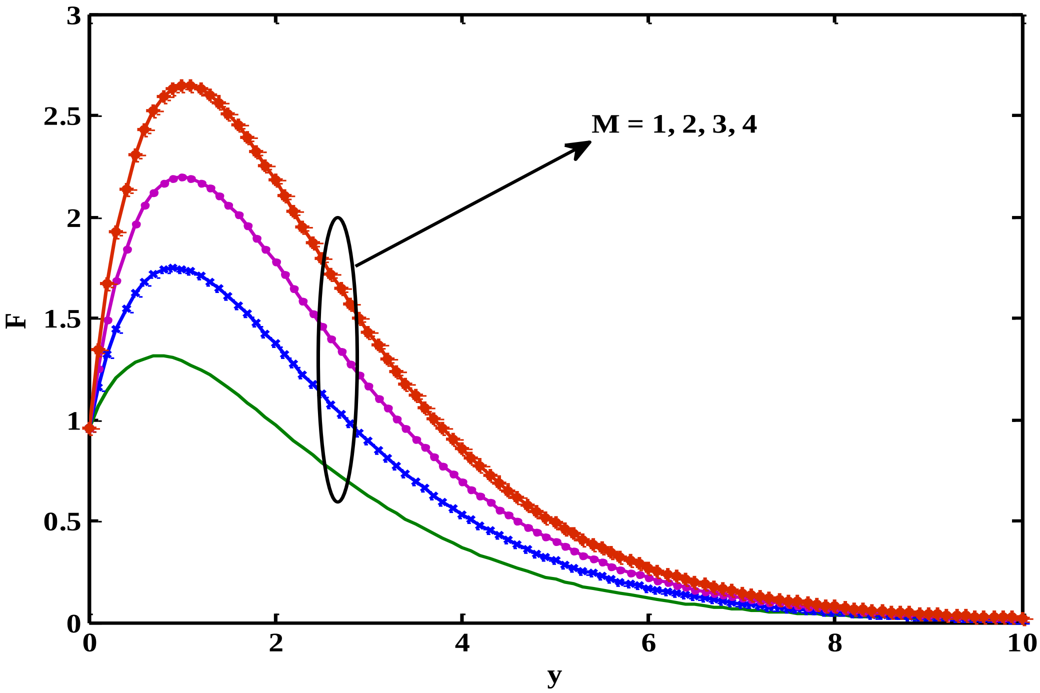

Fig. (4): Axial velocity profiles for different values of M

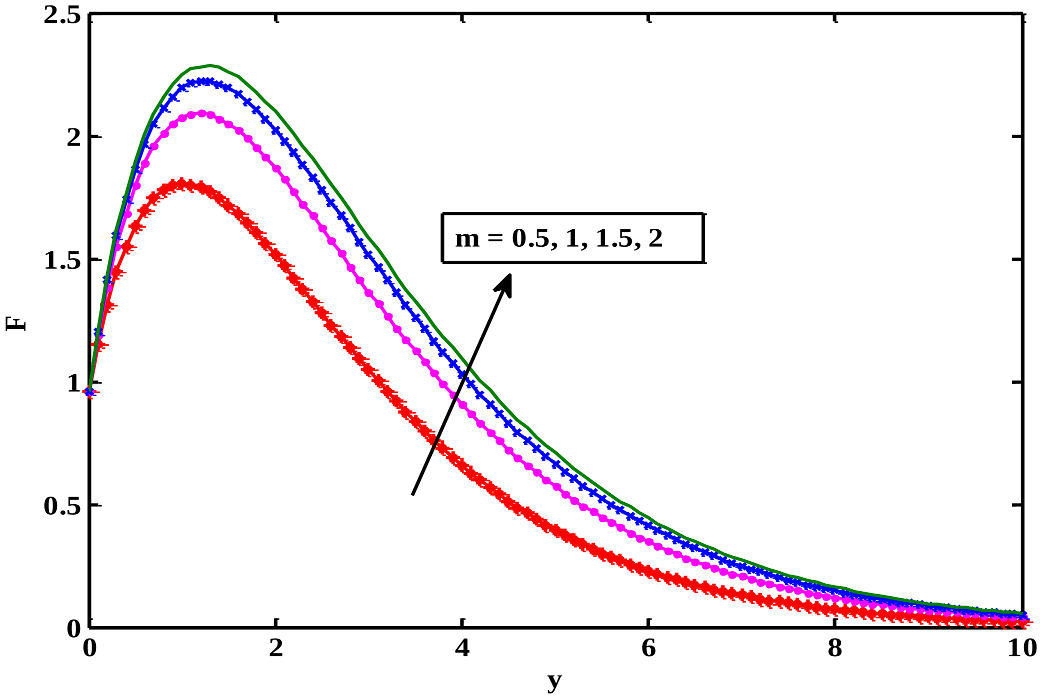

Fig. (5): Axial velocity profiles for different values of m

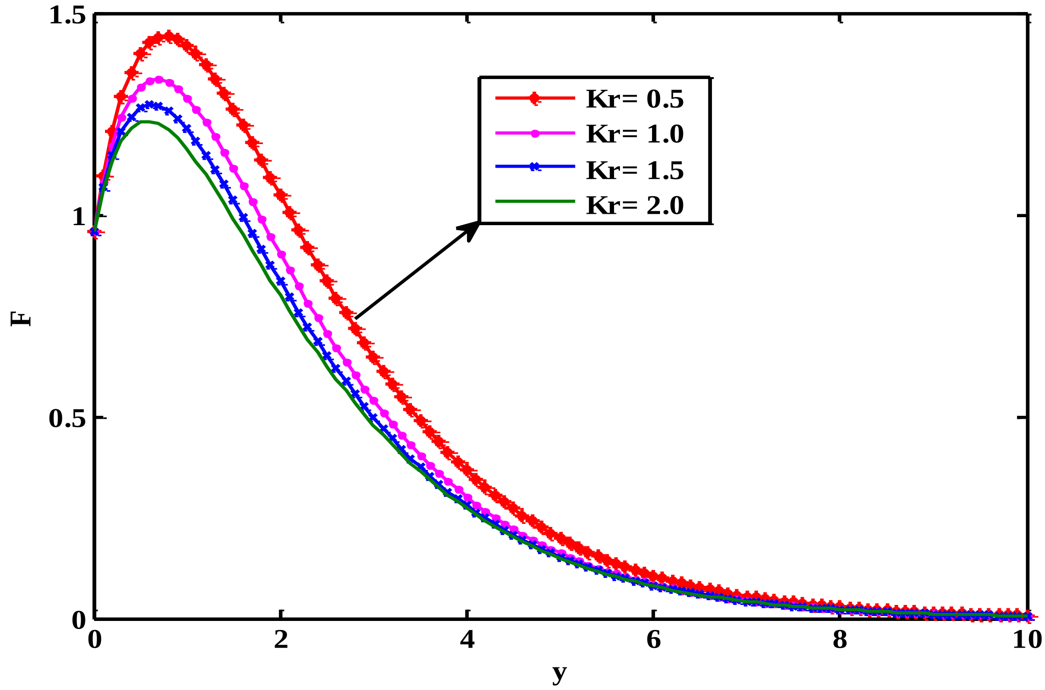

Fig. (6): Axial velocity profiles for different values of Kr

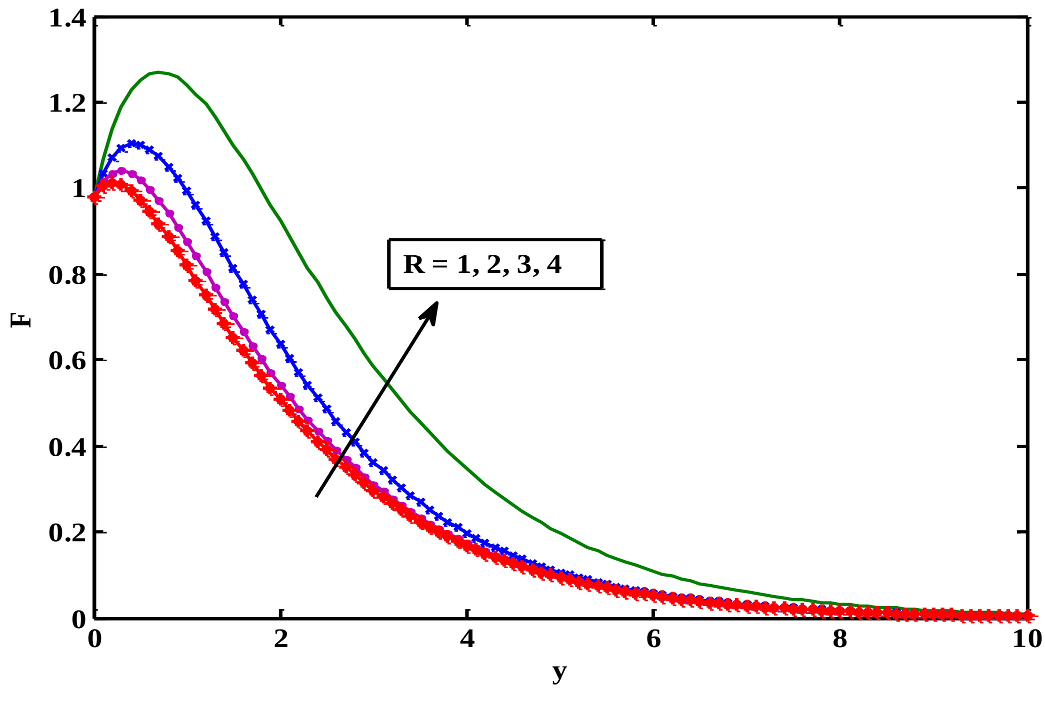

Fig. (7): Axial velocity profiles for different values of R

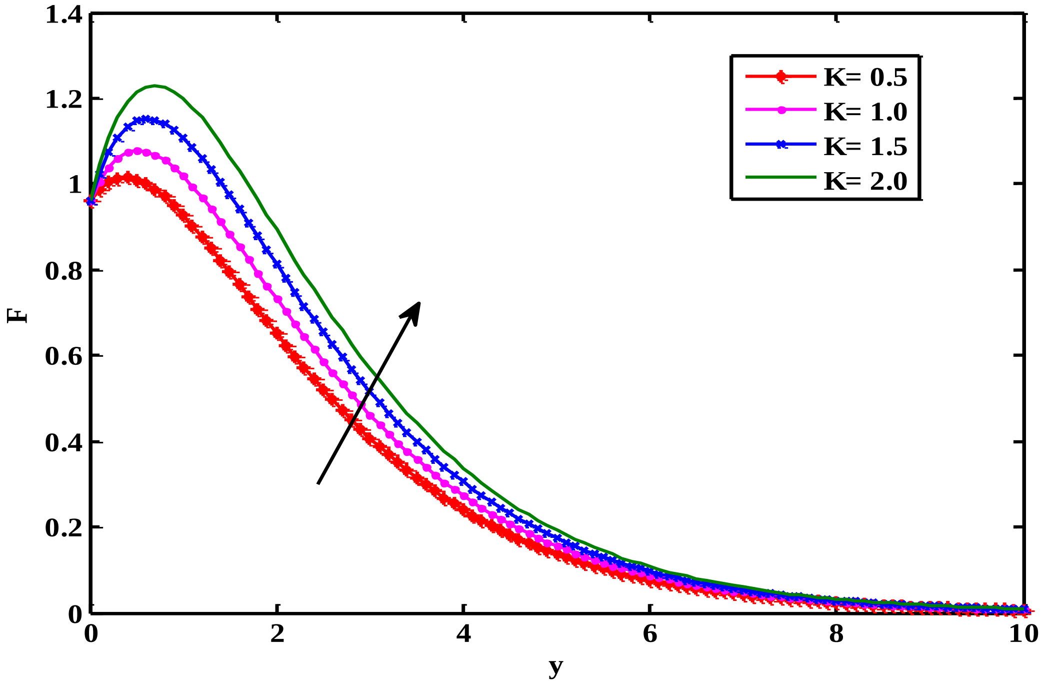

Fig. (8): Axial velocity profiles for different values of K

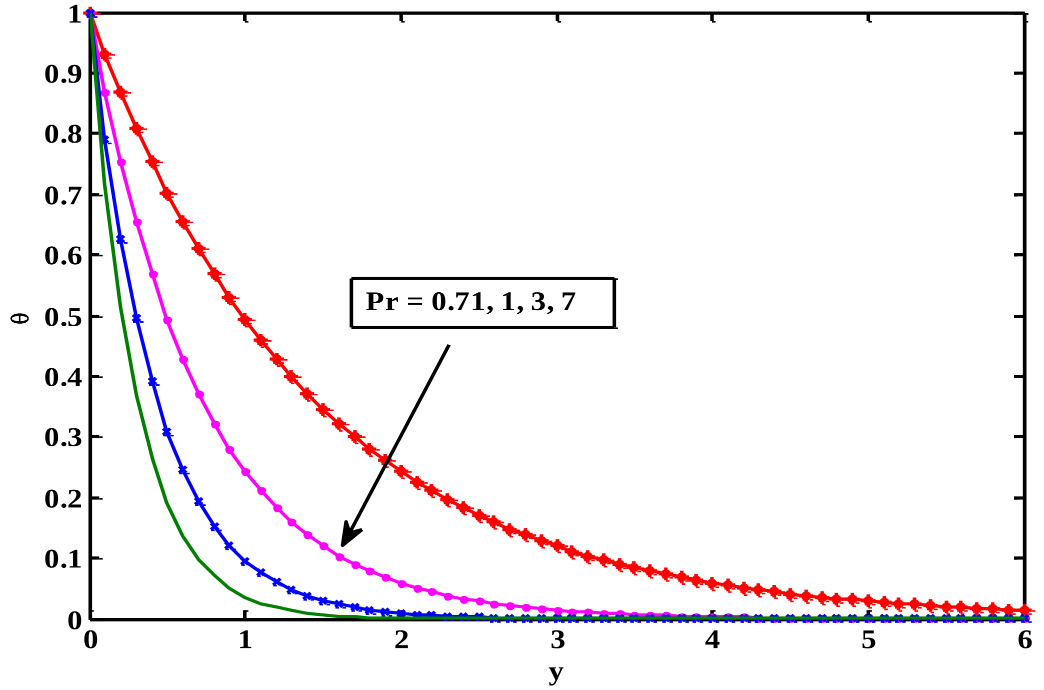

Fig. (9): Temperature profiles for different values of Pr

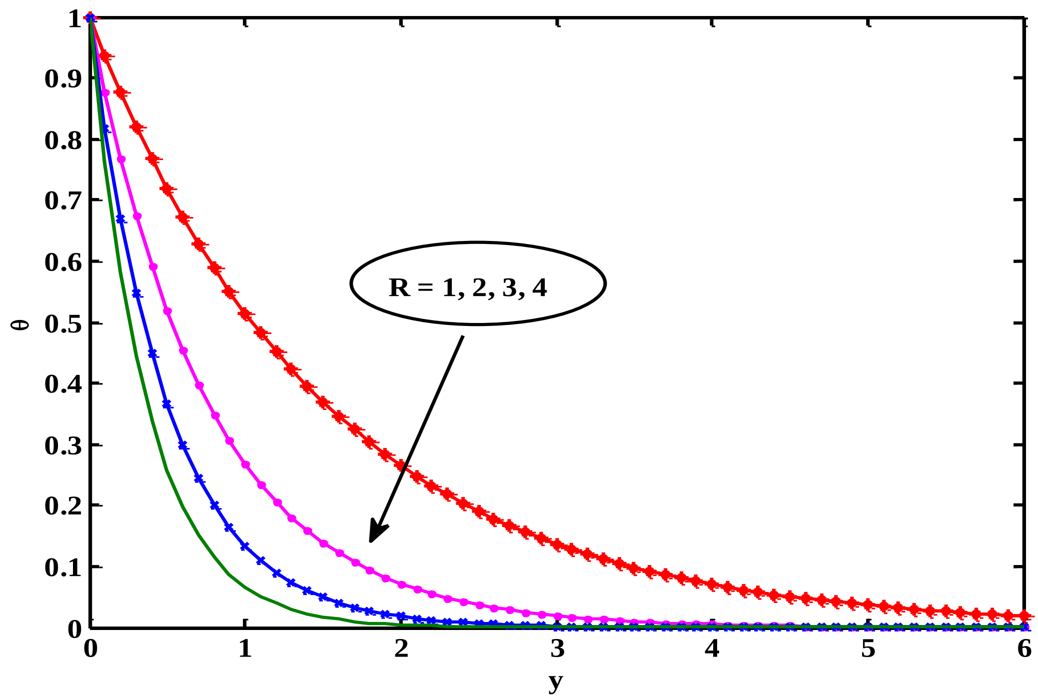

Fig. (10): Temperature profiles for different values of R

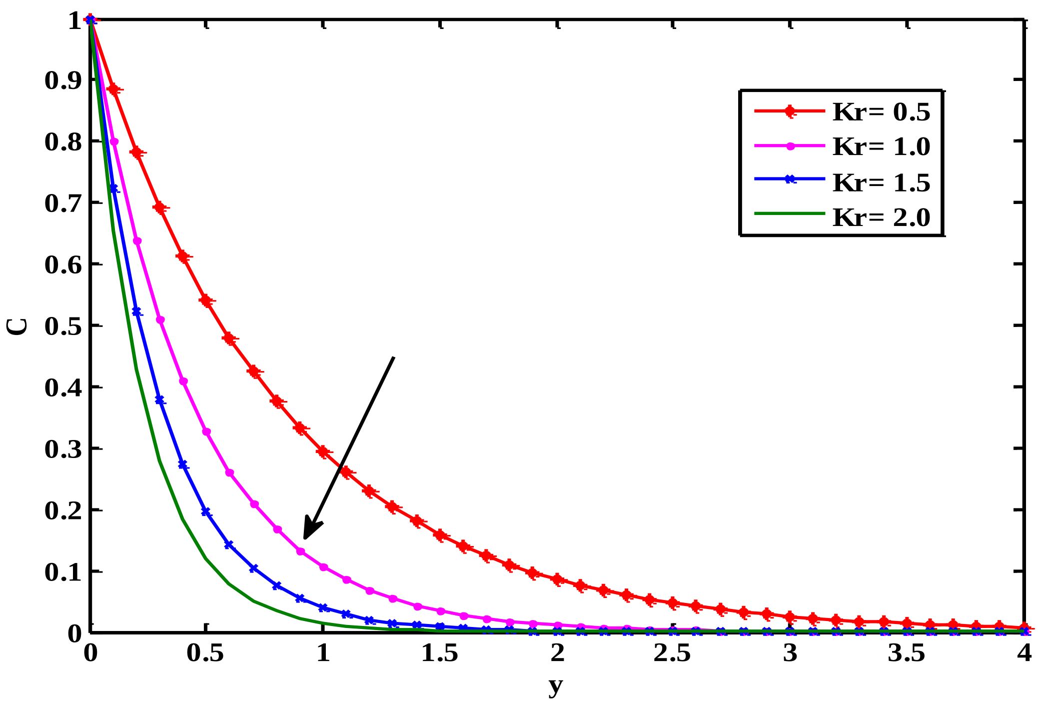

Fig. (11): Concentration profiles for different values of Kr

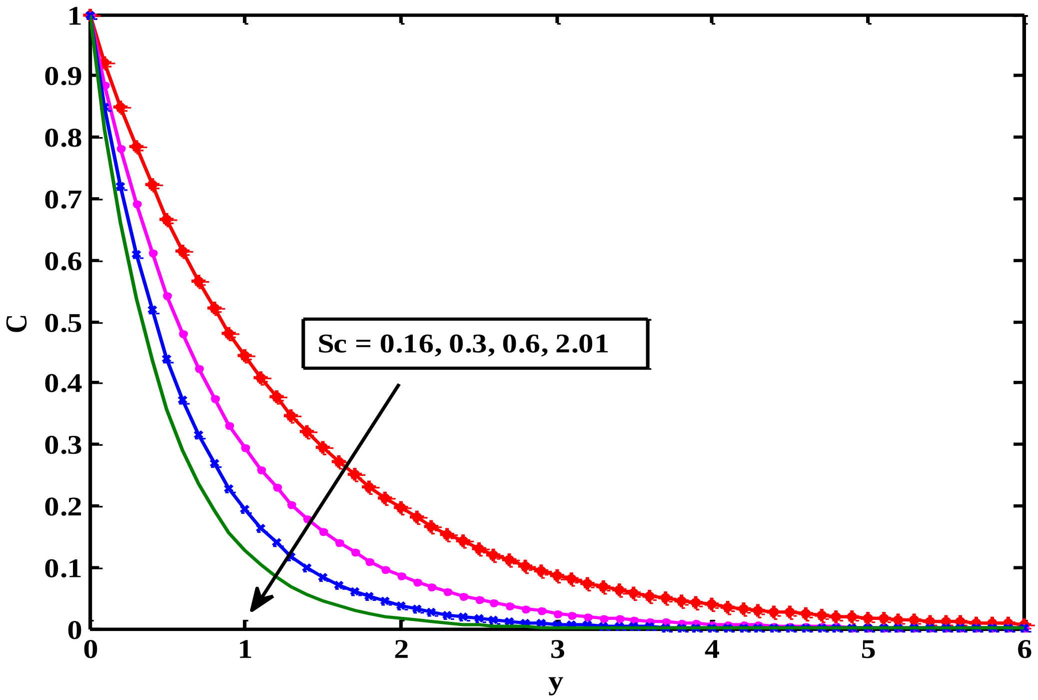

Fig. (12): Concentration profiles for different values of Sc