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

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Abstract

The effects of Hall current, radiation absorption and chemical reaction effects on an unsteady MHD free convection heat and mass transfer flow of a viscous, incompressible and electrically conducting fluid past an infinite vertical plate embedded in a porous medium are investigated. 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 Effect, Chemical reaction, inclined plate, Heat and mass transfer, MHD*

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INTRODUCTION

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, extensive and in-depth research works have been carried out by several researchers in the past.[1-13]

Magnetoconvection plays an important role in various industrial applications. Examples include magnetic control of molten iron flow in the steel industry, liquid metal cooling in nuclear reactors and magnetic suppression of molten semi-conducting materials. It is of importance in connection with many engineering problems, such as sustained plasma confinement for controlled thermonuclear fusion and electromagnetic casting of metals. MHD finds applications in electromagnetic pumps, controlled fusion research, crystal growing, MHD couples and bearings, plasma jets and chemical synthesis. The 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.[14-26]

The Hall Effect can be used to illustrate the effect of a magnetic field on a moving charge to investigate various phenomena of electric currents in conductors and especially semi-conductors. When a current-carrying conductor is placed in a magnetic field such that the field and current directions are perpendicular to each other, a voltage difference will appear as a result of the magnetic field. This Hall voltage is proportional to the product of the current and component of the magnetic field perpendicular to the current. More recently, the Hall

Effect is widely employed throughout industry in modern Hall Effect gauss-meters, automotive speedometers, fluid flow sensors, and pressure sensors to name a few.[27-42]

Hence in view of the above the motivated study on effects of Hall current, radiation absorption and chemical reaction effects on an unsteady MHD free convection heat and mass transfer flow of a viscous, incompressible and electrically conducting fluid past an infinite vertical plate embedded in a porous medium are investigated. The plate temperature and the concentration level near the plate increase linearly with time.

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:

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

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

Equation of Energy

$$\rho C_p \frac{\partial T}{\partial t'} = k\frac{\partial^2 T}{\partial z^2} - Q_0\left(T' - T'_\infty\right) + Q_l'\left(C' - C'_\infty\right) \tag{3}$$

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, κ – Thermal conductivity, β – Volumetric coefficient of thermal expansion, β^* – Volumetric coefficient of expansion with concentration, C' – Species concentration in the fluid, C_w – Wall concentration, C_∞ – 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

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

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

$$\rho C_p \frac{\partial T}{\partial t'} = k \frac{\partial^2 T}{\partial z^2} - Q_0\left(T' - T'_\infty\right) + Q_l'\left(C' - C'_\infty\right) \tag{16}$$

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

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:

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

$$u=0, \quad T=T, \quad C=C_\infty, \ v=0 \qquad \forall\ z,t'\le 0 \tag{18}$$

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

The dimensionless quantities are introduced as follows:

$$
\begin{aligned}
& U=\frac{u}{u_0}, V=\frac{v}{u_0}, t=\frac{t'u_0^2}{v}, Z=\frac{zu_0^2}{v^2}, \Omega=\Omega\frac{v}{u_0^2}, Gr=\frac{g\beta v\left(T_\omega-T_\infty\right)}{u_0^{\ 3}}, Q_l=\frac{Q_l' v}{\rho C_p u_0^{\ 2}} \\
& Gc=\frac{g\beta^* v\left(C'_\omega-C'_\infty\right)}{u_0^{\ 3}}, \ \Pr=\frac{\mu c_p}{\kappa}, \ Kr=\frac{Kr' v}{u_0^2}, \ M^2=\frac{\sigma\mu_e^2 H_0^{\ 2} v}{2\rho u_0^{\ 2}}, \ Q=\frac{Q_0 v}{\rho C_p u_0^{\ 2}}
\end{aligned}
\tag{20}
$$

where $Sc-$ Schmidt number, $Gr-$Thermal Grashof number, $Gc-$Mass Grashof number, $\Pr-$Prandtl number, $M-$Hartman number, $Kr-$Chemical reaction parameter, Q_l-Radiation absorption parameter, $Q-$heat source parameter.

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

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

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

with the boundary conditions

$$
\begin{aligned}
& U=0, \quad \theta=0, \quad C=0, \quad v=0 \qquad \forall \quad Z,t\le 0 \\
& U\to 1, \quad \theta\to 1, \quad C\to t, \quad v\to 0 \qquad \forall \qquad t>0
\end{aligned}
\tag{23}
$$

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

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

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

$$\frac{\partial\theta}{\partial t}=\frac{1}{\Pr}\frac{\partial^2\theta}{\partial Z^2}-Q\ \theta+Q_l\ C \tag{26}$$

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

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

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

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

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

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

$$F_0''-\beta_3^2F_0=-Gr\,\theta_0-GmC_0 \tag{30}$$

$$\theta_0''-\beta_2^2\theta_0=0 \tag{31}$$

$$C_0''-\beta_1^2 Sc\,C_0=0 \tag{32}$$

The corresponding boundary conditions can be written as

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

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:

$$F_0 = A_2 e^{-\beta_1 z} + A_3 e^{-\beta_2 z} + A_4 e^{-\beta_1 z} + A_5 e^{-\beta_3 z}$$

$$\theta_0 = A_1 e^{-\beta_1 z} + A_2 e^{-\beta_2 z}$$

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

In view of the above equation (29) becomes

$$F(z,t) = \left\{A_2 e^{-\beta_1 z} + A_3 e^{-\beta_2 z} + A_4 e^{-\beta_1 z} + A_5 e^{-\beta_3 z}\right\} e^{i\omega t}$$
$$\theta(z,t) = \left\{A_1 e^{-\beta_1 z} + A_2 e^{-\beta_2 z}\right\} e^{i\omega t}$$
$$C(z,t) = \left\{t\ e^{-\beta_1 z}\right\} e^{i\omega t}$$

Coefficient of Skin-Friction

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

$$C_f = \left(\frac{\partial F}{\partial Z}\right)_{z=0} = -\left(\beta_1 A_2 + \beta_2 A_3 + \beta_1 A_4 + \beta_3 A_5\right)$$

Coefficient of Heat Transfer

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

$$Nu = \left(\frac{\partial T}{\partial Z}\right)_{z=0} = -\left(A_1\beta_1 + A_2\beta_2\right)$$

Sherwood number

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

RESULTS AND DISCUSSIONS

The problem has been formulated, analyzed and solved analytically using perturbation technique. The results are shown graphically for various parameters thermal Grashof number(Gr), modified Grashof number(Gc), Prandtl number$(\Pr)$, Schmidt number(Sc), Chemical reaction parameter(Kr), Reaction parameter(K), Heat source parameter(Q), Radiation absorption parameter(Q_l) 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 $\left(Gr, Gc\right)$ 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 $\left(Gr\right)$ 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 $\left(Gc\right)$ 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 $\left(Sc\right)$ 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 $\left(M\right)$ 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 $\left(m\right)$ 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$\left(Kr\right)$. It is pertinent to mention that $\left(Kr > 0\right)$ corresponds to a destructive chemical reaction. It can be seen from the profiles that the axial velocity decreases 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 reaction parameter (K) leads to increases in the axial velocity with increasing values of reaction parameter. It is noticed form Fig. (8) That the effects of heat source parameter (Q) on the axial velocity respectively. It is evident from this figure that, axial velocity decreases on increasing (Q). The effect of radiation absorption parameter (Q_l) observed in Fig. (9), form this figure it is clear that an increasing values of radiation absorption parameter the axial velocity profiles decreases. Fig. (10) Shows the temperature profile for different values of Prandtl number $(\Pr)$. It is observed that temperature decreases with increase in values of Prandtl number and also heat transfer is predominant in air when compared to water. Fig. (11) Indicates that effect of heat source parameter (Q) in the temperature profiles. It is deduced that velocity increase of the fluid near the plate decrease when heat source parameter are increased. The effect of radiation absorption parameter (Q_l) observed in Fig. (12), form this figure it is clear that an increasing values of radiation absorption parameter the temperature profiles also decreases. Fig. (13) 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. (14) 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

$$\beta_1^2 = (i\omega + Kr)Sc;\ \beta_2^2 = (Q + i\omega \Pr);\ \beta_3^2 = (i\omega + a)$$

$$A_1 = -\frac{Q_l\ t}{\beta_1^2 - \beta_2^2},\ A_2 = -(1 - A_1),\ A_3 = -\frac{Gr\ A_1}{\beta_1^2 - \beta_3^2},\ A_4 = -\frac{Gr\ A_2}{\beta_2^2 - \beta_3^2},\ A_5 = -\frac{Gc\ t}{\beta_1^2 - \beta_3^2}$$

$$A_6 = (1 - A_2 - A_3 - A_4 - A_5)$$

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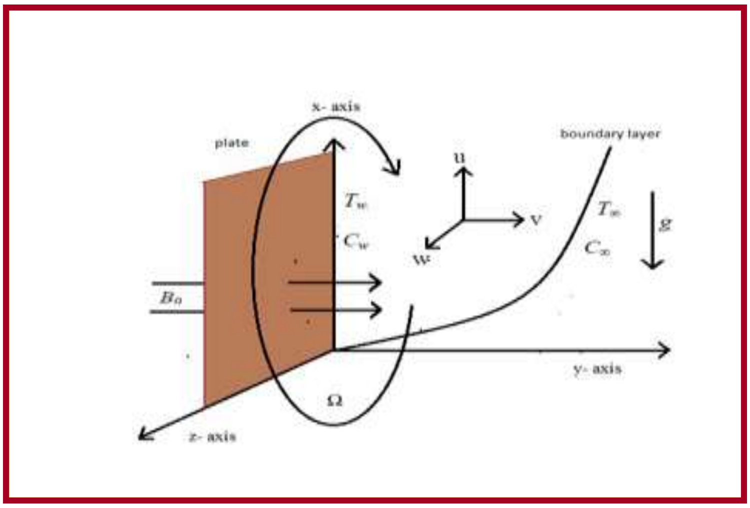

Fig. (1): The geometrical model of the problem

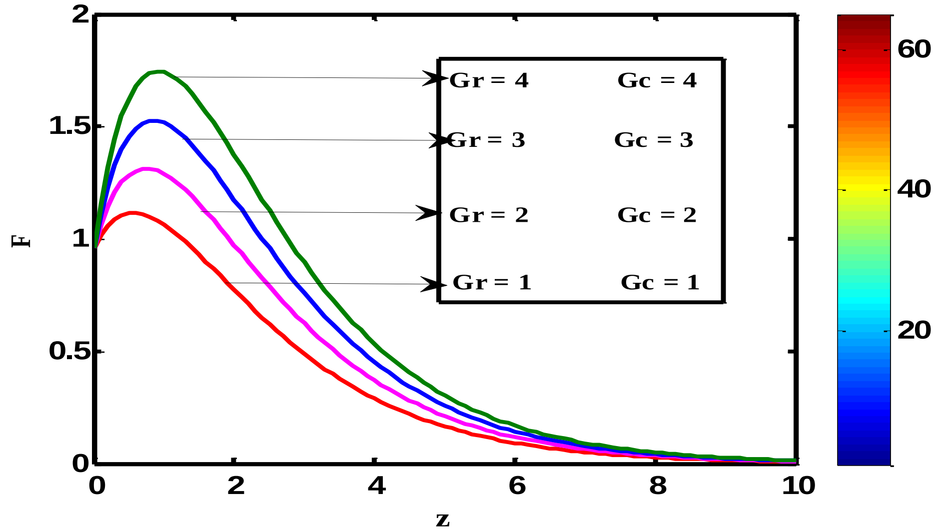

Fig. (2): Axial velocity profiles for different values of Gr, Gc

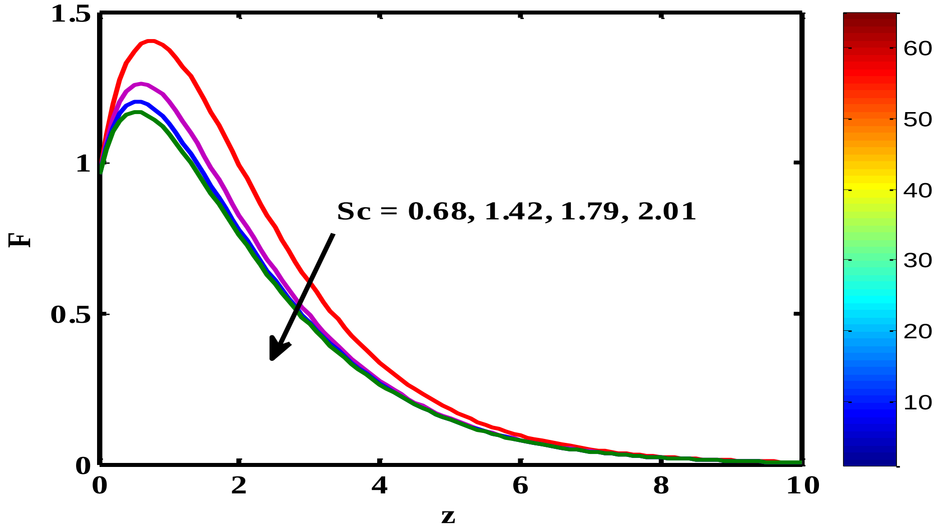

Fig. (3): Axial velocity profiles for different values of Sc

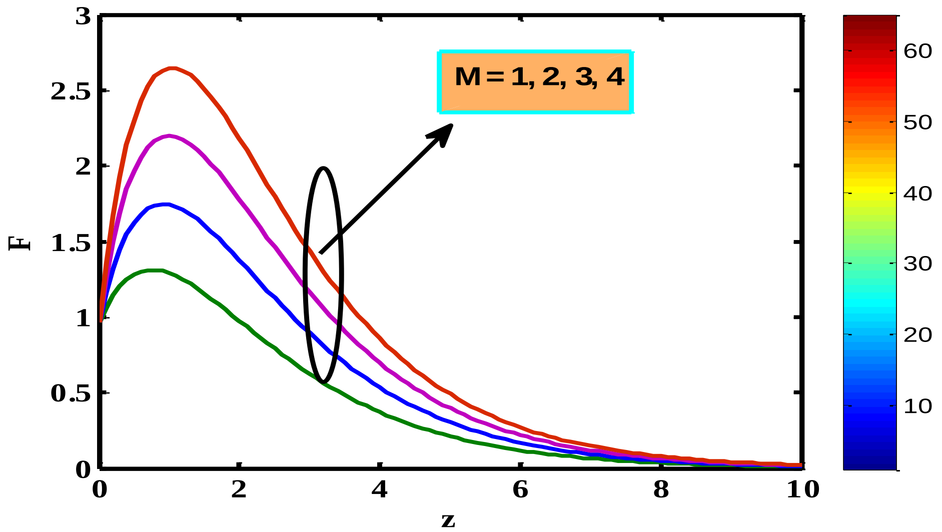

Fig. (4): Axial velocity profiles for different values of M

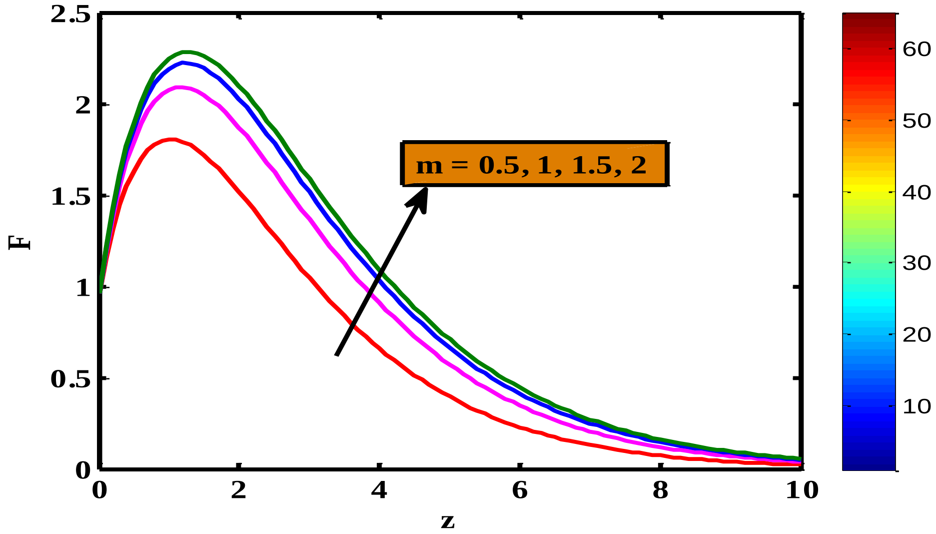

Fig. (5): Axial velocity profiles for different values of m

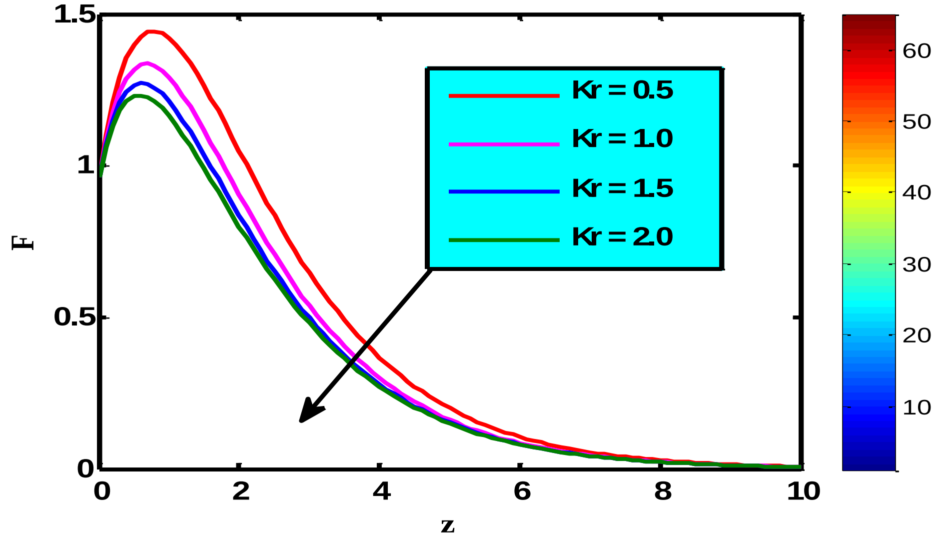

Fig. (6): Axial velocity profiles for different values of Kr

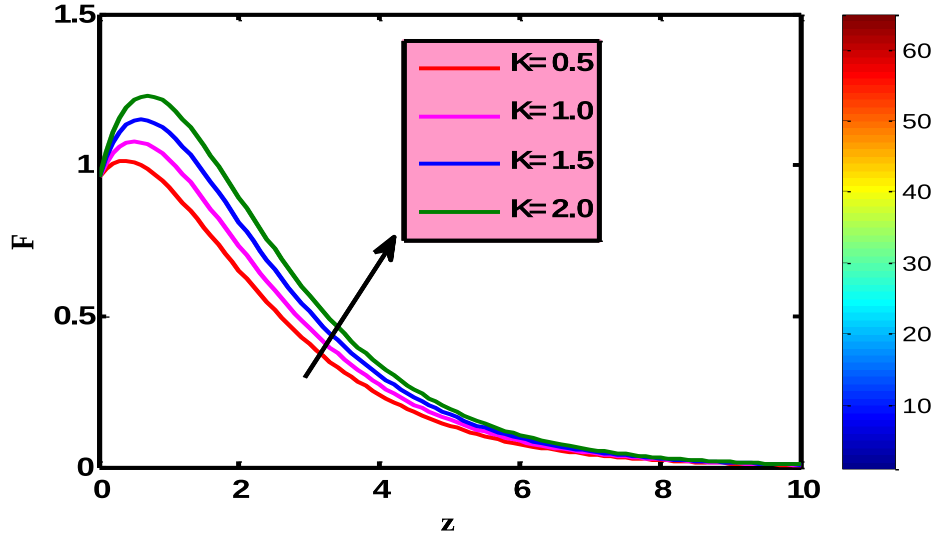

Fig. (7): Axial velocity profiles for different values of K

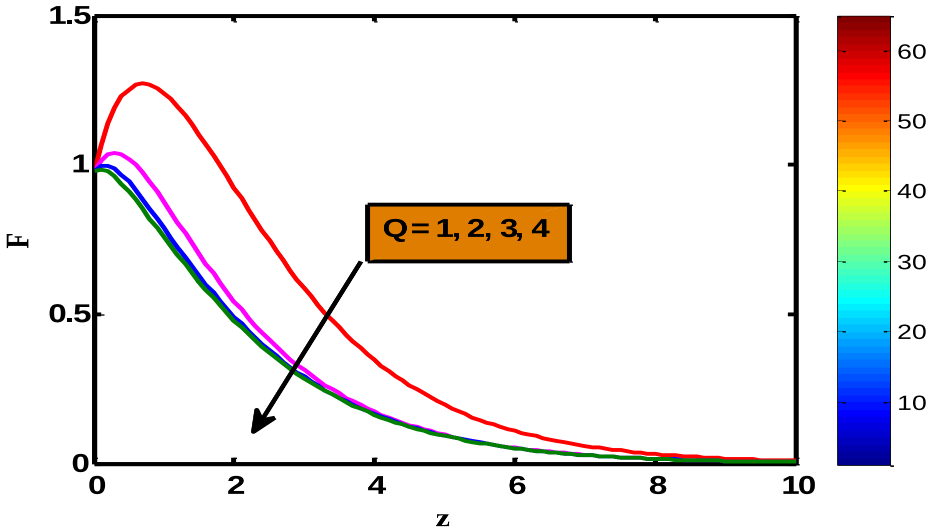

Fig. (8): Axial velocity profiles for different values of Q

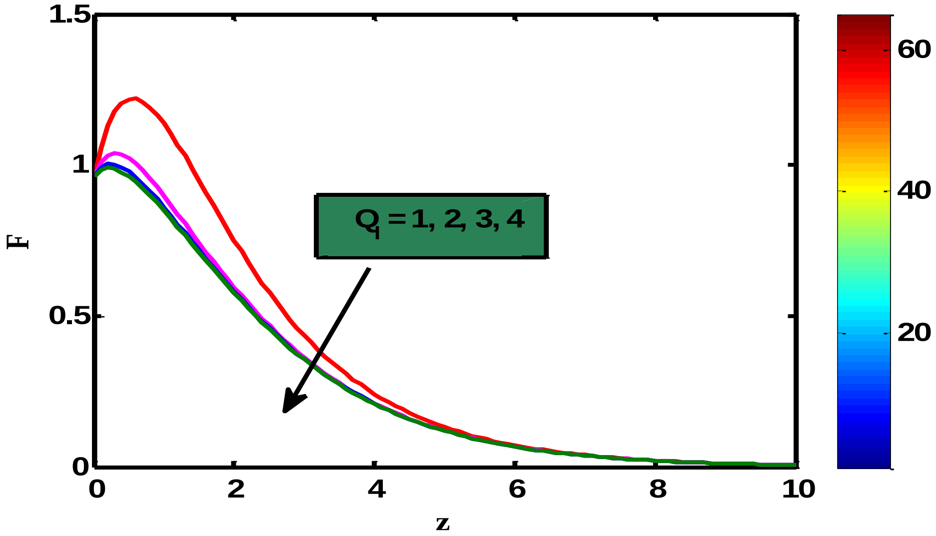

Fig. (9): Axial velocity profiles for different values of Q_l

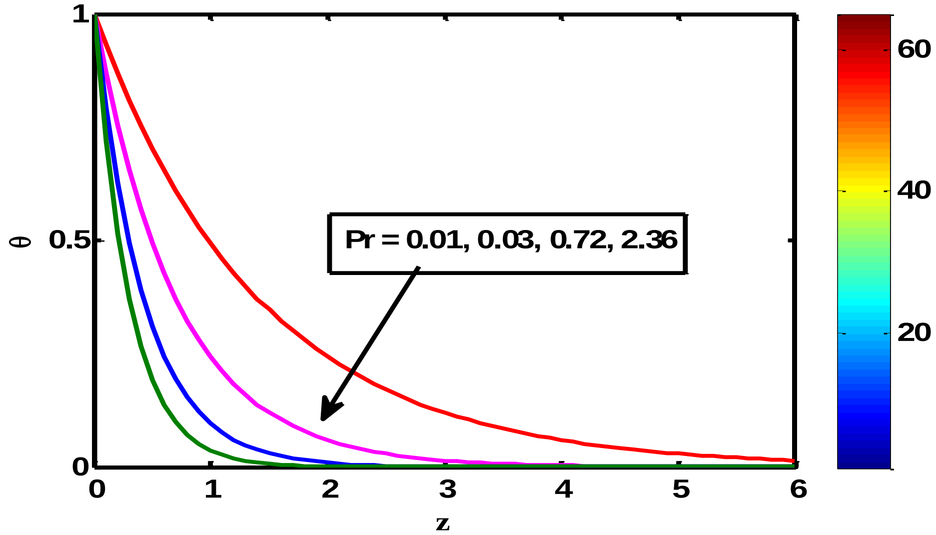

Fig. (10): Temperature profiles for different values of Pr

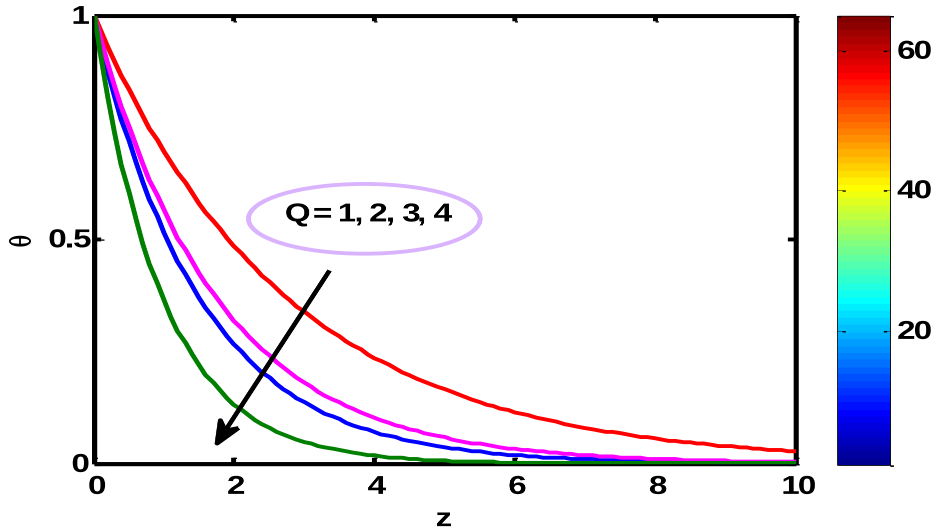

Fig. (11): Temperature profiles for different values of Q

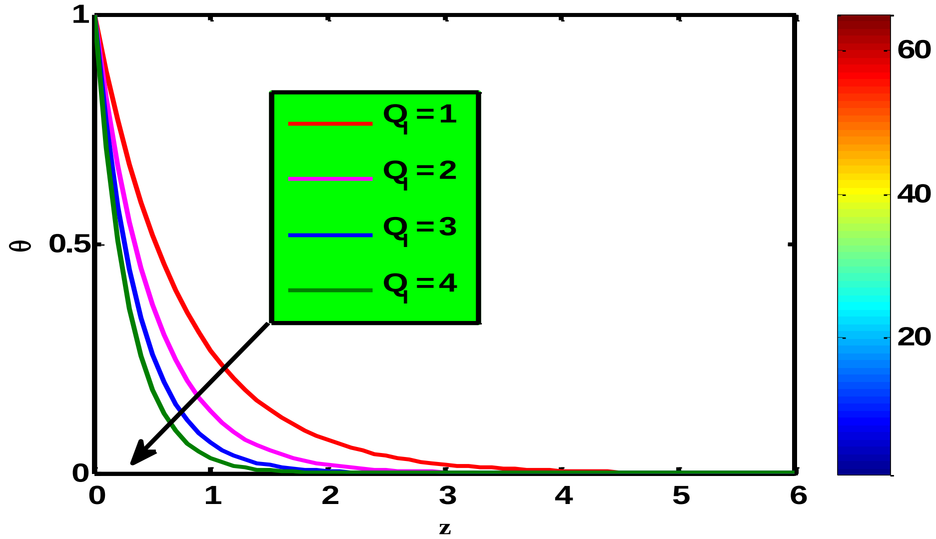

Fig. (12): Temperature profiles for different values of Q_l

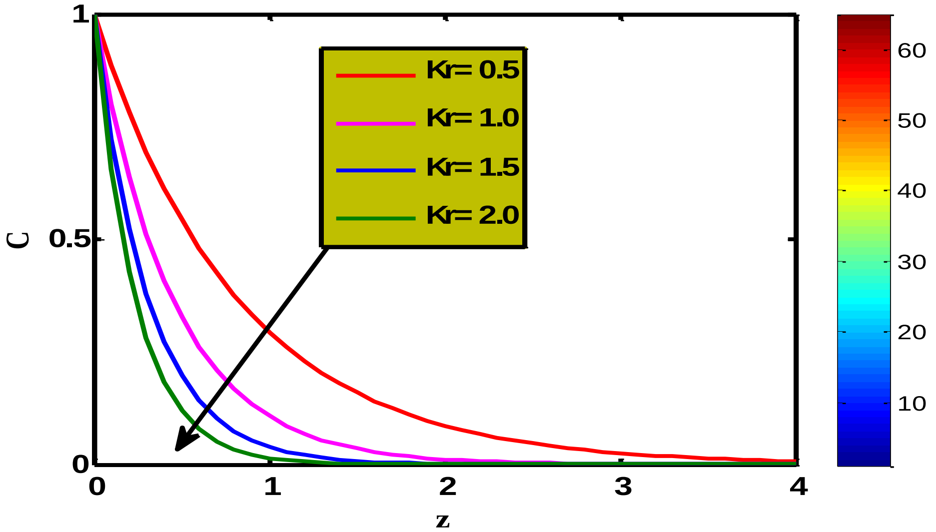

Fig. (13): Concentration profiles for different values of Kr

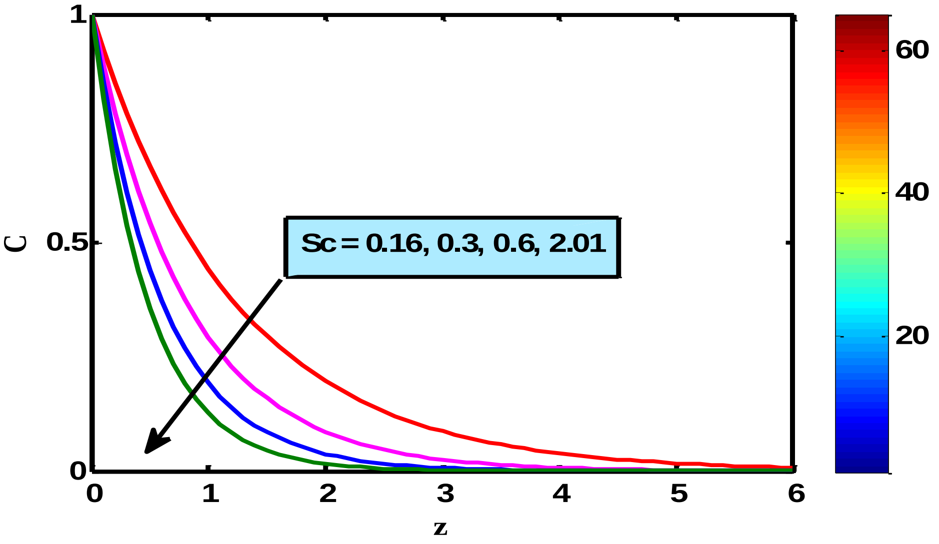

Fig. (14): Concentration profiles for different values of Sc