Effects of hall current and rotation, heat generation on MHD free convection heat and mass transfer flow past an accelerated vertical plate

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Abstract

The effects of radiation, rotation and Hall current effects on MHD free convection heat and mass transfer flow of a viscous, incompressible and electrically conducting fluid past an infinite vertical embedded in a porous medium with heat generation are investigated. It is assumed that the entire system rotates with a uniform angular velocity Ω' about the normal to the plate and a uniform transverse magnetic field is applied along the normal to the plate directed into the fluid region. The magnetic Reynolds number is considered to be so small that the induced magnetic field can be neglected.

Keywords: Hall current, Rotation, MHD, Free convection, Porous medium, Heat generation

Introduction

The study of heat and mass transfer for an electrically conducting fluid past a porous plate under the influence of a magnetic field in a rotating frame of reference has attracted the interest of many investigators in view of its applications in many industrial (in the design of turbines and turbo mechanics), astrophysical (dealing with the sunspot development the solar cycle and the structure of a rotating magnetic stars), geophysical (hydrologists to study the migration of the underground water, petroleum engineers to observe the movement of oil and gas though the reservoir) and many other practical applications, that is in biomechanical problems (blood, flow in the pulmonary alveolar sheet). It is well known that a number of astronomical bodies possess fluid interiors and magnetic fields. Changes that take place in the rate of rotation suggest the possible importance of hydromagnetic spin-up. Also rotating heat exchangers are extensively used by the chemical and automobile industries [1-14].

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 wither 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. 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 [15-30].

Most of the time Hall current was ignored while applying Ohm's law because it has no significant effect for small and average values of the magnetic field. The recent research for the applications of MHD is current is very important. Actually in an ionized gas of low density subjected to a strong magnetic field, the conductivity perpendicular to the magnetic field is decreased by free spiral movement of electrons and ions about the magnetic lines of force before suffering collisions. A current produced in a direction at right angle to the electric and magnetic fields is called Hall current. The important engineering applications for MHD boundary layer flows with heat transfer including the effects of Hall current are encountered in MHD power generators and pumps, in flight MHD, solar physics involved in the sunspot development, the solar cycle, the structure of magnetic stars, electronic system cooling, cool combustors, fiber and granular insulation, oil extraction, thermal energy storage and flow through filtering devices and porous material regenerative heat exchangers [31-41].

It is noticed that when the density of an electrically conducting fluid is low and or applied magnetic field is strong. Hall current is produced in the flow-field which plays an important role in determining flow features of the problems because it induces secondary flow in the flow – filed. Keeping in view this fact, significant investigations on hydromagnetic free convection flow past a flat plate with Hall effects under different thermal conditions are carried out by several researchers in the past. The present study deals with the study of the effects of hall current, rotation and MHD free convection flow of a viscous, incompressible, electrically conducting fluid past an impulsively moving vertical plate in a porous medium. Exact solution of the governing equations is obtained in closed form by perturbation technique. Exact solution is also obtained in case of unit Schmidt number. The expressions for primary and secondary fluid velocity, fluid temperature, spices concentration, skin friction due to primary and secondary velocity fields at the plate are obtained.

Formulation of the problem

Consider unsteady MHD natural convection flow heat and mass transfer of an electrically conducting, viscous, incompressible fluid past an infinite vertical plate embedded in a uniform porous medium in a rotating system taking Hall current into account. Assuming Hall currents, the generalized Ohm's la [49] may be put in the following form:

$$\vec{j} = \frac{\sigma}{1+m^2}\left(\vec{E} + \vec{V} \times \vec{B} - \frac{1}{\sigma n_e}\vec{j} \times \vec{B}\right)$$

where $\vec{V}$ represent the velocity vector, $\vec{E}$ is the intensity vector of the electric field, $\vec{B}$ is the magnetic induction vector, $\vec{j}$ is the electric current density vector, m is the Hall current parameter, is the electrical conductivity and is the number density of the electron. A very interesting fact that the effect of Hall current gives rise to a force in the z' direction which in turn produces a cross flow velocity in this direction and thus the flow becomes three-dimensional.

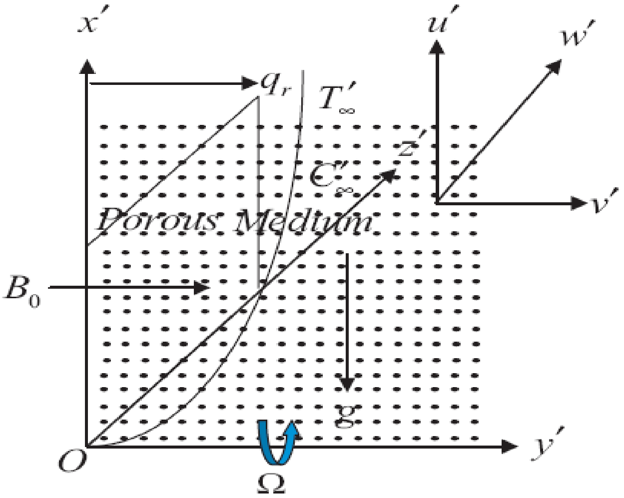

Figure (1): Geometry of the problem

Coordinate system is chosen in such a way that $x'-$is considered along the plate in upward direction and $y'-$axis normal to plane of the plate in the fluid. A uniform transverse magnetic field B_0 is applied in a direction which is parallel to $y'-$axis. The fluid and plate rotate in unison with uniform angular velocity Ω' about $y'-$axis. Initially, i.e. at time $t' \le 0$, both the fluid and plate are at rest and are maintained at a uniform temperature, both the fluid and plate are at rest and are maintained at a uniform temperature T'_∞. Also species concentration at the surface of the plate as well as at every point within the fluid is maintained at uniform concentration C'_∞. At the time $t' > 0$, plate starts moving in $x'-$ direction with a velocity $u'' = U t'$ in its plane. The temperature at the surface of the plate is raised to uniform temperature T'_w and the spices concentration at the surface of the plate is raised to uniform species concentration C'_w and is maintained thereafter. Geometry of the problem is presented in figure (1). Since plate is of infinite extent in x' and z' directions and is electrically non-conducting, all physical quantities except pressure depend on y' and t' only. Also no applied or polarized voltage exists so the effect of polarization of fluid is negligible. This correspondence to the case where no energy is added or extracted from the fluid by electrical means [42]. It is assumed that the induced magnetic field generated by fluid motion is negligible in comparison to the applied one. This assumption is justified because magnetic Reynolds number is very small for liquid metals and partially ionized fluids which are commonly used in industrial applications.

Keeping in view the assumptions made above, governing equations for natural convection flow with heat and mass transfer of an electrically conducting, viscous, incompressible fluid past an infinite vertical plate embedded in a uniform porous medium in a rotating system taking Hall current and chemical reaction with heat source effect into account, are given by

Conservation of momentum

$$\frac{\partial u'}{\partial t'} + 2\Omega w' = \nu \frac{\partial^2 u'}{\partial y'^2} + \frac{\sigma B_0^2}{\rho\left(1+m^2\right)}\left(u' + m w'\right) + g\beta\left(T' - T'_\infty\right) + g\beta^*\left(C' - C'_\infty\right) - \frac{\nu}{K'_1} u' \quad (1)$$

$$\frac{\partial w'}{\partial t'} + 2\Omega u' = \nu \frac{\partial^2 w'}{\partial y'^2} + \frac{\sigma B_0^2}{\rho\left(1+m^2\right)}\left(m u' - w'\right) - \frac{\nu}{K'_1} w' \quad (2)$$

Conservation of energy

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

Conservation of species concentration

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

where $u', w', g, \rho, \beta, \beta', k, C_p, \sigma, \nu, m = \omega_e\tau_e, \omega_e, \tau_e, K_T, T', C', Kr'$ and K_1' are, respectively, the fluid velocity in the x' direction, fluid velocity in z' direction acceleration due to gravity, the fluid density, the volumetric coefficient of thermal expansion, the volumetric coefficient of expansion for concentration, thermal conductivity, specific heat at constant pressure, electrical conductivity, the kinematic viscosity, Hall current parameter, cyclotron frequency, electron collision time, the coefficient of mass diffusivity, the thermal diffusion ratio, the mean fluid temperature, the temperature of the fluid, species concentration, chemical reaction parameter, radiative heat flux vector and permeability of the porous medium.

Initial and boundary conditions for the fluid flow problem are given below

$$\begin{aligned}
&u' = w' = 0, T' - T'_\infty, C' = C'_\infty \quad \text{for all} \quad y' \quad \text{and } t' \le 0\\
&u' = Ut', w' = 0, T' - T'_w, C' = C'_w \quad \text{at} \quad y' = 0 \quad \text{and } t'>0\\
&u' \to 0,\ w \to 0,\ T' \to T'_\infty,\quad C' \to C' \ \ as \ \ y' \to \infty \text{ for } t'>0
\end{aligned} \tag{5}$$

The following dimensionless variables and parameters of the problem are

$$\begin{aligned}
&U = \frac{u'}{U_0},\quad w = \frac{w'}{U_0},\quad y = \frac{y'U_0}{\nu},\quad t = \frac{t'U_0^{\ 2}}{\nu},\ \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}, \phi = \frac{C' - C'_\infty}{C'_w - C'_\infty}\\
&Gr = \frac{g\beta\nu\left(T'_w - T'_\infty\right)}{U_0^3},\quad Gm = \frac{\beta' g\nu\left(C'_w - C'_\infty\right)}{U_0^3},\ \Pr = \frac{\mu C_p}{k},\quad \omega = \frac{\nu\omega'}{U^2}\\
&K^2 = \frac{\nu\Omega}{U_0^2}, Kr = \frac{Kr'\nu}{U_0^2},\ Q = \frac{Q_0\nu}{U_0^2}, M^2 = \frac{\sigma B_0^2\nu}{\rho U_0^2}, K_1 = \frac{K_1' U_0^2}{\nu^2}, Sc = \frac{\nu}{D}
\end{aligned} \tag{6}$$

where $Gr, Gm, M^2, K_1, \Pr, Sc, K^2$ and Q are, respectively, the thermal Grashof number, the solutal Grashof number, the magnetic parameter, Permeability parameter, the Prandtl number, the Schmidt number,, the Soret number, the rotation parameter and heat source parameter.

Using (6) into (1) to (4) yield the following

$$\frac{\partial u}{\partial t} + 2K^2 w = \frac{\partial^2 u}{\partial y^2} - \frac{M^2}{1+m^2}\left(u + mw\right) + Gr\,\theta + Gm\,\phi - \frac{u}{K_1} \tag{7}$$

$$\frac{\partial w}{\partial t} + 2K^2 u = \frac{\partial^2 w}{\partial y^2} + \frac{M^2}{\left(1+m^2\right)}\left(mu - w\right) - \frac{w}{K_1} \tag{8}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} - Q\theta \tag{9}$$

$$\frac{\partial\phi}{\partial t}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2}-Kr\,\phi \qquad (10)$$

The relevant initial and boundary conditions in non- dimensional form are given by

$$\begin{aligned}
&u=w=0,\theta=0,\phi=0 && \text{for all } y \text{ and } t\le 0\\
&u=t,w=0,\theta=1,\phi=1 && \text{at } y=0 \text{ and } t>0 \qquad (11)\\
&u\to 0,\ w\to 0,\ \theta\to 0_\infty,\ \ \phi\to 0\ \ as\ \ y\to\infty && \text{for } t>0
\end{aligned}$$

Equations (7) and (8) are presented, in complex form, as

$$\frac{\partial F}{\partial t}=\frac{\partial^2 F}{\partial y^2}-\alpha F+Gr\,\theta+Gm\,\phi \qquad (12)$$

where $F=u+iv$ and $\alpha=\frac{M^2(1-im)}{1+m^2}+\frac{1}{K_1-2iK^2}$

The initial and boundary conditions (11) in compact form, become

$$\begin{aligned}
&F=0,\theta=0,\phi=0 && \text{for all } y \text{ and } t\le 0\\
&F=t,\theta=1,\phi=1 && \text{at } y=0 \text{ and } t>0 \qquad (13)\\
&F\to 0,\ \ \theta\to 0_\infty,\ \ \phi\to 0 && as\ \ y\to\infty \text{ for } t>0
\end{aligned}$$

The system of differential Equations (9), (10) and (12) together with the initial and boundary conditions (13) describes our model for the MHD free convective heat and mass transfer flow of a viscous, incompressible, electrically conducting fluid past an infinite vertical plate embedded in a porous medium taking Hall current, rotation and Soret effect into consideration.

Method of solution

In order to reduce the above system of partial differential equations (9), (10) and (12) under the boundary conditions given equations (13) we assume in complex form the solution of the problems as

$$\begin{aligned}
F(y,t)&=F_0(y)\,e^{i\omega t}\\
\theta(y,t)&=\theta_0(y)\,e^{i\omega t} \qquad (14)\\
\phi(y,t)&=\phi_0(y)e^{i\omega t}
\end{aligned}$$

Substitute equation (14) in to the equations (9), (10) and (12) the set of ordinary differential equations are the following form

$$F_0''-(i\omega+\alpha)F_0=-Gr\theta_0-Gm\phi_0 \qquad (15)$$

$$\theta_0''-(i\omega+Q)\Pr\theta_0=0 \qquad (16)$$

$$\phi_0''-(i\omega+Kr)Sc\,\phi_0=0 \qquad (17)$$

The initial and boundary conditions (13) in compact form, become

$$
\begin{aligned}
&F=0,\theta=0,\phi=0 && \text{for all } y \text{ and } t\le 0\\
&F_0=t,\theta_0=1,\phi_0=1 && \text{at } y=0 \text{ and } t>0 \qquad (18)\\
&F_0\to 0,\ \theta_0\to 0_\infty,\ \phi_0\to 0 && as\ y\to\infty \text{ for } t>0
\end{aligned}
$$

The exact solution for the fluid temperature $\theta(y,t)$, species concentration $\phi(y,t)$ and fluid velocity $F(y,t)$ are obtained under the boundary conditions of (18) and expressed from equations from (15) - (17) in the following form:

$$F(y,t)=\left(L_1 e^{-\sqrt{Q\Pr}y}+L_2 e^{-\sqrt{KrSc}\,y}+L_3 e^{-\sqrt{\alpha}\,y}\right)e^{i\omega t}$$

$$\theta(y,t)=\left(e^{-\sqrt{Q\Pr}\,y}\right)e^{i\omega t}$$

$$\phi(y,t)=\left(e^{-\sqrt{Kr\,Sc}\,y}\right)e^{i\omega t}$$

Skin-friction

$$\left(\frac{\partial F}{\partial y}\right)_{y=0}=\left(-Q\Pr L_1-KrSc\,L_2-\alpha L_3\right)\cos\omega t$$

Heat transfer

$$\left(\frac{\partial \theta}{\partial y}\right)_{y=0}=\left(-Q\Pr\right)\cos\omega t$$

Sherwood number

$$\left(\frac{\partial \phi}{\partial y}\right)_{y=0}=\left(-KrSc\right)\cos\omega t$$

Results and discussion

In order to get the physical understanding of the problem and for the purpose of analyzing the effect of Hall current, rotation, thermal radiation, thermal buoyancy force, concentration buoyancy force, mass diffusion, thermal diffusion, chemical reaction, Soret number and time on the flow field, compact velocity, temperature and concentration in the boundary layer region were computed from the analytical solution and are displayed graphically versus boundary layer co-ordinate y in Figures (2) – (13) for various values of the thermal Grashof number (Gr), mass Grashof number (Gc), the rotation parameter (K^2), the permeability parameter (K_1), Chemical reaction parameter (Kr), the Hall current parameter (m), the heat source parameter (Q) and Schmidt number (Sc).

Compact velocity Profiles:

Figures (2) – (3) depict the influence of thermal and concentration buoyancy forces on the compact fluid velocities. It is revealed from figure (2) that the compact fluid velocity (F) increases on increasing Gr in a region near to the surface of the plate. From figure (3) it is revealed that u and w increase on increasing Gm which represents the relative strength of concentration buoyancy force to viscous force, therefore, thermal buoyancy force tends to retard the compact fluid velocities whereas concentration buoyancy force tends to accelerate compact velocities throughout the boundary layer region which is clearly evident from figures (2) – (3). Figure (4) illustrate the effects of rotation on the compact fluid velocities respectively. It is evident from figure (4) that, velocity increases on increasing K^2 in the region away from the plate. This implies that rotation retards fluid flow in the 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. Figure (5) present the effect of permeability of porous medium (K_1) on compact fluid velocity. It is noticed from this figure that, velocity increases on increasing permeability parameter. From the flow configuration it is obvious that an increase in porosity of the medium assists the flow along the secondary direction thereby causing the compact velocity to increase due to its orientation through the porous medium. Figure (6) demonstrate the influence of chemical reaction parameter Kr on the compact fluid velocity respectively. As can be seen, an increase in the chemical reaction parameter (Kr) leads to an increase in the thickness of the velocity boundary layer; this shows that diffusion rate can be tremendously altered by chemical reaction (Kr). A temporal maximum of velocity profiles is clearly seen for increasing values of Kr. It should be mentioned here that physically positive values of Kr imply destructive reaction and negative values of Kr imply generative reaction. Figure (7) demonstrate the effect of Hall current on the compact velocity respectively. It is perceived from the compact velocity increases on increasing m throughout the boundary layer region. This implies that, Hall current tends to accelerate compact fluid velocity throughout the boundary layer region which is consistent with the fact that Hall current induces compact flow in the flow-field. The influences of the Schmidt number (Sc) on the compact velocity profiles are plotted in figures (9) respectively. It is noticed decrease the compact velocity and concentration 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).

Temperature Profiles:

It is evident form figure (10), that as the values of Prandtl number $(\Pr)$ increase we can find a decrease in the temperature profiles and hence there is a decrease in thermal boundary layer thickness and more uniform temperature distribution across the boundary layer. Physically, this behaviour is due to the fact that with increasing Prandtl number, the thermal conductivity of the fluid decreases and the fluid viscosity increases which in turn results in a decrease in the thermal boundary layer thickness. Figure (11) has been plotted to depict the variation of temperature profiles against y for different values of heat source parameter (Q) by fixing other parameter. It is observed from this graph that temperature decrease with increasing heat source parameter.

Concentration Profiles:

The effect of chemical reaction parameter (Kr) on the concentration shown in figure (12). It is noticed from this figure that there is a marked effect of increasing values of on concentration distribution in the boundary layer. It is clearly observed from this figure that increasing values of decrease the concentration of species in the boundary layer. This happens because large values of chemical reaction parameter reduce the solutal boundary layer thickness and increase the mass transfer. The influences of the Schmidt number (Sc) on concentration profiles are plotted in figures (13) respectively. It is noticed decrease the concentration 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 concentration (species) boundary layers. 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. The numerical values of skin friction computed form the analytical expression are presented as tabular form in table (1) for various values of Grashof number for fixed values of $Q = 1.0, Pr = 0.71, Kr = 1.0, Sc = 0.22, K = 0.5, \quad m = 0.5; K = 2.0, M = 1.0, Gm = 1.0, t = 1.0$. It is evident form table (1) that, primary and secondary skin friction decreases with increasing values of Grashof number. This implied that, thermal buoyancy force have the tendency to enhance the skin friction at the plate. The numerical values of Nusselt number computed form the analytical expression are presented in table (2) for different values of Prandtl number for fixed values of $N = 1.0, t = 1.0$. It is noticed form table (2) that, Nusselt number increases on increasing Prandtl number. This implies that, thermal diffusion tend to enhance rate of heat transfer at the plate. The numerical values of Sherwood number computed from analytical expression are presented in table (3) for various values of Schmidt number. It is revealed form table (3) that, the rate of mass transfer increases on increasing values of Schmidt number. This implies that Schmidt number tend to enhance the rate of mass transfer at the plate.

APPENDIX

$$L_1 = -\frac{Gr}{Q\,\mathrm{Pr} - \alpha}, L_2 = -\frac{Gm}{KrSc - \alpha}, L_3 = t - L_1 - L_2$$

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Table (1): Skin friction

Gr	τ_x	τ_z
5	- 0.7842	0.1958
10	0.2782	2.0186
15	0.9974	2.1258

Table (2): Nusselt number

Pr	Nu
0.3	0.3145
0.5	0.4586
0.71	0.5124

Table (3): Sherwood number

Sc	Sh
0.1	1.5689
0.22	1.6584
0.78	1.8945

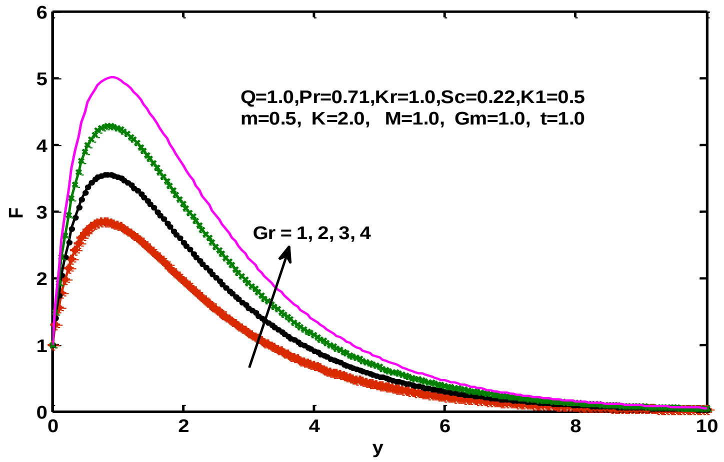

Figure (2): Compact velocity profiles for Gr

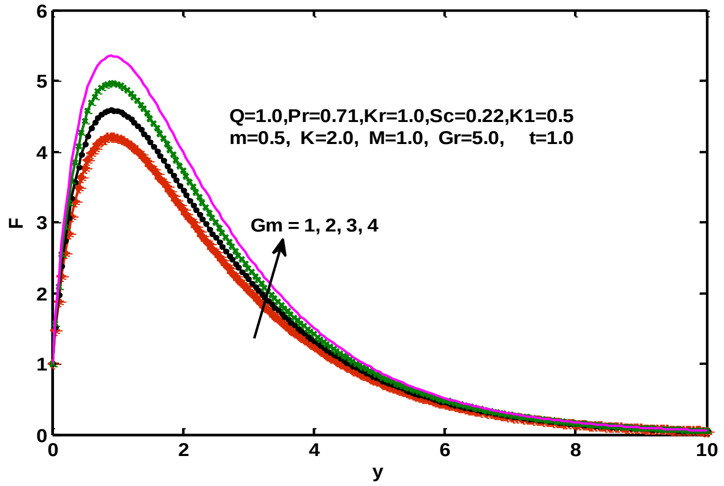

Figure (3): Compact velocity profiles for Gm

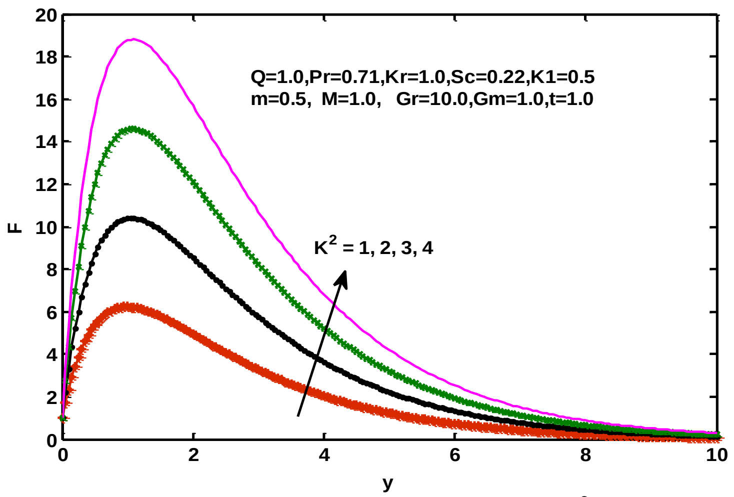

Figure (4): Compact velocity profiles for K^2

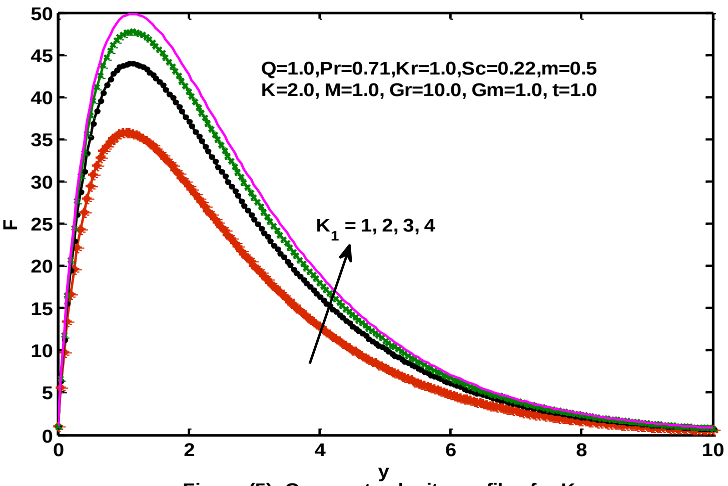

Figure (5): Compact velocity profiles for K_1

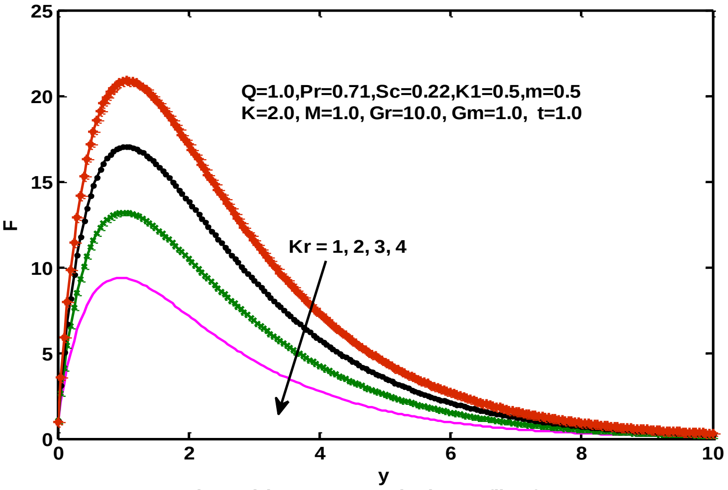

Figure (6): Compact velocity profiles for Kr

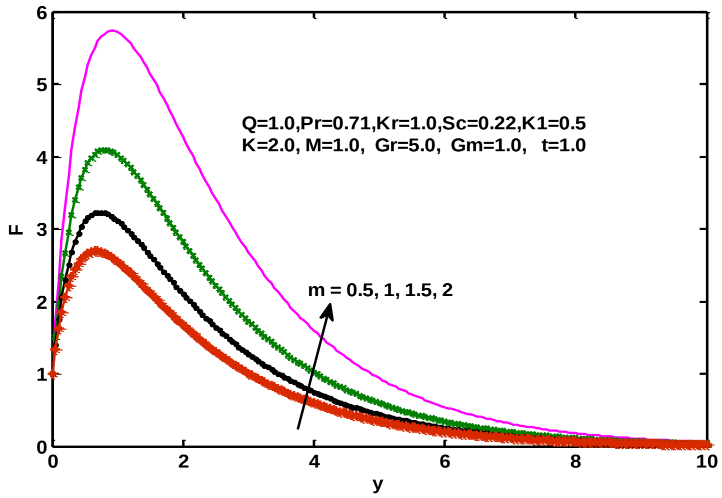

Figure (7): Compact velocity profiles for m

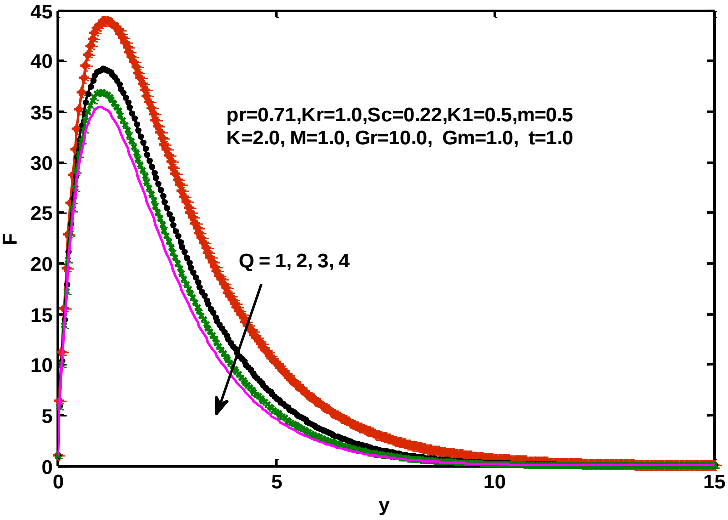

Figure (8): Compact velocity profiles for Q

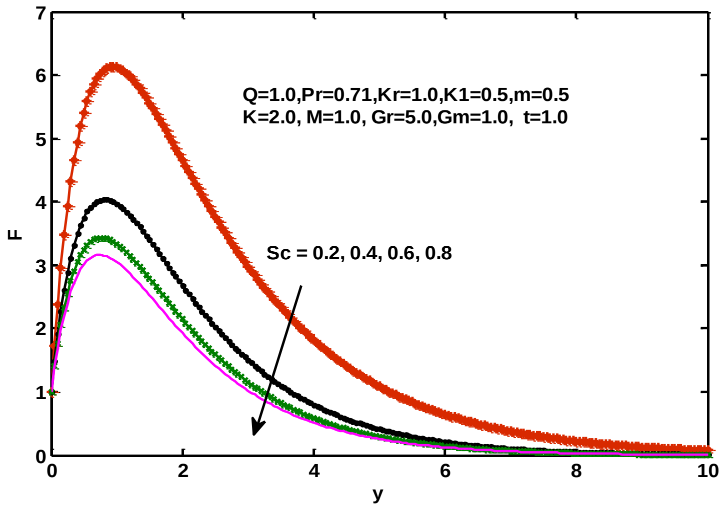

Figure (9): Compact velocity profiles for Sc

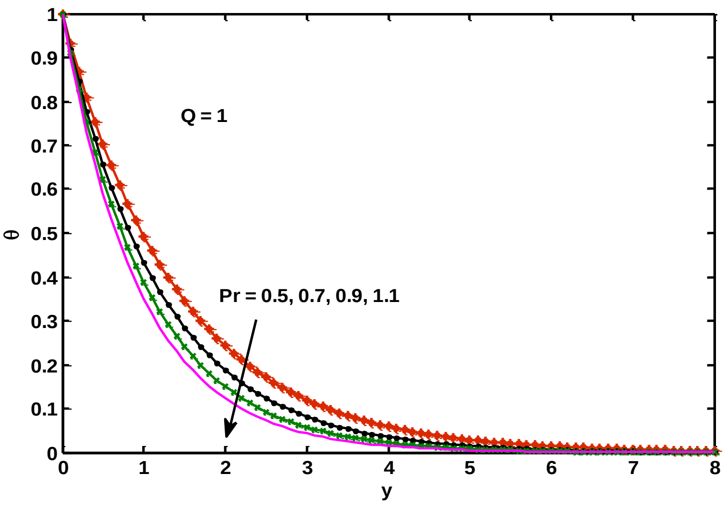

Figure (10): Temperature profiles for Pr

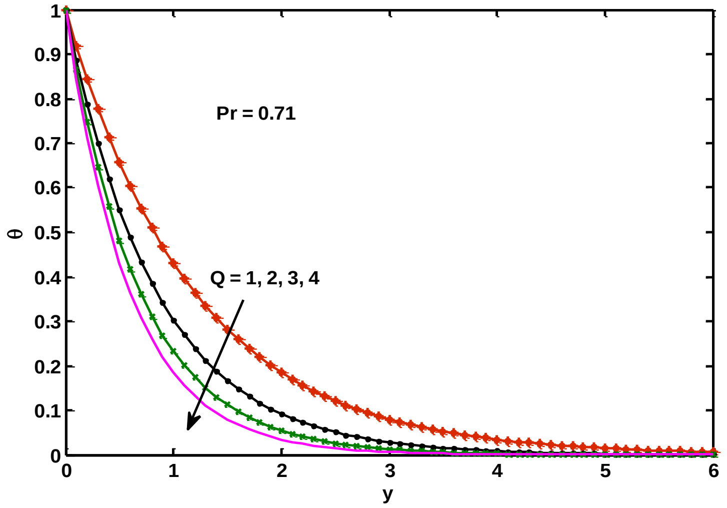

Figure (11): Temperature profiles for Q

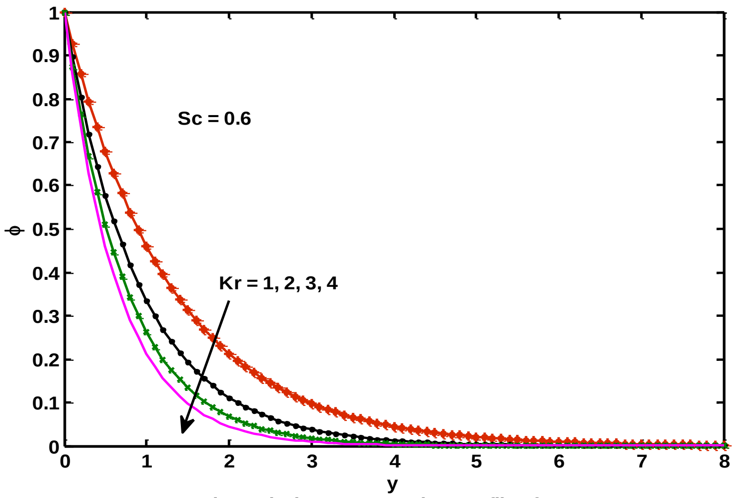

Figure (12): Concentration profiles for Kr

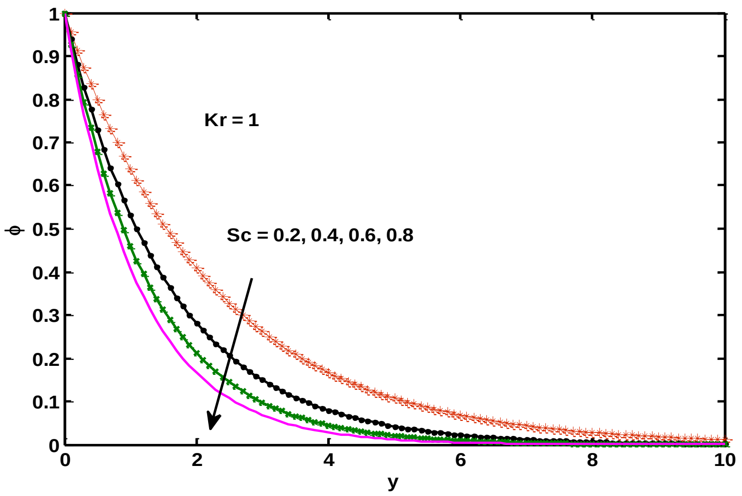

Figure (13): Concentration profiles for Sc