Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 3 (2025)

Chemical Reaction and Soret Effects on Mhd Free Convection Flow Past an Accelerated Vertical Plate Through a Porous Medium with Heat Source

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Article History:
Received: 02-12-2024
Revised : 05-02-2025
Accepted: 10-03-2025

Abstract:

The investigation of the effects of Hall current, rotation, and the Soret effect on the unsteady Magnetohydrodynamics (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. This type of problem typically involves several complex physical phenomena, so breaking it down in steps will help in understanding the dynamics and solving the governing equations by using perturbation technique.

Key words: *Chemical reaction, Soret effect, MHD, Accelerated vertical plate*

Introduction

The interplay between diffusion and chemical reaction rates in various processes is indeed crucial for understanding many practical applications, particularly when both processes occur at comparable speeds. In such cases, the reaction dynamics are influenced not just by the chemical properties of the system but also by how the reactants diffuse toward each other and the product. The technique of thermal diffusion has been used for isotope separation, particularly in gas mixtures with very light molecules like hydrogen and helium. The principle behind this process is that lighter molecules (like hydrogen) tend to diffuse faster than heavier ones (like helium), and when subjected to a temperature gradient, this difference in diffusion rates can be exploited to separate the two isotopes or gases. This phenomenon is essential in industries requiring isotope enrichment, such as nuclear power, medicine (for radioactive tracers), or scientific research. The fine balance between diffusion and temperature gradients is key in optimizing the efficiency of this separation process. The study of diffusion and chemical reaction rates, particularly when they are of comparable speeds, plays a vital role in many physical processes, from industrial applications (like cooling systems for electronics) to more specialized processes (such as isotope separation). The interaction between diffusion and kinetics can lead to complex behaviours that are essential for optimizing efficiency and ensuring the stability of the system [1-12].

Cooling of electronic equipment, especially with the rapid advancement in electronics, is a major application area where both diffusion and heat transfer dynamics are important. Effective cooling systems ensure that heat generated by electronic components (like transistors or microprocessors) is efficiently removed, thus preventing overheating and potential damage. As electronic components become smaller and more densely packed, the heat dissipation challenges also become more complex. In such cases, the principles of heat transfer, including conduction, convection, and radiation, often rely on the diffusion of thermal energy across the system. Moreover, cooling techniques like liquid cooling, heat sinks, or phase-change materials can be used to manage the heat generation from high-power devices. The thermal diffusion and the diffusion thermo effects are an interesting macroscopically physical phenomenon in fluid mechanics, high quality crystal production, oceanography and production of pure medication, solidification of molten alloys, geothermally heated lakes and magmas. For example the quality of the single crystal produced form the melts is limited by chemical and structural in homogeneities. The defect of generation depends on heat and mass transfer rates during solidification. These fluxes are mainly governed by convective phenomena of the liquid phase during processing [13-25].

A chemical reaction takes place in the fluid, typically affecting species concentration. The flow may carry reactants and products, and these reactions can alter the velocity field, temperature distribution, and concentration of the chemical species in the flow. The study of chemical reactions and Soret effects on Magnetohydrodynamics (MHD) free convection flow past an accelerated vertical plate through a porous medium with a heat source is a highly complex and multidisciplinary topic. This type of flow problem finds applications in several engineering and environmental systems, such as in nuclear reactors, cooling systems, geothermal energy extraction, and chemical processing industries [26-37].

The Soret effect is the phenomenon of mass transfer due to a temperature gradient, which causes species to diffuse from regions of high temperature to low temperature (or vice versa). This effect becomes relevant in the context of heat and mass transfer problems, where temperature gradients create diffusive fluxes of chemical species, contributing to changes in the flow dynamics and concentration fields. In view of above consideration, the present investigation is the effects of Hall current, rotation and Soret 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.

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 law [38] 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.

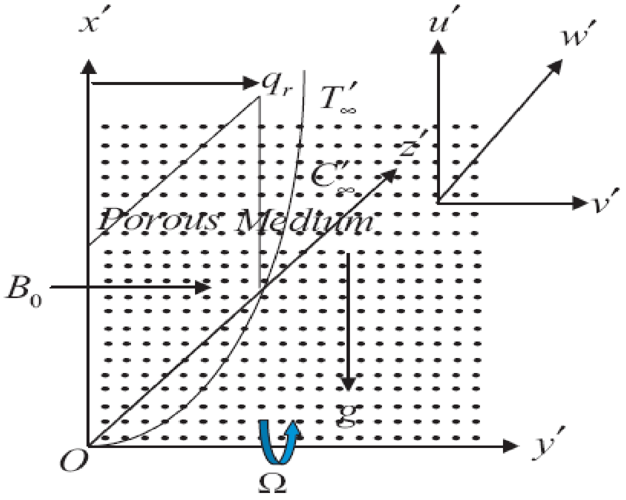

Figure (1): Geometry of the problem

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 $t'\leq 0$, 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 [39]. 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, radiation and chemical reaction effect with heat source into account, are given by

Conservation of momentum

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

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

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 concentration

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

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

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

The following dimensionless variables and parameters of the problem are

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

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

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

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

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

$$\frac{\partial\phi}{\partial t}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2}+Sr\frac{\partial^2\theta}{\partial y^2}-Kr\,\phi \tag{10}$$

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

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

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

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

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

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

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

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

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

$$F_0''-\alpha F_0=-Gr\theta_0-Gm\phi_0 \tag{15}$$

$$\theta_0''-(i\omega+Q)\Pr\theta_0=0 \tag{16}$$

$$\phi_0''-(i\omega+Kr)Sc\,\phi_0=-Sr\theta_0'' \tag{17}$$

The initial and boundary conditions (14) in compact form, become

$$\begin{array}{lll} F_0=t,\theta_0=1,\phi_0=1 & \text{at } y=0 \text{ and } t>0 & \\ F_1\to 0,\ \theta_0\to 0,\ \ \phi_0\to 0 & as\ \ y\to\infty \text{ for } t>0 & \end{array} \tag{18}$$

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

$$F(y,t)=\left\{A_1 e^{m_2 y}+A_2 e^{m_2 y}+A_3 e^{m_4 y}+A_4 e^{m_6 y}\right\}e^{i\omega t}$$

$$\theta(y,t)=\left\{e^{m_2 y}\right\}e^{i\omega t}$$

$$\phi(y,t)=\left\{B_1 e^{m_2 y}+B_2 e^{m_4 y}\right\}e^{i\omega t}$$

Skin-friction

$$\left(\frac{\partial F}{\partial y}\right)_{y=0}=\left(m_2 A_1+m_2 A_2+m_4 A_3+m_6 A_4\right)\cos\omega t$$

Nusselt number

$$\left(\frac{\partial \theta}{\partial y}\right)_{y=0}=\left(m_2\right)\cos\omega t$$

Sherwood number

$$\left(\frac{\partial \phi}{\partial y}\right)_{y=0}=\left(m_2 B_1+m_4 B_2\right)\cos\omega t$$

RESULTS AND DISCUSSION

This analysis integrates the system of equations by using perturbation technique for various parameters involving in the governing partial differential equations. The effect of thermal Grashof number (Gr) on the velocity profiles is seen in figure (2). Increase in thermal Grashof number contributes to the increase in velocity. Also it is noticed that as we move away from the plate the influence of thermal Grashof number is not that significant. The effect of mass Grashof number (Gc) on the velocity profiles is observed in figure (3). Increase in mass Grashof number is found to influence the velocity to increase. Also, it is seen that as we move far away from the plate it is seen that the effect of mass Grashof number is found to be not that significant. The velocity profiles for different values of rotation parameter (K) studied and presented in figure (4). It is observed that the velocity decreases with increasing values of the rotation parameter. The velocity profiles for different values of porous permeability parameter (K_1) shown in figure (5), it is clear that an increasing porous permeability parameter the velocity also increases. The observation that the velocity of the boundary layer decreases with increasing values of the chemical reaction parameter (Kr) shown in figure (6), It suggests that the reaction is consuming energy or modifying the flow in a way that reduces the velocity within the boundary layer. This is due to chemical reactions often release or absorb heat, which can influence the fluid's viscosity and thermal gradients, reducing the velocity near the plate. The influence of magnetic field (M) on the velocity profiles has been studied in figure (7). It is seen that the increase in the applied magnetic intensity contributes to the decrease in the velocity. Further, it is seen that the magnetic influence does not contribute significantly as we move away from the bounding surface. Figure (8) demonstrate the effect of Hall current (m) on the velocity profiles respectively. It is perceived form this figure that, the velocity increasing on increasing the values of Hall current throughout the boundary layer region. This implies that, Hall current tends to accelerate the fluid velocity throughout the boundary layer region which is consistent with the fact that Hall current induces flow in the flow filled. Figure (9) is sketched to show the effects of Prandtl number

$(\Pr)$ on velocity profiles. Four different realistic values of Prandtl number that are physically correspond to air, electrolytic solution, water and engine oil respectively are chosen. It is observed that the velocity decreases with increasing values of Prandtl number. This is due to the fact that fluid with large Prandtl number has high viscosity and small thermal conductivity, which make the fluid thick and causes a decrease in fluid velocity. Figure (10) display the effects of the heat source parameter (Q) on the velocity profiles respectively. Increasing the heat source parameter produces significant decrease in the thermal state of the fluid causing its velocity to decrease. This increase in the fluid temperature induces through the effect of thermal buoyancy more flow in the boundary layer causing the velocity of the fluid there to decrease. The influence of Schmidt number (Sc) on velocity profiles has been illustrated in figure (11). It is observed that, while all other participating parameters are held constant and Schmidt number is increased, it is seen that the velocity decreases in general. Further, it is noticed that as we move far away from the plate, the fluid velocity goes down. The contribution of Soret number (Sr) on the velocity profiles is noticed in figure (12). The increase in Soret number contributes the increase in the velocity field. Further, it is noticed that the velocity decreases as we move away from the plate which is found to be independent of Soret number. It is evident form figure (13), 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 (14) shown the temperature profiles for different values of heat source parameter (Q); it is clear that an increasing values of heat source parameter the temperature profiles decreases. Figure (15) show the influence of the chemical reaction parameter (Kr). Increasing the chemical reaction parameter produces a decrease in the species concentration. In turn, this causes the concentration buoyancy effects to decrease as Kr increases. The concentration profiles decreases with increase in the value of the Schmidt number (Sc) shown in figure (16). The effect of heat source parameter (Q) on concentration profiles shown in figure (17); from this figure we observed that an increasing in heat source parameter the result is decreases. The influence of Schmidt number (Sc) on the concentration is illustrated in figure (18). It is observed that increase in Schmidt number contributes to decrease of concentration of the fluid medium. Further, it is seen that Schmidt number does not contributes much to the concentration field as we move far away from the bounding surface. The influence of Soret number (Sr) on the concentration of the fluid medium is seen in figure (19). In general it is noted that increase in Soret number contributes to increase in concentration of the fluid medium. Further, the effect is found to be diminishing as we move away from the plate. Knowing the velocity profiles, temperature profiles and concentration profiles, it is customary to study the skin friction; Nusselt number and Sherwood number in dimensionless form are as follows. The local values of the skin friction, Nusselt number and Sherwood number for fixed parameters and are depicted in table (1) – (3) respectively. Table (1) shows that the axial coordinate for different values of mass Grashof number, Soret number, Prandtl number, Schmidt member, hall current, chemical reaction, permeability of the porous medium, magnetic parameter, cyclotron frequency, rotation parameter and heat source parameter. It is observed that an increasing values of mass Grashof number, Soret number, Prandtl number, Schmidt member, chemical reaction parameter, magnetic parameter, cyclotron frequency, rotation parameter and heat source parameter the skin friction decreases. But the reverse effects are observed for the parameters of hall current, permeability of the porous medium. Table (2) depicted Nusselt number for different values of Prandtl number and heat source parameter, it is clear that an increasing the both the parameter the results were decreases. Form table (3) we observed that Sherwood number for various values of heat source parameter, Schmidt number, Prandtl number, chemical reaction parameter and Soret number, it is evident that an increasing values of heat source parameter and Prandtl number the results are decreases, but there is no effect for Schmidt number, chemical reaction parameter and Soret number.

Conclusions:

The study of MHD free convection flow past an accelerated vertical plate in a porous medium with a heat source and a chemical reaction, coupled with the Soret effect, involves complex interactions between fluid dynamics, heat transfer, mass transfer, and chemical processes. Numerical simulations are often required to obtain meaningful insights into this type of flow. Understanding these interactions is crucial for designing systems in industries where heat and mass transfer, chemical reactions, and magnetic fields play a significant role.

- The Velocity profiles increase in thermal Grashof number contributes to the increase in velocity.
- The effect of mass Grashof number on the velocity profiles is observed in increase in mass Grashof number is found to influence the velocity to increase.
- The velocity profiles for different values of rotation parameter, it is observed that the velocity decreases with increasing values of the rotation parameter.
- The skin friction coefficient decreases with hall current, permeability of the porous medium.
- The influence of Soret number on the concentration it is noted that increase in Soret number contributes to increase in concentration of the fluid medium.

APPENDIX

$$m_2=-\sqrt{Q\Pr},m_4=-\sqrt{KrSc},m_6=-\sqrt{\alpha}$$

$$B_1=-\frac{Sr\,m_2^2}{m_2^2-KrSc},B_2=\left(1-B_1\right),A_1=-\frac{Gr}{m_2^2-\alpha},A_2=-\frac{GcB_1}{m_2^2-\alpha},A_3=-\frac{GcB_2}{m_4^2-\alpha}$$

$$A_4=\left(t-A_1-A_2-A_3\right)$$

Table (1): Skin friction (τ) versus Gr

Gc	Sr	Pr	Sc	m	Kr	K_1	M	ω	K	Q	t	τ
1.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.401**
2.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.155**
3.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.061**
4.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.068**
5.0	**1.0**	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.4010**
5.0	**2.0**	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.1800**
5.0	**3.0**	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**0.9599**
5.0	**4.0**	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**0.7393**
5.0	1.0	**0.3**	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.7210**
5.0	1.0	**0.5**	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**-0.3907**
5.0	1.0	**0.71**	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**-2.7130**
5.0	1.0	**1.0**	0.22	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**-4.809**
5.0	1.0	0.71	**0.16**	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.521**

5.0	1.0	0.71	**0.22**	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.401**
5.0	1.0	0.71	**0.31**	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.274**
5.0	1.0	0.71	**0.60**	0.5	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.076**
5.0	1.0	0.71	0.22	**0.5**	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.401**
5.0	1.0	0.71	0.22	**1.0**	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.523**
5.0	1.0	0.71	0.22	**1.5**	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.564**
5.0	1.0	0.71	0.22	**2.0**	1.0	1.0	1.0	0.5	1.0	1.0	1.0	**1.577**
5.0	1.0	0.71	0.22	0.5	**1.0**	1.0	1.0	0.5	1.0	1.0	1.0	**1.401**
5.0	1.0	0.71	0.22	0.5	**2.0**	1.0	1.0	0.5	1.0	1.0	1.0	**1.155**
5.0	1.0	0.71	0.22	0.5	**3.0**	1.0	1.0	0.5	1.0	1.0	1.0	**1.061**
5.0	1.0	0.71	0.22	0.5	**4.0**	1.0	1.0	0.5	1.0	1.0	1.0	**1.068**
5.0	1.0	0.71	0.22	0.5	1.0	**1.0**	1.0	0.5	1.0	1.0	1.0	**1.401**
5.0	1.0	0.71	0.22	0.5	1.0	**2.0**	1.0	0.5	1.0	1.0	1.0	**1.55**
5.0	1.0	0.71	0.22	0.5	1.0	**3.0**	1.0	0.5	1.0	1.0	1.0	**1.594**
5.0	1.0	0.71	0.22	0.5	1.0	**4.0**	1.0	0.5	1.0	1.0	1.0	**1.614**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	**1.0**	0.5	1.0	1.0	1.0	**1.401**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	**2.0**	0.5	1.0	1.0	1.0	**0.9255**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	**3.0**	0.5	1.0	1.0	1.0	**-**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	**4.0**	0.5	1.0	1.0	1.0	**0.1377**
												-0.867
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	**0.5**	1.0	1.0	1.0	**1.401**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	**1.0**	1.0	1.0	1.0	**0.6151**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	**1.5**	1.0	1.0	1.0	**-3.42**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	**2.0**	1.0	1.0	1.0	**-11.10**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	**0.5**	1.0	1.0	**1.808**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	**1.0**	1.0	1.0	**1.401**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	**1.5**	1.0	1.0	**0.2321**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	**2.0**	1.0	1.0	**-1.916**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	**1.0**	1.0	**3.439**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	**2.0**	1.0	**1.401**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	**3.0**	1.0	**-1.332**
5.0	1.0	0.71	0.22	0.5	1.0	1.0	1.0	0.5	1.0	**4.0**	1.0	**-11.31**

Table (2): Nusselt number versus ω

Pr	*Q*	*t*	*Sh*
0.3	1.0	0.1	**- 0.5477**
0.5	1.0	0.1	**- 1.1400**
0.71	1.0	0.1	**- 1.5170**
1.0	1.0	0.1	**- 1.8170**
0.71	**1.0**	0.1	**- 0.8426**
0.71	**2.0**	0.1	**- 1.1920**
0.71	**3.0**	0.1	**-1.4590**
0.71	**4.0**	0.1	**- 1.6850**

Table (3): Sherwood number versus ω

Q	*Sc*	Pr	*Kr*	*Sr*	*t*	*Nu*
1.0	0.22	0.71	1.0	1.0	0.1	**-0.8426**
2.0	0.22	0.71	1.0	1.0	0.1	**-1.1920**

3.0	0.22	0.71	1.0	1.0	0.1	**-1.4590**
4.0	0.22	0.71	1.0	1.0	0.1	**-1.6850**
1.0	**0.16**	0.71	1.0	1.0	0.1	**-0.8426**
1.0	**0.22**	0.71	1.0	1.0	0.1	**-0.8426**
1.0	**0.31**	0.71	1.0	1.0	0.1	**-0.8426**
1.0	**0.60**	0.71	1.0	1.0	0.1	**-0.8426**
1.0	0.22	**0.3**	1.0	1.0	0.1	**-0.5477**
1.0	0.22	**0.5**	1.0	1.0	0.1	**-0.7071**
1.0	0.22	**0.71**	1.0	1.0	0.1	**-0.8426**
1.0	0.22	**1.0**	1.0	1.0	0.1	**-0.6967**
1.0	0.22	0.71	**1.0**	1.0	0.1	**-0.8426**
1.0	0.22	0.71	**2.0**	1.0	0.1	**-0.8426**
1.0	0.22	0.71	**3.0**	1.0	0.1	**-0.8426**
1.0	0.22	0.71	**4.0**	1.0	0.1	**-0.8426**
1.0	0.22	0.71	1.0	**1.0**	0.1	**-0.8426**
1.0	0.22	0.71	1.0	**2.0**	0.1	**-0.8426**
1.0	0.22	0.71	1.0	**3.0**	0.1	**-0.8426**
1.0	0.22	0.71	1.0	**4.0**	0.1	**-0.8426**

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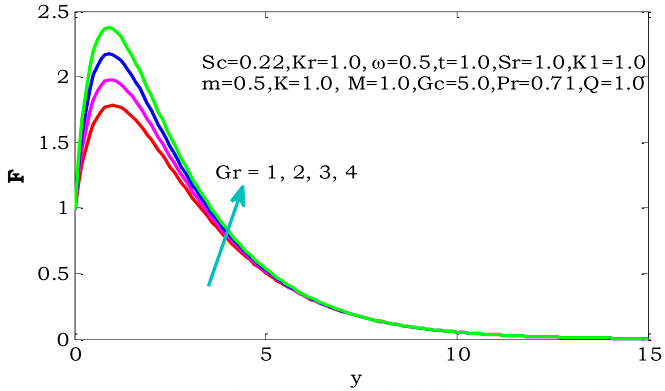


Figure (2): Velocity profiles for different values of Gr

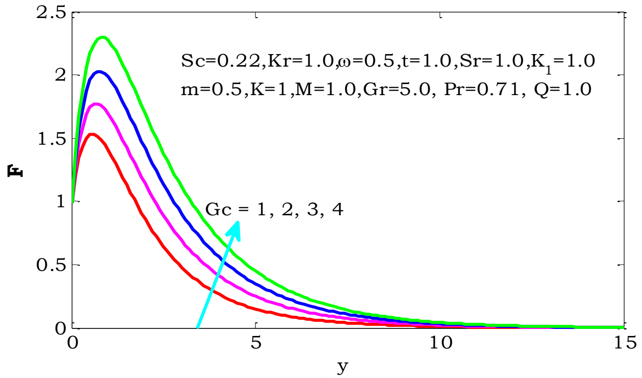


Figure (3): Velocity profiles for different values of Gc

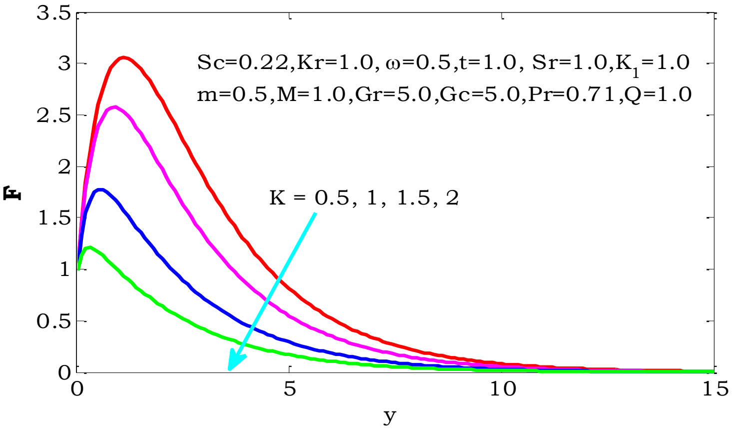


Figure (4): Velocity profiles for different values of K

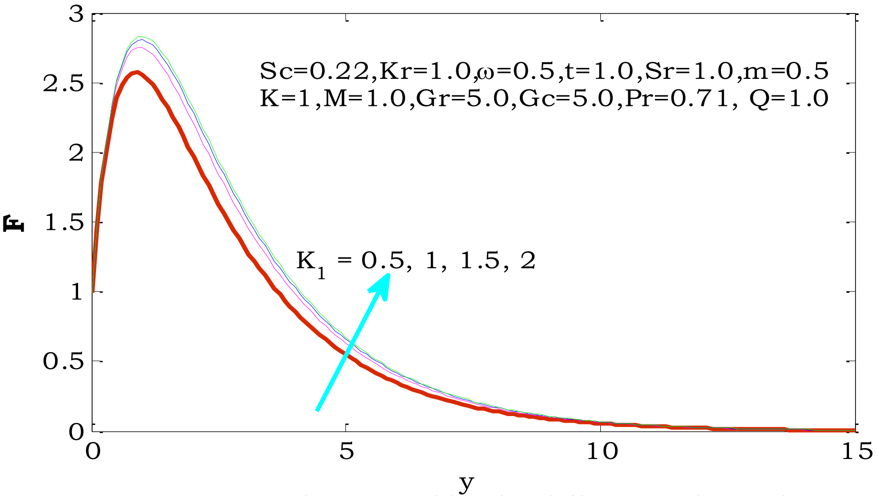
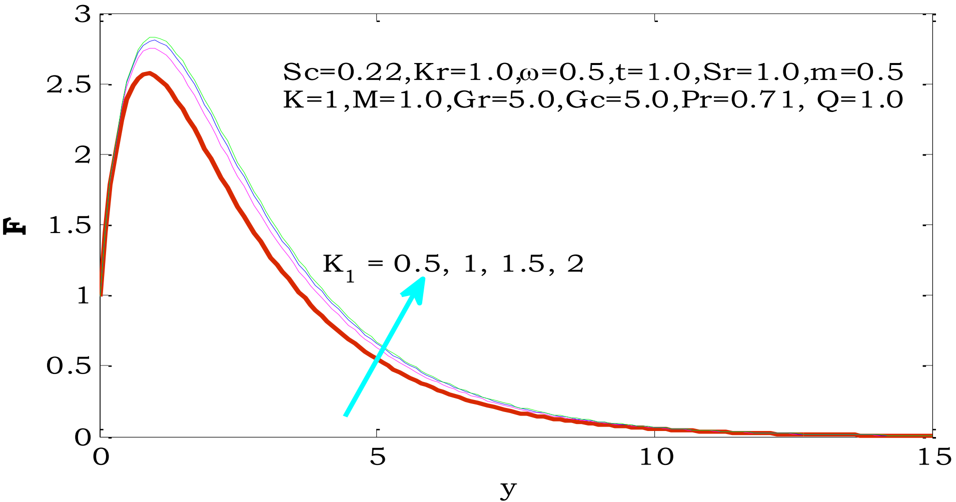


Figure (5): Velocity profiles for different values of K_1



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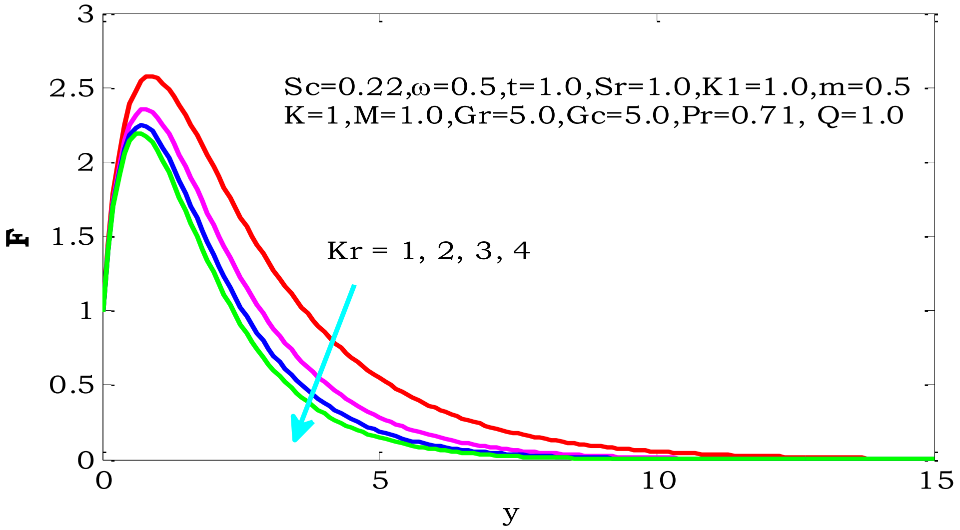

Figure (6): Velocity profiles for different values of Kr

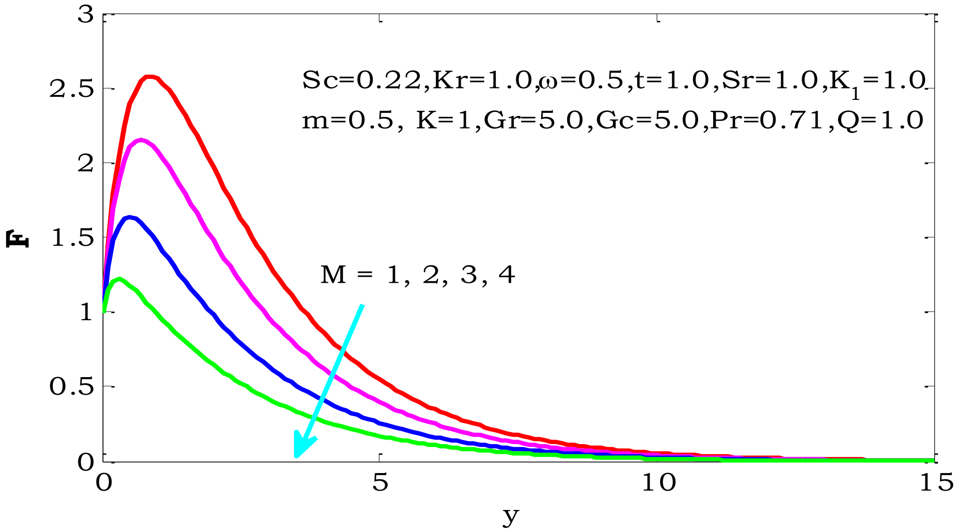

Figure (7): Velocity profiles for different values of M

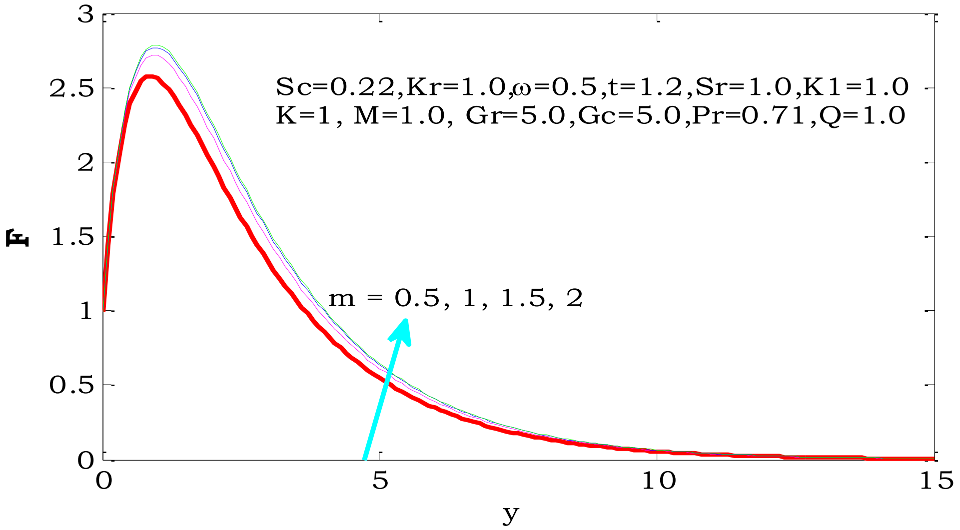

Figure (8): Velocity profiles for different values of m

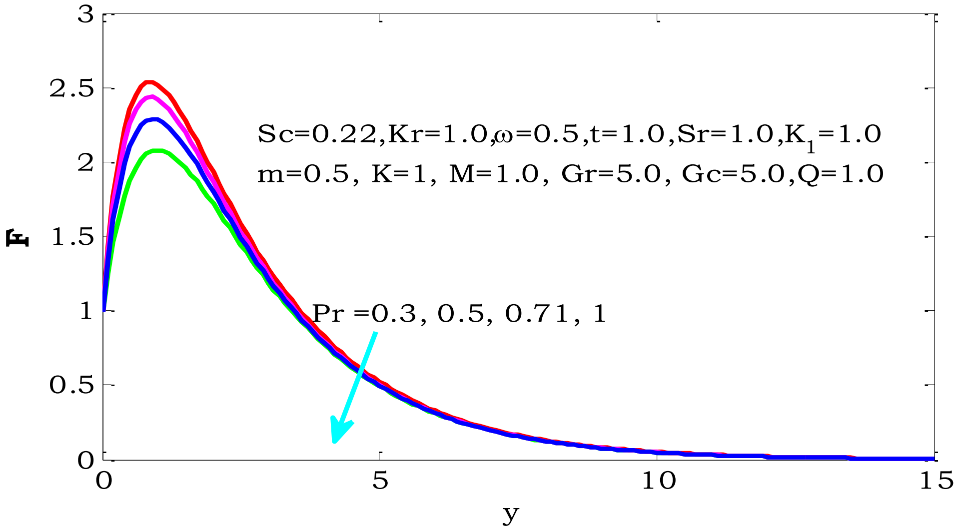

Figure (9): Velocity profiles for different values of Pr

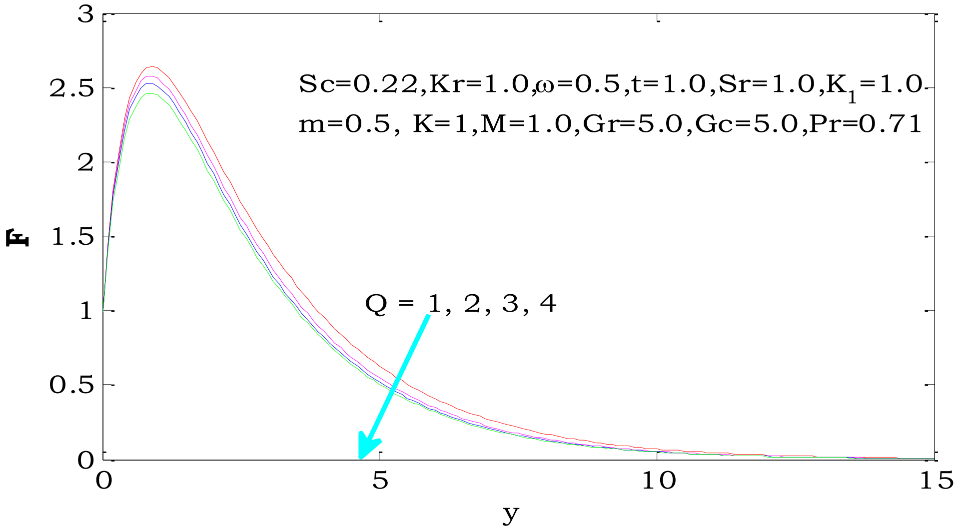

Figure (10): Velocity profiles for different values of Q

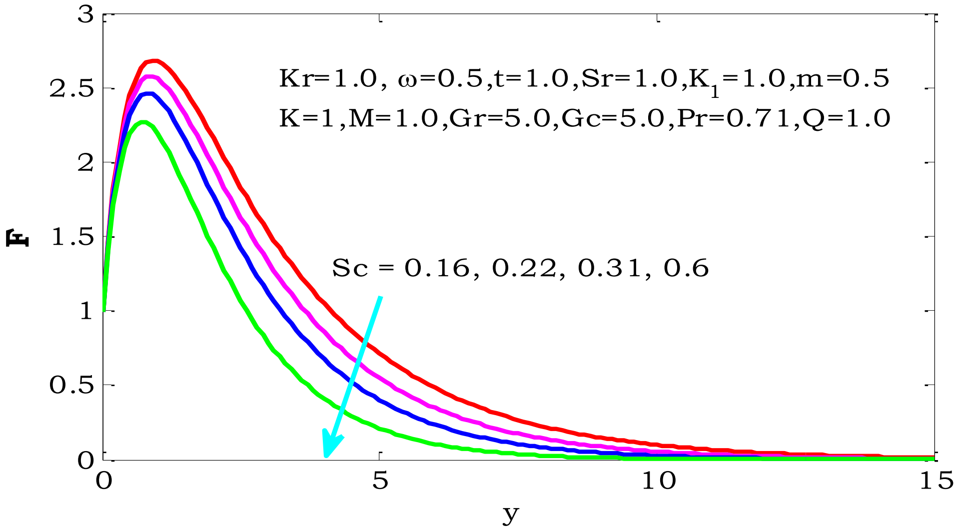

Figure (11): Velocity profiles for different values of Sc

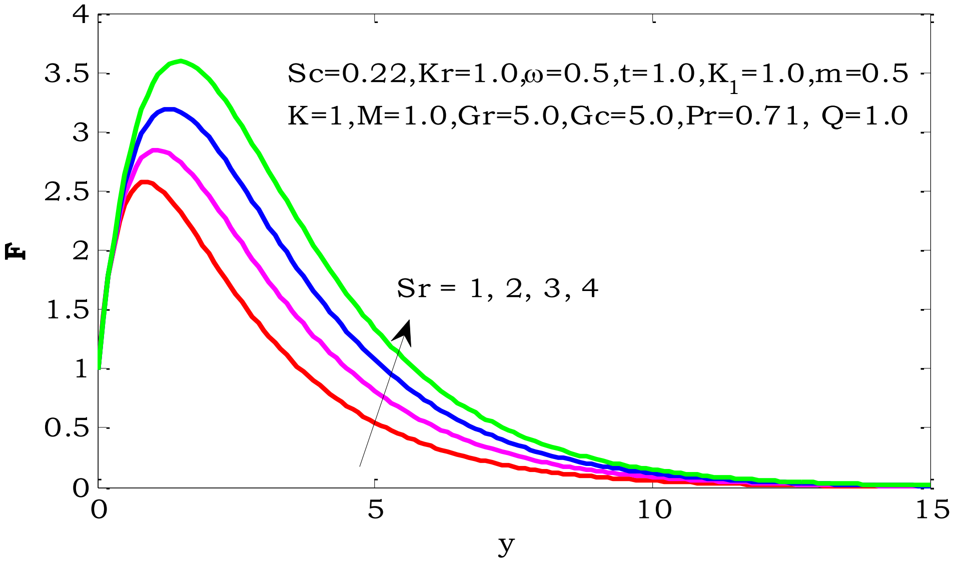

Figure (12): Velocity profiles for different values of Sr

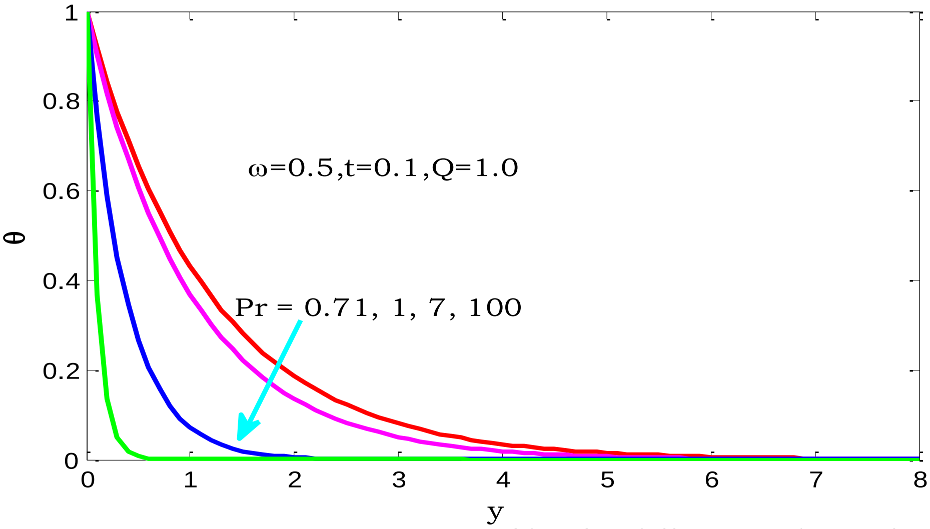

Figure (13): Temperature profiles for different values of Pr

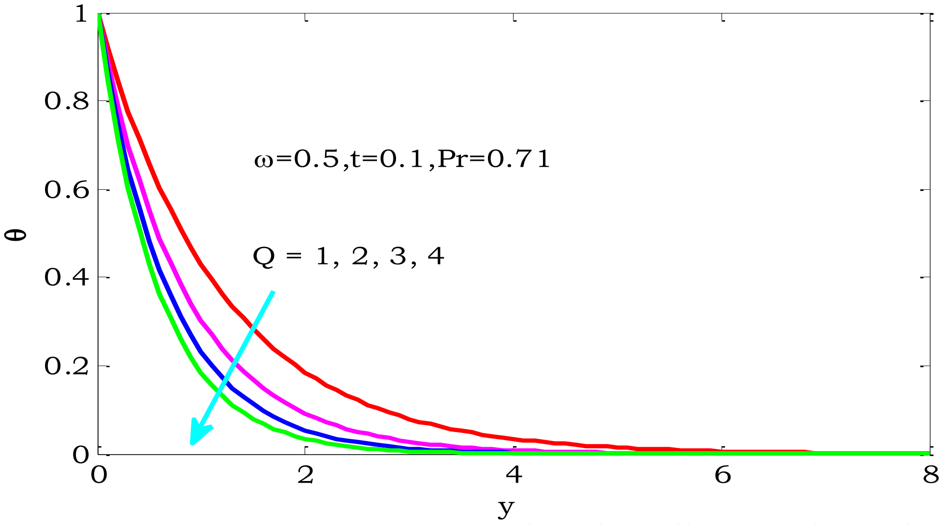

Figure (14): Temperature profiles for different values of Q

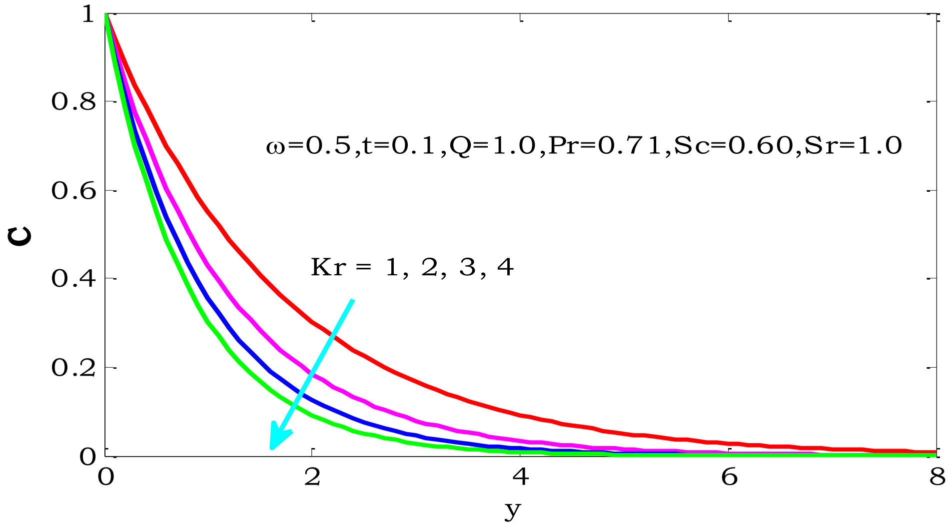

Figure (15): Concentration profiles for different values of Q

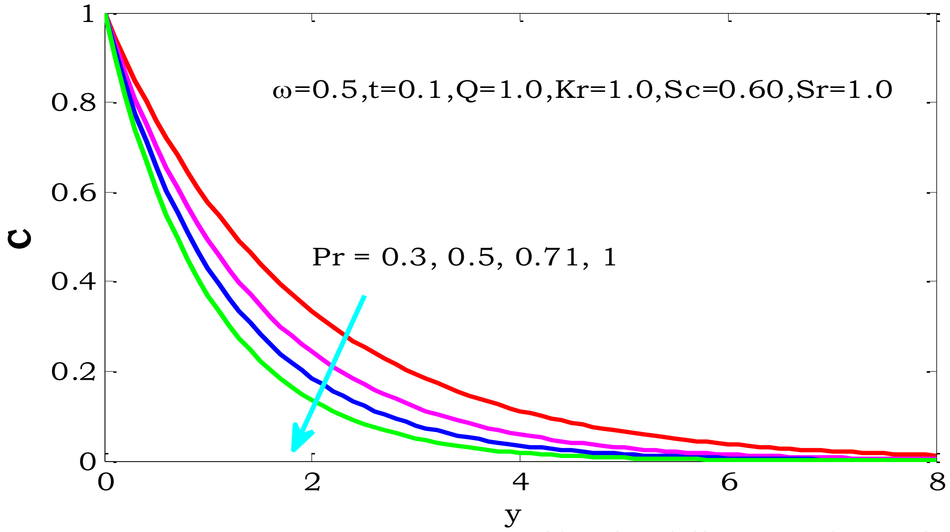

Figure (16): Concentration profiles for different values of Pr

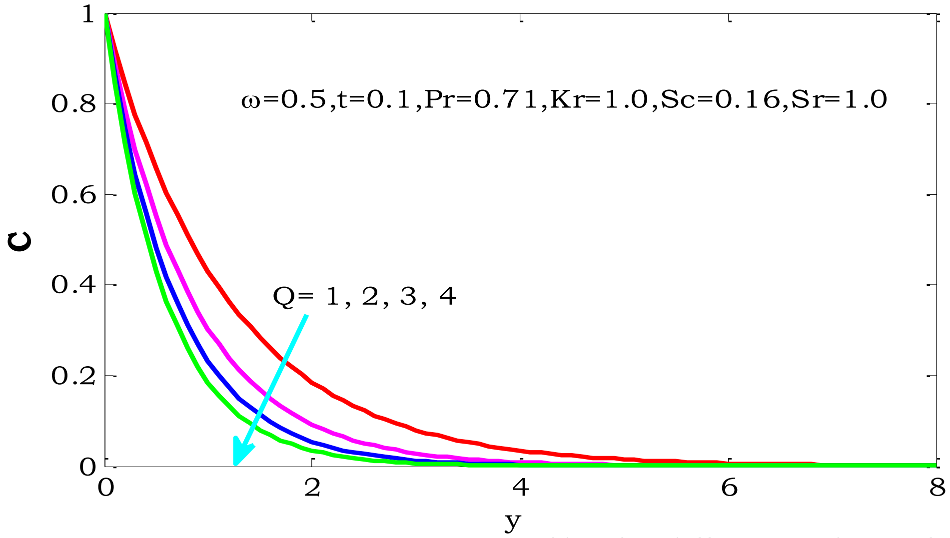

Figure (17): Concentration profiles for different values of Q

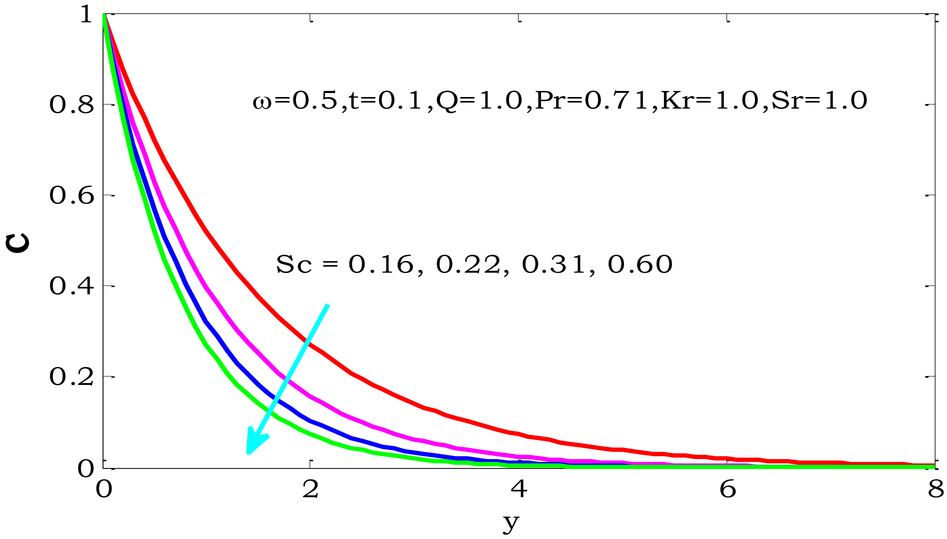

Figure (18): Concentration profiles for different values of Sc

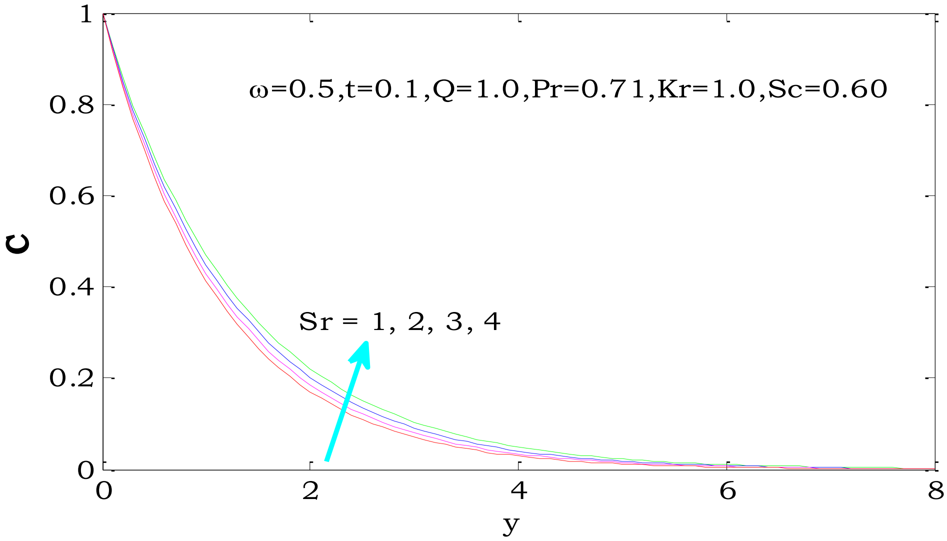

Figure (19): Concentration profiles for different values of Sr