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Radiation and Chemical Reaction Effects on Unsteady MHD Free Convection Flow Past a Linearly Accelerated Vertical Porous Plate with Variable Temperature and Mass Diffusion

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Abstract

The objective of the present study is to investigate radiation and chemical reaction effects on unsteady MHD flow past a linearly accelerated vertical porous plate with variable temperature and also with variable mass diffusion in presence of heat source or sink under the influence of applied transverse magnetic field. The dimensionless governing equations involved in the present analysis are solved using the closed analytical method. The velocity, temperature, concentration, Skin-friction, the rate or heat transfer and the rate of mass transfer are studied through graphs in terms of different physical parameters.

Key words: MHD, radiation, chemical reaction, heat source or sink, heat and mass transfer.

1. INTRODUCTION

The study of magneto hydrodynamics with mass and heat transfer in the presence of radiation and diffusion has attracted the attention of a large number of scholars due to diverse applications. In astrophysics and geophysics, it is applied to study the stellar and solar structures, radio propagation through the ionosphere, etc. In engineering we find its applications like in MHD pumps, MHD bearings, etc. Combined heat and mass transfer problems with chemical reaction are of importance in many processes and have, therefore, received a considerable amount of attention in recent years. In processes such as drying, evaporation on the surface of a water, energy transfer in a wet cooling tower and the flow in a desert cooler, heat and mass transfer occur simultaneously. Possible applications of this type of flow can be found in many industries. For example, in the power industry, one of the methods of generating electric energy is directly from a moving conducting fluid. The effects of radiation on MHD flow and heat transfer problem have become more important in industries. At high operating temperature, radiation effect can be quite significant. Many processes in engineering areas occur at high temperature and knowledge of radiation heat transfer becomes very important for the design of the pertinent equipment. Nuclear power plants, gas turbines and the various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such engineering areas. Angirasa et al. [1] have investigated heat and mass transfer by natural convection with opposing buoyancy effects in a fluid saturated porous medium. Abel et al. [2] have reported viscoelastic fluid flow and heat transfer over stretching sheet with variable viscosity. Makinde [3] examined the transient free convection interaction with thermal radiation of an absorbing-emitting fluid along moving vertical permeable plate. Kandasamy et al. [4] have investigated the influence of chemical reaction on MHD flow with heat and mass transfer over a vertical stretching sheet in presence of heat source and thermal stratification effect. The effect of chemical reaction on free convection and heat transfer past an oscillating infinite vertical plate has been studied by Muthucumaraswamy and Meenakshisundaram [5]. Raju et al. [6] have studied unsteady MHD free convection and chemically reactive flow past an infinite vertical porous plate. Satya Narayana et al. [7] have investigated MHD free convective heat and mass transfer past a vertical porous plate with variable temperature. Michiyochi *et al.* [8] considered natural convection heat transfer from a horizontal cylinder to the mercury under a magnetic field.

Watanabe and Pop [9] were investigated the heat transfer in the thermal boundary layers in magneto hydrodynamic flow over a flat plate in the presence of transverse magnetic field.

Unsteady free convective flow on taking into account the mass transfer phenomenon past an infinite vertical porous plate with constant suction was studied by Soundalgekar and Wavre [10]. Callahan and Manner [11] first considered the transient free convection flow past a semi infinite plate by explicit finite difference method. They also considered the presence of species concentration. However this analysis is not applicable for other fluids whose Prandtl number is different from unity. Soundalgekar and Ganesan [12] analyzed transient free convective flow past a semi infinite vertical flat plate, taking into account mass transfer by an implicit finite difference method of Crank-Nicolson type. In their analysis they observed that an increase in the N leads to an increase in the velocity but a decrease in the temperature and concentration. Elbashbeshy [13] studied heat and mass transfer along a vertical plate with variable surface temperature and concentration in the presence of magnetic field. Aboeldahab and Elbarbary [14] took into account the Hall current effect on the MHD free convection heat and mass transfer over a semi infinite vertical plate upon which the flow subjected to a strong external magnetic field. Chen [15] studied heat and mass transfer in HD flow by natural convection from a permeable inclined surface with variable temperature and concentration using Keller box finite difference method and found that an increase in the value of temperature exponent m leads to a decrease in the local skin friction, Nusselt and Sherwood numbers. Takhar*et al.* [16] considered the unsteady free convection flow over a semi infinite vertical plate. Ganesan and Rani [17] studied the unsteady free convection on vertical cylinder with variable heat and mass flux. Heat transfer by simultaneous radiation and convection has applications in numerous technological problems, including combustion, furnace design, the design of high temperature gas cooled nuclear reactors, nuclear reactor safety, fluidized bed heat exchanger, fire spreads, advance energy conversion devices such as open cycle coal and natural gas fired MHD, solar fans, solar collectors natural convection in cavities, turbid water bodies, photo chemical reactors and many others when heat transfer by radiation is of the same order of magnitude as by convection, a separate calculation of radiation and convection and their superposition without considering the interaction between them can lead to significant errors in the results, because of the presence of the radiation in the medium, which alters the temperature distribution within the fluid. Therefore, in such situation heat transfer by convection and radiation should be solved for simultaneously. In this context, Abd El-Naby *et al.* [18] studied the effects of radiation on unsteady free convective flow past a semi infinite vertical plate with variable surface temperature using Crank-Nicolson finite difference method. They observed that, both the velocity and temperature are found to decrease with an increase in the temperature exponent. Chamkha *et al.* [19] analyzed the effects of radiation on free convection flow past a semi-infinite vertical plate with mass transfer by taking into account the buoyancy ratio parameter N. In their analysis they found that, as the distance from the leading edge increase, both the velocity and temperature decrease, where as the concentration increases. Ganesan and Loganadhan [20] studied the radiation and mass transfer effects on flow of incompressible viscous fluid past a moving vertical cylinder using Resseland approximation by The Crank-Nicolson finite difference method. Takhar *et al.* [21] considered the effects of radiation on MHD free convection flow of a radiating gas past a semi infinite vertical plate. In most of the studies mentioned above, viscous dissipation is neglected. Gebhart and Mollendorf [22] considered the effects of viscous dissipation for external natural convection flow over a surface. Soundalgekar [23] analyzed viscous dissipative heat on the two dimensional unsteady flow past an infinite vertical porous plate when the temperature oscillates in time there is constant suction on the plate. Israel-Cookey *et al.* [24] investigated the influence of viscous dissipation and radiation on MHD free convection flow past an infinite heated vertical plate ina porous medium with time dependent suction. Gokhaleand Samman [25] studied the effects of mass transfer on the transient free convection flow of a dissipative fluid along a semi infinite vertical plate with constant heat flux. Ramana Reddy *et al.* [26] considered effects of radiation and mass transfer on MHD free convective dissipative fluid in the presence of heat source/sink. Recently, Ramana Reddy *et al.* [27] investigated the chemical and radiation absorption effects on MHD convective heat and mass transfer flow past a semi-infinite vertical moving porous plate with time dependent suction.

In spite of all the previous studies, the effects of radiation and chemical reaction on unsteady MHD flow past an impulsively started linearly accelerated infinite vertical porous plate with variable temperature and also with variable mass diffusion in the presence of heat source or sink and transverse applied magnetic field. The dimensionless governing equations involved in the present analysis are solved using closed analytical method. The behavior of the velocity, temperature, concentration, skin-friction, Nusselt number and Sherwood number has been discussed qualitatively for variations in the governing parameters.

2. FORMATION OF THE PROBLEM

Let us consider the unsteady one dimensional flow of a viscous incompressible, electrically conducting, radiating fluid past an impulsively started linearly accelerated infinite vertical plate with variable temperature and mass diffusion in the presence of Heat source/sink under the influence of applied transverse magnetic field. The plate is taken along $x-$axis in vertically upward direction and $y-$axis is taken normal to the plate. Initially it is assumed that the plate and fluid are at the same temperature T'_∞ and concentration level C'_∞ in stationary condition for all the points. At time $t' > o$, the plate is linearly accelerated with a velocity $u = u_0 t'$ in the vertical upward direction against to the gravitational field and at the same time the plate temperature is raised linearly with time t and also the mass is diffused from the plate to the fluid is linearly with time. A transverse magnetic field of uniform strength B_0 is assumed to be applied normal to the plate. The viscous dissipation and induced magnetic field are assumed to be negligible. The chemical reaction takes place in the flow and all thermo physical properties which are assumed to constant. The fluid considered here is gray, absorbing/emitting radiation but a non-scattering medium. Then under by usual Boussinesq’s approximation, the unsteady flow is governed by the following equations.

$$\frac{\partial u'}{\partial t'}=\nu\frac{\partial^2 u'}{\partial y'^2}+g\beta\left(T'-T'_\infty\right)+g\beta^*\left(C'-C'_\infty\right)+\frac{\sigma B_0}{\rho}u'-\frac{\nu}{K'}u' \tag{2.1}$$

$$\frac{\partial T'}{\partial t'}=\frac{1}{\rho C_p}\left[k\frac{\partial^2 T'}{\partial y'^2}-Q_0\left(T'-T'_\infty\right)\right]-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y'} \tag{2.2}$$

$$\frac{\partial C'}{\partial t'}=D\frac{\partial^2 C'}{\partial y'^2}+D_1\frac{\partial^2 T'}{\partial y'^2}-Kr\left(C'-C'_\infty\right) \tag{2.3}$$

where x', y' are the dimensional distance along and perpendicular to the plate, respectively. u' and v' are the velocity components in the x', y' directions respectively, g is the gravitational acceleration, ρ is the fluid density, β and β^* are the thermal and concentration expansion coefficients respectively, K' is the Darcy permeability, B_0 is the magnetic induction, T' is the thermal temperature inside the thermal boundary layer and C' is the corresponding concentration, σ is the electric conductivity, C_p is the specific heat at constant pressure, D is the diffusion coefficient, q_r is the heat flux, Q_0 is the dimensional heat absorption coefficient, D_1 is the Coefficient of thermal diffusivity and Kr chemical reaction parameter..

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

$$\begin{aligned}
&t'\le 0:\quad u'=0,\quad T'=T'_\infty\ \ C'=C'_\infty \ \text{ for all } y'\\
&t'>0:\ \begin{cases} u'=u_0\,t',\quad T'=T'_\infty+\varepsilon\left(T'_w-T'_\infty\right)At',\ C'=C'_\infty+\varepsilon\left(C'_w-C'_\infty\right)At' & \text{at}\quad y'=0\\ u'=0,\quad T'\to T'_\infty,\quad C'\to C'_\infty, & \text{as}\quad y'\to\infty\end{cases}
\end{aligned} \tag{2.4}$$

where $A=\frac{u_0^2}{\nu}$

The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial y'}=-4a^*\sigma T'^3_\infty\left(T'^4_\infty-T'^4\right) \tag{2.5}$$

It is assumed that the temperature differences within the flow are sufficiently small and that T'^4 may be expressed as a linear function of the temperature. This is obtained by expanding T'^4 in a Taylor series about T'_∞ and neglecting the higher order terms, thus we get

$$T'^4\cong 4T'^3_\infty T'-3T'^4_\infty \tag{2.6}$$

From equations (2.5) and (2,6), equation (2.2) reduces to

$$\rho C_p \frac{\partial T'}{\partial t'} = k\frac{\partial^2 T'}{\partial y'^2} + 16a^*\sigma T_\infty'^3\left(T_\infty' - T'\right) \tag{2.7}$$

On introducing the following non-dimensional quantities:

$$\begin{gathered} y = \frac{u_0 y'}{\nu}, u = \frac{u'}{u_0}, t = \frac{t' u_0^2}{4\nu}, \theta = \frac{T' - T_\infty'}{T_w' - T_\infty'}, C = \frac{C' - C_\infty'}{C_w' - C_\infty'}, K = \frac{K' u_0^2}{\nu^2}, \\ Gr = \frac{g\beta\nu(T_w' - T_\infty')}{v_0^3}, \mathrm{Pr} = \frac{\mu\rho C_p}{k}, Gm = \frac{g\beta^*\nu(C_w' - C_\infty')}{u_0^3}, Sc = \frac{\nu}{D}, \\ \mathrm{R} = \frac{16a^*\nu^2\sigma T_\infty'^3}{k u_0^2}, M = \frac{\sigma B_0^2 \nu}{\rho u_0^2}, So = \frac{D_1(T_w' - T_\infty')}{\nu(C_w' - C_\infty')}, H = \frac{Q'\nu^2}{\kappa u_0^2}, Kr = \frac{K' r\nu}{u_0{}^2} \end{gathered} \tag{2.8}$$

The governing equations for the momentum, the energy, and the concentration in a dimensionless form are

$$\frac{\partial u}{\partial t} = Gr\theta + GmC + \frac{\partial^2 u}{\partial y^2} - \left(M + \frac{1}{K}\right)u \tag{2.9}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 \theta}{\partial y^2} - \left(\frac{R + H}{\mathrm{Pr}}\right)\theta \tag{2.10}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} + So\frac{\partial^2 \theta}{\partial y^2} - KrC \tag{2.11}$$

where $Gr, Gm, \mathrm{M}, \mathrm{K}, \mathrm{Pr}, R, \mathrm{H}, \mathrm{Sc}, So, Kr$ are the Grashof number, modified Grashof number, magnetic parameter, permeability parameter, Prandtl number, radiation parameter, heat source parameter, Schmidt number, Soret number and chemical reaction parameter respectively.

The relevant corresponding boundary conditions for $t > 0$ are transformed to:

$$\begin{gathered} u = t, \quad \theta = t, \quad C = t \quad \text{at} \quad y = 0 \\ u \to 0, \quad \theta \to 0, \quad C \to 0 \quad \text{as} \quad \mathrm{y} \to \infty \end{gathered} \tag{2.12}$$

3. SOLUTION OF THE PROBLEM

In order to solve equations (2.9) - (2.11) with respect to the boundary conditions (2.12) for the flow, let us take

$$u\left(y,t\right) = u_0\left(y\right)e^{i\omega t} \tag{3.1}$$

$$\theta\left(y,t\right) = \theta_0\left(y\right)e^{i\omega t} \tag{3.2}$$

$$C\left(y,t\right) = C_0(y)e^{i\omega t} \tag{3.3}$$

Substituting the Equations (3.1) - (3.3) in Equations (2.9) – (2.11), we obtain:

$$u_0'' - \left(M + i\omega + \frac{1}{K}\right)u_0 = -\left[Gr\theta_0 + GmC_0\right] \tag{3.4}$$

$$\theta_0'' - A_1^2\theta_0 = 0 \tag{3.5}$$

$$C_0'' - A_2^2 C_0 = -ScSo\theta_0'' \tag{3.6}$$

where prime denotes ordinary differentiation with respect to y.

The corresponding boundary conditions can be written as

$$\begin{aligned} &u_0 = te^{-i\omega t},\ \theta_0 = te^{-i\omega t}, C_0 = te^{-i\omega t} \quad \text{at} \quad y = 0 \\ &u_0 \to 0, \quad \theta_0 \to 0, \quad C_0 \to 0 \quad \text{as} \quad y \to \infty \end{aligned} \tag{3.7}$$

Solving equations (3.4) – (3.6) under the boundary conditions (3.7), we obtain the velocity, temperature and concentration distribution in the boundary layer as:

$$u(y,t) = A_6 e^{-A_1 y} + A_7 e^{-A_2 y} + A_8 e^{-A_1 y} + A_9 e^{-A_5 y} \tag{3.8}$$

$$\theta(y,t) = te^{-A_1 y} \tag{3.9}$$

$$C(y,t) = A_4 e^{-A_1 y} + A_3 e^{-A_1 y} \tag{3.10}$$

where

$$A_1 = \sqrt{R + H + i\omega \Pr}, \quad A_2 = \sqrt{(i\omega + Kr)Sc}, \quad A_3 = -\frac{ScSoA_1^2 t}{A_1^2 - A_2^2},$$

$$A_4 = t - A_3, \quad A_5 = \sqrt{M + i\omega + \frac{1}{K}}, \quad A_6 = -\frac{t\,Gr}{A_1^2 - A_5^2},$$

$$A_7 = -\frac{A_4\,Gm}{A_2^2 - A_5^2}, \quad A_8 = -\frac{A_3\,Gm}{A_1^2 - A_5^2}, \quad \mathrm{A}_9 = -\left[A_6 + A_7 + A_8 + t\right]$$

NUSSELT NUMBER

From temperature field, now we study Nusselt number (rate of change of heat transfer) which is given in non dimensional form as

$$Nu = -\left(\frac{\partial\theta}{\partial y}\right)_{y=0} = tA_1$$

SHERWOOD NUMBER

From concentration field, now we study Sherwood number (rate of change of mass transfer) which is given in non dimensional form as

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = A_2 A_4 + A_1 A_3$$

4. RESULTS AND DISCUSSION

In order to get the physical insight into the problem, we have plotted velocity, temperature, concentration, the rate of heat transfer and the rate of mass transfer for different values of the physical parameters like Radiation parameter (R), Magnetic parameter (M), Heat source parameter (H), Soret number (So), Schmidt number (Sc), Thermal Grashof number (Gr), Mass Grashof number (Gm) and Prandtl number (Pr) in figures 1 to 17.

The contribution of the Magnetic field on the velocity profiles is noticed in Fig .1. It is observed that as the magnetic intensity increases, the velocity field decreases throughout the analysis as long as the radiation parameter is held constant. Further, it is also noticed that the velocity of the fluid medium raises within the boundary layer region and thereafter, it decreases which clearly indicates that the radiation parameter has not that much of significant effect as was in the initial stage. Fig.2 illustrates that the velocity profiles for the different values of permeable parameter K. It is noticed that the increasing values of permeability parameter (K) the velocity profiles is also increases due to the fact that increases with increasing values of permeability parameter (K) reduces the drag force which assists the fluid considerably to move fast. The influence of thermal Grashof number (Gr) and modified Grashof number (Gm) on the velocity profiles are illustrated graphically in Fig.3 and Fig.4 respectively. The other parameters are held constant, and as the thermal Grashof number or modified Grashof number is increased, in general the fluid velocity increases and also reverse effect is observed when modified Grashof number is increases. Fig. 5 and Fig.6 represents the effects of the chemical reaction parameter (Kr) on the velocity and concentration profiles respectively. It is observed that the velocity and concentration are decreases with an increasing the chemical reaction parameter (Kr). Fig.7 and Fig.8 are illustrated the effect of velocity and temperature profiles for different values of radiation parameter (R). It is observed that the increases of radiation parameter (R), the velocity and temperature profiles are decreases. Fig.9 and Fig.10 are illustrated the effect of velocity and temperature profiles for different values of heat absorption parameter (Q). It is can be seen that the both velocity and temperature profiles are decreases with an increasing the heat absorption parameter (Q). The influence of the Prandtl number (Pr) on velocity and temperature profiles is shown in Fig. 11 and Fig.12 respectively. It is observed that both the velocity and temperature are decreases with an increasing of the Prandtl number (Pr). Fig.13 and Fig. 14 show the dimensionless velocity and concentration profiles for different values of Soret number (So). It is noticed that the velocity and concentration profiles are increases with the increase of Soret number (So).

The velocity and concentration profiles for different values of Schmidt number (Sc) is shown in Fig.15 and Fig.16. It is observed that both the velocity and concentration are decreases with an increasing of the Schmidt number (Sc). This causes the concentration buoyancy effects to decrease yielding a reduction in the fluid velocity. The reduction in the velocity and concentration profiles are accompanied by simultaneous reductions in the velocity and concentration boundary layers.

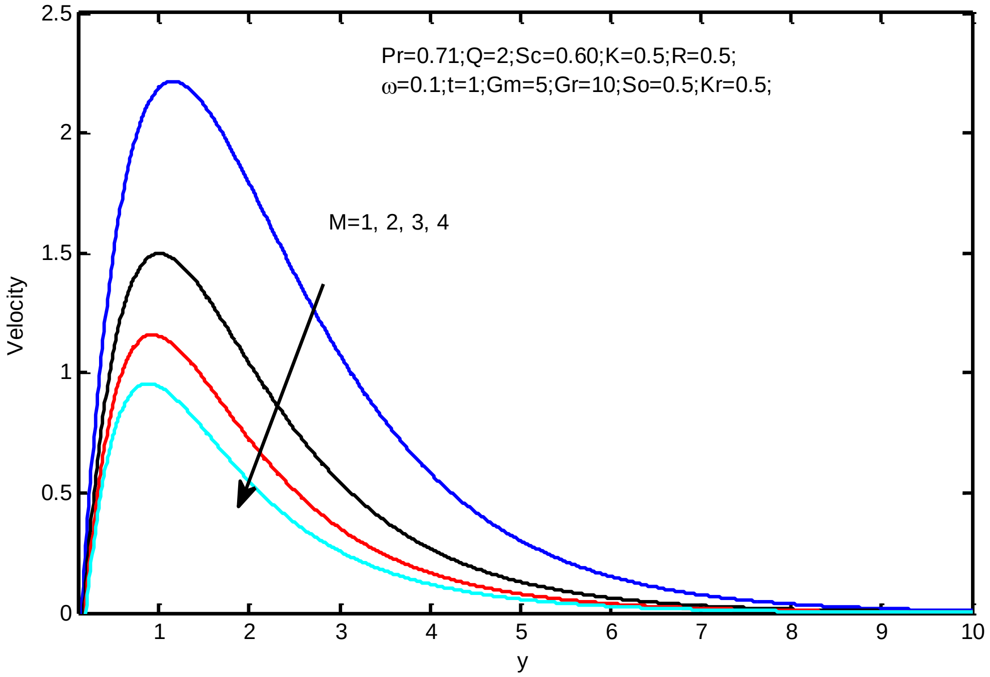

Fig.1. Velocity profiles for different values of magnetic parameter (M).

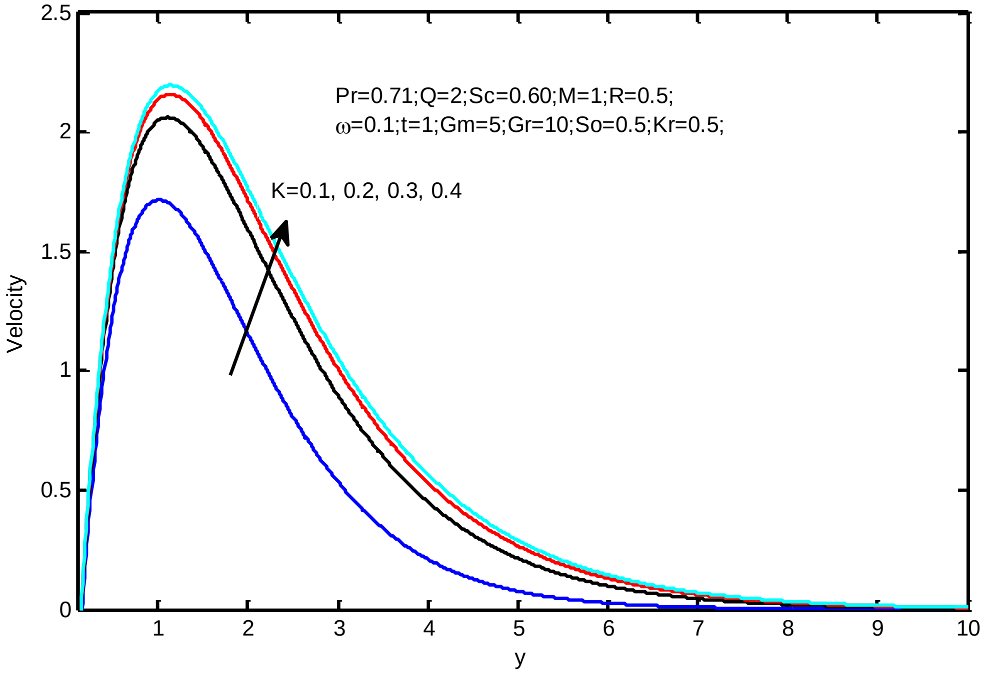

Fig.2. Velocity profiles for different values of permeability parameter (K).

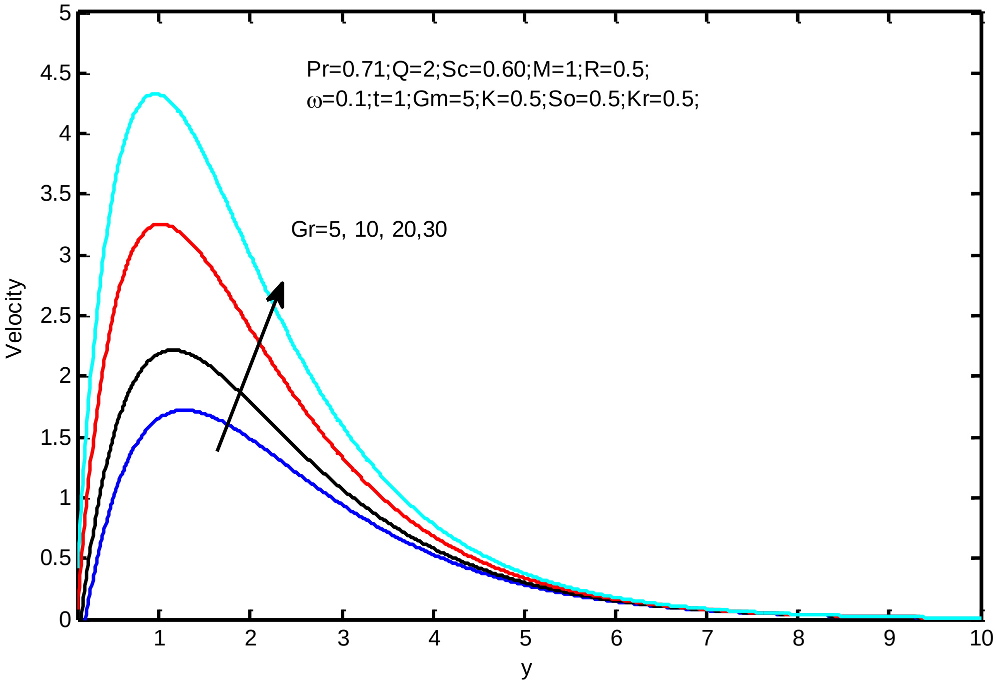

Fig.3. Velocity profiles for different values of Grashof number (Gr).

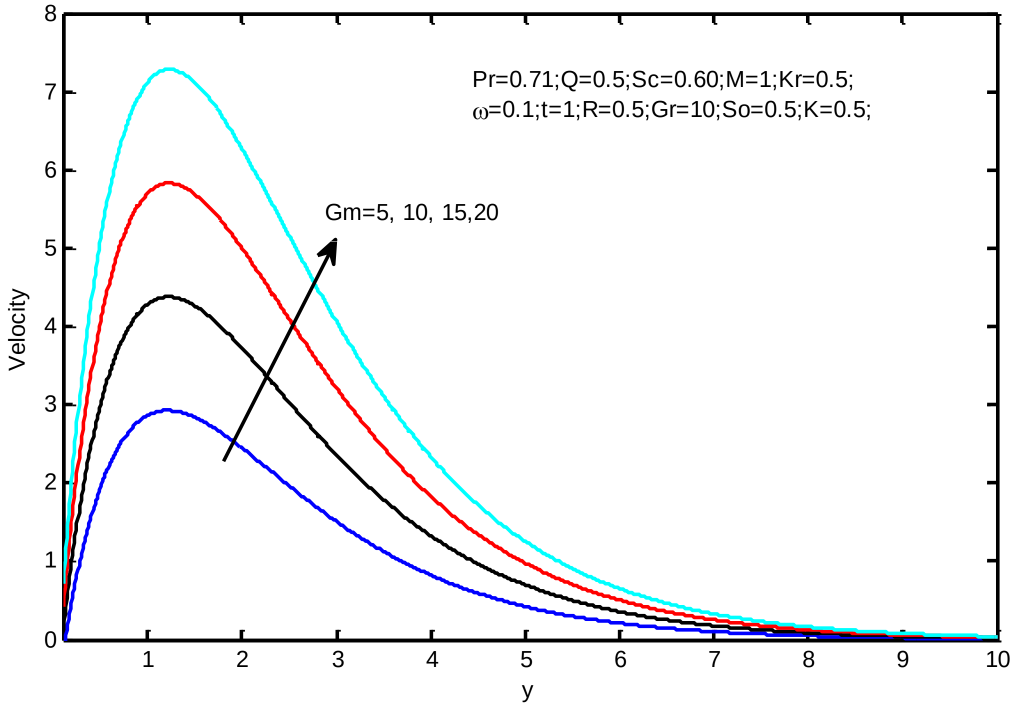

Fig.4. Velocity profiles for different values of modified Grashof number (Gm).

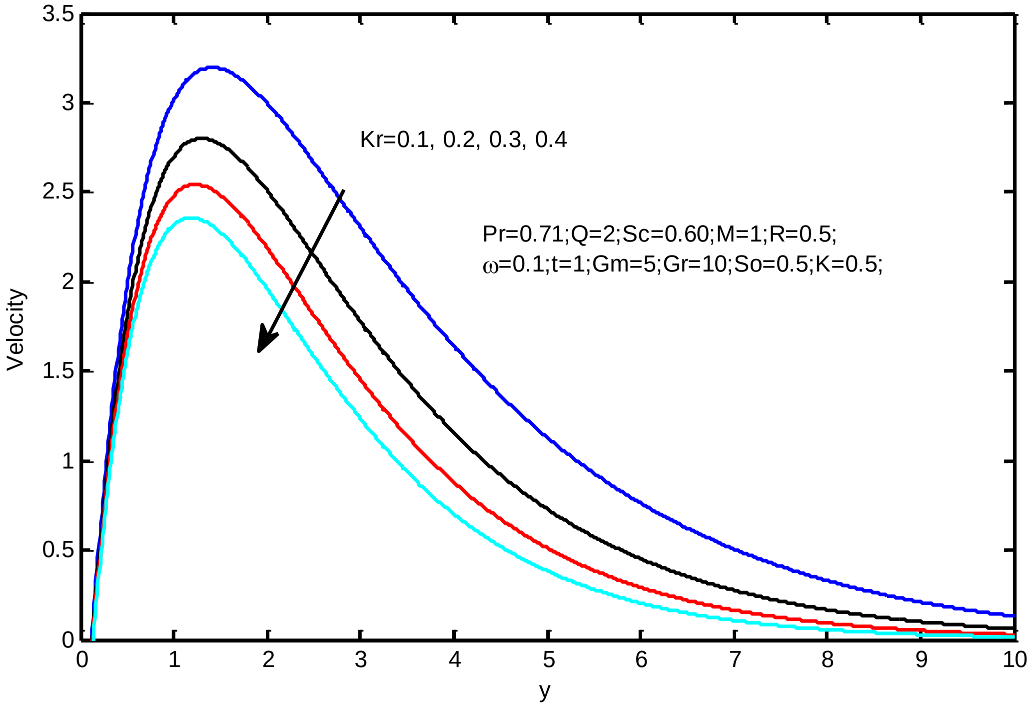

Fig.5. Velocity profiles for different values of chemical reaction parameter (Kr).

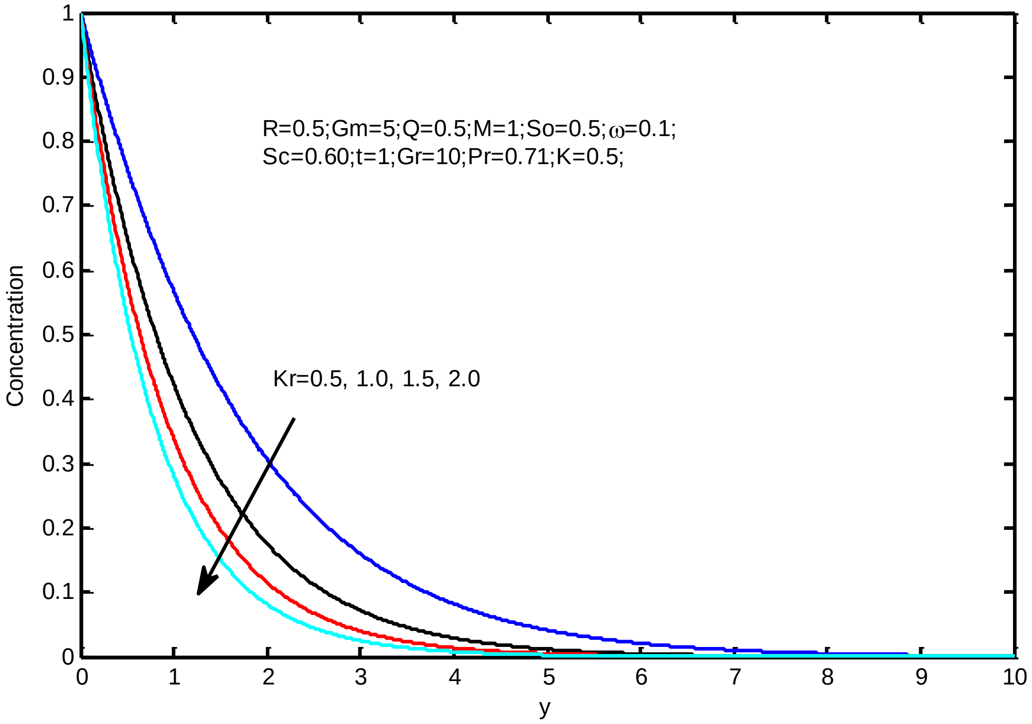

Fig.6. Concentration profiles for different values of Chemical reaction (Kr).

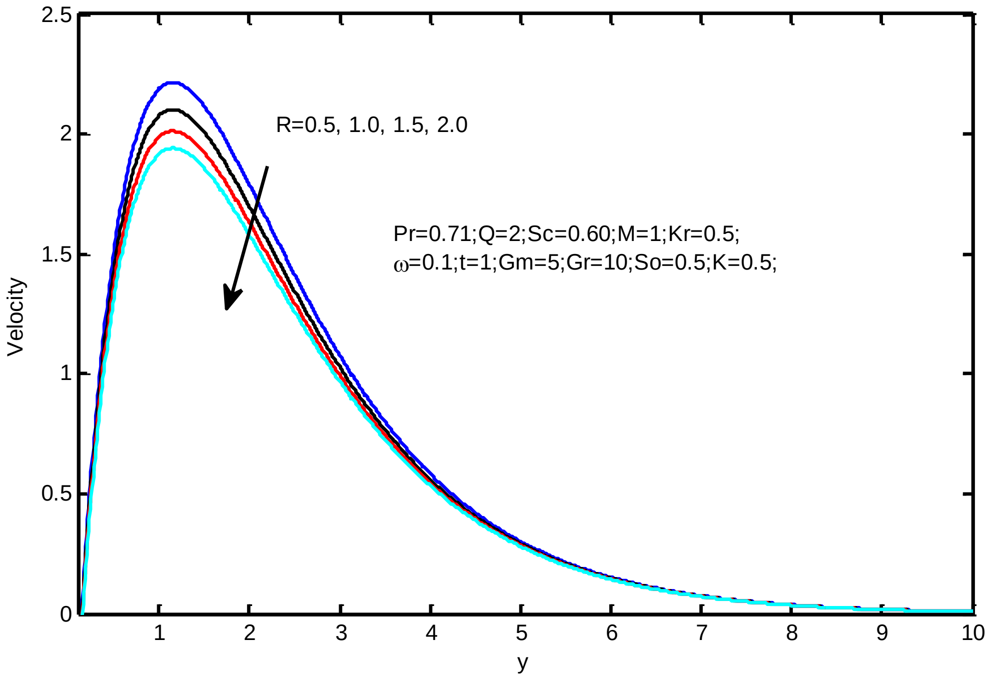

Fig.7. Velocity profiles for different values of radiation parameter (R).

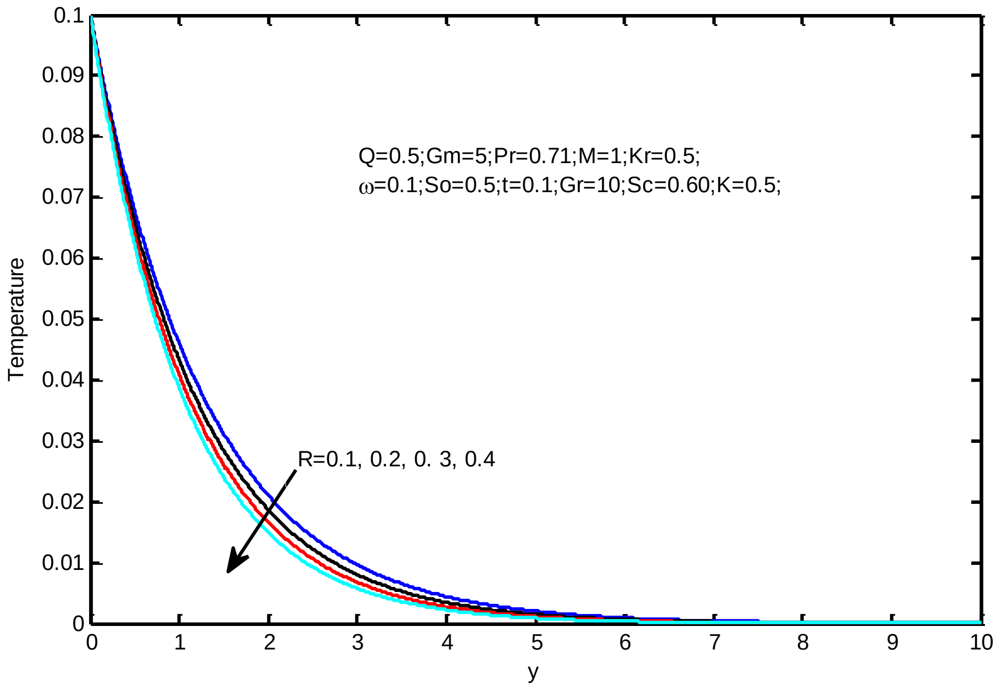

Fig.8. Temperature profiles for different values of radiation parameter(R).

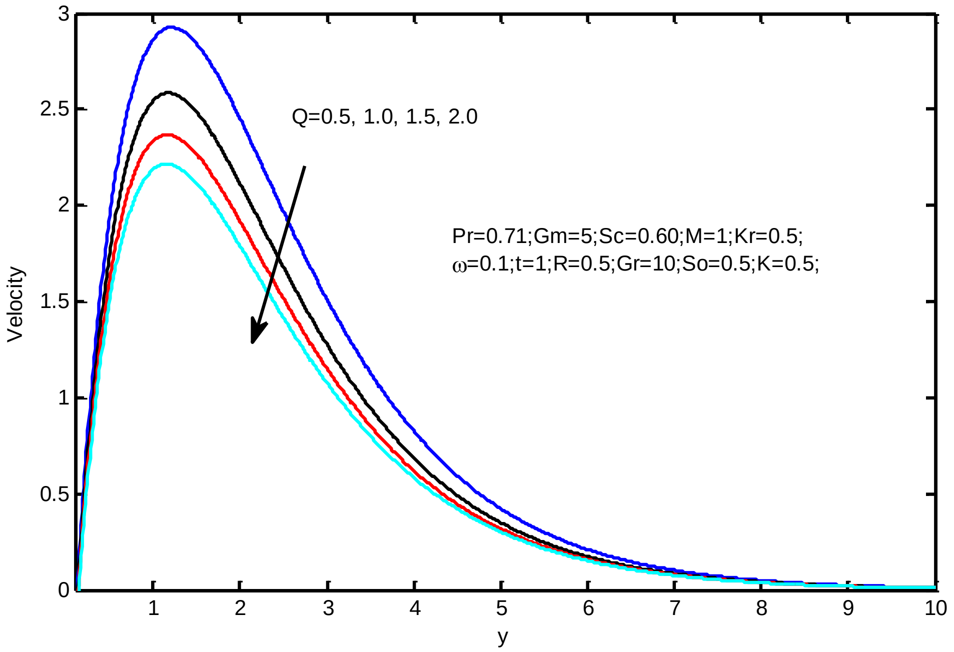

Fig.9. Velocity profiles for different values of heat source parameter (Q).

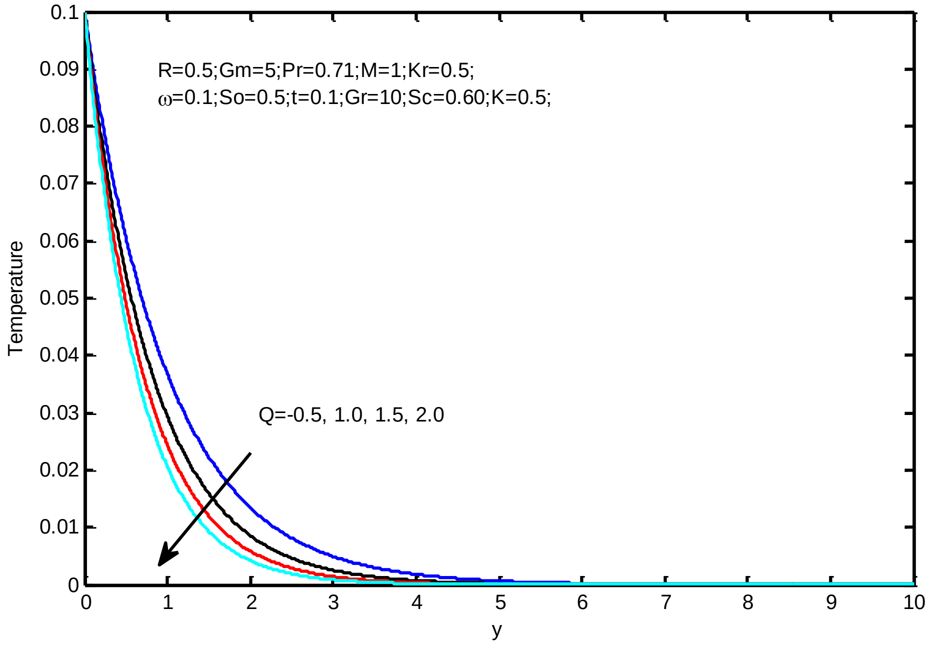

Fig.10. Temperature profiles for different values of heat source parameter (Q).

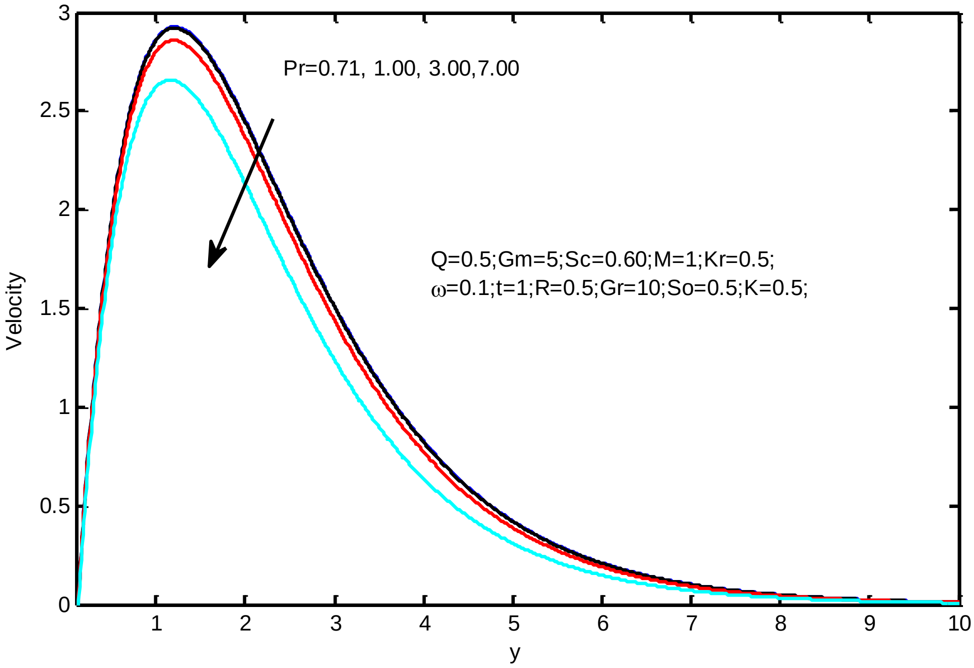

Fig.11. Velocity profiles for different values of Prandtl number (Pr).

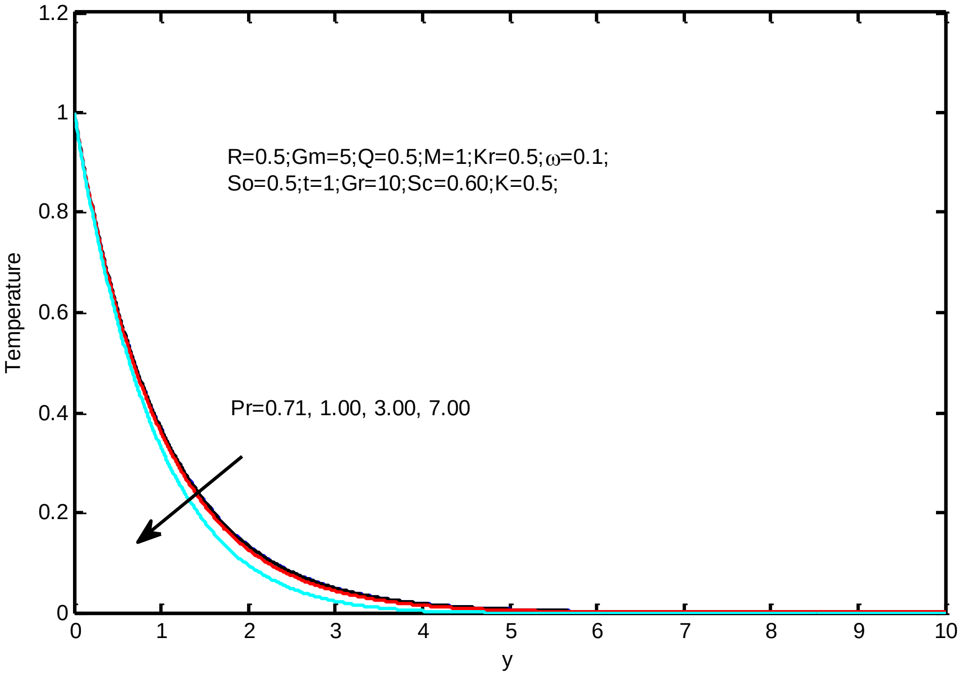

Fig.12. Temperature profiles for different values of Prandtl number (Pr).

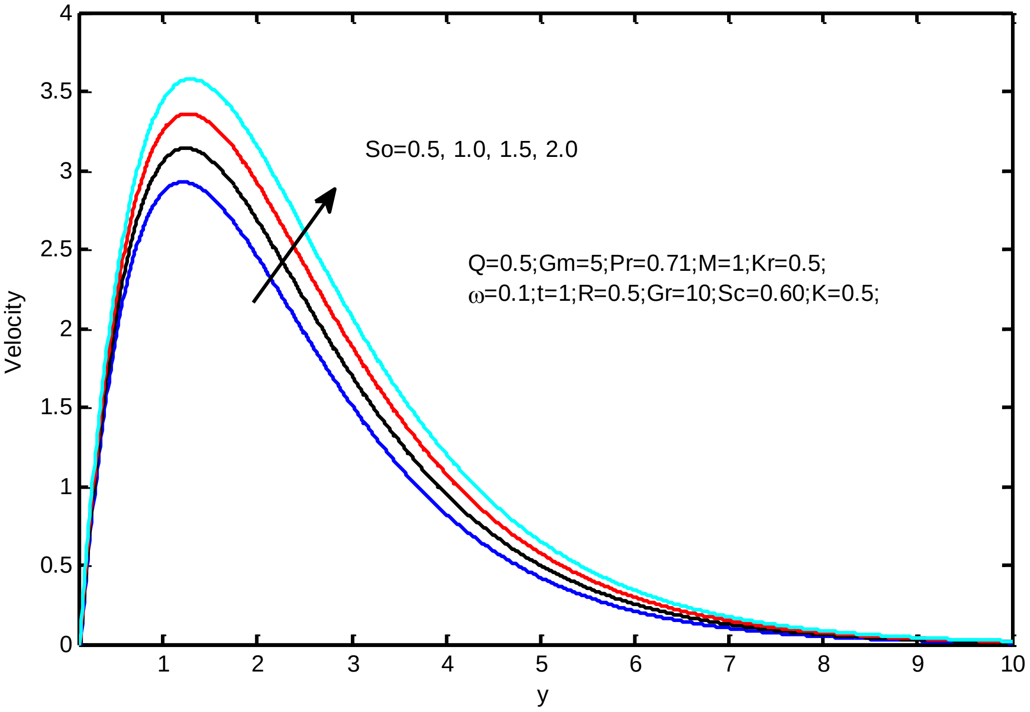

Fig.13. Velocity profiles for different values of Schmidt number (Sc).

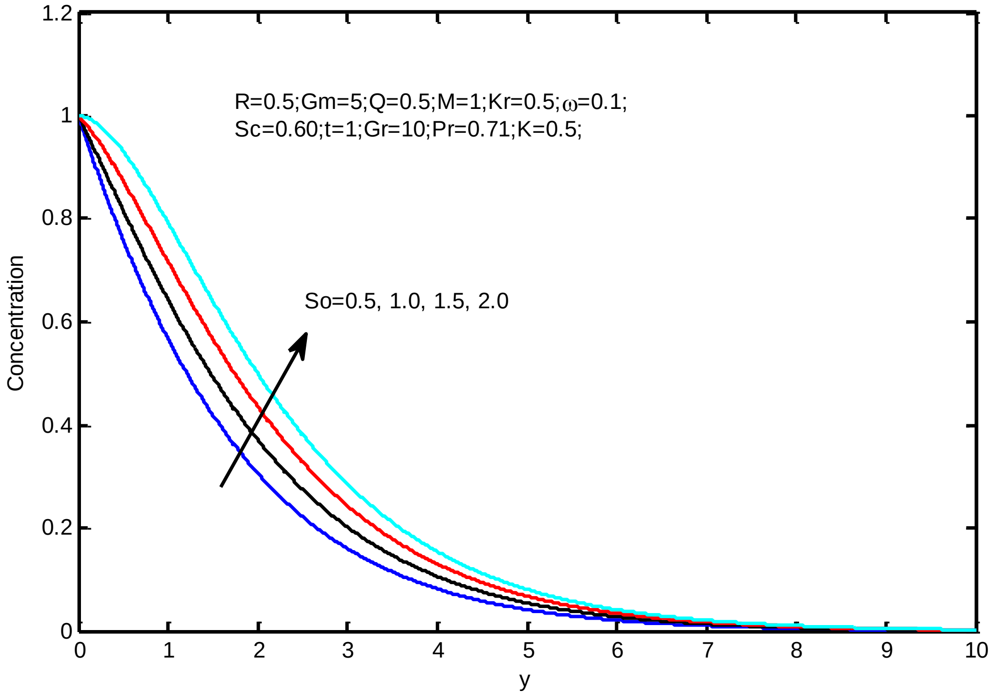

Fig.14. Concentration profiles for different values of Soret number (So).

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