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Effect of Second Order Chemical Reaction on MHD Free Convective Radiating Flow over an Impulsively Started Vertical Plate

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Abstract An attempt has been made to study laminar convective heat and mass transfer flow of an incompressible, viscous and electrically conducting fluid over an impulsively started vertical plate with conduction-radiation embedded in a porous medium in presence of transverse magnetic field. The influence of both second order chemical reaction and heat generation are taken into account. The governing coupled partial differential equations are solved by Crank-Nicolson method. The effects of important physical parameters on the velocity, temperature and concentration have been analyzed through graphs. The results of the present study agree well with the previous solutions. Applications of the present study are shown in material processing systems and different industries. The important findings of present study are: chemical reaction parameter acts as resistive force to reduce the velocity whereas heat source parameter enhances the velocity.

Keywords MHD, Porous medium, Chemical reaction, Radiation, Heat source.

MSC(2010) 76D, 76W, 76S.

1. Introduction

In several processes, there is a great importance of chemical reaction in the problems of MHD flow with heat and mass transfer and have therefore attracted a considerable amount of attention in the last several decades. If the rate of reaction is proportional to the nth power of concentration then the chemical reaction is said to be of order n. Also, we can say the order of a chemical reaction is defined as the sum of the powers of the concentration of the reactants in the rate equation of that particular chemical reaction. In a first order reaction, the rate of the reaction is doubled while in a second order reaction, the rate of the reaction is quadrupled. In first order reactions, the rate is proportional to the concentration raised to the first power. In second order reactions, the rate is proportional to the concentration raised to the second power. A second order reaction is a type of chemical reaction that depends on the concentrations of one second order reactant or on two first order reactants. This reaction proceeds at a rate proportional to the square of the concentration of one reactant or the product of the concentrations of two reactants. Some examples of second order reactions are

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$2NO2 \rightarrow 2NO + O2$, Nitrogen dioxide decomposing into nitrogen monoxide and oxygen molecule.

$2HI \rightarrow I2 + H2$, Hydrogen Iodide decomposing into iodine gas and hydrogen gas

$2NOBr \rightarrow 2NO + Br2$,In the gas phase, nitrosyl bromide decomposes into nitrogen oxide and bromine gas.

$NH4CNO \rightarrow H2NCONH2$, Ammonium cyanate in water isomerizes into urea.

According to the collision theory, the reactions occurs due to the collision of the reactant molecules. In the first and second order reactions the probability of collision is quite high as compared to the third and higher order reactions (It is quite unlikely that three or more than three molecules will collide at the same time). Due to this very low probability of colliding of molecules, the higher order reactions (> 3) are quite rare. Therefore, here only the second order reaction is considered. Possible applications of fluid flow with the second order equation can be found in many industries such as the power industry and chemical process industries. In many chemical engineering processes, there does occur the chemical reaction between a foreign mass and the fluid in which the plate is moving. These processes take place in numerous industrial applications viz., polymer production, manufacturing of ceramics or glassware and food processing.

Study of MHD flow with heat and mass transfer in porous and non-porous media due to the effect of magnetic fields on the boundary layer flow control and on the performance of many systems using electrically conducting fluids, has been a renewed interest for the researchers and scientists . This type of flow has also many applications in many engineering problems such as MHD generators, plasma studies, nuclear reactors, and geothermal energy extractions. Soundalgekar et al. [1] analysed the problem of free convection effects on Stokes problem for a vertical plate under the action of transversely applied magnetic field. Elbashbeshy [2] studied heat and mass transfer along a vertical plate under the combined buoyancy effects of thermal and species diffusion, in the presence of magnetic field. Helmy [3] presented an unsteady two-dimensional laminar free convection flow of an incompressible, electrically conducting (Newtonian or polar) fluid through a porous medium bounded by an infinite vertical plane surface of constant temperature. Ahmed et al. [4] studied the finite difference approach in porous media transport modelling for Magneto hydrodynamic unsteady flow over a vertical plate. Sheikholeslami et al. [5] investigated the impact of Lorentz forces on Fe3O4-water ferrofluid entropy and energy treatment within a permeable semi annulus. In their study, the behavior of magnetic nanofluid through a porous space with innovative computational method has been displayed and for involving porous media, non-Darcy approach was considered. Abro et al. [6] elucidated the heat transfer in magnetohydrodynamic free convection flow of generalized ferrofluid with magnetite nanoparticles. Lund et al. [7] reported the Dual solutions and stability analysis of a hybrid nanofluid over a stretching/shrinking sheet executing MHD flow.

In several processes, there is a great importance of chemical reaction in the combined heat and mass transfer problems and have therefore attracted a considerable amount of attention in the last several decades. Chemical reactions are either homogeneous or heterogeneous processes. The reaction is homogeneous, if it occurs uniformly through a given phase. In well mixed system, it takes place in the solution while a heterogeneous reaction occurs at the interface, i.e. in a restricted region or within the boundary of a phase. If the rate of reaction is proportional to the nth power of concentration then the chemical reaction is said to be of order n. Possible applications of this type of flow can be found in many industries such as the power industry and chemical process industries. In many chemical engineering processes, there does occur the chemical reaction between a foreign mass and the fluid in which the plate is moving. These processes take place in numerous industrial applications viz., polymer production, manufacturing of ceramics or glassware and food processing. Nasser El-Fayez [8] analyzed the chemical reaction effects on an unsteady free convection flow past an infinite vertical permeable moving plate with variable temperature. An unsteady MHD convective heat and mass transfer past an infinite vertical plate embedded in a porous medium with radiation and chemical reaction under the influence of Dufour and Soret effects was investigated by Ibrahim [9]. Chemical reaction and radiation effects on an unsteady MHD heat and mass transfer flow past a moving inclined porous heated plate were studied by Uddin and Kumar [10]. Ahmed et al. ([11], [12]) investigated the magneto hydrodynamic chemically reacting and radiating fluid past an impulsively started vertical plate using numerical technique. Recently, a new model of fractional Casson fluid based on generalized Ficks and Fourier s laws together with heat and mass transfer was reported by Sheikh et al. [13]. Khan et al. [14] also presented a modern fractional approach to study the influence in a Darcy's medium with heat production and radiation on MHD convection flow. Bilal et al. [15] used finite element method to visualize the heat transfer analysis of Newtonian material in triangular cavity with square cylinder.

Solar collectors, nuclear reactor safety and combustion system to mention just a few includes the transporting process, which are directed by coupled action of buoyancy forces due to both heat and mass transfer under higher order chemical reaction effects. A species molecular diffusion with chemical reaction in or at the boundary involves number of concrete diffusive operations and still a topic of great interest. The effect logs of thermal stratification, chemical reaction by way of heat source along a stretching sheet was studied by Kandasamy et al. [16]. Li et al. [17] considered the influence of strong endothermic chemical reaction under non-thermal equilibrium flow model of porous medium. Azam et al. presented a numerical modeling and theoretical analysis of a nonlinear advection-reaction epidemic system [18]. Saqib et al. [19] also gave an idea on symmetric MHD channel flow of nonlocal fractional model of BTF containing hybrid nanoparticles. Viscous dissipation effect on MHD free convective flow in the presence of thermal radiation and chemical reaction has been examined by Parida et al. [20]. Senapati et al. [21] studied MHD free convective flow in a composite medium between co-axial vertical cylinders with temperature dependent heat flux on inner cylinder. Viscous dissipation and joule heating effect on MHD flow and heat transfer past a stretching sheet embedded in a porous medium. Swain et al. [22] elucidated the viscous dissipation and joule heating effect on MHD flow and heat transfer past a stretching sheet embedded in a porous medium.

The novelty of present analysis is to study the effects of second order chemical reaction and heat generation. The works of Ahmed and Batin [23] and Swain and Senapati [24] may be taken as the special cases. In the earlier works, second order chemical reaction and heat generation effects were not considered. Application of chemical reaction and heat generation are often seen in chemical industries, physiological functions in our body and etc. The rate of performance of kidney cells in regulating the volume of water/salts in the body is affected by drugs. Hence, by

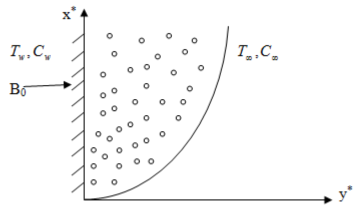

Figure 1. Flow geometry

considering chemical reaction, the velocity of the flow can be controlled. Similarly, by using heat source one can affect the flow of fluid. The above discussion emphasizes the need for paying importance to the presence of chemical reaction and heat source and motivates for the present analysis.

2. Mathematical formulation

The laminar convective heat and mass transfer flow of an incompressible, viscous and electrically conducting fluid over an impulsively started vertical plate with conduction-radiation embedded in a porous medium in presence of transverse magnetic field has been studied. As in Figure 1, the x^* axis is taken along the plate in the vertical upward direction and the y^* axis is taken normal to the plate. A transverse magnetic field of uniform strength B_0 is assumed to be applied normal to the plate. It is also assumed that the thermal radiation along the plate is negligible as compared with that in the normal direction. The induced magnetic field and viscous dissipation is assumed to be negligible.

Initially, it is assumed that the plate and 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 given an impulsive motion in its own plane with velocity u_0. The temperature of the plate and the concentration level are also raised to T_w^* and C_w^*. They are maintained at the same level for all time $t^* > 0$. Then, under the above assumption the unsteady flow with usual Boussinesq approximation is governed by the following equations as [cf. 23, 24]

$$\frac{\partial u^*}{\partial t^*} = g\beta\Big(T^* - T^*_\infty\Big) + g\beta_c\Big(C^* - C^*_\infty\Big) + \nu\frac{\partial^2 u^*}{\partial {y^*}^2} - \Big(\frac{\sigma B_0^2}{\rho} + \frac{\nu}{K^*}\Big)u^*, \tag{2.1}$$

$$\rho C_p\frac{\partial T^*}{\partial t^*} = k\frac{\partial^2 T^*}{\partial {y^*}^2} - \frac{\partial q_r}{\partial y^*} + Q^*\Big(T^* - T^*_\infty\Big), \tag{2.2}$$

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial {y^*}^2} - R_c^*\Big(C^* - C^*_\infty\Big)^m. \tag{2.3}$$

The initial and boundary conditions are

$$t^* \le 0\colon u^* = 0, T^* = T^*_\infty, C^* = C^*_\infty \; for\ every\ y,$$
$$t^* > 0\colon u^* = u_0, T^* = T^*_w, C^* = C^*_w \; at\ y = 0,$$

$$t^* > 0\colon u^* \to 0, T^* \to T^*_\infty, C^* \to C^*_\infty \; as \; y \to \infty. \tag{2.4}$$

The radiative heat flux term is simplified by making use of the Rosseland approximation [25] as

$$q_r = \frac{-4}{3}\frac{\sigma^* \partial T^{*4}}{a^* \partial y^*} \tag{2.5}$$

where σ^* and a^* are the Stefan-Boltzmann constant and the mean absorption coefficient respectively. It should be noted that by using the Rosseland approximation, we limit our analysis to optically thik fluids. If temperature differences within the flow are sufficiently small, such that T^{*4} may be expressed as a linear function of the temperature, then the Taylor series for T^{*4} about T^*_∞ , after neglecting higher order terms, is given by

$$T^{*4} \cong 4T^* {T^*_\infty}^3 - 3{T^*_\infty}^4. \tag{2.6}$$

Substituting (2.5) and (2.6) in (2.2) we have

$$\rho C_p \frac{\partial T^*}{\partial t^*} = \Big[k + \frac{16}{3}\frac{\sigma^*}{a^*}{T^*_\infty}^3\Big]\frac{\partial^2 T^*}{\partial {y^*}^2}. \tag{2.7}$$

Let us introduce the following non dimensional terms in (2.1), (2.7) and (2.3).

$$\begin{aligned}
&y = \frac{u_0 y^*}{\nu}, u = \frac{u^*}{u_0}, Pr = \frac{\rho\nu C_p}{k}, Sc = \frac{\nu}{D}, t = \frac{u_0^2 t^*}{\nu}, Kr = \frac{u_0^2 K^*}{\nu^2},\\
&\theta = \frac{T^* - T^*_\infty}{T^*_w - T^*_\infty}, \phi = \frac{C^* - C^*_\infty}{C^*_w - C^*_\infty}, M = \frac{\sigma B_0^2 \nu}{\rho u_0^2}, Na = \frac{k a^*}{4\sigma^* {T^*_\infty}^3}, Q = \frac{Q^* \nu}{\rho C_p u_0^2}\\
&Gr = \frac{\nu g \beta \Big(T^*_W - T^*_\infty\Big)}{u_0^3}, Gm = \frac{\nu g \beta_c \Big(C^*_W - C^*_\infty\Big)}{u_0^3}, R = \frac{R^*_c \nu \Big(C^*_w - C^*_\infty\Big)^m}{u_0^2 \Big(C^*_w - C^*_\infty\Big)}.
\end{aligned} \tag{2.8}$$

Hence, the nondimensional form of (2.1), (2.7) and (2.3) are respectively

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} - \Big(M + Kr^{-1}\Big)u + Gr\theta + Gm\phi, \tag{2.9}$$

$$\frac{\partial \theta}{\partial t} = \Big(\frac{3Na + 4}{3NaPr}\Big)\frac{\partial^2 \theta}{\partial y^2} + Q\theta, \tag{2.10}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} - R\phi^m. \tag{2.11}$$

The transformed initial and boundary conditions are

$$\begin{aligned}
&t \le 0\colon u = 0, \theta = 0, \phi = 0 \; for \; every \; y,\\
&t > 0\colon u = 1, \theta = 1, \phi = 1 \; at \; y = 0,\\
&t > 0\colon u \to 0, \theta \to 0, \phi \to 0 \; as \; y \to \infty.
\end{aligned} \tag{2.12}$$

3. Method of solution

The equations (2.9) to (2.11) suject to the conditions (2.12) have been solved aplly-ing Crank-Nicolson method, a kind of implicit finite difference method, which is unconditionally stable. The corresponding difference equations are as follows:

$$\frac{u_{i,j+1}-u_{i,j}}{\Delta t} = \frac{1}{2(\Delta y)^2}[u_{i-1,j}-2u_{i,j}+u_{i+1,j}+u_{i-1,j+1}-2u_{i,j+1}+u_{i+1,j+1}] + Gr\frac{(\theta_{i,j+1}+\theta_{i,j})}{2}+Gm\frac{(\phi_{i,j+1}+\phi_{i,j})}{2}-(M+Kr^{-1})\frac{(u_{i,j+1}+u_{i,j})}{2}, \tag{3.1}$$

$$\frac{\theta_{i,j+1}-\theta_{i,j}}{\Delta t} = \Big(\frac{3Na+4}{3NaPr}\Big)\frac{1}{2(\Delta y)^2}[\theta_{i-1,j}-2\theta_{i,j}+\theta_{i+1,j}+\theta_{i-1,j+1}-2\theta_{i,j+1}+\theta_{i+1,j+1}] + Q\frac{(\theta_{i,j+1}+\theta_{i,j})}{2}, \tag{3.2}$$

$$\frac{\phi_{i,j+1}-\phi_{i,j}}{\Delta t} = \frac{1}{Sc}\frac{1}{2(\Delta y)^2}[\phi_{i-1,j}-2\phi_{i,j}+\phi_{i+1,j}+\phi_{i-1,j+1}-2\phi_{i,j+1}+\phi_{i+1,j+1}] - R\Big(\frac{\phi_{i,j+1}+\phi_{i,j}}{2}\Big)^m, \tag{3.3}$$

The mesh sizes are taken as $\Delta y = 0.1$ and $\Delta t = 0.002$. The unknown quantities u, θ and ϕ at $(j+1)^{th}$ time level are found using the known values at j^{th} level. The difference equation (3.3) at every interior nodes on a specific i-level form a traditional system which is solved utilizing Thomas algorithm. Here, the value of 'm' is taken as 2 since second order chemical reaction is considered.

4. Validation

To validate the present study, the earlier published results of Ahmed and Batin [23], Swain and Senapati [24] are taken into account and compared with present results as particular cases in Table 1 and Table 2 respectively. It is obtained that the present results are in well Agreement l with earlier results, and thus confirms the validity.

Table 1 (when Kr=1, Gr=5, Gm=5, Q=0, R=0, Na=2, Pr=0.71, Sc=0.78, m=1, t=0.8)

M	u (Swain and Senapati [24])	u (present result)
1	1.7184	1.7267
2	1.4971	1.4924
3	1.3155	1.3124

Table 2 (when $\phi = 0,\ Kr = 1, Gr = 5, Gm = 5, Q = 0, R = 0, Na = 2, Pr = 0.71, Sc = 0.78, m = 1, t = 0.8$)

M	u (Ahmed and Batin [23])	u (present result)
1	1.1574	1.1568
2	0.9978	0.9969
3	0.8752	0.8746

5. Results and discussion

The effects of the various parameters entering in the governing equations on the velocity, temperature, concentration are shown through graphs.

In Figures (2) and (11), it is seen that the velocity and concentration profiles decrease with increases in the chemical reaction parameter, while a small change in the temperature profiles occurs. This shows that the diffusion rates can be tremendously altered by chemical reactions. It is also important to note that increasing the chemical reaction parameter significantly alters the concentration boundary layer thickness without any significant effect on the momentum and thermal boundary layers.

Figure (3) shows that the velocity decreases with an increase in Prandial number. Physically, this is true because the increase in the Prandial number Pr is due to increase in the viscosity of the fluid which makes the fluid thick and hence causes a decrease in the velocity of the fluid.

It is seen from Figure (4) that the velocity increases with an increase in heat generation parameter Q. As Q increases, heat generating capacity of the fluid increases which increases fluid temperature and hence the fluid velocity.

Figure (5) presents velocity profiles in the boundary layer for various values of Thermal Grashof number (Gr). Increasing the value of Thermal Grashof number have the tendency to induce more flow in the boundary layer due to the effect of thermal buoyancy, this buoyancy effect produces an increase in the velocity flow.

In Figure (6), it is observed that increasing the porosity parameter Kr leads to decrease in the fluid velocity, which resulted to velocity boundary layer thinning.

Figure (7) represents the effect of parameter Gm on velocity profiles. It is noticed that velocity increases with increase in Gm.

In Figure (8), it is seen that temperature increases with increasing values of Q.

It is seen from Figure (9) that the temperature θ decreases as the radiation parameter Na increases. This result qualitatively agrees with expectations, since the effect of radiation is to decrease the rate of energy transport to the fluid, thereby decreasing the temperature of the fluid.

The effect of Prandial number (Pr) on the temperature profiles is shown in Figure (10). It is observed that an increase in the Prandial number results in a decrease of the thermal boundary layer thickness and in general lower average temperature within the boundary layer. The reason is that smaller values of Prandial number are equivalent to increase in the thermal conductivity of the fluid and therefore heat is able to diffuse away from the heated surface more rapidly for higher values of Prandial number. Hence, there is a reduction in temperature with increase in the Prandial number.

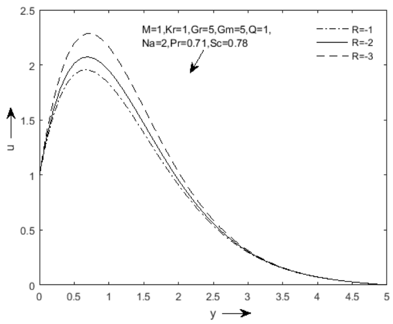

Figure 2. Velocity profiles for R

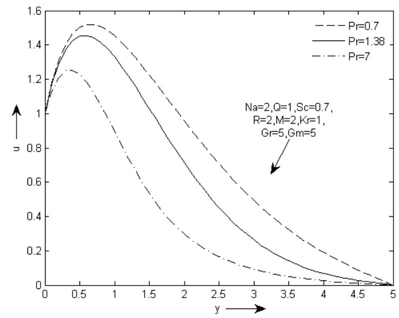

Figure 3. Velocity profiles for Pr

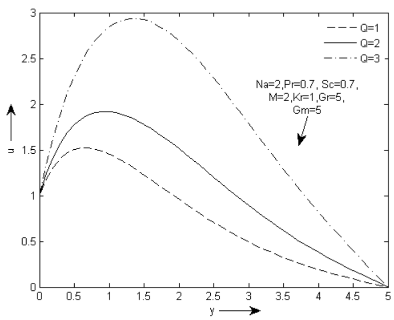

Figure 4. Velocity profiles for Q

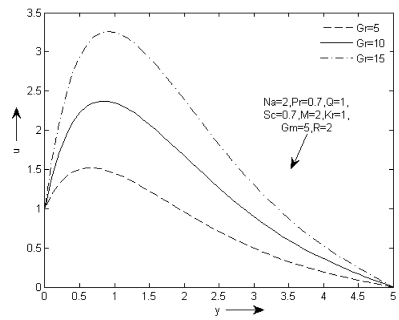

Figure 5. Velocity profiles for Gr

It is shown from Figure (12) that an increasing in Sc result in a decreasing the concentration distribution, because the smaller values of Sc are equivalent to the chemical molecular diffusivity.

6. Conclusion

In this paper, the influence of chemical reaction and heat source on MHD free convective radiating flow over an impulsively started vertical plate embedded in a porous medium was analysed. The governing system of equations was solved by Crank-Nicolson method. The effects of different parameters on velocity, temperature and concentration were shown through graphs. Some important conclusions are given below:

- Velocity and concentration profiles decrease with increases in the chemical reaction parameter;
- Velocity increases with an increase in heat generation parameter Q;
- Increasing the porosity parameter Kr leads to decrease in the fluid velocity;
- Temperature increases with increasing values of Q;
- Velocity decreases with an increase in Prandial number;
- There is a reduction in temperature with increase in the Prandial number;

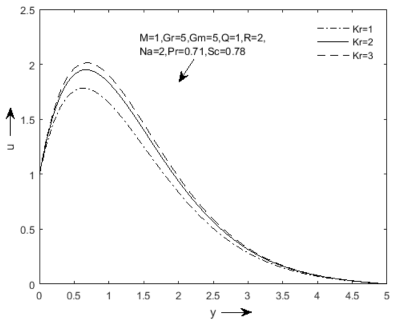

Figure 6. Velocity profiles for Kr

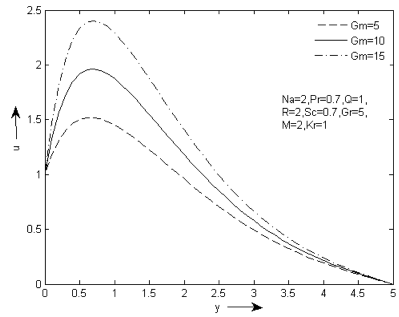

Figure 7. Velocity profiles for Gm

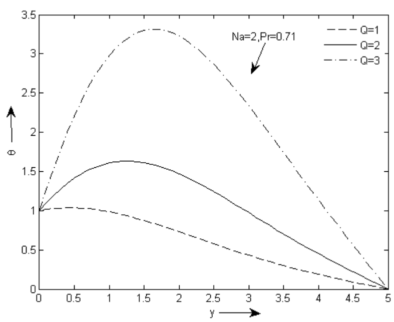

Figure 8. Temperature profiles for Q

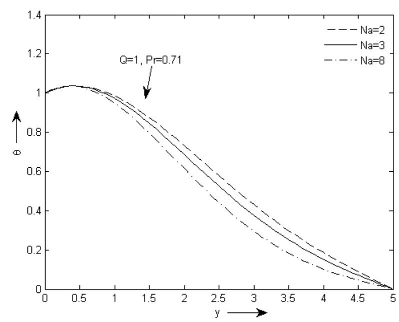

Figure 9. Temperature profiles for Na

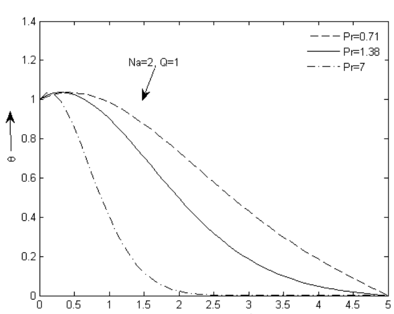

Figure 10. Temperature profiles for Pr

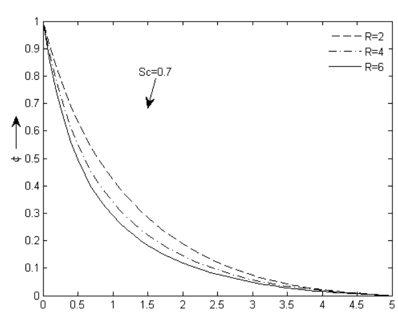

Figure 11. Concentrationprofiles for R

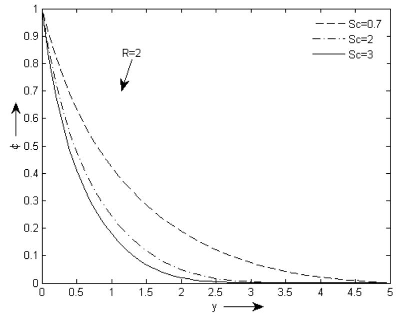

Figure 12. Concentrationprofiles for Sc

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