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MHD Free Convective Flow over an Impulsively Started Vertical Plate With Second Order Chemical Reaction and Heat Source

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Abstract

Present study has been carried out to elucidate a laminar free convective flow of an incompressible chemically reactive fluid over an impulsively started vertical plate embedded in a porous medium. The influence of both second order chemical reaction and heat source make the study interesting. The governing coupled partial differential equations are solved by using Crank-Nicolson method. The impacts of pertinent parameters on the velocity, temperature and concentration have been explored through graphs. The results of the present study agree well with the previous solutions. Some important findings are: velocity and concentration profiles decrease with increase in chemical reaction parameter, there is a reduction in temperature with increase in the Prandtl number, temperature improves with higher values of Q. Applications of the present study are shown in material processing systems and chemical industries etc.

Keywords: MHD, Porous medium, Second order chemical reaction, Radiation, Heat source

2010 MSC: 76D, 76W

Nomenclature

C^*	Concentration (kgm^{-3})	Pr	Prandtl number
C_p	Specific heat ($Jkg^{-1}K$)	q_r	Radiative heat flux
C^*_∞	Free stream concentration in (kgm^{-3})	Q	Heat generation parameter
C^*_w	Concentration at surface (kgm^{-3})	R	Chemical reaction parameter
D	Diffusivity (m^2s^{-1})	Sc	Schmidt number
g	Acceleration due to gravity (ms^{-2})	Sh	Sherwood number
Gr	Grashof number	T^*	Temperature (K)
Gm	Modified Grashof number	T^*_w	Fluid temperature at surface
Kr	Porosity parameter	T^*_∞	Free stream temperature (K)
M	Hartmann number	u	Velocity (ms^{-1})
Nu	Nusselt number	u_0	Velocity of the plate (ms^{-1})

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Greek symbols

β Thermal expansion coefficient(K^{-1})	ν Kinematic viscosity (m^2s^{-1})
β_c Concentration expansion coefficient(K^{-1})	ρ Density (kgm^{-3})
θ Temperature of fluid (K)	σ Electrical conductivity
k Thermal conductivity ($Wm^{-1}K^{-1}$)	ϕ Concentration (kgm^{-3})

1. Introduction

There is a great importance of chemical reactive MHD flow problems and have therefore attracted a considerable amount of attention in the last several decades. During various physiological functions, the importance of the chemical reaction is shown such as the rate of blood flow through vessels, secretion of insulin, mucus, stomach acid etc. by the glands, transmission of message by nerves, performance of kidney cells to regulate volume of water/salt in the body. To define the order of chemical reaction, power of concentration is taken care of. Chemical reaction is described to be of order n, if the rate of reaction becomes proportional to the nth power of concentration. Therefore, in first order reactions, the rate is directly proportional to the unit power of concentration whereas the rate is proportional to the concentration raised to the second power in case of second order reactions. Some of such reactions are

2 HI $\rightarrow I_2 + H_2$, Hydrogen Iodide breaking down into iodine and hydrogen gas

2 NOBr $\rightarrow 2NO + Br_2$, nitrosyl bromide breaks downs into nitrogen oxide and bromine gas.

Collision theory says that, the reaction occurs because of the collision of the reactant molecules. In first and second order reactions, the chance of collision is higher as compared to the third and higher order reactions. Because 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. The application of fluid flow with second order equation is generally visible in polymer production, manufacturing of ceramics or glassware and food processing etc.. Mohammed Nasser El-Fayez [15] has described nicely the impact of an unsteady free convective and chemical reactive flow. Mohammed Ibrahim [14] and Uddin and Kumar [28] have also investigated the variation in mass transfer due to chemical reactive MHD flow. Ahmed et al. ([1, 3]) and Swain et al. [25, 26] also illuminate the chemically reactive and radiative MHD flows past an impulsively moving plate respectively.

Coupled action of buoyancy forces because of heat and mass transfer under second order reaction is very relevant in solar collectors, nuclear reactor safety and combustion system etc.. Molecular diffusion with Chemical reaction has many importance and attracts the researchers towards it. Kandasamy et al. [8] have bestowed the idea on thermal stratification and chemical reaction considering the fluid flow on a stretching sheet. Mingchun et al. [12] have illuminated the impact of sturdy endothermic reaction discussing non-thermal equilibrium flow model of porous medium. Kishan and Amrutha [11] enlightened the thermally stratified flow on a stretching surface with chemical reaction. Kandasamy et al. [7] delineated chemically reactive flow past a stretching surface with thermophoresis result. Makinde and Sibanda [13] have described numerically the impact of chemical reaction of 1st order considering the fluid flow over a vertical stretching surface. Tripathy et al. [27] exemplified the chemical reaction impact on free convective MHD fluid flow over a moving vertical permeable plate. Ferdows et al. [6] ascertained the results of chemical reaction doing their research on the fluid flow streching the sheet linearly.

On the other hand the heat transfer issues with heat source/sink is sort of necessary within the field of commercial technology. Ostrach [16] and Raptis [19] have investigated heat transfer issues analytically using heat generators. Singh [22] has solved a problem concerning MHD flow taking care of heat source as well as thermal diffusion. Sharma et al. [20] have elucidated heat source and hall effect on MHD mixed convective flow. Khan et al. [9] described chemically reactive flow of casson fluid keeping in mind that generation of heat and newtonian heating. Khalili et al. [10] have analyzed the roles of chemical reaction and radiation on MHD flow regarding the presence of heat sink. Ibrahim M. Alarifi et al. [4] mentioned the heat transfer analysis taking the fluid flow over a vertical stretching sheet concerning heat sink or source effect. Sreenivasulu et al. [23] took micropolar fluid and illustrated the result of interior heat generation and variable wall heat flux on radiative and dissipative MHD flow. Kashyap et al. [18] and Patel [17] have elucidated the heat source impact on MHD flow of UCM fluid and Casson fluid respectively.

The objective of present work is to analyse a laminar flow of an incompressible fluid incorporating second order chemical reaction and heat source. The fluid flows over an vertical plate that is impulsively started. The governing system of partial differential differential equations has been treated with Cranck-Nicolson method. This method is a kind of implicit method which is unconditionally stable. The present results are observed to be in well agreement with earlier analytical results [24, 2].

2. Mathematical Formulation

A laminar unsteady MHD flow over an vertical plate has been considered. The flow system is set in a porous medium. The x^* axis is fixed in the direction of the plate vertically upward and the y^* axis is located normal to the plate. An external magnetic field of uniform strength B_0 has been bestowed normal to the plate. Again, it is presumed that induced magnetic field are vary small and are therefore neglected. Applying Boussinesq's approximation, the governing equations can be written as

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

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

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

The corresponding boundary conditions are given by

$$\begin{aligned} &t^* \le 0: u^* = 0, T^* = T^*_\infty, C^* = C^*_\infty \; for\ every\ y, \\ &t^* > 0: u^* = u_0, T^* = T^*_w, C^* = C^*_w \; at\ y = 0, \\ &t^* > 0: u^* \to 0, T^* \to T^*_\infty, C^* \to C^*_\infty \; as\ y \to \infty. \end{aligned} \tag{2.4}$$

Now utilising the Rosseland approximation [21], radiative heat flux becomes

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

where σ^*, the Stefan-Boltzmann constant and a^*, the Rosseland mean absorption coefficient. Again T^{*4} can be approximated by Taylor's series about T^*_∞ dropping higher order terms as

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

Now, putting (2.5) and (2.6) in (2.2) we get

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

Introducing the following dimensionless terms in (2.1), (2.7) and (2.3),

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

The nondimensional form of equations (2.1), (2.7) and (2.3) are respectively

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

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

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

From (2.4), the reduced conditions are given by

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

3. Method of Solution

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

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

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

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

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 tridiagonal system which is solved utilizing Thomas algorithm as expressed by Carnahan et al. [5]. 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 Swain and Senapati [24], Ahmed and Batin [2] 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 agreementl 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 [2])	u (present result)
1	1.1574	1.1568
2	0.9978	0.9969
3	0.8752	0.8746

5. Results and Discussion

The impacts of pertinent parameters are illustrated as follows

In Figures 1a and 1b, it is seen that the velocity diminishes for highervalues of chemical reaction parameter, R. For both the cases $R > 0$ and $R < 0$, same trend is noticed. The physics is that higher values of chemical reaction parameter make the fluid thick and so fluid flows slowly.

Figure 2 illustrated that increasing the order of chemical reaction, higher velocity is obtained. Keeping R fixed, as the order is increased fluid becomes thin and gives rise to a higher velcity.

Figure 3 represents the influence of Magnetic parameter, M on velocity profile. It is found that velocity diminishes when the magnetic parameter increases. Due to resistive force generated and acted upon the main directional flow, the velocity decreases. Again for low intensity magnetic field, the significant increase in velocity is marked. Therefore, during clinical or mechanical necessity to control the flow of fluid, one can regulate M to obtain the desired flow rate.

Figure 4 shows that increasing values of Prandtl number reduce the velocity. Since higher value of Pr means higher viscosity that resist the fluid flow and hence results a reduction in velocity.

It is illuminated from Figure 5 that the velocity is enhanced with improve in heat generation parameter Q. Increase in Q means , more heat is generated that increases fluid temperature as well as fluid velocity.

In Figure 6, it is observed that increasing values of porosity parameter, Kr lead to decrease the velocity that results thinning of momentum boundary layer. Physically higher porosity means big holes or less tight which diminishes the velocity of the flow.

Figure 7 presents velocity distribution for several values of Grashof number (Gr). It is marked that larger Gr enhances the velocity of fluid. Because larger Grashof numbers lead to more flow in the boundary layer because of the influence of thermal buoyancy that produces higher velocity.

Figure 8 represents the influence of parameter Gm on velocity profiles. It is examined that larger values of Gm boost the flow velocity.

In Figure 9, it is delineated that temperature raises with higher values of Q. That means more the heat more the temperature.

Figure 10 describes that temperature θ drops significantly as the radiation parameter, Na is increased. This consequence goes along with expectation since the impact of radiation weaken the rate of transport energy and so reduces the fluid temperature.

Figure 11 elucidates the impact of Pr on the temperature distribution. It is detected that the higher values of Pr diminishes the temperature and also reduces the thermal boundary layer thickness. Because smaller Prandtl number means more is the thermal conductivity of the fluid for which heat diffuses more rapidly from the warm surface and therefore temperature raises.

Figure 12 expressed that improve in the chemical reaction parameter R significantly reduces concentration and the related boundary layer thickness.

From Figure 13, It is shown that higher Sc results a lower concentration. Larger values of Schimdt number lead to weaker diffusion coefficient. This weaker diffusion coefficient causes lower concentration and also shorten the boundary layer thickness.

Figure 14a and 14b presents the concentration distribution against the order of chemical reaction for destructive ($R > 0$) as well as generative chemical reaction ($R < 0$). It is found that concentration improves with improving order in case of destructive chemical raction. But in case of generative chemical reaction, concentration acts in opposite fashion for higher order of chemical reaction.

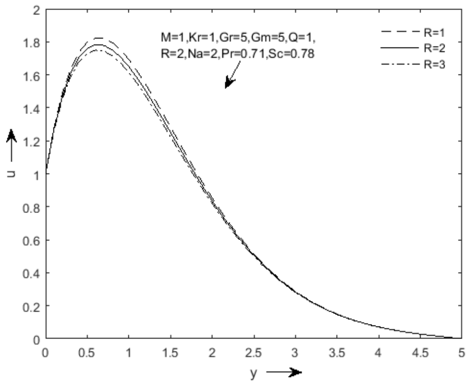

Figure 1a. Velocity profiles for R(> 0)

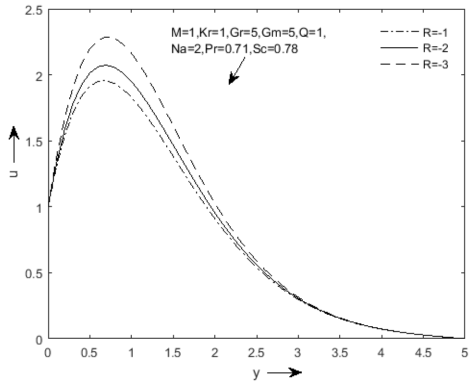

Figure 1b. Velocity profiles for R(< 0)

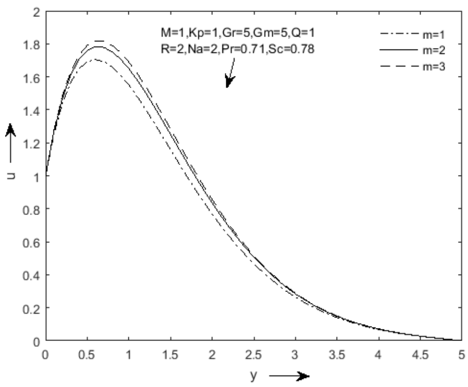

Figure 2. Velocity profiles for different m

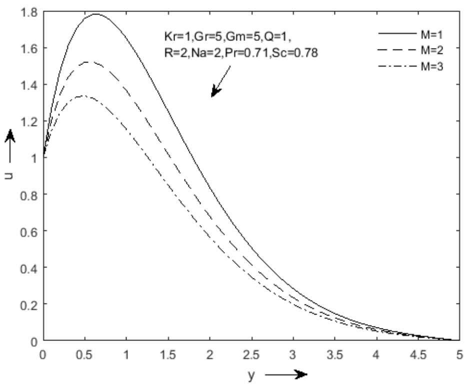

Figure 3. Velocity profiles for M

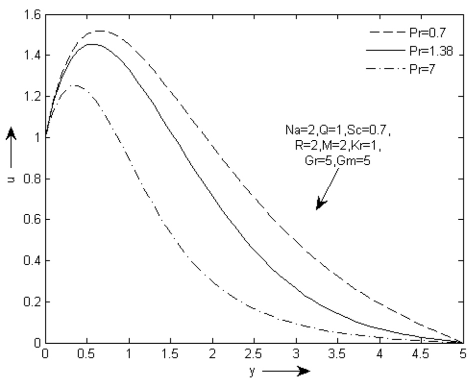

Figure 4. Velocity profiles for different Pr

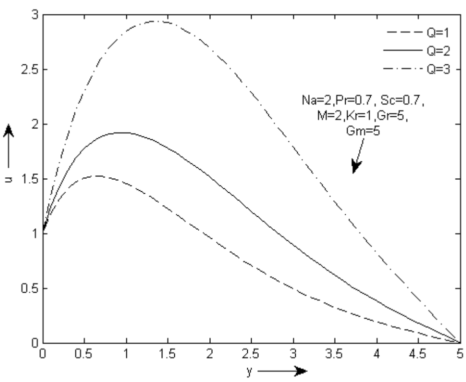

Figure 5. Velocity profiles for Q

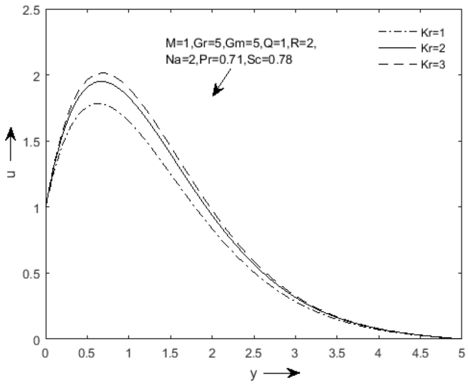

Figure 6. Velocity profiles for Kr

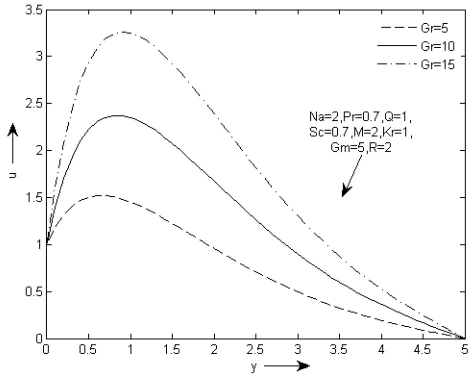

Figure 7. Velocity profiles for Gr

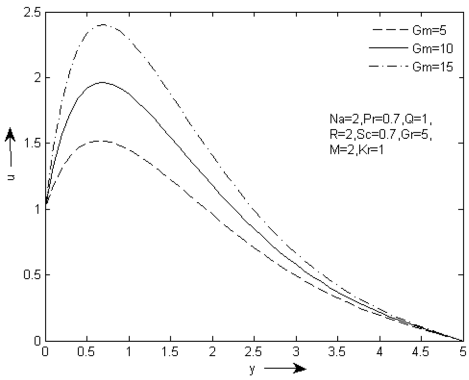

Figure 8. Velocity profiles for Gm

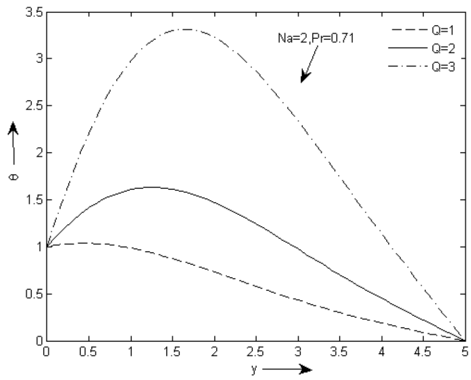

Figure 9. Temperature profiles for Q

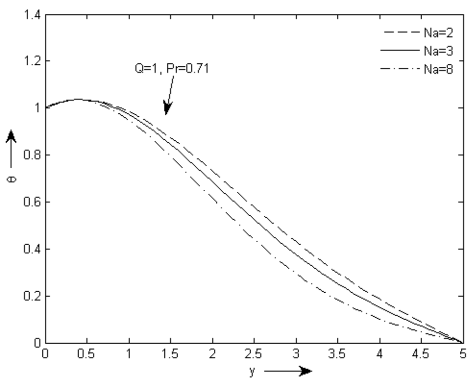

Figure 10. Temperature profiles for Na

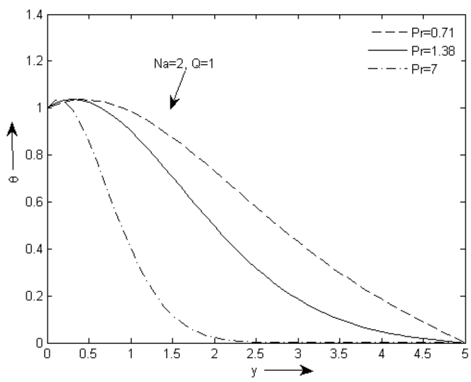

Figure 11. Temperature profiles for Pr

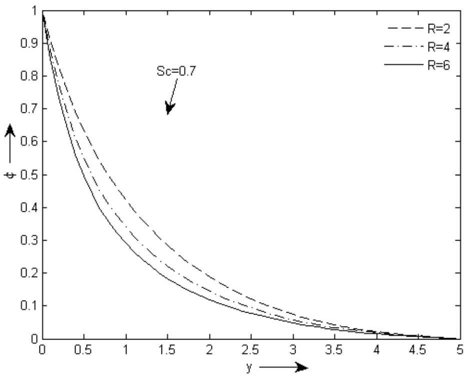

Figure 12. Concentration profiles for R

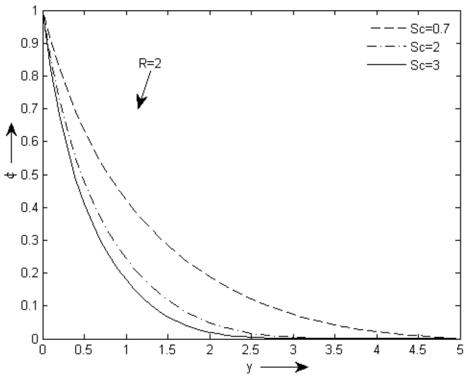

Figure 13. Concentration profiles for Sc

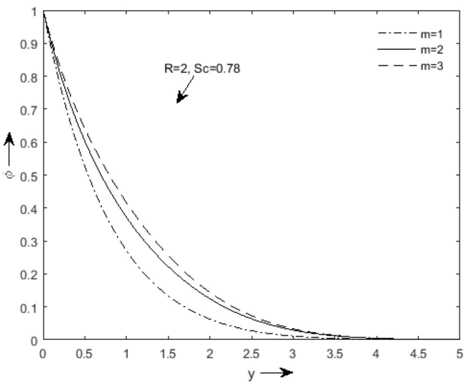

Figure 14a. Concentration profiles for m

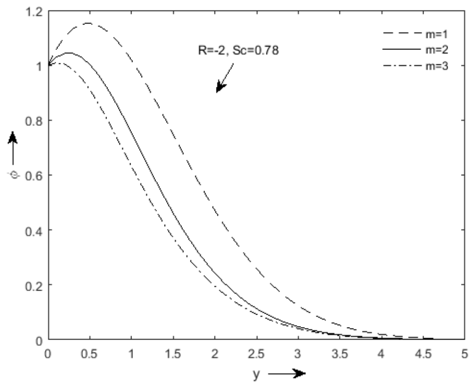

Figure 14b. Concentration profiles for m

6. Conclusion

In the present analysis, the impacts of chemical reaction as well as heat generation on laminar MHD flow was figured out. The governing equations was dealt with Crank Nicolson method. Some important conclusions are given below.

- Velocity as well as concentration profiles scale down with improve in the chemical reaction parameter.
- Improving values of heat generation parameter enhances the fluid velocity.
- Increasing values of porosity parameter make the momentum boundary layer thin.
- Higher heat generation result thicker thermal boundary layer.
- Temperature is diminished for larger values of Prandtl number.

Acknowledgments

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