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# Radiation and Chemical Reaction Effects on MHD Convective Flow over a Porous Plate through a Porous Medium with Heat Generation

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## ABSTRACT

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The present paper analyzes the radiation and chemical reaction effects on a steady laminar forced convection flow of a viscous incompressible electrical conducting fluid over a flat plate embedded in a porous medium in the presence of heat generation. The governing equations are transformed by using similarity transformation and resultant dimensionless equations are solved numerically using the Runge-Kutta method with Shooting technique. The effects of various governing parameters on velocity, temperature, concentration, skin-friction coefficient, Nusselt number and Sherwood number are shown in figures and tables and analyzed in details.

### Keywords:

MHD, Porous, Heat generation

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## 1. Introduction

Combined heat and mass transfer in fluid-saturated porous media finds applications in a variety of engineering processes such as heat exchanger devices, petroleum reservoirs, chemical catalytic reactors and processes, geothermal and geophysical engineering, moisture migration in a fibrous insulation and nuclear waste disposal and others. Lai and Kulacki [1] discussed the coupled heat and mass transfer by mixed convection from a vertical plate in a saturated porous medium. Many problems of Darcian and non-Darcian mixed convection about a vertical plate had been reported, as in Hsu and Cheng [2], Vafai and Tien [3]. Bejan and Khair [4] investigated the free convection boundary layer flow in a porous medium owing to combined heat and mass transfer.

Magnetohydrodynamic(MHD) flows have applications in meteorology, solar physics, cosmic fluid dynamics, astrophysics, geophysics and in the motion of earth's core. In addition, from the technological point of view, MHD free convection flows have significant applications in the field of stellar and planetary magnetospheres, aeronautical plasma flows, chemical engineering and electronics. Raptis [5] studied mathematically the case of time varying two dimensional natural

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convective flow of an incompressible, electrically conducting fluid along an infinite vertical porous plate embedded in a porous medium. Helmy [6] analyzed MHD unsteady free convection flow past a vertical plate embedded in a porous medium. Elabashbeshy [7] studied heat and mass transfer along a vertical plate in the presence of magnetic field. Chamkha and Khaled [8] investigated the problem of coupled heat and mass transfer by MHD free convection from an inclined plate in the presence of internal heat generation or absorption.

In the context of space technology and in the processes involving high temperature, the effects of radiation are vital importance. Recent developments in hypersonic flights, missile re-entry, rocket, rocket combustion chambers, power plants for inter planetary flight and gas cooled nuclear reactors, have focused attention on thermal with laminar free convection heat transfer from a vertical plate was investigate by Cess [9] for an absorbing, emitting fluid in the optically thick region, using the singular perturbation technique. Arpacı [10] considered a similar problem in both the optically thick regions and used the approximate integral technique and firstorder profiles to solve the energy equation. Raptis [11] analyzed the thermal radiation and free convection flow through a porous medium bounded by a vertical infinite porous plate by using a regular perturbation technique. Mohammed Ibrahim and Bhaskar Reddy [12] studied the effects of radiation and mass transfer effects on MHD free convection flow a long a stretching surface with viscous dissipation and heat generation. Damesh *et al.*, [13] found the similarity analysis of magnetic field and radiation effects on forced convection flow.

The study of heat generation or absorption effects in moving fluids is important in the view of several physical problems, such as fluids undergoing exothermic or endothermic chemical reactions. Vajravelu and Hadjinicolaou [14] studied the heat transfer characteristics in the laminar boundary layer of a viscous fluid over a stretching sheet with viscous dissipation or frictional heating and internal heat generation. Hossain *et al.*, [15] studied problem of the natural convection flow along a vertical wavy surface with uniform surface temperature in the presence of heat generation/absorption. Few other recent related researches can be found in [16-20].

However, the interaction of radiation and chemical reaction effects on steady MHD forced convection flow in a porous medium with heat generation has received little attention. Hence, the object of the present paper is to analyze the radiation and chemical reaction effects on steady MHD forced convection boundary layer flow past a semi-infinite moving vertical plate embedded in a porous medium by taking heat generation into account. The governing equations are transformed by using similarity transformation and resultant dimensionless equations are solved numerically using the Runge-Kutta method with Shooting technique. The effects of various governing parameters on the velocity, temperature, concentration, skin-friction coefficient, Nusselt number and Sherwood number are shown in figures and tables and analyzed in detail.

## 2. Methodology

A steady two-dimensional laminar forced convection flow of a viscous incompressible electrically conducting and radiating fluid over a flat plate of very small thickness and much larger breadth, embedded in a porous medium, in the presence of heat generation or absorption is considered. The flow is assumed to be in the  $x$ -direction, which is taken along the semi-infinite plate and  $y$ -axis normal to it. The plate is maintained at a constant temperature  $T_w$ , which is higher than the constant free stream temperature  $T_\infty$  and a constant concentration  $C_w$ , which is greater than the constant concentration  $C_\infty$  of the surrounding fluid. A uniform magnetic field is applied in the direction perpendicular to the plate. The fluid is assumed to be slightly conducting, and hence the magnetic Reynolds number is much less than unity and the induced magnetic field is negligible

in comparison with the applied magnetic field. It is further assumed that there is no applied voltage, so that electric field is absent. In the analysis of the flow in porous media, the differential equations governing the fluid motion is based on Darcy's law, which accounts for the drag exerted by the porous media. Thermal radiation is included in the energy equation. The governing equations of such type of flow are (with the application of Darcy's law)

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

Momentum equation:

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = v \frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) + \frac{v}{K'}(u - U_\infty) - \frac{\sigma B_0^2}{\rho} u \quad (2)$$

Energy equation:

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p} \frac{\partial q_r}{\partial y} + \frac{Q_0}{\rho c_p} (T - T_\infty) \quad (3)$$

Species equation:

$$u \frac{\partial D}{\partial x} + v \frac{\partial D}{\partial y} = D \frac{\partial^2 C}{\partial y^2} - K_r (T - T_\infty) \quad (4)$$

Here  $u$  and  $v$  are the components of velocity respectively in the  $x$  and  $y$  directions.  $T$  - the temperature,  $\mu$  - the coefficient of fluid viscosity,  $C$  - the concentration,  $\rho$  - the fluid density,  $\nu = \frac{\mu}{\rho}$  - the kinematic viscosity,  $c_p$  - the specific heat at constant pressure,  $g$  - the acceleration due to gravity,  $\beta$  - the coefficient of thermal expansion and  $\beta^*$  - the coefficient of concentration expansion,  $K'$  - the permeability of the porous medium,  $k_r$  - the chemical reaction parameter,  $U_\infty$  - the free stream velocity,  $\sigma$  - electrical conductivity  $B_0$  - the magnetic field intensity,  $k$  - the thermal conductivity of the fluid,  $q_r$  - the radiative heat flux,  $D$  - the mass diffusivity.

Using Rosseland approximation for radiation (Brewster [21]) we can write

$$q_r = -\frac{4\sigma_s}{3K_e} \frac{\partial T^4}{\partial y} \quad (5)$$

where  $\sigma_s$  is the Stefan-boltzman constant

$K_e$  - The absorption coefficient

Assuming that the temperature difference within the flow is such that  $T^4$  may be expanded in Taylor series and expanding  $T^4$  about  $T_\infty$  and neglecting higher orders.

we get  $T^4 = 4T_\infty^3 T - 3T_\infty^4$

Therefore eq. (3) becomes

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial y^2} - \frac{16\sigma T_\infty^3}{3K' \rho c_p} \frac{\partial q_r}{\partial y} + \frac{Q_0}{\rho c_p} (T - T_\infty) \quad (6)$$

The appropriate boundary conditions for the velocity, temperature and concentration field are

$$u = 0, \quad v = 0, \quad T = T_w, \quad C = C_w \quad \text{at } y = 0,$$

$$u = U_\infty, \quad T = T_\infty, \quad C = C_\infty \quad \text{as } y \rightarrow \infty. \quad (7)$$

Here  $T_w$  is the wall temperature.

For the consideration of porous plate, embedded in a porous medium, a suction velocity is given through the plate. The boundary condition for the velocity component  $v$ , then becomes  $v = v_w$ ,  $v_w = \frac{v_0}{\sqrt{x}}$  is the velocity of suction,  $v_0$  is the initial value of the suction.

The eqs. (2) - (4) are coupled and nonlinear partial differential equations and hence analytical solution is not possible. Therefore, numerical technique is employed to obtain the required solution. Numerical computations are greatly facilitated by non-depersonalization of the equations. Proceeding with the analysis, we introduce the following similarity transformations and dimensionless variables which will convert the partial differential equations from two independent variables ( $x, y$ ) to a system of coupled, non-linear ordinary differential equation in a single variable ( $\eta$ ) i.e., coordinate normal to the plate.

In order to write the governing equations and boundary conditions in dimensionless form, the following non-dimensional quantities are introduced.

$$u = \frac{\partial \phi}{\partial y}, \quad v = \frac{\partial \phi}{\partial x}, \quad G_r = \frac{g\beta(T_w - T_\infty)x}{U_\infty^2}, \quad G_c = \frac{g\beta^*(C_w - C_\infty)x}{U_\infty^2}, \quad \theta = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi = \frac{C - C_\infty}{C_w - C_\infty},$$

$$M = \frac{\sigma B_0^2 x}{\rho U_\infty}, \quad Q = \frac{Q_0 x}{\rho C_p U_\infty}, \quad K_r = \frac{2K_r' x}{U_\infty}, \quad \eta = y \sqrt{\frac{U_\infty}{\nu x}}, \quad \psi = \sqrt{U_\infty \nu x} f(\eta), \quad Sc = \frac{\nu}{D}, \quad Pr = \frac{\mu c_p}{k}$$

$$R = \frac{kk^*}{4\sigma T_\infty^3}, \quad K = \frac{\nu x}{K' U_\infty} \tag{8}$$

where  $\psi$  is the stream function,  $\theta$ - the non-dimensional temperature function,  $\phi$ - the non-dimensional concentration,  $Gr$  – the thermal Grashof number,  $Gc$  – the solutal Grashof number,  $M$  – the magnetic field parameter,  $K$  – the permeability parameter,  $Pr$  – the Prandtl number,  $Sc$  – the Schmidt number,  $Q$  – the heat generation or absorption coefficient,  $Kr$  – chemical reaction parameter.

The mass conservation equation (1) is satisfied by Cauchy-Riemann Equations

$$u = \frac{\partial \phi}{\partial y} \quad \text{and} \quad v = \frac{\partial \phi}{\partial x}$$

In view of the Equation (8), the equations (2),(3) and (4) reduce to the following nondimensional form

$$f''' + \frac{1}{2}ff'' - K(f-1) + Gr\theta + Gc\phi - Mf' = 0 \tag{9}$$

$$\frac{1}{Pr} \left[ 1 + \frac{4}{3R} \right] \theta'' + \frac{1}{2}f\theta' + Q\theta = 0 \tag{10}$$

$$\phi'' + Scf\phi' - Kr\phi = 0 \tag{11}$$

The corresponding boundary conditions are

$$\begin{aligned} f' = 0, \quad f = S, \quad \theta = 1, \quad \phi = 1 \quad \text{at} \quad \eta = 0, \\ f' = 1, \quad \theta = 0, \quad \phi = 0 \quad \text{at} \quad \eta \rightarrow \infty \end{aligned} \tag{12}$$

where  $f$  is the dimensionless stream function,  $S = \frac{-2v_0}{u_\infty \nu}$  is the dimensionless suction velocity and primes denote partial differentiation with respect to the variable  $\eta$ . The skin-friction coefficient,

Nusselt number and Sherwood number are important physical parameters for this type of boundary layer flow. Knowing the velocity field, the skin-friction at the plate can be obtained, which in non-dimensional form is given by

$$C_f = 2(\text{Re})^{\frac{1}{2}} f''(0)$$

Knowing the temperature field, the rate of heat transfer coefficient can be obtained, which in non-dimensional form, in terms of the Nusselt number, is given by

$$Nu = -(\text{Re})^{\frac{1}{2}} \theta'(0)$$

Knowing the concentration field, the rate of mass transfer coefficient can be obtained, which in non-dimensional form, in terms of the Sherwood number, is given by

$$Sh = -(\text{Re})^{\frac{1}{2}} \phi'(0)$$

where  $\text{Re} = \frac{U_\infty x}{\nu}$  is the Reynolds number.

### 3. Solution of the Problem

The set of coupled non-linear governing boundary layer eqs. (9) - (11) together with the boundary conditions (12) are solved numerically by using Runge Kutta fourth order technique along with shooting method. First of all, higher order non-linear differential Eqs. (9) - (11) are converted into simultaneous linear differential equations of first order and they are further transformed into initial value problem by applying the shooting technique [22]. The resultant initial value problem is solved by employing Runge-Kutta fourth order technique. The step size  $\Delta\eta=0.05$  is used to obtain the numerical solution with decimal place accuracy as the criterion of convergence. From the process of numerical computation, the skin friction coefficient, the Nusselt number and the Sherwood number, which are respectively proportional to  $f''(0)$ ,  $-\theta'(0)$  and  $-\phi'(0)$ , are also sorted out and their numerical values are presented in a tabular form.

### 4. Results and Discussion

As a result of the numerical calculations, the dimensionless velocity, temperature and concentration distributions for the flow under consideration are obtained and their behaviour have been discussed for variations in the governing parameters viz., In the present study we adopted the following default parameter values  $Gr = 3.0$ ,  $Gc = 2.0$ ,  $M = 0.5$ ,  $K = 0.5$ ,  $Pr = 0.71$ ,  $R = 0.5$ ,  $Q = 0.5$ ,  $Sc = 0.6$ ,  $S = 1.0$ ,  $Kr = 1.0$ . All the graphs therefore correspond to these values unless specifically indicated on the appropriate graph.

The influence of the thermal Grashof number  $Gr$  on the velocity is presented in Figure 1. it is observed that there is a rise in the velocity due to enhancement of thermal buoyancy force. Figure 2 presents typical velocity profiles in the boundary layer for various values of the solutal Grashof number  $Gc$ , while all other parameters are kept at some fixed values. As expected, the fluid velocity increases and the peak value is more distinctive due to increase in the species buoyancy force

For various values of the magnetic parameter  $M$ , the velocity profiles are plotted in Figure 3. It can be seen that as  $M$  increases, the velocity decreases. This result qualitatively agrees with the expectations, since the magnetic field exerts a retarding force on the free convection flow. The effect of the permeability parameter  $K$  on the velocity field is shown in Figure 4. An increase in  $K$  will therefore increase the resistance of the porous medium (as the permeability physically

become less with increasing  $K'$ ) which will tend to decelerate the flow and reduce the velocity. This behavior is evident from Figure 4.

Figures 5(a) and 5(b) illustrate the velocity and temperature profiles for different values of the Prandtl number  $Pr$ . The numerical results show that the effect of increasing values of Prandtl number results in a decreasing velocity (Fig.5 (a)). From Figure 5 (b), it is observed that an increase in the Prandtl number results a decrease of the thermal boundary thickness and in general lower average temperature within the boundary layer.

The influence of the thermal radiation parameter  $N$  on the velocity and temperature are shown in Figs. 6(a) and 6(b) respectively. It is obvious that an increase in the radiation parameter results in a decrease in the velocity and temperature within the boundary layer.

For different values of the heat generation parameter  $Q$ , the velocity and temperature profiles are plotted in Figs. 7 (a) and 7(b) respectively. From Figure 7 (a), it is seen that due to the heat generation the buoyancy force increases which induces the flow rate to increase giving rise to an increase in the velocity profiles. Figure 7 (b) shows the variation of the temperature profiles for different values of  $Q$ . It is seen that, the temperature profiles increase with an increase in the heat generation parameter  $Q$ .

For different values of the Schmidt number  $Sc$ , the velocity and concentration profiles are plotted in Figs. 8 (a) and 8(b) respectively. As the Schmidt number  $Sc$  increases the concentration decreases. The reductions in the velocity and concentration profiles are accompanied by simultaneous reductions in the velocity and concentration boundary layer, which is evident from Figs. 8 (a) and 8(b).

Figures 9 (a) and 9(b) show the velocity and concentration profiles for different values of chemical reaction parameter  $Kr$ . It is observed that an increase in the chemical reaction parameter results in a decrease in the velocity and concentration.

The effects of various governing parameters on the skin-friction coefficient  $C_f$ , Nusselt number  $Nu$ , and Sherwood number  $Sh$  are shown in Tables 1 and 2. From Table 1, it is noticed that as  $Gr$  or  $Gc$  increases, there is a rise in the skin-friction coefficient, Nusselt number and the Sherwood number. It is seen that, as  $M$  or  $K$  increases, there is a fall in the skin-friction coefficient, Nusselt number and the Sherwood number. From Table 2, it is observed that an increase in the Prandtl number  $Pr$  leads to a fall in the skin-friction coefficient and the Sherwood number, while a rise in the Nusselt number. It is observed that an increase in radiation parameter  $R$  leads to a decrease in the skin-friction and Sherwood number, while a rise in the Nusselt number. It is noticed that an increase in heat generation parameter  $Q$  leads to rise in the skin-friction and Sherwood number, while a decrease in the Nusselt number. It is found that as the Schmidt number  $Sc$  increases, there is a fall in the skin friction coefficient and Nusselt number, while a rise in the Sherwood number. It is found that as the chemical reaction parameter increases, there is a fall in the skin friction coefficient and Nusselt number, while a rise in the Sherwood number.

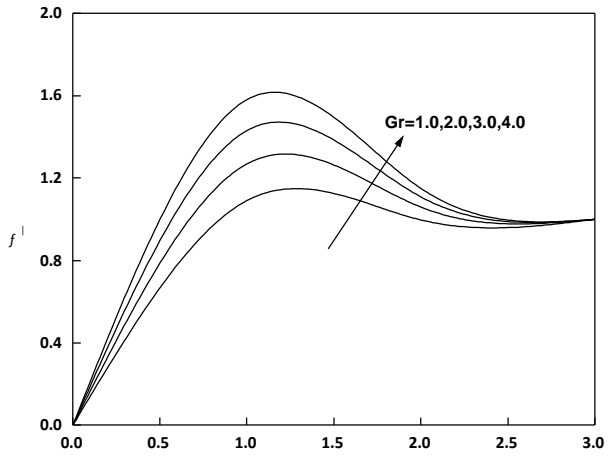


Fig. 1. Velocity profiles for different values of  $Gr$

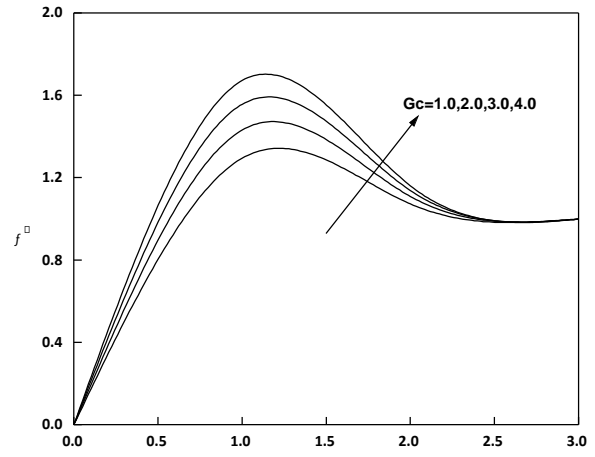


Fig. 2. velocity profiles for different values of  $Gc$

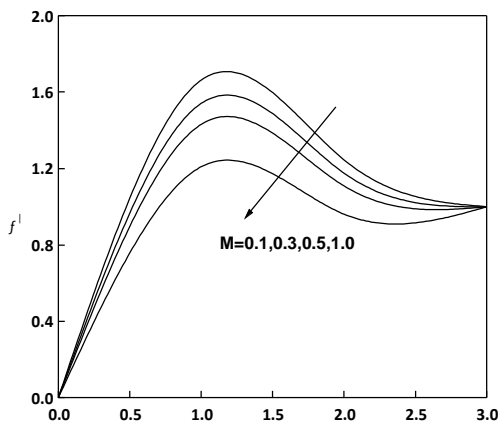


Fig. 3. Velocity profiles for different values of  $M$

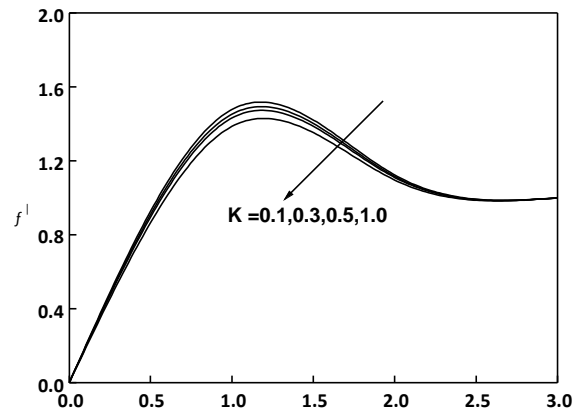


Fig. 4. Velocity profiles for different values of  $K$

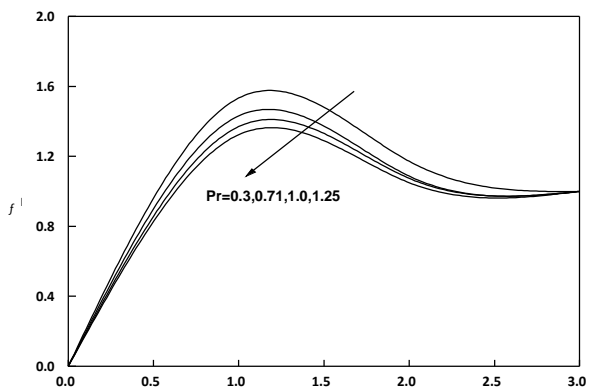


Fig. 5(a). Velocity profiles for different values of  $Pr$

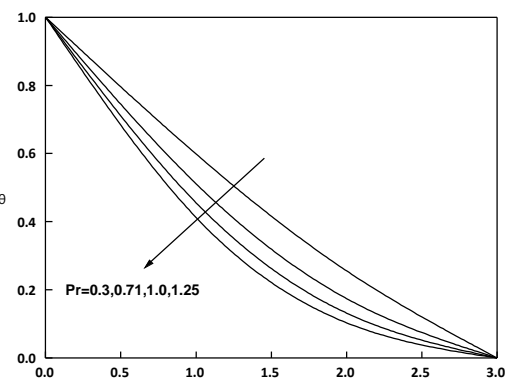
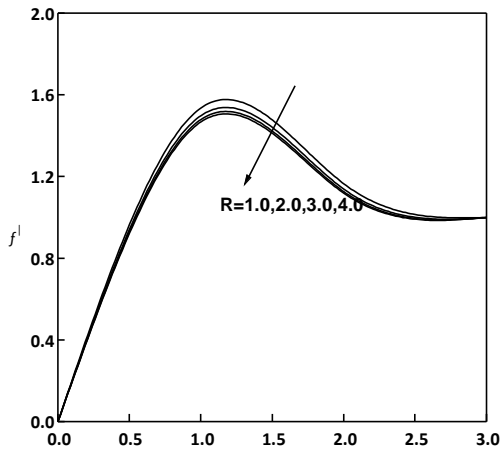
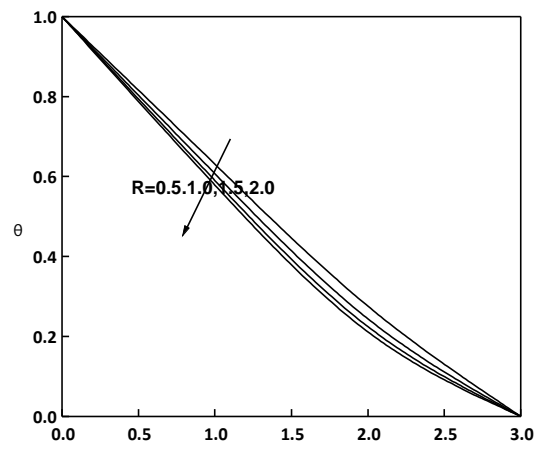


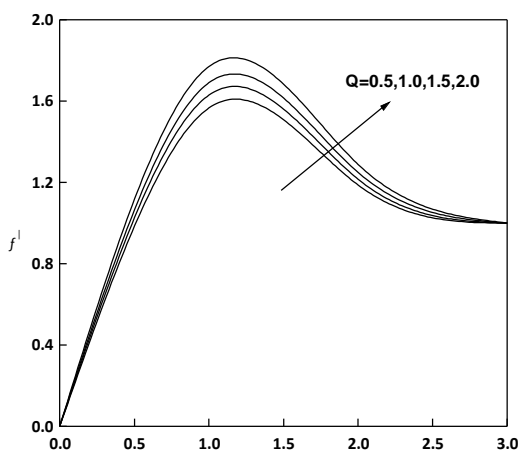
Fig. 5(b). Velocity profiles for different values of  $Pr$



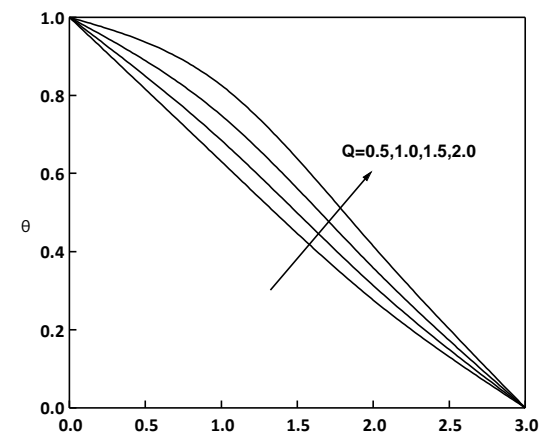
**Fig. 6(a).** Velocity profiles for different values of  $R$



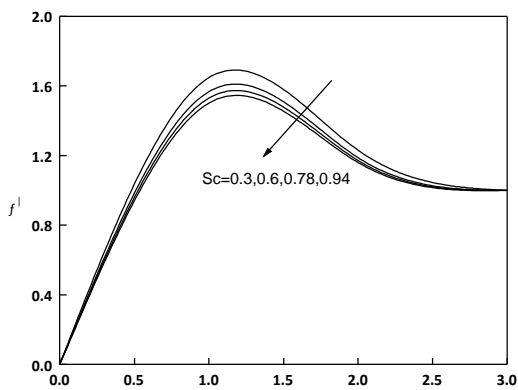
**Fig. 6(b).** Temperature profiles for different values of  $R$



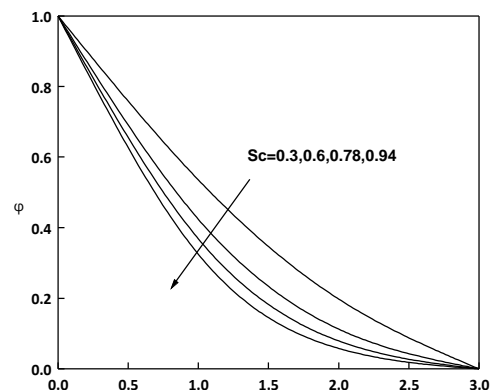
**Fig. 7(a).** Velocity profiles for different values of  $Q$



**Fig. 7(b).** Temperature profiles for different values of  $Q$

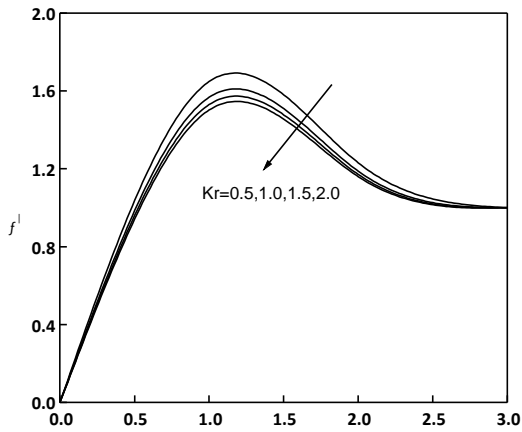


**Fig. 8(a).** Velocity profiles for different values of  $Sc$

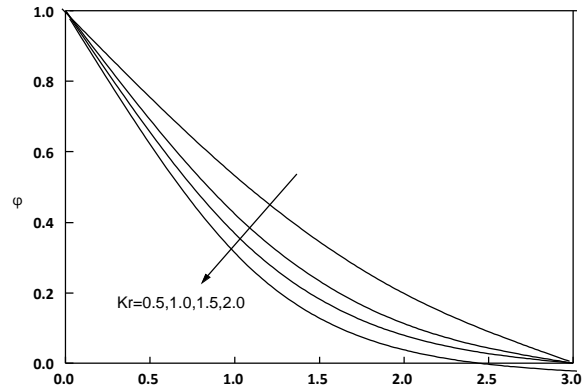


**Fig. 8(b).** Concentration profiles for different values of  $Sc$





**Fig. 9(a).** Velocity profiles for different values of  $Kr$



**Fig. 9(b).** Concentration profiles for values of  $Kr$

**Table 1**

Numerical values of the skin-friction coefficient  $C_f$ , Nusselt number  $Nu$  and Sherwood number  $Sh$  for  $Pr = 0.71, R = 0.5, Q = 0.5, Sc = 0.6, S = 0.5, Kr = 1.0$

$Gr$	$Gm$	$M$	$K$	$C_f$	$Nu$	$Sh$
2.0	2.0	0.5	0.5	3.4448	0.339924	0.665842
4.0	2	0.5	0.5	4.77245	0.357057	0.71032
2.0	4	0.5	0.5	4.51994	0.351674	0.697203
2.0	2	1.0	0.5	3.03587	0.331013	0.643118
2.0	2	0.5	1.0	3.34856	0.338677	0.662785

**Table 2**

Numerical values of the skin-friction coefficient  $C_f$ , Nusselt number  $Nu$  and Sherwood number  $Sh$  for  $Gr = 2.0, Gm = 2.0, M = 0.5, K = 0.5, S = 1.0$

$Pr$	$R$	$Q$	$Sc$	$Kr$	$C_f$	$Nu$	$Sh$
0.71	0.5	0.5	0.6	1.0	3.4448	0.339924	0.665842
1.0	0.5	0.5	0.6	1.0	3.42564	0.3463	0.664573
0.71	1.0	0.5	0.6	1.0	3.41767	0.349432	0.664051
0.71	0.5	1.0	0.6	1.0	3.51712	0.235045	0.669766
0.71	0.5	0.5	1.0	1.0	3.30131	0.216948	0.685779
0.71	0.5	0.5	1.0	2.0	3.2654	0.19812	0.7569

## 5. Conclusions

In this paper The effects of various governing parameters on the velocity, temperature, concentration, skin-friction coefficient, Nusselt number and Sherwood number are shown in figures and tables and analyzed in detail.

- It is noticed that an increase in heat generation parameter  $Q$  leads to rise in the skin-friction and Sherwood number, while a decrease in the Nusselt number.
- It is found that as the Schmidt number  $Sc$  increases, there is a fall in the skinfriction coefficient and Nusselt number, while a rise in the Sherwood number.
- It is found that as the chemical reaction parameter increases, there is a fall in the skinfriction coefficient and Nusselt number, while a rise in the Sherwood number.

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