Original Research Article

MHD Free Convection, Heat and Mass Transfer Chemical Reaction, Radiation and Heat Source or Sink over a Rotating Inclined Permeable Plate Variable Reactive Index

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ABSTRACT

MHD free convection, heat and mass transfer flow over a rotating inclined permeable plate with the influence of magnetic field, thermal radiation and chemical reaction of various order has been investigated numerically. The governing boundary-layer equations are formulated and transformed into a set of similarity equations with the help of similarity variables derived by lie group transformation. The governing equations are solved numerically using the Nactsheim-Swigert Shooting iteration technique together with the Runge-Kutta six order iteration schemes. The simulation results are presented graphically to illustrate influence of magnetic parameter (M), porosity parameter (γ), rotational parameter (R'), Grashof number (G_r), modified Grashof number (G_m), thermal conductivity parameter (T_c), Prandtl number (P_r), radiation parameter (R), heat source parameter (Q), Eckert number (E_c), Schmidt number (S_c), reaction parameter (λ) and order of chemical reaction (n) on the all fluid velocity components, temperature and concentration distribution as well as Skin-friction coefficient, Nusselt and Sherwood number at the plate.

Keywords: MHD; Inclined permeable plate; Thermal radiation; Chemical reaction;

NOMENCLATURE

B_0	Constant magnetic flux density
c	Constant depends on the properties of the fluid
C	Concentration of the fluid
C_p	Specific heat at constant pressure
D_m	Mass diffusivity
f'	Dimensionless primary velocity
g	Acceleration due to gravity
g_0	Dimensionless secondary velocity
k	Thermal conductivity
k_∞	Undisturbed thermal conductivity
k_0	Reaction rate

K	Permeability of the porous medium
n	Order of chemical reaction
P	Pressure distribution in the boundary layer
q_r	Radiative heat flux in the *y* direction
Q_T	Heat generation
Q_0	Heat source
t	Time
T	Fluid temperature
U	Uniform velocity
u, v	Velocity components along x and y axes respectively
x'	Dimensionless axial distance along x axis

Dimensionless parameters

E_c	Eckert number
R'	Rotational parameter
G_r	Grashof number
G_m	Modified Grashof number
M	Magnetic parameter
P_r	Prandtl number
Q	Heat source parameter
R	Radiation parameter
S_c	Schmidt number
T_c	Thermal conductivity parameter
γ	Permeability of the porous medium
λ	Reaction parameter

Greek Symbols

υ	Kinematic viscosity of the fluid
μ	Dynamic viscosity of the fluid
σ	Electrical conductivity
σ_0	Constant electrical conductivity
σ_s	Stefan-Boltzmann constant
ρ	Density of the fluid

α Thermal diffusivity

$\alpha_1 - \alpha_6$ Arbitrary real number

β Inclination angle

β_T Thermal expansion coefficient

β_C Concentration expansion coefficient

κ^* Mean absorption coefficient

ε Parameter of the group

ψ Stream function

η Similarity variable

θ Dimensionless temperature

φ Dimensionless concentration

Ω Angular velocity of the plate

Subscripts

w Condition of the wall

∞ Condition of the free steam

1. INTRODUCTION

Coupled heat and mass transfer problems in the presence of chemical reactions are of importance in many processes and have, therefore, received considerable amount of attention of researchers in recent years. Chemical reactions can occur in processes such as drying, distribution of temperature and moisture over agricultural fields and groves of fruit trees, damage of crops due to freezing, evaporation at the surface of a water body, energy transfer in a wet cooling tower and flow in a desert cooler. Chemical reactions are classified as either homogeneous or heterogeneous processes. A homogeneous reaction is one that occurs uniformly throughout a given phase. On the other hand, a heterogeneous reaction takes a restricted area or within the boundary of a phase. Analysis of the transport processes and their interaction with chemical reactions is quite difficult and closely related to fluid dynamics. Chemical reaction effects on heat and mass transfer has been analyzed by many researchers over various geometries with various boundary conditions in porous and nonporous media. Symmetry groups or simply symmetries are invariant transformations that do not alter the structural form of the equation under investigation which is described by Bluman and Kumei [1]. MHD boundary layer equations for power law fluids with variable electric conductivity is studied by Helmy [2]. In the case of a scaling group of transformations, the group-invariant solutions are nothing but the well known similarity solutions which is studied by Pakdemirli and Yurusoy [3]. Symmetry groups and similarity solutions for free convective boundary-layer problem was studied by Kalpakides and Balassas [4]. Makinde [5] investigated the effect of free convection flow with thermal radiation and mass transfer past moving vertical porous plate. Seddeek and Salem [6] investigated the Laminar mixed convection adjacent to vertical continuously stretching sheet with variable viscosity and variable thermal diffusivity.Ibrahim, Elaiw and Bakr [7] studied the effect of the chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi infinite vertical permeable moving plate with heat source and suction. El-Kabeir, El-Hakiem and Rashad [8] studied Lie group analysis of unsteady MHD three dimensional dimensional by natural convection from an inclined stretching surface saturated porous medium. Rajeswari, Jothiram and Nelson [9] studied the effect of chemical reaction, heat and mass transfer on nonlinear MHD boundary layer flow through a vertical porous surface in the presence of suction. Chandrakala [10] investigated chemical reaction effects on MHD flow past an impussively started semi-infinite vertical plate. Joneidi, Domairry and Babaelahi [11] studied analytical treatment of MHD free convective flow and mass transfer over a stretching sheet with chemical reaction. Muhaimin, Kandasamy and Hashim [12] studied the effect of chemical reaction, heat and mass transfer on nonlinear boundary layer past a porous shrinking sheet in the presence of suction. Rahman and Salahuddin [13] studied hydromagnetic heat and mass transfer flow over an inclined heated surface with variable viscosity and electric conductivity. As per standard text and works of previous researchers, the radiative flow of an electrically conducting fluid and heat and mass transfer situation arises in many practical applications such as in electrical power generation, astrophysical flows, solar power technology, space vehicle re-entry, nuclear reactors.

The objective of this study is to present a similarity analysis of boundary layer flow past a rotating inclined permeable plate with the influence of magnetic field, thermal radiation, thermal conductivity and chemical reaction of various orders.

2. MATHEMATICAL MODEL OF THE FLOW AND GOVERNING EQUATIONS

Steady two dimensional MHD heat and mass transfer flow with chemical reaction and radiation over an inclined permeable plate $y = 0$ in a rotating system under the influence of transversely applied magnetic field is considered. The *x*-axis is taken in the upward direction and *y*-axis is normal to it. Again the plate is inclined at an angle β with the *x*-axis. The flow takes place at $y \geq 0$, where *y* is the coordinate measured normal to the *x*-axis. Initially we consider the plate as well as the fluid is at rest with the same velocity $U\left(=U_\infty\right)$, temperature $T\left(=T_\infty\right)$ and concentration $C\left(=C_\infty\right)$. Also it is assumed that the fluid and plate is at rest after that the whole system is allowed to rotate with a constant angular velocity $R=\left(0,-\Omega,0\right)$ about the y-axis and then the temperature and species concentration of the plate are raised to $T_w\left(>T_\infty\right)$ and $C_w\left(>C_\infty\right)$ respectively, which are thereafter maintained constant, where T_w and C_w is the temperature and concentration respectively at wall and T_∞ and C_∞ is the temperature and concentration respectively far away from the plate.

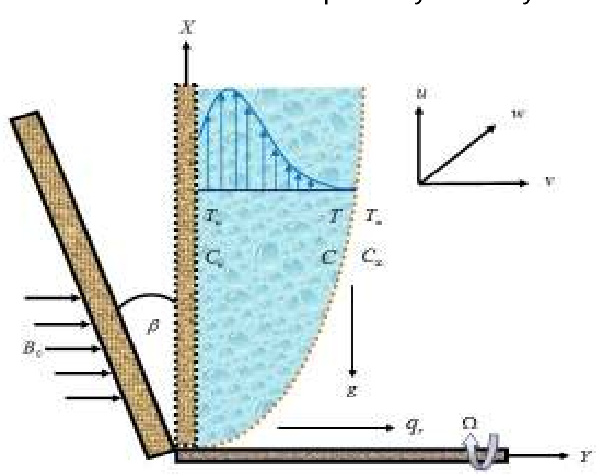


Fig. 1. Physical configuration of the flow

The electrical conductivity is assumed to vary with the velocity of the fluid and have the form [2],

$\sigma = \sigma_0 u$, σ_0 is the constant electrical conductivity.

The applied magnetic field strength is considered, as follows [13]

$$B(x) = \frac{B_0}{\sqrt{x}}$$

The temperature dependent thermal conductivity is assumed to vary linearly, as follows [6]

$$k(T) = k_\infty \left[1 + c(T - T_\infty)\right]$$

Where k_∞ is the undisturbed thermal conductivity and c is the constant depending on the properties of the fluid.

The governing equations for the continuity, momentum, energy and concentration in laminar MHD incompressible boundary-layer flow is presented follows

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \upsilon\frac{\partial^2 u}{\partial y^2} + 2\Omega w - \frac{\upsilon}{K}u - \frac{\sigma_0 B_0^2 u^2}{\rho x} + g\beta_T (T - T_\infty) cos\beta + g\beta_C (C - C_\infty) cos\beta \tag{2}$$

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} = \upsilon\frac{\partial^2 w}{\partial y^2} - 2\Omega u - \frac{\upsilon}{K}w - \frac{\sigma_0 B_0^2\, u\, w}{\rho x} \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{1}{\rho C_p}\frac{\partial}{\partial y}\left[k(T)\frac{\partial T}{\partial y}\right] + \frac{Q_0 (T - T_\infty)}{\rho C_p} - \frac{\alpha}{k_\infty}\left(\frac{\partial q_r}{\partial y}\right) + \frac{\upsilon}{C_p}\left(\frac{\partial u}{\partial y}\right)^2 \tag{4}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} - k_0 (C - C_\infty)^n \tag{5}$$

and the boundary conditions for the model is

$$\left.\begin{array}{l} u = U, v = 0, w = 0, T = T_w, C = C_w \quad \text{at} \quad y = 0 \\ u \to 0, w \to 0, T \to T_\infty, C \to C_\infty \quad \text{as} \quad y \to \infty \end{array}\right\} \tag{6}$$

where, *U* is the uniform velocity, β is the inclination angle of the plate with *x*-axis, C_p is the specific heat at constant pressure, $k(T)$ is the temperature dependent thermal conductivity, Q_0 is the heat source, D_m is the mass diffusivity, k_0 is the reaction rate, $k_0 > 0$ for destructive reaction, $k_0 = 0$ for no reaction and $k_0 < 0$ for generative reaction, *n* (integer) is the order of chemical reaction, q_r is the chemical reaction parameter, T_w and C_w is the temperature and concentration respectively at wall and T_∞ and C_∞ is the temperature and concentration respectively far away from the plate.

2.1 METHOD OF SOLUTION

Introducing the following dimensionless variables

$$x' = \frac{xU}{\upsilon}, y' = \frac{yU}{\upsilon}, u' = \frac{u}{U}, v' = \frac{v}{U}, w' = \frac{w}{U}, \theta = \frac{T - T_\infty}{T_w - T_\infty} \text{ and } \varphi = \frac{C - C_\infty}{C_w - C_\infty}$$

the following equations are obtained,

$$u = U\,u', v = U\,v', w = U\,w', T = T_\infty + (T_w - T_\infty)\theta \text{ and } C = C_\infty + (C_w - C_\infty)\varphi \tag{7}$$

Now, by using equation (7), the equations (1), (2), (3), (4) and (5) are transformed to

$$\frac{\partial u'}{\partial x'} + \frac{\partial v'}{\partial y'} = 0 \tag{8}$$

$$u'\frac{\partial u'}{\partial x'}+v'\frac{\partial u'}{\partial y'}=\frac{\partial^2 u'}{\partial y'^2}+2R'w'-\gamma u'-\frac{M\,u'^2}{x'}+G_r\,\theta cos\beta+G_m\,\varphi cos\beta \tag{9}$$

$$u'\frac{\partial w'}{\partial x'}+v'\frac{\partial w'}{\partial y'}=\frac{\partial^2 w'}{\partial y'^2}-2R'u'-\gamma w'-\frac{M\,u'w'}{x'} \tag{10}$$

$$u'\frac{\partial \theta}{\partial x'}+v'\frac{\partial \theta}{\partial y'}-\frac{1}{P_r}\left[\left(1+T_c\,\theta+R\right)\frac{\partial^2\theta}{\partial y'^2}+T_c\left(\frac{\partial\theta}{\partial y'}\right)^2\right]-Q\theta-E_c\left(\frac{\partial u}{\partial y}\right)^2=0 \tag{11}$$

$$u'\frac{\partial \varphi}{\partial x'}+v'\frac{\partial \varphi}{\partial y'}-\frac{1}{S_C}\frac{\partial^2\varphi}{\partial y'^2}+\lambda\varphi^n=0 \tag{12}$$

using equation (7), the boundary condition (6) becomes,

$$\left.\begin{array}{l} u'=1, v'=0, w'=0, \theta=1, \varphi=1 \text{ at } y'=0 \\ u'\to 0, w'\to 0, \theta\to 0, \varphi\to 0 \text{ as } y'\to\infty \end{array}\right\} \tag{13}$$

where,

$$R'=\frac{\Omega\upsilon}{U^2},\gamma=\frac{\upsilon^2}{KU^2},M=\frac{\sigma_0 B_0^2}{\rho},G_r=\frac{g\beta_T\left(T_w-T_\infty\right)\upsilon}{U^3},G_m=\frac{g\beta_c\left(C_w-C_\infty\right)\upsilon}{U^3},T_c=c\left(T_w-T_\infty\right),$$

$$R=\frac{16\sigma_S T_\infty^3}{3\kappa^* k_\infty},P_r=\frac{\upsilon}{\alpha},Q=\frac{Q_0\upsilon}{\rho C_p U^2},E_c=\frac{U^2}{C_p\left(T_w-T_\infty\right)},S_c=\frac{\upsilon}{D_m} \text{ and } \lambda=\frac{k_0\left(C_w-C_\infty\right)^{n-1}\upsilon}{U^2}$$

In order to deal with the problem, we introduce the stream function ψ (since the flow is incompressible) defined by

$$u'=\frac{\partial\psi}{\partial y'},v'=-\frac{\partial\psi}{\partial x'} \tag{14}$$

The mathematical significance of using equation (14) is that the continuity equation (8) is satisfied automatically.

by equation (14), equations (9), (10), (11) and (12) transformed as follows,

$$\frac{\partial\psi}{\partial y'}\frac{\partial^2\psi}{\partial x'\partial y'}-\frac{\partial\psi}{\partial x'}\frac{\partial^2\psi}{\partial y'^2}-\frac{\partial^3\psi}{\partial y'^3}-2R'w'+\gamma\frac{\partial\psi}{\partial y'}+\frac{M}{x'}\left(\frac{\partial\psi}{\partial y'}\right)^2-G_r\theta\,cos\beta-G_m\varphi\,cos\beta=0 \tag{15}$$

$$\frac{\partial\psi}{\partial y'}\frac{\partial w'}{\partial x'}-\frac{\partial\psi}{\partial x'}\frac{\partial w'}{\partial y'}-\frac{\partial^2 w'}{\partial y'^2}+2R'\frac{\partial\psi}{\partial y'}+\gamma w'+\frac{M}{x'}\frac{\partial\psi}{\partial y'}w'=0 \tag{16}$$

$$\frac{\partial\psi}{\partial y'}\frac{\partial\theta}{\partial x'}-\frac{\partial\psi}{\partial x'}\frac{\partial\theta}{\partial y'}-\frac{1}{P_r}\left[\left(1+T_c\,\theta+R\right)\frac{\partial^2\theta}{\partial y'^2}+T_c\left(\frac{\partial\theta}{\partial y'}\right)^2\right]-Q\,\theta-E_c\left(\frac{\partial^2\psi}{\partial y'^2}\right)^2=0 \tag{17}$$

$$\frac{\partial\psi}{\partial y'}\frac{\partial\varphi}{\partial x'}-\frac{\partial\psi}{\partial x'}\frac{\partial\varphi}{\partial y'}-\frac{1}{S_c}\frac{\partial^2\varphi}{\partial y'^2}+\lambda\varphi^n=0 \tag{18}$$

and the boundary conditions (13) become,

$$\left.\begin{array}{l} \frac{\partial\psi}{\partial y'}=1,\frac{\partial\psi}{\partial x'}=0, w'=0, \theta=1, \varphi=1 \text{ at } y'=0 \\ \frac{\partial\psi}{\partial y'}\to 0, w'\to 0, \theta\to 0, \varphi\to 0 \quad \text{as } y'\to\infty \end{array}\right\} \tag{19}$$

Finding the similarity solution of the equations (15) to (18) is equivalent to determining the invariant solutions of these equations under a particular continuous one parameter group. Introducing the simplified form of Lie-group transformations [8] namely, the scaling group of transformations

$$G_1: x^*=x'e^{\varepsilon\alpha_1}, y^*=y'e^{\varepsilon\alpha_2}, \psi^*=\psi e^{\varepsilon\alpha_3}, w^*=w'e^{\varepsilon\alpha_4}, \theta^*=\theta e^{\varepsilon\alpha_5} \text{ and } \varphi^*=\varphi e^{\varepsilon\alpha_6} \tag{20}$$

Here, $\varepsilon(\neq 0)$ is the parameter of the group and $\alpha's$ are arbitrary real numbers whose interrelationship will be determined by our analysis. Equations (20) may be considered as a point transformation which transforms the coordinates $(x', y', \psi, w', \theta, \varphi)$ to the coordinates $(x^*, y^*, \psi^*, w^*, \theta^*, \varphi^*)$.

The system will remain invariant under the group transformation G_1, so the following relations among the exponents are obtained from equations (15) to (18),

$$\left.\begin{aligned}&\alpha_1+2\alpha_2-2\alpha_3=3\alpha_2-\alpha_3=-\alpha_4=\alpha_2-\alpha_3=-\alpha_5=-\alpha_6\\&\alpha_1+\alpha_2-\alpha_3-\alpha_4=2\alpha_2-\alpha_4=\alpha_2-\alpha_3=-\alpha_4\\&\alpha_1+\alpha_2-\alpha_3-\alpha_5=2\alpha_2-\alpha_5=2\alpha_2-2\alpha_5=4\alpha_2-2\alpha_3\\&\alpha_1+\alpha_2-\alpha_3-\alpha_6=2\alpha_2-\alpha_6=-n\,\alpha_6\end{aligned}\right\} \tag{21}$$

Again, the following relations are obtained from the boundary conditions (19),

$$\begin{aligned}&\alpha_2=\alpha_3\\&\alpha_5=\alpha_6=0\end{aligned} \tag{22}$$

Solving the system of linear equations (21) and (22), the following relationship are obtained,

$$\alpha_1=2\alpha_2=2\alpha_3,\ \alpha_4=\alpha_5=\alpha_6=0$$

by using the above relation the equation (20) reduces to the following group of transformation

$$x^*=x'e^{2\varepsilon\alpha_2},\ y^*=y'e^{\varepsilon\alpha_2},\psi^*=\psi e^{\varepsilon\alpha_2},w^*=w',\theta^*=\theta,\varphi^*=\varphi \tag{23}$$

expanding equation (23) by Taylor's method in powers of ε and keeping terms up to the order ε, we have

$$x^*-x'=2\varepsilon x'\alpha_2,\ y^*-y'=\varepsilon y'\alpha_2,\psi^*-\psi=\varepsilon\psi\alpha_2,w^*-w'=0,\theta^*-\theta=0,\varphi^*-\varphi=0$$

In terms of differentials

$$\frac{dx'}{2\alpha_2 x'}=\frac{dy'}{\alpha_2 y'}=\frac{d\psi}{\alpha_2\psi}=\frac{dw'}{0}=\frac{d\theta}{0}=\frac{d\varphi}{0} \tag{24}$$

Solving the equation (24) the following similarity variables are introduced,

$$\eta=\frac{y'}{\sqrt{x'}},\ \psi=\sqrt{x'}\,f(\eta),w'=g_0(\eta),\theta=\theta(\eta)\text{ and }\varphi=\varphi(\eta)$$

By using the above mentioned variables, equations (15), (16), (17) and (18) becomes

$$f'''+\frac{1}{2}ff''-Mf'^2+2R'g_0-\gamma f'+G_r\,\theta\cos\beta+G_m\,\varphi\cos\beta=0 \tag{25}$$

$$g_0''+\frac{1}{2}fg_0'-2R'f'-\gamma g_0-Mf'g_0=0 \tag{26}$$

$$\frac{1}{P_r}(1+T_c\,\theta+R)\theta''+\frac{1}{P_r}T_c\,\theta'^2+\frac{1}{2}f\theta'+Q\theta+E_c f''^2=0 \tag{27}$$

$$\frac{1}{S_c}\varphi''+\frac{1}{2}f\varphi'-\lambda\varphi^n=0 \tag{28}$$

The corresponding boundary conditions (19) become

$$\left.\begin{aligned}&f'=1,\ f=0,g_0=0,\theta=1,\varphi=1\text{ at }\eta=0\\&f'\to 0,g_0\to 0,\theta\to 0,\varphi\to 0\ \text{ as }\eta\to\infty\end{aligned}\right\} \tag{29}$$

where primes denote differentiation with respect to η only and the parameters are defined as

$M=\dfrac{\sigma_0 B_0^2}{\rho}$ is the magnetic parameter,

$\gamma = \frac{\upsilon^2 x'}{KU^2}$ is the porosity parameter

$R' = \frac{\Omega \upsilon x'}{U^2}$ is the rotational parameter

$G_r = \frac{g\beta_T (T_w - T_\infty)\upsilon x'}{U^3}$ is the Grashof number

$G_m = \frac{g\beta_c (C_w - C_\infty)\upsilon x'}{U^3}$ is the modified Grashof number

$T_c = c(T_w - T_\infty)$ is the thermal conductivity parameter

$P_r = \frac{\upsilon}{\alpha}$ is the Prandtl number

$R = \frac{16\sigma_s T_\infty^3}{3\kappa^* k_\infty}$ is the radiation parameter

$Q = \frac{Q_0 \upsilon}{\rho C_p U^2}$ is the heat source parameter

$E_c = \frac{U^2}{C_p (T_w - T_\infty)}$ is Eckert number

$S_c = \frac{\upsilon}{D_m}$ is the Schmidt number

$\lambda = \frac{k_0 (C_w - C_\infty)^{n-1} \upsilon}{U^2}$ is the reaction parameter

and *n* (integer) is the order of chemical reaction

2.2 SKIN-FRICTION COEFFICIENTS, NUSSELT AND SHERWOOD NUMBER

The physical quantities of the skin-friction coefficients, the reduced Nusselt number and reduced Sherwood number are calculated respectively by the following equations,

$$C_f (R_e)^{\frac{1}{2}} = -f''(0) \tag{30}$$

$$C_{g_0} (R_e)^{\frac{1}{2}} = -g_0'(0) \tag{31}$$

$$N_u (R_e)^{-\frac{1}{2}} = -\theta'(0) \tag{32}$$

$$S_h (R_e)^{-\frac{1}{2}} = -\varphi'(0) \tag{33}$$

where, $R_e = \frac{Ux'}{\upsilon}$ is the Reynolds number.

3. RESULTS AND DISCUSSION

Heat and mass transfer problem associated with laminar flow past an inclined plate of a rotating system are studied in this work. In order to investigated the physical representation of the problem, the numerical values of primary velocity, secondary velocity, temperature and species concentration from equations (25), (26), (27) and (28) with the boundary layer have been computed for different parameters as the magnetic parameter (M), the rotational parameter (R'), the porosity parameter (γ), the Grashof number (G_r), the modified Grashof number (G_m), the radiation parameter (R), the Prandtl number (P_r), the Eckert number (E_c), the thermal conductivity parameter (T_c), the heat source parameter (Q), the Schmidt number (S_c), the reaction parameter (λ), the inclination angle (β) and the order of chemical reaction (n) respectively.

Figs. 2a and 2b show that with the increases of magnetic parameter, primary velocity profiles decreases but secondary velocity profiles increases. Figs. 3a-3d represents that with the increase of rotational parameter, primary velocity decreases but secondary velocity, temperature and concentration profiles increases.

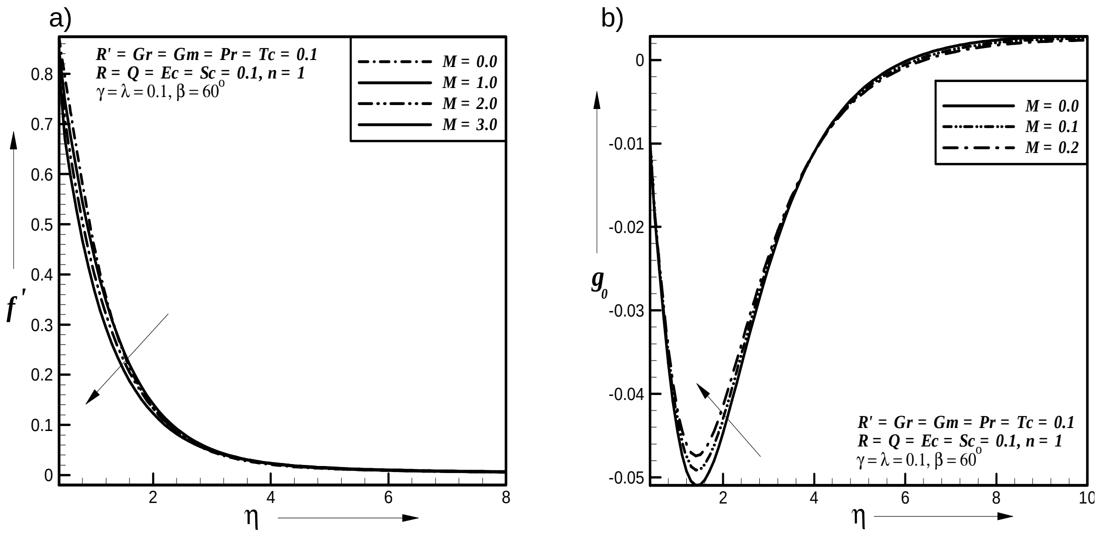
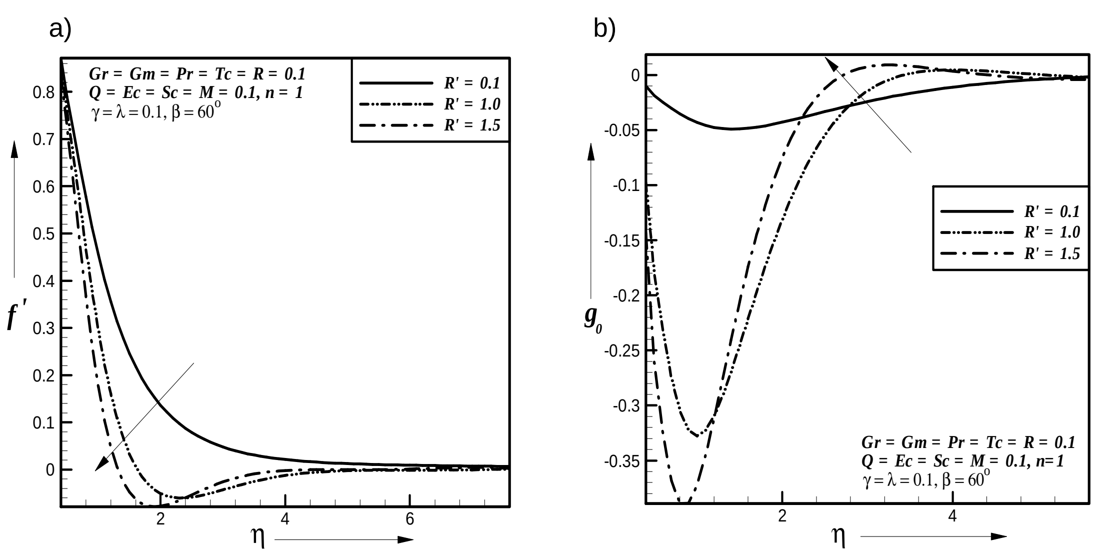


Fig. 2. Effect of magnetic parameter on a) primary velocity b) secondary velocity profiles



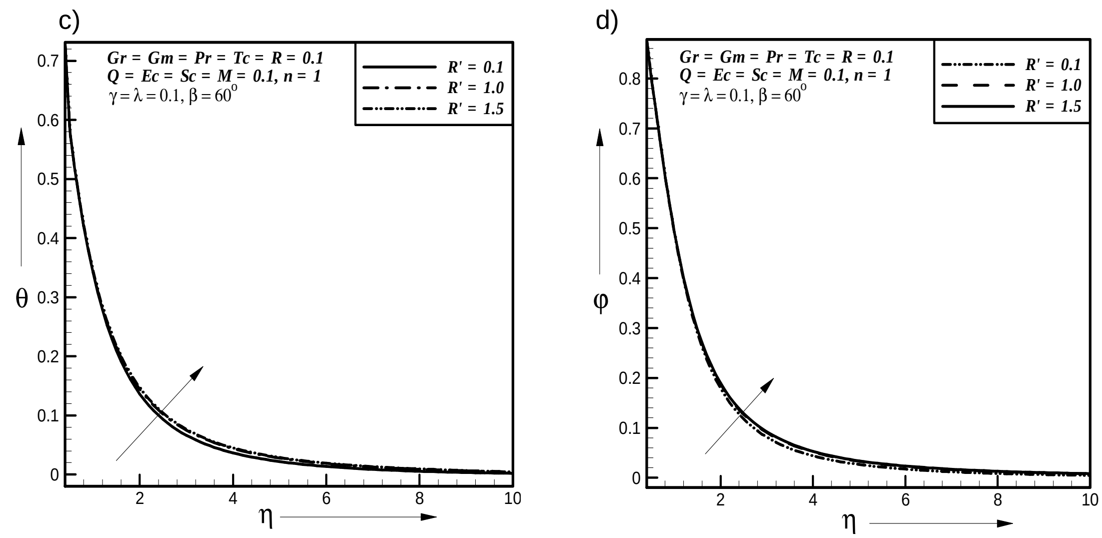
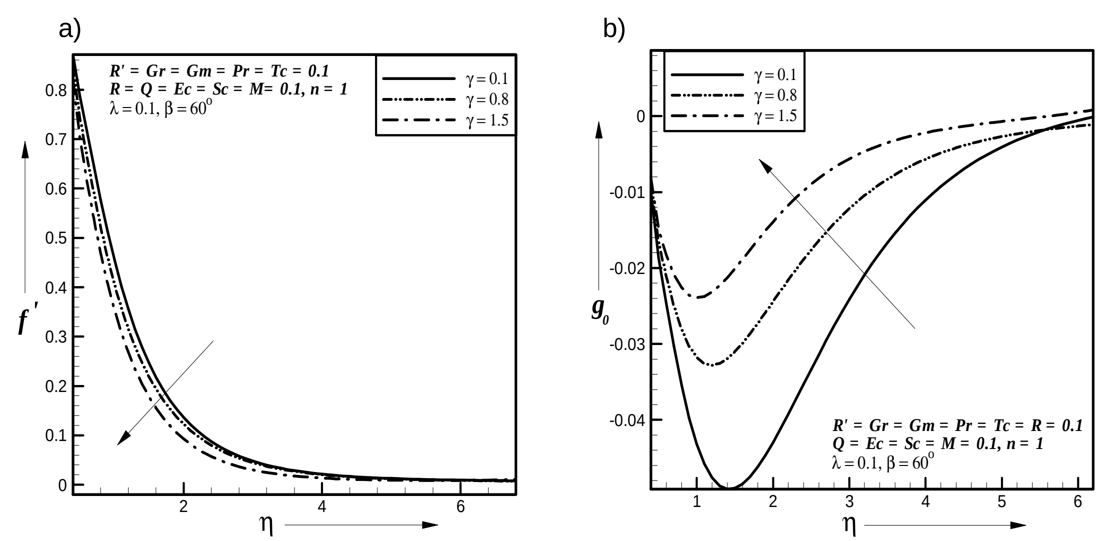


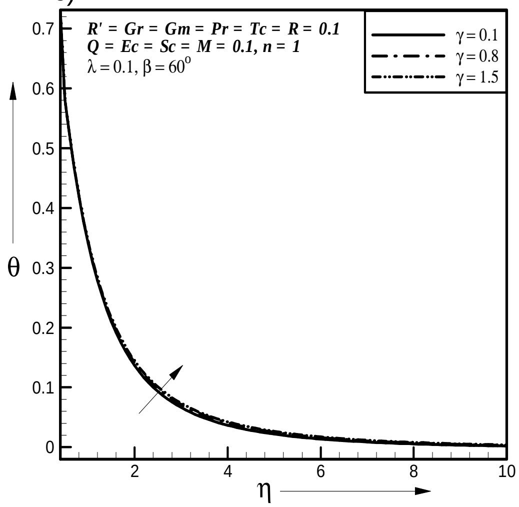
Fig. 3. Effect of rotational parameter on a) primary velocity b) secondary velocity c) temperature d) concentration profiles

In Figs. 4a-4d, primary velocity profiles decreases but the secondary velocity, temperature and concentration profiles increases with the increase of porosity parameter. With the increase of inclination angle, primary velocity profiles decreases but secondary velocity profiles increases(Figs. 5a and 5b).

In Figs. 6a-6c, we see that with the increase of Grashof number, primary velocity profiles increases but secondary velocity and temperature profiles decreases. Figs. 7a- 7c show that with the increase of modified Grashof number, primary velocity profiles increases but secondary velocity and concentration profiles decreases. With the increase of Prandtl number, primary velocity profiles increases but temperature decreases (Figs. 8a and 8b).



c)



d)

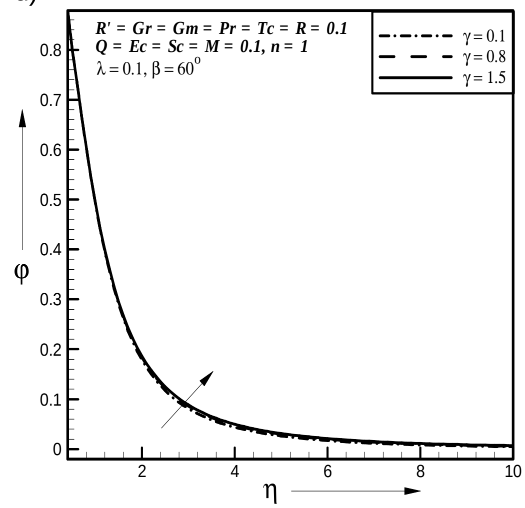
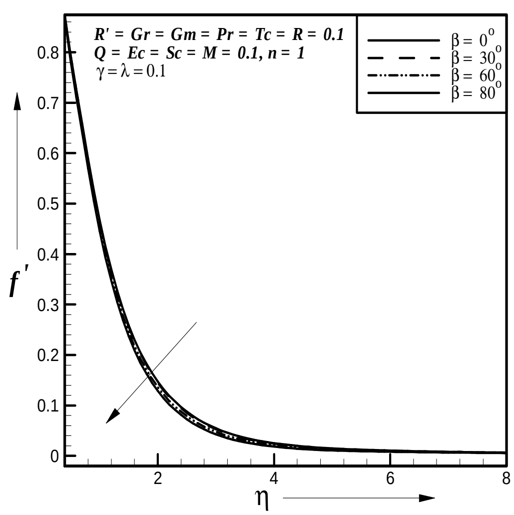


Fig. 4. Effect of porosity parameter on a) primary velocity b) secondary velocity c) temperature d) concentration profiles

a)



b)

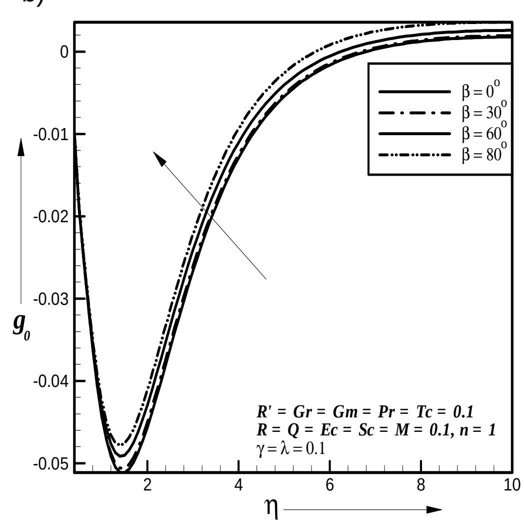
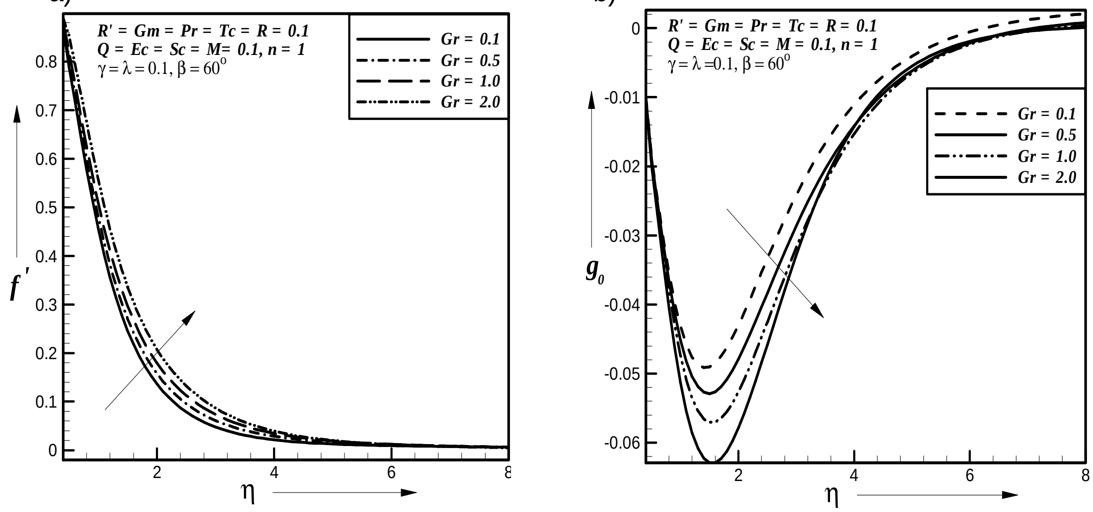


Fig. 5. Effect of inclination angle on a) primary velocity b) secondary velocity profiles

a) b)



c)

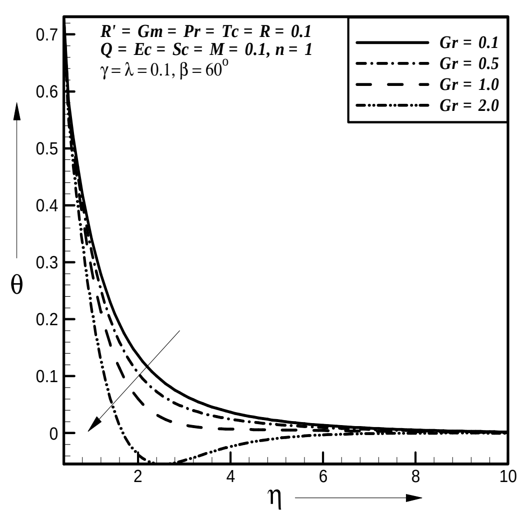


Fig. 6. Effect of Grashof number on a) primary velocity b) secondary velocity c) temperature profiles

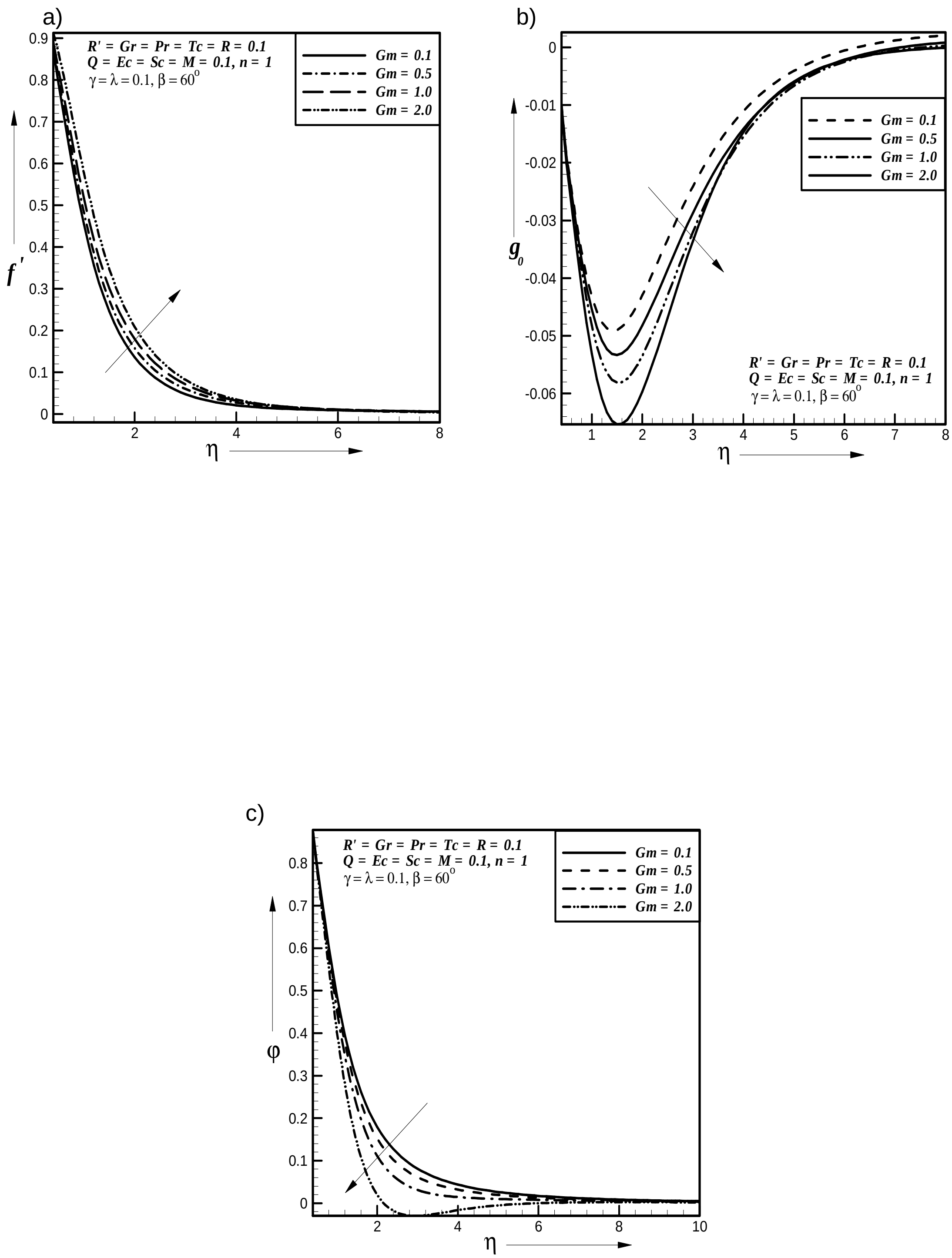


Fig. 7. Effect of modified Grashof number on a) primary velocity b) secondary velocity c) concentration profiles

Fig. 9a, It is observe that the primary velocity profile increases with the increase of Eckert number. In Fig. 9b, temperature profile increases with the increase of Thermal conductivity parameter.

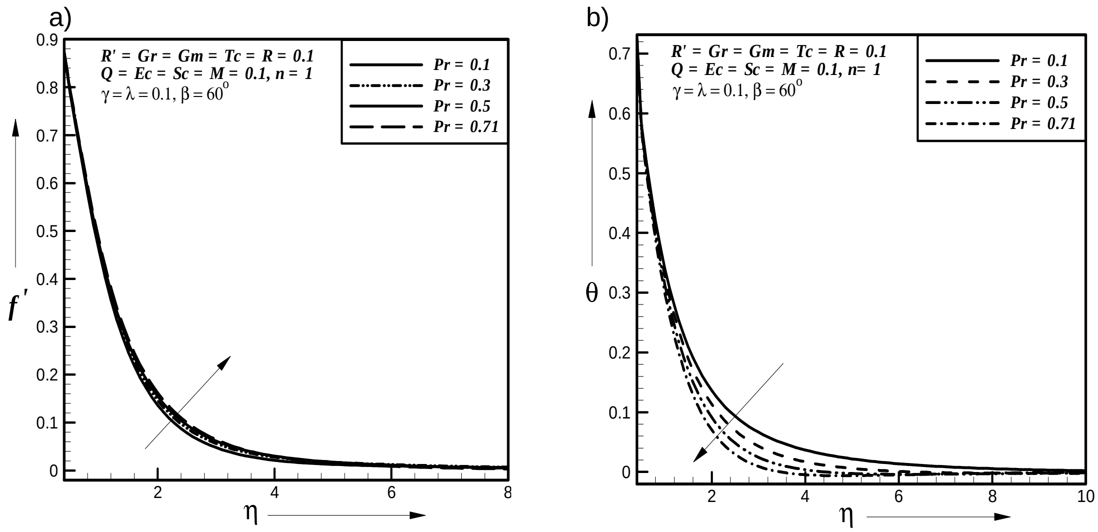


Fig. 8. Effect of Prandtl number on a) primary velocity b) temperature profiles

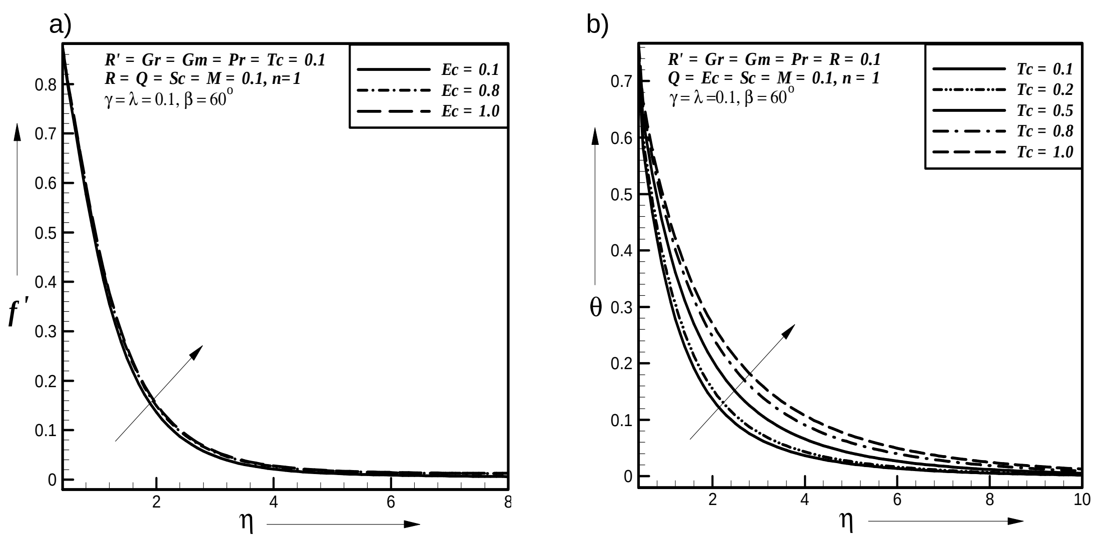


Fig. 9. Effect of a) Eckert number on primary velocity profiles b) thermal conductivity parameter on temperature profiles

In Fig. 10a, concentration profiles decreases with the increase of Schmidt number. Fig. 10b represents no reaction $(\lambda = 0.0)$ and destructive reaction $(\lambda > 0.0)$, where the concentration profiles decreases with the increase of reaction parameter.

a) b)

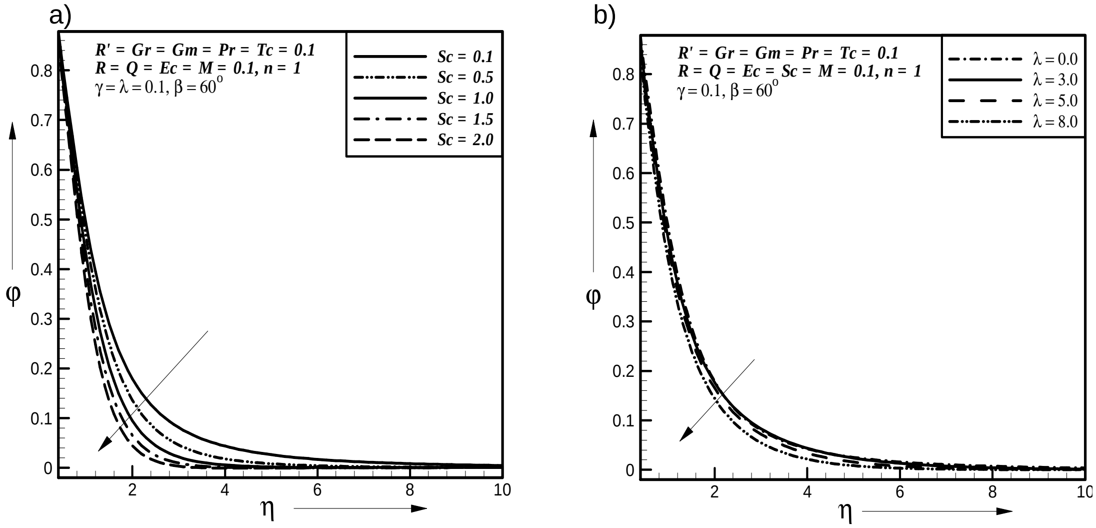


Fig. 10. Effect of a) Schmidt number on concentration profiles b) reaction parameter on concentration profiles

For the physical interest of the problem, the dimensionless skin-friction coefficient $(-f'')$ $(-g_0')$, the dimensionless heat transfer rate $(-\theta')$ and the dimensionless mass transfer rate $(-\varphi')$ at the plate are plotted against Heat source parameter (Q) and illustrated in Figs. 11-19.

In Figs. 11a-11b and 12a-12b, primary shear stress decreases but secondary shear stress increases with the increase of magnetic parameter and heat source parameter (Q) respectively.

a) b)

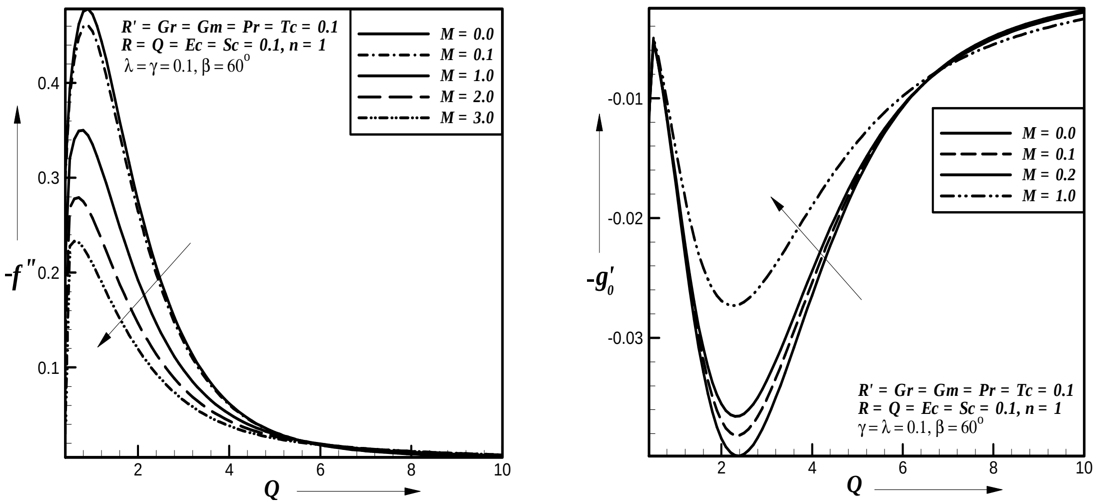


Fig. 11. Effect of magnetic parameter on a) primary shear stress b) secondary shear stress

a) b)

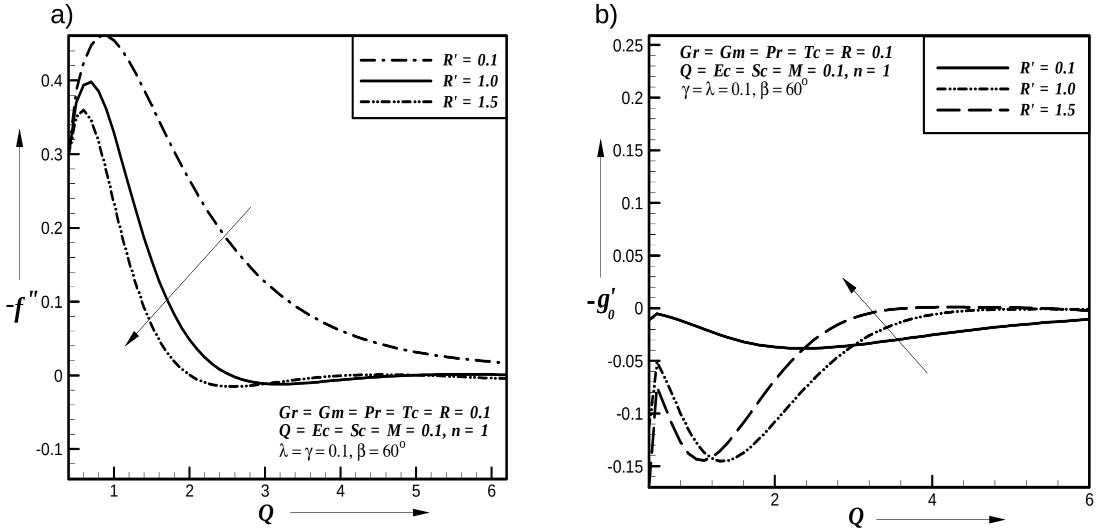


Fig. 12. Effect of rotational parameter on a) primary shear stress b) secondary shear stress

Figs. 13a and 13b represent that primary shear stress decreases but secondary shear stress increases with the increase of porosity parameter.

a) b)

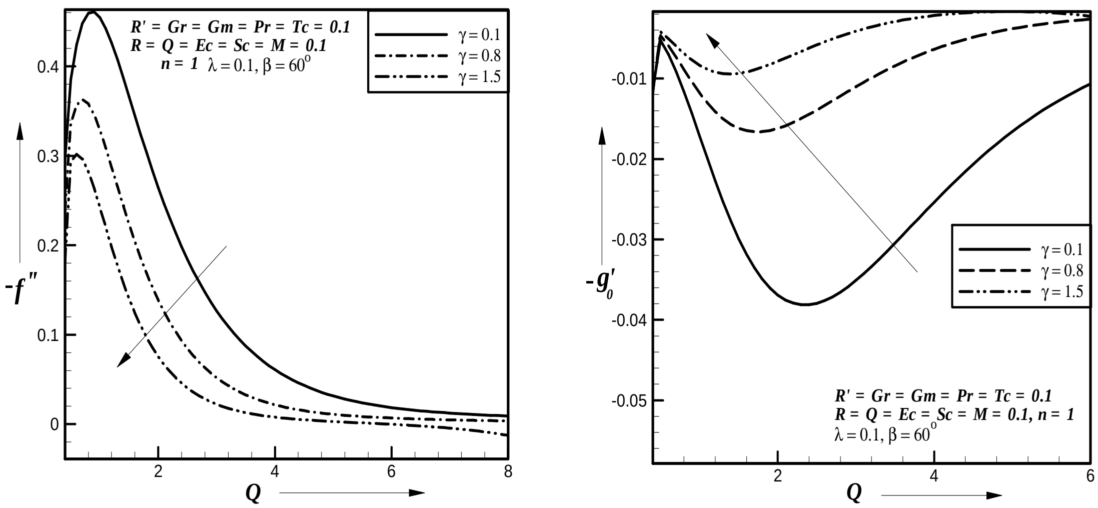


Fig. 13. Effect of porosity parameter on a) primary b) secondary shear stress

In Fig. 14a and Fig. 14b, primary shear stress increases with the increase of Grashof number and modified Grashof number respectively.

a) b)

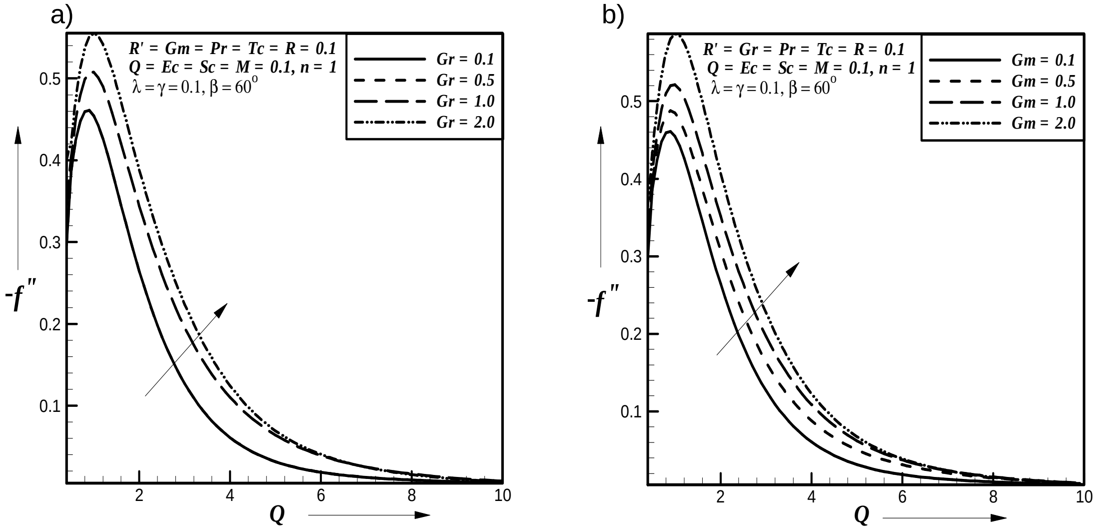


Fig. 14. Effect of a) Grashof number b) modified Grashof on primary shear stress

In Fig. 15a,primary shear stress decreases with the increase of inclination angle. In Fig. 15b, the heat transfer rate increases with the increase of thermal conductivity parameter. Fig. 16a, the heat transfer rate decreases with the increase of Prandtl number. Fig. 16b, the heat transfer rate increases with the increase of heat source parameter.

a) b)

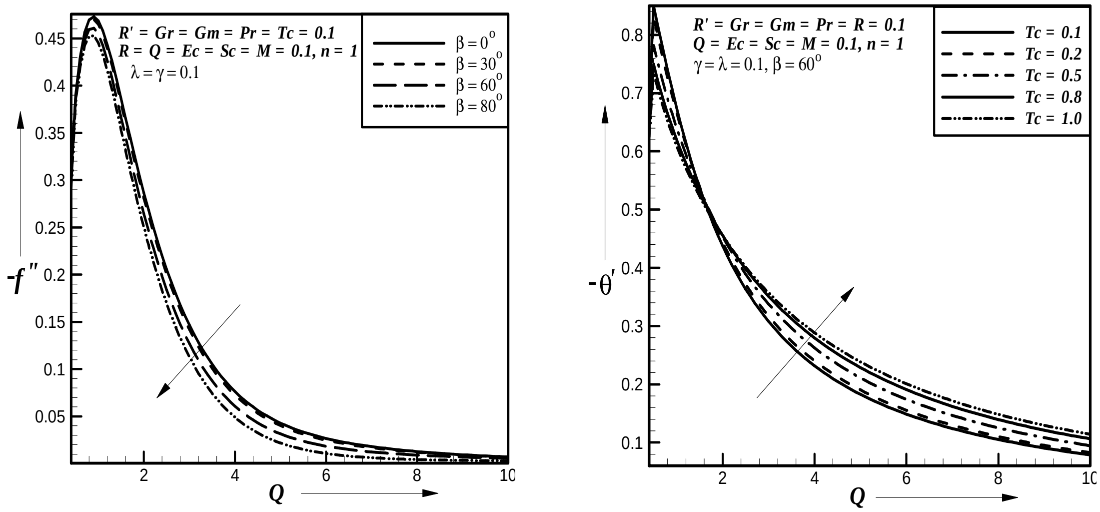


Fig. 15. Effect of a) inclination angle on primary shear stress b) thermal conductivity parameter on heat transfer rate

a) b)

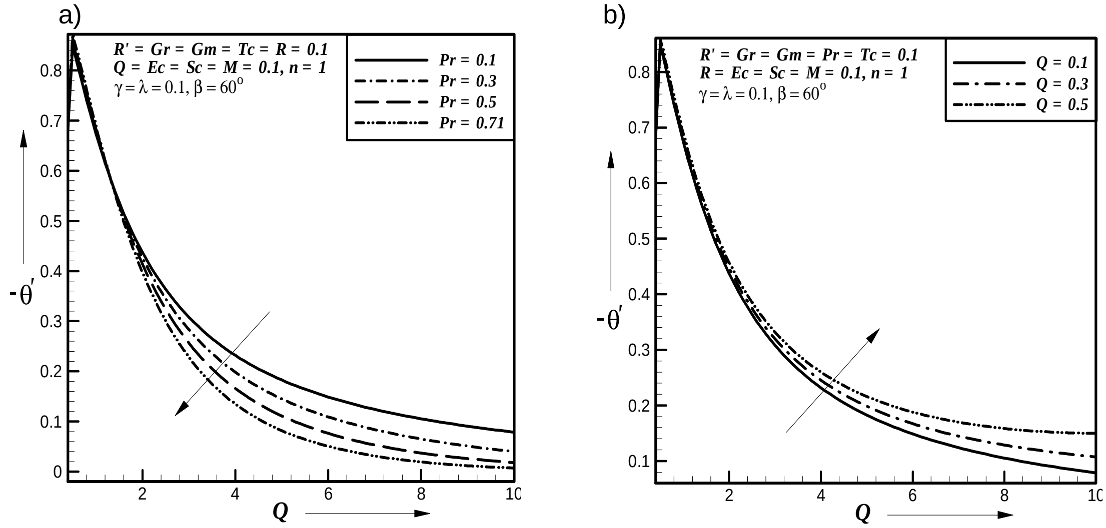


Fig. 16. Effect of a) Prandtl number b) heat source parameter on heat transfer rate

In Fig. 17a -17b, the heat transfer rate increases with the increase of Eckert number and radiation parameter. Fig. 18a -Fig. 18b, the mass transfer rate decreases with the increase of Schmidt number and reaction parameter. Fig. 19 represents that the mass transfer rate increases with the increase of order of chemical reaction parameter.

a) b)

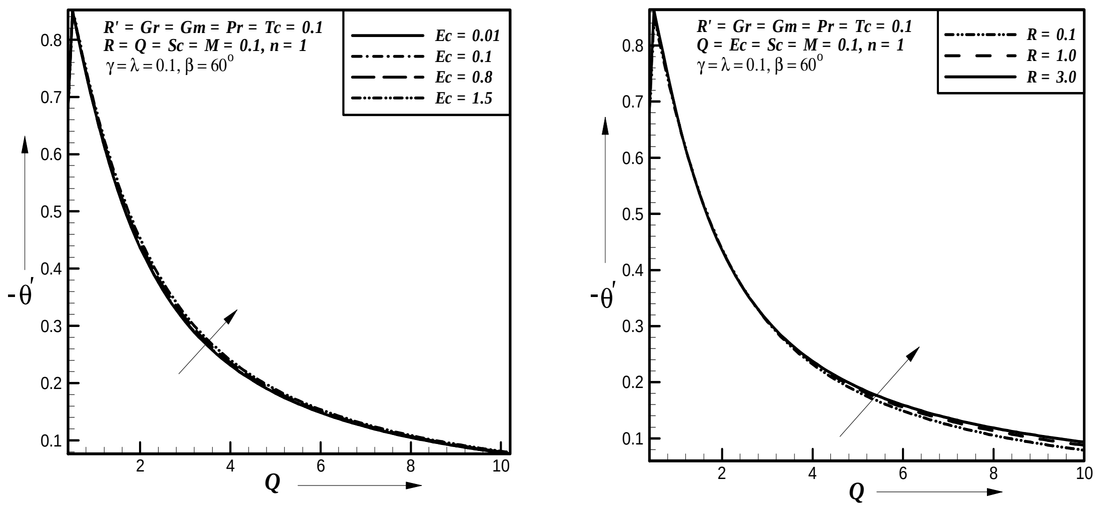


Fig. 17. Effect of a) Eckert number b) radiation parameter on heat transfer rate

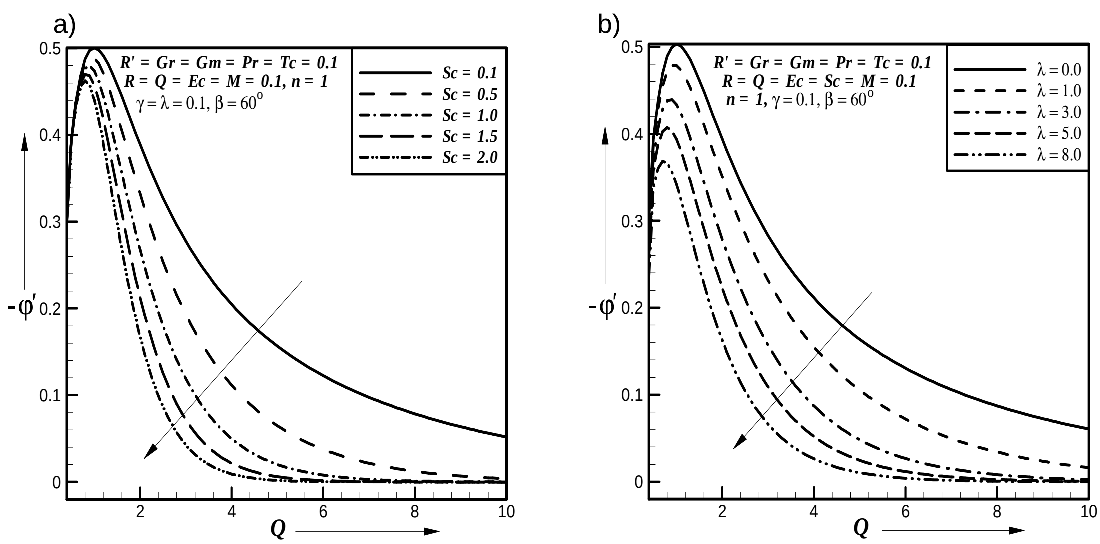


Fig. 18. Effect of a) Schmidt number b) reaction parameter on mass transfer rate

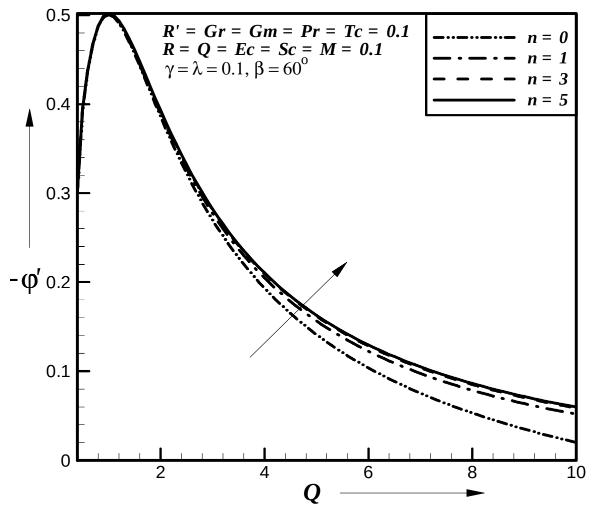


Fig. 19. Effect of order of chemical reaction on mass transfer rate

4. CONCLUSION

Primary velocity profiles decreases and primary shear stress with the increase of magnetic parameter, rotational parameter, but reverse effect is found for the secondary velocity profiles and secondary shear stress. Primary shear stress decreases due to increase of magnetic parameter where as the reverse effect is found for secondary shear stress.

Temperature and concentration boundary layer thickness increases due to increase of rotational parameter.

The primary velocity profiles and primary shear stress decreases due to increase of permeability of the porous medium and inclination angle but reverse effect is found for the secondary velocity profiles and secondary shear stress. Temperature and concentration boundary layer thickness are increases due to increase of permeability of the porous medium.

The primary velocity profiles and primary shear stress increases due to increase of Grashof number where as the reverse effect is found for the secondary velocity profiles. Also the temperature boundary layer thickness is decreases due to increase of Grashof number.

The primary velocity profiles and primary shear stress increases due to increase of modified Grashof number where as the reverse effect is found for the secondary velocity profiles. Also the concentration boundary layer thickness decreases due to increase of modified Grashof number.

The primary velocity profiles increases due to increase of Prandtl number. The thermal boundary layer thickness as well as the heat transfer rate at the plate decreases as the Prandtl number increases.

The heat transfer rate at the plate as well as the primary velocity is increases due to increase of Eckert number and thermal conductivity parameter.

The heat transfer rate at the plate increases due to increase of heat source parameter and radiation parameter.

The concentration boundary layer thickness as well as the mass transfer rate at the plate decreases due to increase of Schmidt number, no reaction and destructive reaction.

The mass transfer rate at the plate increases due to increase of order of chemical reaction.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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