THE INTERNATIONAL JOURNAL OF SCIENCE & TECHNOLEDGE

Thermal Diffusion Effect on MHD Heat and Mass Transfer Flow Past a Semi Infinite Moving Vertical Porous Plate with Heat Generation and Chemical Reaction

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Abstract:
The objective of present chapter is to study the thermo diffusion effect on an unsteady simultaneous convective heat and mass transfer flow of an incompressible, electrically conducting, heat generating/absorbing fluid along a semi-infinite moving porous plate embedded in a porous medium with the presence of pressure gradient, thermal radiation field and chemical reaction. It is assumed that the permeable plate is embedded in a uniform porous medium and moves with a constant velocity in the flow direction in the presence of a transverse magnetic field. It is also assumed that the free stream to consist of a mean velocity, temperature and concentration over which are super imposed an exponentially varying with time the equations of continuity, momentum, energy and diffusion, which govern the flow field, are solved by using a regular perturbation method. The behavior of the velocity, temperature, concentration, Skin-friction, rate of heat transfer and rate of mass transfer has been discussed for variations in the physical parameters.

Keywords: *Heat generation/absorption, Chemical reaction, MHD, Thermal radiation, Thermal diffusion, heat and mass transfer, semi-infinite vertical plate.*

1. Introduction

The study of magneto hydrodynamic flows through porous media is of considerable interest because of its abundant applications in several branches of science and technology; such as in astrophysical, geo-physical problem and in developing magnetic generator for obtaining electrical energy at minimum cost. The theory developed by viscous flow through porous media is useful in analyzing the influence of temperature and pressure on the flow of soil water. The unsteady free convection flows over semi-infinite vertical plate have been studied by Takhar *et al.* (1997). Thakar and Ram (1994) also studies the MHD free porous convection heat transfer of water at 40^0C through a porous medium. Raju and Varma (2011) considered the unsteady MHD free convection oscillatory couette flow through a porous medium with periodic wall temperature.

In the context of space technology in process involving high temperatures, the effects of radiation are of vital importance. Recent developments in hypersonic flights, missile recently, rocket combustion chambers, power plants for inter planetary flight and gas cooled nuclear reactors, have focused attention on thermal radiation as a mode of energy transfer, and emphasize the need for improved understanding of radiative transfer in these process. Several authors (Raju *et al.*, 2012; Nath *et al.*, 1991; Raptis and Perdikis, 1999; Bakier, 2001; Kim, 2000; Chamkha *et al.*, 2001) have studied thermal radiating MHD boundary layer flows with applications in astrophysical fluid dynamics. Combined the heat and mass transfer problems with chemical reaction are of importance in many processors and have therefore received a considerable amount of attention in recent years. Das *et al.* (1994) have studied the effect of homogeneous first order chemical reaction on the flow past an impulsively started infinite vertical plate with uniform heat flux. Unsteady MHD free convection and chemically reactive flow past an infinite vertical porous plate was studied by Raju *et al.* (2013). Chamka (2000) studied the MHD flow past a uniformly stretched vertical permeable surface presence of heat generation/absorption. The Soret effect for instance has been utilized by isotope separation, and in mixture between gasses with very light molecular weight (H_2, He). Raju *et al.* (2008) analyzed the Soret effects due to natural convection between heated inclined plates with magnetic field. Recently Ablel-Rahman (2008) studied the thermal diffusion effect on MHD combined free forced convection and mass transfer flow of a viscous fluid flow through a porous medium with heat generation. Thermo diffusion and chemical effects with simultaneous thermal and mass diffusion in MHD mixed convection flow with ohmic heating was considered by Reddy *et al.* (2009).

Motivated by the above studies, in this paper we have considered thermo diffusion effect on an unsteady simultaneous convective heat and mass transfer flow of an incompressible, electrically conducting, heat generating/absorbing fluid along a semi-infinite moving porous plate embedded in a porous medium with the presence of pressure gradient, thermal radiation field and chemical reaction.

2. Mathematical Analysis

Consider a two- dimensional unsteady flow of a laminar incompressible electrically conducting and heat generating/absorbing fluid with mass transfer, past a semi-infinite vertical porous medium in the presence of thermal radiation, chemical reaction and thermal diffusion. A uniform magnetic field is applied perpendicular to the plate. There is no applied voltage which implies the absence of the electric field. The transversely applied magnetic field and magnetic Reynolds number are assumed to be small and hence the induced magnetic field is negligible. Since the plate semi-infinite in length all the flow variables are functions of y and t only. Under the above conditions and the usual Boussinesq's approximation the governing equations are given as

$$\frac{\partial v^*}{\partial y^*} = 0 \tag{1}$$

$$\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + v\frac{\partial^2 u^*}{\partial y^{*2}}$$

$$+ g\beta(T - T_\alpha) + g\beta^*(C - C_\infty) - \frac{v}{k^*}u - \frac{\sigma}{\rho}\beta_0^2 u^* \tag{2}$$

$$\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T}{\partial y^*} = \alpha\left(\frac{\partial^2 T}{\partial y^{*2}} - \frac{1}{k}\frac{\partial q_r}{\partial y^*}\right) + Q(T - T_\infty) \tag{3}$$

$$\frac{\partial C^*}{\partial t^*} + v^* \frac{\partial C^*}{\partial y^*} = D\left(\frac{\partial^2 C^*}{\partial y^{*2}}\right)$$

$$+ D_1 \frac{\partial^2 T}{\partial y^{*2}} - K_1(C - C_\infty) \tag{4}$$

By using the Roseland approximation (Brewster [24]) the radiative heat flux in y direction is given by

$$q_r = -\frac{4}{3}\frac{\sigma_s}{k_e}\frac{\partial T^4}{\partial y^*} \tag{5}$$

Where and 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 is limited to optically thick fluids. If we assume that the temperature differences with in the flow sufficiently small, then Eq. (5) can be linearized by expanding into Taylor series about T, and neglecting higher order terms to give:

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \tag{6}$$

The heating due to viscous dissipation is neglected for small velocities in energy conservation Eq. (3) and Boussinesq approximation is used to describe buoyancy force in Eq. (2). It is assumed that the free stream velocity, the suction velocity and the plate temperature follow an exponentially increasing or decreasing small perturbation law.

Under these assumptions, the appropriate boundary conditions for the velocity, temperature and concentration fields are

$$u^* = u_p^*,\ T = T_w + \varepsilon(T_w - T_\infty)e^{n^* t^*},$$

$$C = C_w + \varepsilon(C_w - C_\infty)e^{n^* t^*} \qquad at \qquad y^* = 0$$

$$u^* \to U_\infty^* = U_0\left(1 + \varepsilon A e^{n^* t^*}\right),$$

$$T \to T_\infty,\ \ C \to C_\infty \qquad s \qquad y^* \to \infty \tag{7}$$

From the continuity equation it is clear that the suction velocity normal to the plate is a function of time only and we shall take it in the form

$$v^* = -V_0\left(1 + \varepsilon A e^{nt}\right) \tag{8}$$

Where A is a real positive constant, ε and εA are small less than unity, and V0 is scale of suction velocity which has non-zero positive constant. Outside the boundary layer, Eq. (2) gives

$$-\frac{1}{\rho}\frac{\partial p}{\partial x} = \frac{dU_\infty}{dt} + \frac{v}{k}U_\infty + \frac{\sigma}{\rho}B_0^2 U_\infty \tag{9}$$

Now introduce non-dimensional parameters as follows

$$u = \frac{u^*}{U_0}, v = \frac{v^*}{V_0}, U_\infty = \frac{U_\infty^*}{U_0}, y = \frac{V_0 y^*}{\nu}, U_p = \frac{u_p^*}{U_0},$$

$$t = \frac{V_0^2 t^*}{\nu}, \theta = \frac{T - T_\infty}{T_w - T_\infty}, C = \frac{C - C_\infty}{C_w - C_\infty}, \quad Sc = \frac{\upsilon}{D},$$

$$\Pr = \frac{\rho \upsilon C_p}{k} = \frac{\upsilon}{\alpha}, Gr = \frac{\upsilon \beta g (T_w - T_\infty)}{U_0 V_0^2}, \quad Kr = \frac{K_1 \upsilon}{V_0^2},$$

$$Gm = \frac{\upsilon \beta^* g (C_w - C_\infty)}{U_0 V_0^2}, \delta = \frac{Q\upsilon}{V_0^2}, R = \frac{k k_e}{4\sigma_s T_\infty^3}, \quad So = \frac{D_1 (T_w - T_\infty)}{\upsilon (C_w - C_\infty)}, M = \frac{\sigma B_0^2}{\rho V_0^2} \tag{10}$$

After substituting boundary conditions and dimensionless parameters, the governing Eqs. (2)-(5) are reduce to

$$\frac{\partial u}{\partial t} - \left(1 + \varepsilon A e^{nt}\right)\frac{\partial u}{\partial y} = \frac{dU_\infty}{dt} + \frac{\partial^2 u}{\partial y^2} + G_r \theta + G_m C + N\left(U_\infty - U\right) \tag{11}$$

$$\frac{\partial \theta}{\partial t} - \left(1 + \varepsilon A e^{nt}\right)\frac{\partial \theta}{\partial y} = \frac{1}{\Gamma}\frac{\partial^2 \theta}{\partial y^2} + \delta\theta \tag{12}$$

$$\frac{\partial C}{\partial t} - \left(1 + \varepsilon A e^{nt}\right)\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} + So\frac{\partial^2 \theta}{\partial y^2} - K_r C \tag{13}$$

Where N=M+1/K and Γ= (1-4/(3R+4))

The boundary conditions (7) are given by the following non-dimensional form

$$u = U_p, \theta = 1 + \varepsilon e^{nt}, C = 1 + \varepsilon e^{nt} \ at \ y = 0$$
$$u \to U_\infty, \theta \to 0, C \to 0 \qquad as \ y \to \infty \tag{14}$$

3. Solution of the Problem

In order to reduce the above system of partial differential equations to a system of ordinary differential equations in dimensionless form, we may represent the velocity, temperature and concentration as

$$u = U_o(y) + \varepsilon e^{nt} U_1(y) + O\left(\varepsilon^2\right) + ---- \tag{15}$$

$$\theta = \theta_o(y) + \varepsilon e^{nt} \theta_1(y) + O\left(\varepsilon^2\right) + ---- \tag{16}$$

$$C = C_o(y) + \varepsilon e^{nt} C_1(y) + O\left(\varepsilon^2\right) + ---- \tag{17}$$

Substituting these Equations (15) – (17) into Equations (11) – (13) and equating the harmonic and non-harmonic terms, also neglecting the coefficient of O (ε^2), we get the following pairs of equations.

$$u_0'' + u_0' - N u_0 = -N - G_r \theta_0 - G_m C_0 \tag{18}$$

$$u_1'' + u_1' - (N + n) u_1 = -(N + n) - A u_0^1 - G_r \theta_1 - G_m C_1 \tag{19}$$

$$\theta_o'' + \Gamma \theta_0' + \Gamma \delta \theta_0 = 0 \tag{20}$$

$$\theta_1'' + \Gamma \theta_1' + \Gamma(\delta - n)\theta_1 = -A\Gamma\theta_0' \tag{21}$$

$$C_0'' + ScC_0' - KrScC_0 = -SoSc\theta_0'' \tag{22}$$

$$C_1'' + ScC_1' - (Kr + n)ScC_1 = -SoSc\theta_1'' - AScC_0' \tag{23}$$

Here primes denote differentiate with respect to y.

The corresponding boundary conditions are

$$u_0 = U_p, u_1 = 0, \theta_0 = 1, \theta_1 = 1, C_0 = 1, C_1 = 1 \ at \ y = 0 \ u_0 = 1, u_1 = 1, \theta_0 \to 0, \theta_1 \to 0, C_0 \to 0, C_1 \to 0 \ as \ y \to \infty \tag{24}$$

The solutions of Eqs. (18 – 23) with satisfying boundary conditions (24) are given by

$$u_o(y) = 1 + (A_{10}e^{-b_5 y} + A_{11}e^{-b_1 y} + A_{12}e^{-b_3 y}) \tag{25}$$

$$u_1(y) = 1 + A_{13}e^{-b_6 y} + A_{14}e^{-b_1 y} + A_{15}e^{-b2y}$$
$$+A_{16}e^{-b3y} + A_{17}e^{-b4y} + A_{18}e^{-b5y} \tag{26}$$

$$\theta_0(y) = e^{-b_1 y} \tag{27}$$

$$\theta_1(y) = A_2 e^{-b_2 y} + A_3 e^{-b_1 y} \tag{28}$$

$$C_0(y) = A_4 e^{-b3y} + A_5 e^{-b_1 y} \tag{29}$$

$$C_1(y) = A_6 e^{-b4y} + A_7 e^{-b_1 y} + A_8 e^{-b2y} + A_9 e^{-b3y} \tag{30}$$

By virtue of equations (15-17) we obtain for the velocity, temperature and concentration as follows

$$u(y,t) = (1 + A_{10}e^{-b_5 y} + A_{11}e^{-b_1 y} + A_{12}e^{-b_3 y})$$
$$+\varepsilon e^{nt}(1 + A_{13}e^{-b_6 y} + A_{14}e^{-b_1 y} + A_{15}e^{-b2y}\ A_{16}e^{-b3y} + A_{17}e^{-b4y} + A_{18}e^{-b5y}) \tag{31}$$

$$\theta(y,t) = e^{-b_1 y} + \varepsilon e^{nt}(A_2 e^{-b_2 y} + A_3 e^{-b_1 y}) \tag{32}$$

$$C(y,t) = A_4 e^{-b3y} + A_5 e^{-b_1 y} + \varepsilon e^{nt}$$
$$(A_6 e^{-b4y} + A_7 e^{-b_1 y} + A_8 e^{-b2y} + A_9 e^{-b3y}) \tag{33}$$

Given the velocity field in the boundary layer, we can now calculate the skin friction at the wall of the plate is given by

$$\tau_w = \tau_w^* / \rho u_0 v_0 = \left.\frac{\partial u}{\partial y}\right|_{y=0} = (b_5 A_{10}$$
$$-A_{11}b_1 - A_{12}b_3) + \varepsilon e^{nt}(-A_{13}b_6 - A_{14}b_1$$
$$-A_{15}b_2 - A_{16}b_3 - A_{17}b_4 - A_{18}b_5) \tag{34}$$

We calculate the heat transfer coefficient in terms of Nusselt number as follows

$$N_u = x\frac{\partial T/\partial Y^*|w}{T_w - T_\infty} = N_u \operatorname{Re}_x^{-1} = \left.\frac{\partial \theta}{\partial y}\right|_{y=0}$$
$$= -b_1 + \varepsilon e^{nt}\left[-A_2 b_2 - A_3 b_1\right] \tag{35}$$

Where $\mathrm{Re}_x = \mathrm{Vox}/\upsilon$ is the Reynolds number

Similarly, the mass transfer coefficient in terms of Sherwood number, as follows

$$S_h = x\frac{\partial c/\partial y|w}{C_w - C_\infty} = S_h \operatorname{Re}_x^{-1} = \left.\frac{\partial c}{\partial y}\right|_{y=0}$$
$$= (-A_4 b_3 - A_5 b_1) + \varepsilon e^{nt}(-b_4 A_6 - b_1 A_7$$
$$-b_2 A_8 - b_3 A_9) \tag{36}$$

4. Results and Discussion

In order to assess the accuracy of the numerical results, we have compared our results with accepted data sets for the velocity, temperature and concentration profiles for a stationary vertical porous plate corresponding to the case computed by Y.J. Kim. i.e., in the absence of the diffusion effects we observed that the effects of all parameters on velocity and temperature profiles are in good agreement with the comparison of Y.J. Kim (2001).

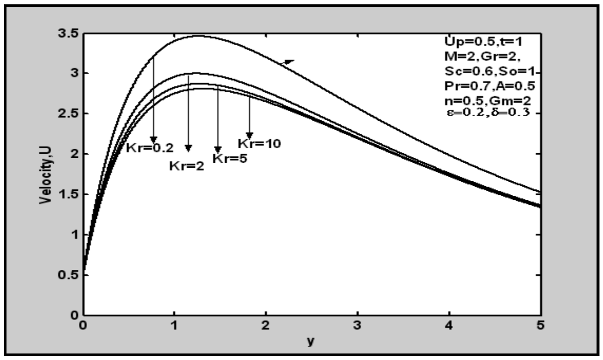

Figure 1: Effect of Kr on velocity

Fig.1 illustrates the behavior of the velocity for different values of chemical reaction parameter Kr. It is seen that the velocity decreases with the increasing chemical reaction parameter Kr. For large value of chemical reaction parameter as its effect on velocity is negligible as y increases. Fig.2 shows that the velocity profiles for the different values of Magnetic Parameter M.

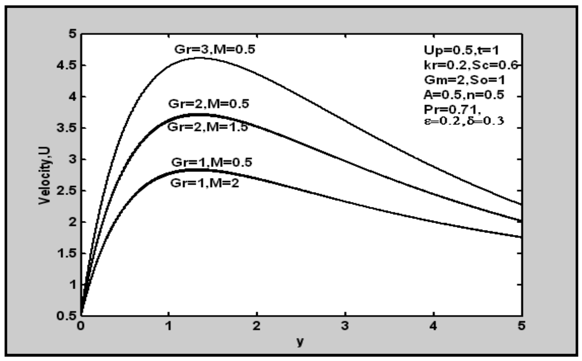

Figure 2: Effect of M on Velocity

It is noticed that the velocity decreases slightly with the increase of magnetic parameter M slightly at Gr and Gm are fixed. But when the value of Gr changes the effect of Magnetic parameter on velocity has been observed specifically. The effect of the porosity parameter K on the velocity profiles has been shown in Fig.3. It is observed that the velocity increases as porosity parameter increases in the fluid region on the other hand its effect on velocity is almost negligible. For different values of prandtl number Pr and radiation parameter R, the temperature profiles are plotted in Fig.4 The results show that an increase of both prandtl number Pr and radiation parameter R results in a decreasing the thermal boundary layer thickness and more uniform temperature distribution across the boundary layer. Fig.5 displays the effects of heat generation and exponential index n on temperature profiles across the boundary layer. It was found that an increase in the value of n leads to an increase in the velocity distribution across the boundary layer. Also it is observed that the effect of increasing values of δ results in a decreasing temperature distribution. Fig.6 depicts the effect of Schmidt number Sc and chemical reaction parameter Kr on concentration profiles. The concentration decreases as the chemical reaction parameter Kr increases. Also the figure shows that an increase in Sc results in a decreasing the concentration distribution, because the smaller values of Sc are equivalent to increasing the chemical molecular diffusivity. The influence of soret effect So and heat generation parameter δ on the concentration profiles are shown in Fig.7.

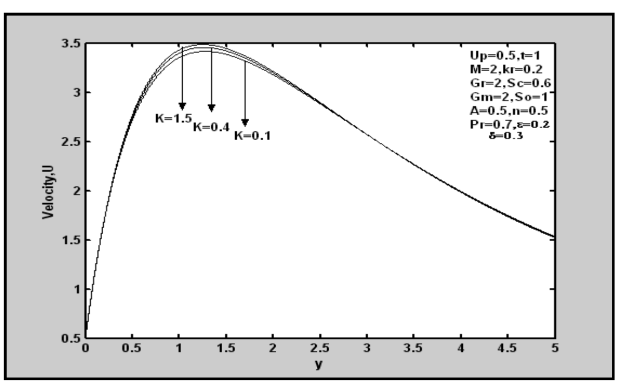

Figure 3: Effect of K on Velocity

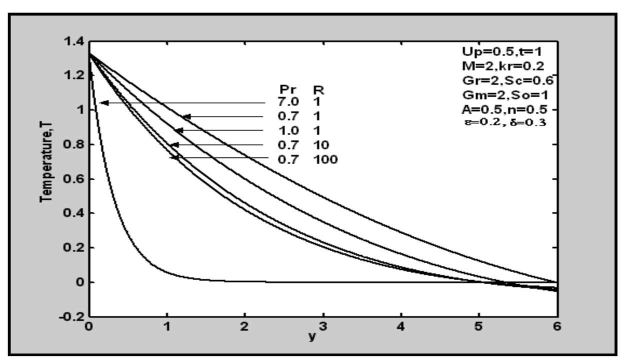

Figure 4: Effect of Pr and R on Temperature

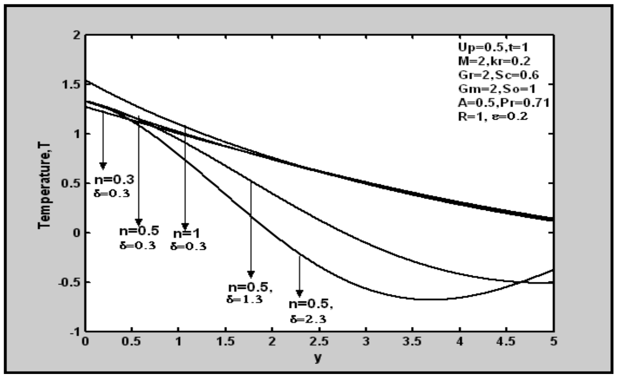

Figure 5: Effect of δ and n on Temperature

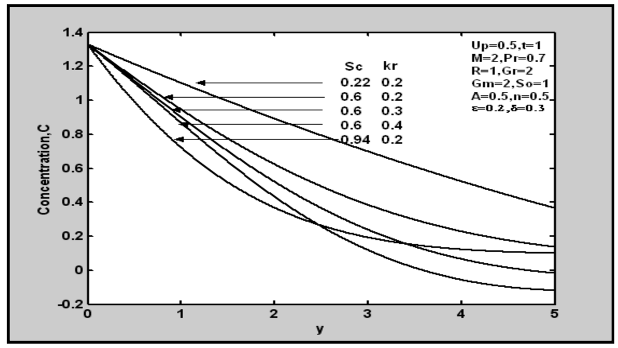

Figure 6: Effect of Sc and Kr on Concentratio

From this figure we see that the concentration increases with the increase of both soret number So and heat generation parameter. We have also shown some tables of the skin-friction, rate of heat transfer and rate of mass transfer by the effects of the Gr, Gm, K, M, Pr, Sc, R, Kr, δ and So. From the tables it is noticed that the skin-friction at the wall increases as Grashoff number Gr or modified Grashoff number Gm or Magnetic parameter M or Soret number So or heat generation/absorption parameter δ increases. And it decreases with increasing Prandtl number Pr or Schmidt number Sc or Radiation parameter R or Chemical reaction parameter Kr or permeability parameter K. From the analytical results, it can be seen that the rate of heat transfer depends on Radiation parameter R, Prandtl number Pr and heat generation/absorption parameter δ and the rate of mass transfer depends on Chemical reaction parameter Kr, Schmidt number Sc and Soret number So.

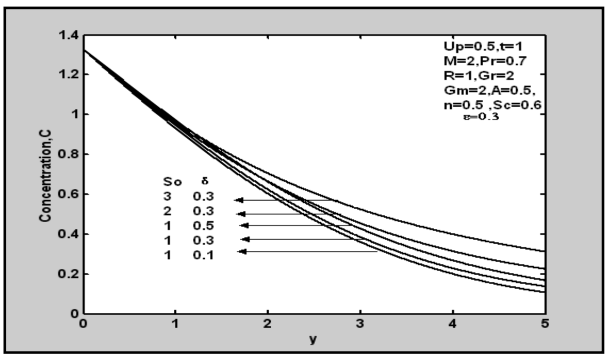

Figure 7: Effect of So and δ on Concentration

The mentioned tables reveal that as Schmidt number or chemical reaction parameter increases, the rate of mass transfer (Sh) increases but it decreases with the increase of Prandtl number Pr or Soret number So or Radiation parameter R. Also we observe that the rate of heat transfer (Nu) increases with the increase of Prandtl number or Radiation parameter but it decreases with decreasing heat generation parameter.

R	δ	Pr	S_f	Nu	S_h
1	0.1	0.71	4.4530	0.0804	0.3438
1	0.1	1	4.2160	0.1392	0.3281
1	0.1	5	3.3527	0.9944	0.0766
1	0.2	0.71	4.4780	0.0708	0.3462
1	0.3	0.71	4.5065	0.0602	0.3489
10	0.1	0.71	3.9634	0.2354	0.3010
100	0.1	0.71	3.8931	0.2719	0.2905

Table 1: Effect of R, δ and Pr on skin-friction, Nusselt number and Sherwood number

So	Sc	Kr	S_f	S_h
0.5	0.6	0.2	4.4530	0.3438
1	0.6	0.2	4.5413	0.3277
1.5	0.6	0.2	4.6296	0.3116
1	0.94	0.2	4.2269	0.5111
1	1.17	0.2	4.1269	0.6233
1	0.6	0.4	4.3389	0.4427
1	0.6	0.8	4.2059	0.5850

Table 2: Effect of So, Sc, Kr on skin-friction and rate of mass transfer

Gr	Gm	K	M	Sf
2	2	0.2	0.5	7.3024
5	2	0.2	0.5	12.4800
10	2	0.2	0.5	21.1093
2	5	0.2	0.5	10.6732
2	10	0.2	0.5	16.2912
2	2	1	0.5	4.3351
2	2	2	0.5	4.3269
2	2	0.2	1	4.3404
2	2	0.2	2	4.3291

Table 3: Effects of Gr, Gm, K and M on skin-friction

5. Conclusion

i. An increase in K leads to a raise in the velocity but a reverse effect is seen in the case of Kr and M.
ii. An increase of both Pr and R results in a decreasing the thermal boundary layer thickness whereas concentration decreases as Kr, Sc increase but it increases with the increase of both So and δ.
iii. The skin-friction at the wall increases as Gr and Gm or M or So or δ increase. And it decreases with increasing in Pr or Sc or R or Kr or K.
iv. As Sc or Kr increase, the rate of mass transfer increases but it decreases with the increase in Pr or So or R. Also we observe that the rate of heat transfer increases with the increase of Pr or R but it decreases with decreasing δ.

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Annexure

NOMENCLATURE

A	Real positive constant
B_0	Magnetic induction
C	Concentration
C_p	Specific heat for constant pressure
D	Chemical molecular diffusivity
D_1	Thermal diffusivity
g	Gravity(m/s^2)
k	Thermal conductivity
k*	Permeability of porous medium
K	Permeability parameter
Kr	Chemical reaction parameter
M	Magnetic parameter
N	Dimensionless material parameter
Nu	Nusselt number
Pr	Prandtl number
Q	Heat generation / absorption
q_r	Radiation heat flux density
R	Radiation parameter
Sc	Schmidt number
S_f	Skin-friction coefficient
So	Soret number
Sh	Sherwood number
T	Temperature
t	time
U0	Scale of free stream velocity
V0	Scale of suction velocity
u,v	Longititudinal and transverse components of velocity vector
Greek Symbols	
β	Spin gradient viscosity
β^*	Coefficient of volumetric expansion
δ	Heat generation parameter
μ	Fluid dynamic viscosity
υ	Fluid kinematic viscosity
θ	Non dimensional temperature
σ	Electrical conductivity
ρ	Fluid density
ε	Scalar constant(<<1)
Subscripts	
P	Plate
W	Wall condition
∞	Free stream condition
x,y	Distances along and perpendicular to the plate