# Effects of Variable Viscosity and Thermal Conductivity with Chemical Reaction on a Transient MHD Flow past an Impulsively Started Vertical Plate with Ramped Temperature and Concentration with Viscous Dissipation

G.C. Hazarika
Department of Mathematics,
Dibrugarh University,Dibrugarh, Assam, India

Sachin Doley
Simen Chapari College, Dhemaji
Assam, India

## ABSTRACT
A numerical study based on finite difference scheme to investigate the effect of variab**le** viscosity and thermal conductivity with chemical reaction on a transient MHD free convective mass transfer flow of an incompressible viscous electrically conducting, Newtonian fluid past a suddenly started infinite vertical plate with ramped wall temperature and concentration in presence of appreciable radiation heat transfer with viscous dissipation and Joulian heat and uniform transverse magnetic field is presented. The fluid is assumed to be optically thin and the Magnetic Reynolds number considered small enough to neglect the induced hydro magnetic effects. The equations governing the flow are solved by an iterative technique based on Gauss-Seidal method. Effects of various flow governing parameters on the fluid velocity, temperature, concentration, skin friction , heat transfer rate and Sherwood number at the plate are presented graphically and in tabular form. The results are physically interpreted. It is observed that the fluid motion is retarded due to the effect of chemical reaction irrespective of the plate temperature being ramped or isothermal.

## Keywords
Variable viscosity, variable thermal conductivity, thermal diffusion, thermal radiation, ramped temperature, chemical reaction, viscous dissipation.

## 1. INTRODUCTION
Magnetohydrodynamics is concerned with the study of mutual interaction of magnetic fields and electrically conducting fluids in motion and the fluids must be non-magnetic which limits us to liquid metals such as mercury, gallium, sodium, molted-iron and hot isonised gases(plasma), strong electrolytes etc. The magnetic field influence many natural and man-made flow. There is the terrestrial magnetic field which is maintained by fluid motion in earth's core, the solar magnetic field which generates sunspots and solar flares and the galactic magnetic field which is thought to influence the formation of stars from intersteller clouds. For the last several decades this subject has been interested by many scientists and engineerings due to its fascination and importance in various technology devices and for understanding the diverse cosmic phenomena. There are numerous examples of applications of MHD principles like MHD generators, MHD pumps, MHD flow meters stir and levitate liquid metals etc. Convection problems of electrically conducting fluid in presence of transverse magnetic field have got much importance because of its wide applications in Geophysics, Astrophysics, Plasma-Physics, Missile technology etc. MHD principles find its applications in Medicine and Biology also. The present stage of MHD is due to the pioneer contributions of several notable authors like Cowling[1], Shercliff[2], Ferraro and Plumpton[3] and Crammer and Pai[4].

Heat transfer is energy in transit which occurs as a result of a temperature gradient or difference. It is generally associated with fluid dynamics and also supplements the law of thermodynamics by providing additional experimental rules to establish the energy transfer rate. The natural flow arises in fluid when the temperature change due to density variation leading to buoyancy forces acting on the fluid. Free convection is a process of heat transfer in natural flow. The heating of room by use of radiator is an example of heat transfer by free convection. Radiation is another process of heat transfer through electromagnetic waves. Radiative convective flows are encountered in countless industrial and environment processes like heating and cooling chambers, evaporation from large open water reservoirs, astrophysical flows and solar power technology. Due to increased importance of the above physical aspects, a few numbers scholars has carried out model studies on the problems of free convective flows of incompressible viscous fluid under different flow geometries taking into account of the thermal radiation. Some of them are Lai and Kulacki[5],Mansor[6], Raptis and Perdikis[7], Ganesan and Logonathan[8], Mbeledogue et al. [9], Makinde[10] and Sattar and Kalim[11]. Investigation of problems on natural convective radiating flow of electrically conducting fluid past an infinite plate becomes very interesting and fruitful when a magnetic field is applied normal to the plate. The comprehensive literature on various aspects of free convective radiative MHD flows and its applications can be found in Sattar and Maleque[12], Samad and Rahman[13], Prasad et al. [14], Takhar et al. [15], Ahmed and Sarmah[16] and Ahmed[17]. The effect of rotation on unsteady hydromagnetic natural convection flow of a viscous incompressible electrically conducting fluid past an impulsively moving vertical plate with ramped wall temperature has been investigated recently by Seth et al.[18].

A chemical reaction is a process that leads to the transformation of one set of chemical substances to another. Chemical reaction may be either spontaneous, requiring no input of energy, or non-spontaneous, typically input of some type of energy like- heat, light, etc. In many times, it has been observed that the foreign mass makes reaction with the fluid and in such a situation chemical reaction plays an important role in chemical industry.

The study of effect of chemical reaction on heat and mass transfer in a flow is of great practical importance to the Engineers and Scientists because of its almost universal occurrence in many branches of Science and technology. In processes such as drying, distribution of temperature and moisture over agricultural fields, energy transfer in a wet cooling tower and flow in a cooler, heat and mass transfer occur simultaneously. Possible applications of this type of flow can be found in many industries. Many investigators have studied the effect of chemical reaction in different convective heat and mass transfer flows of whom Apelblat[19] and Anderson et.al [20] are worth mentioning. Chambre and Young[21] have presented a first order chemical reaction in the neighbourhood of a horizontal plate. Muthucumaraswamy[22] presented heat and mass transfer effects on a continuously moving isothermal vertical surface with uniform suction by taking into account the homogeneous chemical reaction of first order. Muthucumaraswamy and Meenakshisundaram[23] investigated theoretical study of chemical reaction effects on vertical oscillating plate with variable temperature and mass diffusion. Ahmed and Sinha[24] studied the effect of chemical reaction on a transient MHD flow past an impulsively started vertical plate with ramped temperature and concentration. The same problem was studied by Hazarika[25] by taken into account the viscous dissipation and Joule heating.

In the present work an attempt has been made to study the effects of the variable viscosity and thermal conductivity, to the problem discussed by Ahmed and Sinha[24] and Hazarika[25]. Here our main objective is to solve the governing boundary value problem in non-linear partial differential equations base on Gauss-seidal scheme by employing an iterative method.The effects of the viscosity and thermal conductivity parameters on velocity, temperature, concentration, wall shear stress, rate of heat transfer and rate of mass transfer are investigated. The effects of all other physical parameters are also studied. It is seen that effects are quite significant.

## 2. MATHEMATICAL FORMULATION OF THE PROBLEM

The equations governing the motion of an incompressible, the variable viscosity and thermal conductivity, electrically conducting radiating fluid past a solid surface in presence of a magnetic field are:

Continuity equation: $\vec{\nabla}.\vec{q} = 0$ (1)

Magnetic field continuity equation:

$$\vec{\nabla}.\vec{B} = 0 \quad (2)$$

Ohm's law for moving conductor:

$$\vec{J} = \sigma\left(\vec{E} + \vec{q} \times \vec{B}\right) \quad (3)$$

Momentum equation:

$$\rho\left[\frac{\partial \vec{q}}{\partial t'} + \left(\vec{q}.\vec{\nabla}\right)\vec{q}\right] = -\vec{\nabla}p + \vec{J}\times\vec{B} + \rho\vec{g} + \nabla.\left(\mu\vec{\nabla}.\vec{q}\right) \quad (4)$$

Energy equation:

$$\rho C_p\left[\frac{\partial T'}{\partial t'} + \left(\vec{q}.\vec{\nabla}\right)T'\right] = \vec{\nabla}.\left(K_T\vec{\nabla}.T'\right) + \varphi + \frac{\vec{J}^2}{\sigma} - \frac{\partial q_r}{\partial n'} \quad (5)$$

Species Concentration equation:

$$\frac{\partial C'}{\partial t'} + \left(\vec{q}.\vec{\nabla}\right)\vec{C}' = \vec{\nabla}.\left(D_M\vec{\nabla}C'\right) + \vec{\nabla}.\left(D_T\vec{\nabla}C'\right) \quad (6)$$

All the physical quantities are defined in the Nomenclature.

Our investigation is restricted to the following assumptions:

i) All the fluid properties are considered constants except the influence of the variation in density in the buoyancy force and the viscosity and thermal conductivity.

ii) The magnetic Reynolds number is so small for that the induced magnetic field can be neglected in comparison to the applied magnetic field.

iii) The plate is electrically non-conducting.

iv) The radiation heat flux in the direction of the plate velocity is considered negligible in comparison to that in the normal direction.

v) No external electric field is applied for which the polarization voltage is negligible leading to $\vec{E} = \vec{0}$

vi) Viscosity and thermal conductivity are assumed to vary with temperature.

Initially the plate and the surrounding fluid were at rest at the same temperature $T'_\infty$ and concentration $C'_\infty$. At time $t' > 0$, the plate is suddenly moved in its own plane with a constant velocity $U_0$ and the temperature and concentration of the wall is raised to $T'_\infty + \left(T'_w - T'_\infty\right)\frac{t'}{t_0}$ and $C'_\infty + \left(C'_w - C'_\infty\right)\frac{t'}{t_0}$ for $0 < t' \le t_0$ and the constant temperature $T'_w\left(T'_w > T'_\infty\right)$ and concentration $C'_w\left(C'_w > C'_\infty\right)$ are maintained at $t' > t_0$.

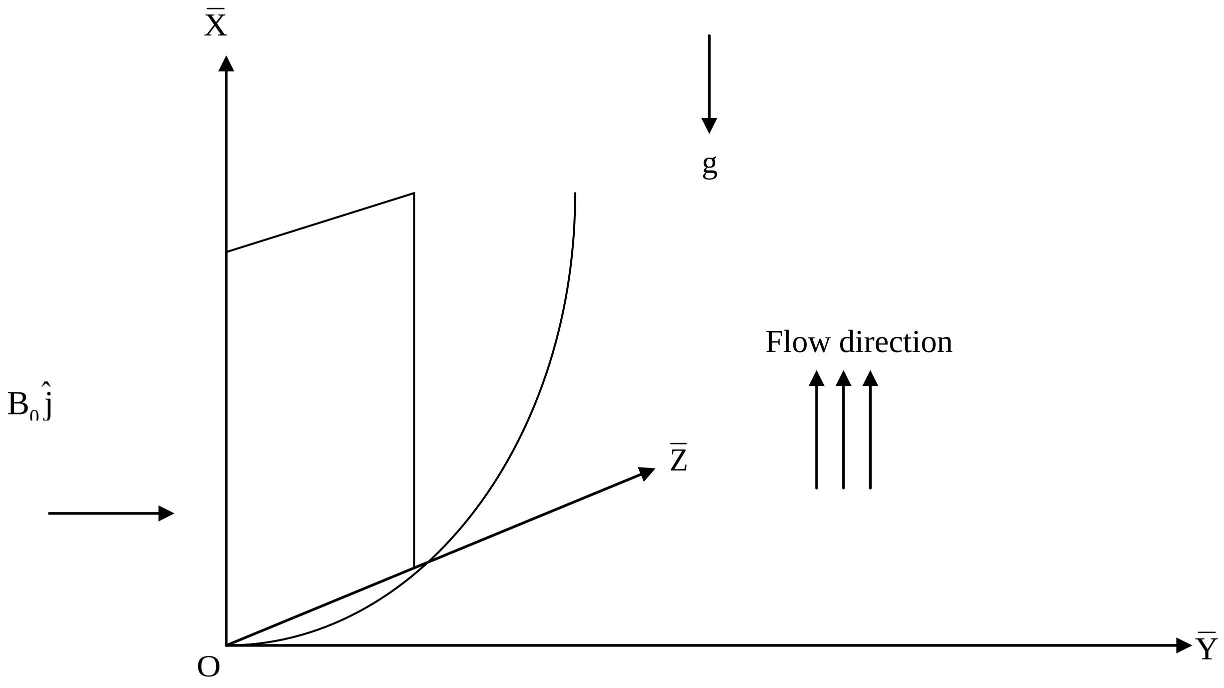


**Fig. 1: Flow Configuration**

We now introduce a coordinate system $(x', y', z')$ with $\bar{X}$ - axis along the plate in the upward vertical direction, $\bar{Y}$ -axis normal to the plate directed into the fluid region and $\bar{Z}$ -axis along the width of plate. Let $\vec{q} = (u', o, o)$ denotes the fluid velocity and $\vec{B} = (0, B_0, 0)$ be the applied magnetic field at the point $(x', y', z', t')$ in the fluid.

With the foregoing assumptions and under the usual boundary layer and Boussinesq approximations, the Eqns.(1), (4), (5) and (6) reduce to

$$\frac{\partial u'}{\partial x'} = 0 \text{, which yields } u' = u'(y', t') \tag{7}$$

$$\rho \frac{\partial u'}{\partial t'} = \frac{\partial}{\partial y'}\left(\mu \frac{\partial u'}{\partial y'}\right) + \rho[g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty)] - \sigma B_0^2 u' \tag{8}$$

$$\rho C_p \frac{\partial T'}{\partial t'} = \frac{\partial}{\partial y'}\left(K_T \frac{\partial T'}{\partial y'}\right) + \mu\left(\frac{\partial u'}{\partial y'}\right)^2 + \sigma B_0^2 u'^2 - \frac{\partial q_r}{\partial y'} \tag{9}$$

$$\frac{\partial C'}{\partial t'} = \frac{\partial}{\partial y'}\left(D_M \frac{\partial C'}{\partial y'}\right) + \frac{\partial}{\partial y'}\left(D_T \frac{\partial C'}{\partial y'}\right) + K'(C'_\infty - C') \tag{10}$$

The appropriate initial and boundary conditions are

$$u' = 0,\ T' = T'_\infty, C' = C'_\infty \ \forall y',\ t' \le 0 \tag{11}$$

$$u' = U_0, T' = T'_\infty + \frac{T'_w - T'_\infty}{t_0} t', C' = C'_\infty + \frac{C'_w - C'_\infty}{t_0} t' \text{ at } y' = 0,\ 0 < t' \le t_0 \tag{12}$$

$$u' = U_0,\ T' = T'_w, C' = C'_w \ \text{ at } \ y' = 0,\ t' > t_0 \tag{13}$$

$$u' \to 0,\ T' \to T'_\infty, C' \to C'_\infty \ \text{ at } \ y' \to \infty,\ t' > 0 \tag{14}$$

It is emphasized by Cogley et al. [26] that the rate of radiative flux in optically thin limit is given by

$$\frac{\partial q_r}{\partial y'} = 4I(T' - T'_\infty) \tag{15}$$

where, $I = \int_0^\infty k_w \left(\frac{\partial e_{b\lambda}}{\partial T'}\right)_w d\lambda$

On use of (15), (9) reduces to

$$\rho C_p \frac{\partial T'}{\partial t'} = \frac{\partial}{\partial y'}\left(K_T \frac{\partial T'}{\partial y'}\right) + \mu\left(\frac{\partial u'}{\partial y'}\right)^2 + \sigma B_0^2 u'^2 - 4I(T' - T'_\infty) \quad (16)$$

Following Lai and Kulacki[5], we take

$$\frac{1}{\mu} = \frac{1}{\mu_\infty}\left[1+\delta\left(T' - T'_\infty\right)\right], T'_r = T'_\infty - \frac{1}{\delta}, \theta_r = -\frac{1}{\delta\left(T'_w - T'_\infty\right)} \quad (17)$$

$$\frac{1}{K_T} = \frac{1}{K_\infty}\left[1+\xi\left(T' - T'_\infty\right)\right], T'_K = T'_\infty - \frac{1}{\xi}, \theta_K = -\frac{1}{\xi\left(T'_w - T'_\infty\right)} \quad (18)$$

Proceeding with the analysis, we introduce the following non-dimensional variables and similarity parameters to normalize the flow model:

$$u = \frac{u'}{U_0},\ y = \frac{y'}{U_0 t_0},\ t = \frac{t'}{t_0}, \text{and}$$

$$Gr = \frac{\upsilon g\beta\left(T'_w - T'_\infty\right)}{U_0^3}, Gm = \frac{\upsilon g\beta^*\left(C'_w - C'_\infty\right)}{U_0^3}, \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}$$

$$\phi = \frac{C' - C'_\infty}{C'_w - C'_\infty}, Pr = \frac{\mu C_p}{K_T}, Q = \frac{4I\upsilon}{\rho C_p U_0^2}, M = \frac{\sigma B_0^2 \upsilon}{\rho U_0^2}, Re = \frac{U_0^2 t_0}{\upsilon},$$

$$Sr = \frac{D_T\left(T'_w - T'_\infty\right)}{\upsilon\left(C'_w - C'_\infty\right)}, Sc = \frac{\upsilon}{D_M}, K = K' t_0, Ec = \frac{U_0^2}{C_p\left(T'_w - T'_\infty\right)} \quad (19)$$

All the physical quantities are defined in the Nomenclature.

By virtue of transformations cum definitions (17),(18) and (19) the Eqns.(8), (16) and (10) in normalized form respectively become

$$\frac{\partial u}{\partial t} = \frac{1}{Re}\frac{\theta_r}{(\theta_r - \theta)^2}\frac{\partial \theta}{\partial y}\frac{\partial u}{\partial y} + \frac{1}{Re}\frac{\theta_r}{(\theta_r - \theta)}\frac{\partial^2 u}{\partial y^2} + ReGr\theta + ReGr\phi - MReu \quad (20)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{PrRe}\frac{\theta_k}{(\theta_k - \theta)^2}\left(\frac{\partial \theta}{\partial y}\right)^2 + \frac{1}{PrRe}\frac{\theta_k}{(\theta_k - \theta)}\frac{\partial^2 \theta}{\partial y^2} + \frac{Ec}{Re}\frac{\theta_r}{(\theta_r - \theta)}\left(\frac{\partial u}{\partial y}\right)^2 + MReEcu^2 - QRe\theta \quad (21)$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{ScRe}\frac{\theta_r}{(\theta_r - \theta)^2}\frac{\partial \theta}{\partial y}\frac{\partial \phi}{\partial y} + \frac{1}{ScRe}\frac{\theta_r}{(\theta_r - \theta)}\frac{\partial^2 \phi}{\partial y^2} + \frac{Sc}{Re}\frac{\theta_r}{(\theta_r - \theta)^2}\left(\frac{\partial \theta}{\partial y}\right)^2 + \frac{Sc}{Re}\frac{\theta_r}{\theta_r - \theta}\frac{\partial^2 \theta}{\partial y^2} - K\phi \quad (22)$$

With the above mentioned transformations, the initial and boundary conditions (11)-(14)

$$u = 0,\ \theta = 0,\ \phi = 0\ \forall\, y \ge 0 \text{ and } t \le 0 \quad (23)$$

$$u = 1,\ \theta = t,\ \phi = t \text{ at } y = 0,\ 0 < t \le 1 \quad (24)$$

$$u = 1,\ \theta = 1,\ \phi = 1 \text{ at } y = 0,\ t > 1 \quad (25)$$

$$u = 0,\ \theta = 0,\ \phi = 0 \text{ as } y \to \infty,\ t > 0 \quad (26)$$

## 3. METHOD OF SOLUTION

The differential equations (20) to (22) together with the initial and boundary conditions (23) to (26) are reduced to a system of difference equations using the following general finite difference scheme. The scheme for an independent variable f is given by,

$$\frac{\partial f}{\partial T} = \frac{f_{i+1,j} - f_{i,j}}{\Delta T}$$

$$\frac{\partial^2 f}{\partial \eta^2} = \frac{f_{i,j+1} - 2f_{i,j} + f_{j-1}}{(\Delta\eta)^2}$$

The system of difference equations are then solved numerically by an iterative scheme mentioned above in the introduction part.

The physical quantities of interest in this problem are (1) the Skin Friction Coefficient $C_f$, (2) Nusselt number $Nu$ and (3) Sherwood number $Sh$ which indicate physically wall shear stress, rate of heat transfer and rate of mass transfer respectively. These are expressed as below:

### 3.1 Coefficient of Skin Friction

The viscous drag at the plate per unit area in the direction of the plate velocity is given by the Newton's law of viscosity in the form:

$$\tau' = \mu \frac{\partial u'}{\partial y'}\bigg]_{y'=0} = \frac{\mu}{t_0}\frac{\partial u}{\partial y}\bigg]_{y=0} \quad (27)$$

The coefficient of skin friction at the plate is given by

$$C_f = \frac{2}{t_o \rho U_o^2}\left[(\mu)\ \frac{\partial u}{\partial y}\right]_{y=0} = 2\ Re\ \left[\frac{\partial u}{\partial y}\right]_{y=0} \quad (28)$$

### 3.2 Coefficient of Rate of Heat Transfer

The heat flux $q^*$ from the plate to the fluid is given by the Fourier law of conduction in the form

$$q^* = -K_T \frac{\partial T'}{\partial y'}\bigg]_{y'=0} = -\frac{K_T}{U_0 t_0}(T'_w - T'_\infty)\frac{\partial \theta}{\partial y}\bigg]_{y=0} \quad (29)$$

The co-efficient of the rate of heat transfer from the plate to the fluid in terms of Nusselt number is given by

$$Nu = \frac{q^* U_0 t_0}{K_T\left(T'_w - T'_\infty\right)} = -\frac{\partial \theta}{\partial y}\bigg]_{y=0} \quad (30)$$

### 3.3 Coefficient of Rate of Mass Transfer

The mass flux at the wall is given by

$$M_w = -D\left[\frac{\partial C}{\partial y}\right]_{y=0}$$

Sherwood number is given by-

$$S_h = \frac{M_w U_0}{D(C_w - C_\infty)\alpha} = -\left[\frac{\partial C}{\partial y}\right]_{y=0} \quad (31)$$

## 4. RESULTS AND DISCUSSION

Numerical solutions are obtained by solving the finite difference equations using an iterative technique base on Gauss-Seidal method for the velocity field, temperature field, concentration field, and the coefficient of skin friction, rate of heat transfer in terms of Nusselt number and rate of mass transfer in terms of Sherwood number have been carried out by assigning some arbitrarily chosen specific values to the physical parameters involved in this problem. Our investigation is carried out in general for Ec=.1, Gr=5, Gm=5, Pr=.71, Re=1.5, Q=1, M=1, Sc=.22, Sr=1 and K=1 unless otherwise stated. The results computed from the numerical method of the problem have been displayed in Figs.( 2-19).

Figs.(2-9) present the velocity profiles under the influence of chemical reaction parameter K, Magnetic parameter M (Hartmann number) viscosity parameter $\theta_r$ and thermal conductivity parameter $\theta_k$ virsus y for the cases $0 < t \leq 1\ and\ t > 1$. From Fig.2 and Fig.3 it is inferred that the fluid motion retards uniformly due to enhance of chemical reaction and then decreases asymptotically towards $u = 0\ as\ y \rightarrow \infty$ i.e. in the free stream. It is observed from Fig.4 and Fig.5 that, for ramped temperature and isothermal plates, an increase in Magnetic parameter M has an inhibiting effect on the fluid velocity. The fluid velocity is continuously reduced with increasing M. So the imposition of the transverse magnetic field leads to retard the fluid flow irrespective of ramped plate temperature or uniform plate temperature. This phenomenon has an exceptional agreement with the physical fact that the Lorentz force is generated in this flow model due to interaction of the transverse magnetic field and the fluid motion and the force acts as a resistive force to the fluid flow which serves to decelerate the flow. Further the Fig.5 reveals that the fluid velocity initially increases in a thin layer adjacent to the plate and there after it decreases asymptotically as move away from the plate indicating the fact that the buoyancy force plays a significant role on the flow near the plate and its effect is nullified in the free stream. The Figs.6&7 show the velocity variation against viscosity parameter $\theta_r$ that fluid motion retards due to increase of $\theta_r$ for 0< t< 1 and reverse activity is inferred for t >1. A stagnation behaviour is observed in the flow motion due to $\theta_r$ and is seen at a dimensionless distance 0.2 and 0.5 within the boundary layer in y-direction respectively for 0 < t < 1 and t >1. Fig.8 and Fig.9 indicate the velocity variation due to $\theta_k$ and it is observed that the fluid motion decreases with enhance of the thermal conductivity.

The temperature profiles versus y are exhibited in Figs.(10-13) for variation of the viscous parameter $\theta_r$ and radiation parameter Q. It is observed that temperature decreases with increasing of both $\theta_r$ and Q and hence the fluid losses heat on account of enhance of viscous dissipation and radiation flux.

The Figs.(14-19) inferred the species concentration profiles due to chemical reaction parameter K, viscous parameter $\theta_r$ and thermal conductivity parameter $\theta_k$. The Fig.14 Fig.15 indicate that the species concentration decreases with an increment of K for 0 < t < 1 but it enhances for t > 1.The increment of viscous dissipation makes retardation of the rate of concentration and the species concentration increases with increase of $\theta_k$ for 0 < t < 1 but for t > 1 it about remains unchanged i.e., in free stream.

Tables 1-4 demonstrate the effect on coefficient of skin friction $C_f$, which represent the plate shearing stress, heat transfer coefficient in term of Nusselt number *Nu* and mss transfer in term of Sherwood number *Sh* for 0<t<1 and t>1. From Table 1 and Table 2 it is observed that the skin friction force increases with the increment of both $\theta_r$ and *M*, and the rate of heat and mass transfer enhance with $\theta_r$ whereas decrease with *M*. It is learned from Tables 3-4 that the rate of skin friction, heat transfer and mass flux reduce due to increase of $\theta_k$ for both ramped temperature plates and isothermal plates. And the skin friction and mass transfer increase with the applied transverse magnetic field and the rate of heat flux retards with it.

Tables 5-8 indicate the influence of chemical reaction on coefficient of the skin friction, the rate of heat transfer and the rate of mass transfer on account of variation the viscosity and thermal conductivity at the ramped temperature plates and isothermal plates. Table 5 and Table 6 present that the rate of the skin friction and heat transfer reduce with an increment of viscosity parameter $\theta_r$ and the mass flux increases proportionally with it. The skin friction force and mass transfer increase due to raise the chemical reaction rate but the rate of heat transfer decreases with it. Table 7 and Table 8 reveal that the enhancement of the thermal conductivity makes raise skin friction force and heat transfer but mass transfer decreases. Again the skin friction force and mass transfer significantly increase whereas heat transfer decrease with increase of the rate of chemical reaction. The high consumption (chemical reaction) and large viscosity of the fluid resist the rate of heat transfer but leads the substantial rise in the mass transfer rate.

## 5. CONCLUSIONS

All these investigations lead to the following conclusions:

1. The fluid motion is retarded under the application of transverse magnetic field as well as chemical reaction.
2. The rate of the skin friction, heat flux and mass flux retard due to increment of thermal conductivity of the fluid in present transverse magnetic field.
3. The concentration level of the fluid falls due to increasing chemical reaction. i.e the consumption of chemical species leads to fall in the species concentration field.
4. Shear stress and rate of mass transfer at the plate are considerably increased due of chemical reaction.
5. Mass transfer increases with the enhance of viscosity and decreases with the increase of thermal conductivity in the chemical reaction.
6. Heat flux decreases with the increasing of chemical reaction and viscosity, and increases with increase of thermal conductivity.
7. Increase of viscocity lead to increase the shear the stress whereas the increase of thermal conductivity reduces shear stress.
8. Dissipation enhances both velocity and fluid temperature conductivity.

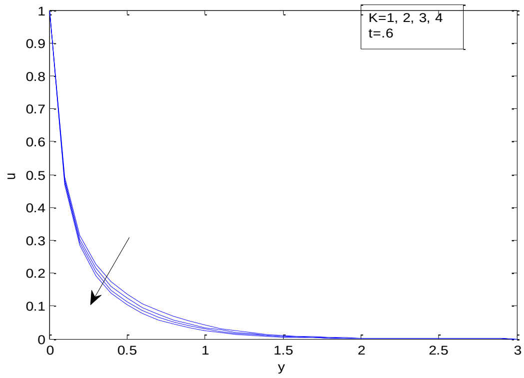


**Fig-2: Velocity distribution for different K at t=0.6**

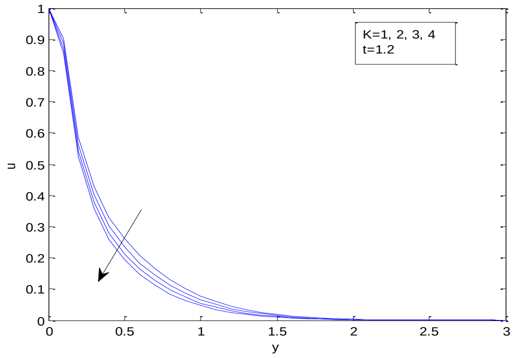


**Fig-3: Velocity distribution for different K at t=1.2**

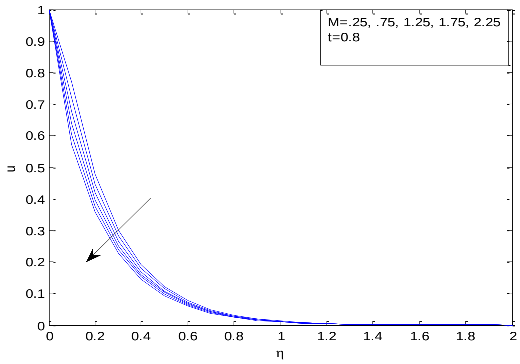


**Fig-4: Velocity distribution for different M at t=0.8**

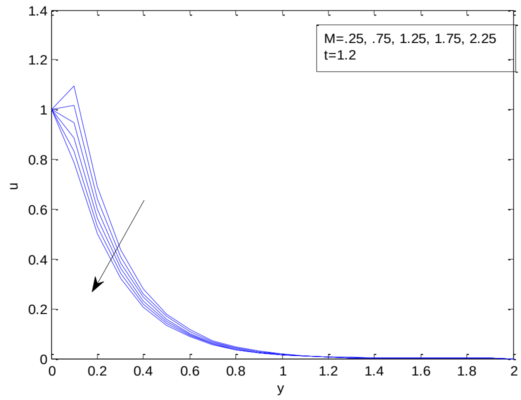


**Fig-5: Velocity distribution for different M at t=1.2**

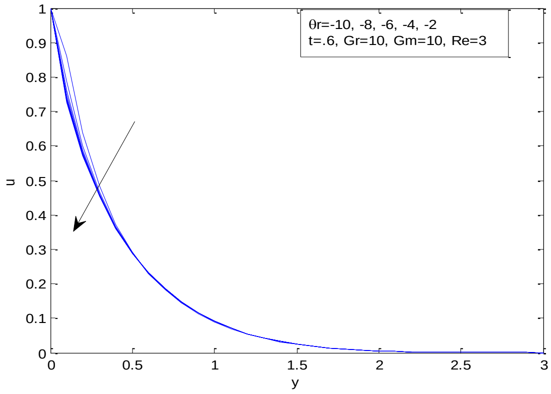


**Fig-6: Velocity distribution against $\theta_r$ at t=0.6**

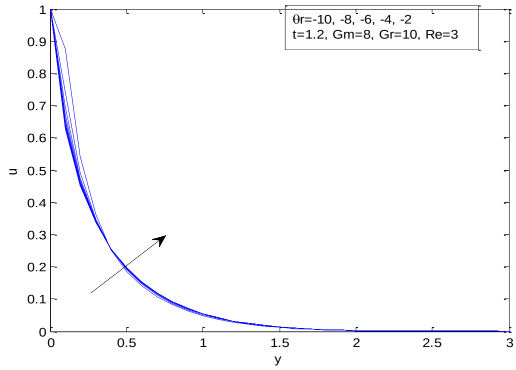


**Fig-7: Velocity profile against $\theta_r$ at t=1.2**

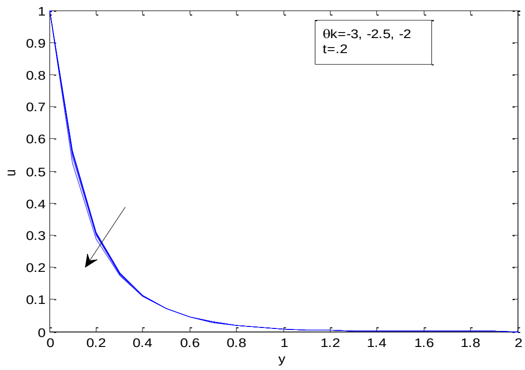


**Fig-8: Velocity profile against $\theta_k$ at t=0.2**

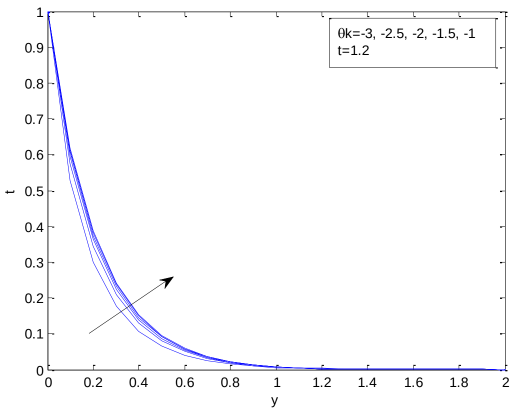


**Fig-9: Temperature distribution against $\theta_k$ at t=1.2**

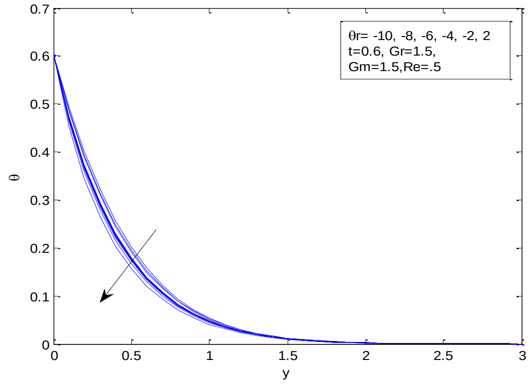


**Fig-10: Temperature distribution against $\theta_r$ at t=0.6**

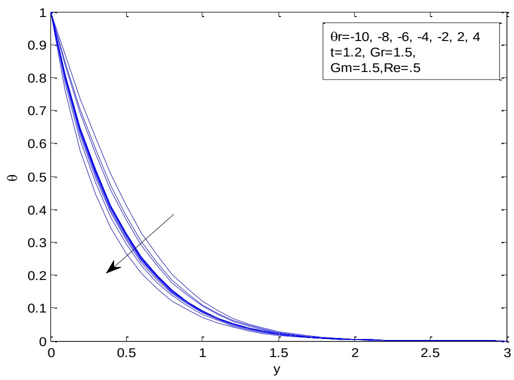


**Fig-11: Temperature distribution against $\theta_r$ at t=1.2**

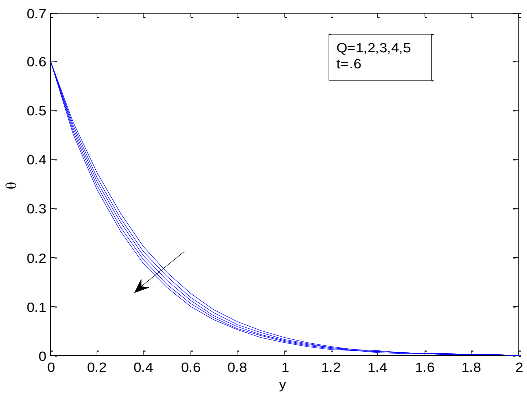


**Fig-12: Temperature distribution against Q at t=.6**

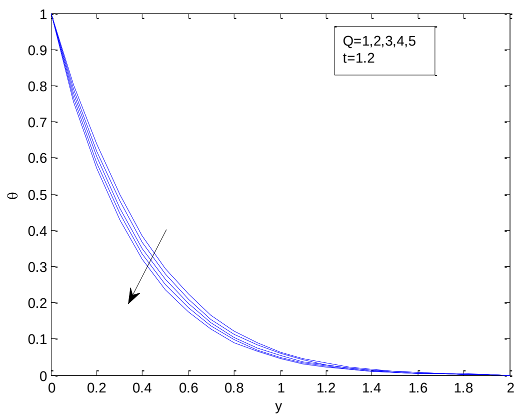


**Fig-13: Temperature distribution against Q at t=1.2**

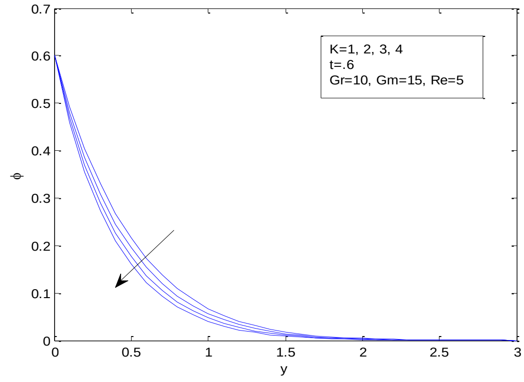


**Fig-14: Species concentration against K at t=.6**

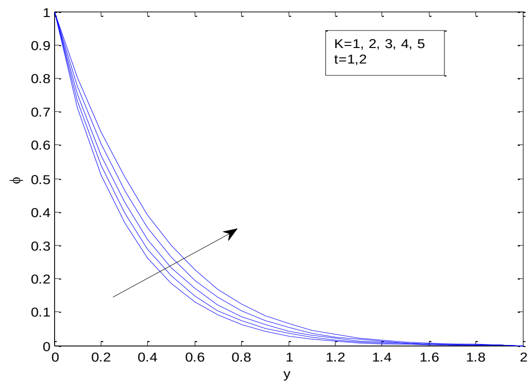


**Fig-15: Species concentration against K at t=1.2**

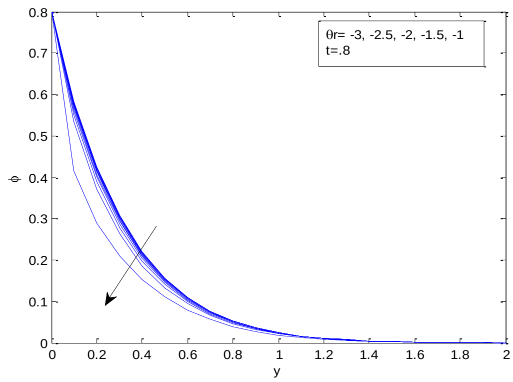


**Fig-16: Species concentration against $\theta_r$ at t=.8**

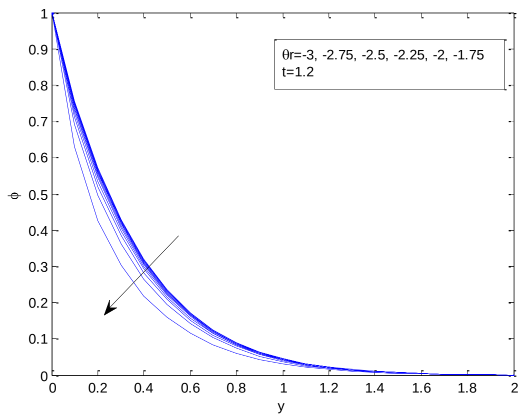


**Fig-17: Species concentration against $\theta_r$ at t=1.2**

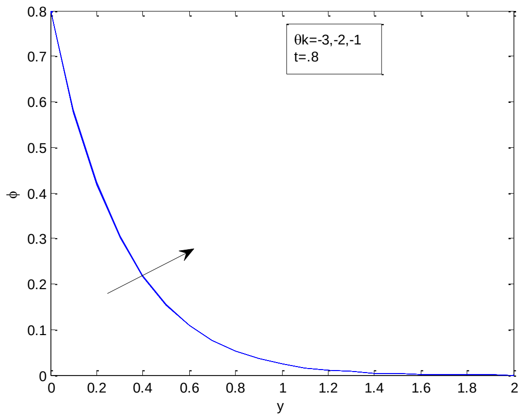


**Fig-18: Species concentration against $\theta_k$ at t=.8**

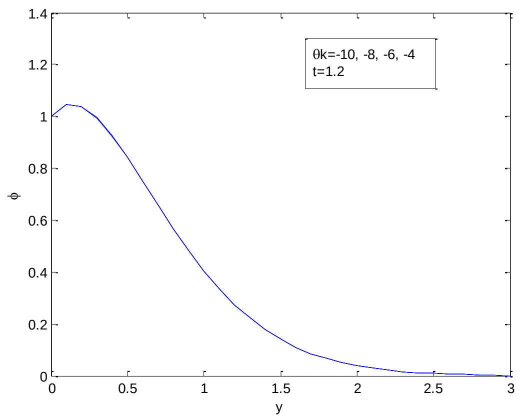


**Fig-19: Species concentration against $\theta_k$ at t=1.2**

**Table - 1**

| t=0.6, M→ | 0.25 | | | 0.75 | | | 1.25 | | | 1.75 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\theta_r$ | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh |
| -12 | 1.0734 | 2.2094 | -0.2357 | 1.3125 | 2.1982 | -0.2358 | 1.5400 | 2.1881 | -0.2358 | 1.7567 | 2.1791 | -0.2359 |
| -10 | 1.0821 | 2.2161 | -0.2356 | 1.3208 | 2.2049 | -0.2350 | 1.5480 | 2.1948 | -0.2358 | 1.7645 | 2.1857 | -0.2359 |
| -8 | 1.0950 | 2.2260 | -0.2356 | 1.3332 | 2.2148 | -0.2357 | 1.5600 | 2.2046 | -0.2358 | 1.7760 | 2.1956 | -0.2359 |
| -6 | 1.1160 | 2.2422 | -0.2356 | 1.3534 | 2.2309 | -0.2357 | 1.5794 | 2.2208 | -0.2358 | 1.7947 | 2.2117 | -0.2350 |
| -4 | 1.1564 | 2.2734 | -0.2355 | 1.3924 | 2.2621 | -0.2356 | 1.6170 | 2.2519 | -0.2357 | 1.8309 | 2.2428 | -0.2358 |
| -2 | 1.2672 | 2.3593 | -0.2354 | 1.4990 | 2.3479 | -0.2355 | 1.6170 | 2.2519 | -0.2357 | 1.9301 | 2.3284 | -0.2356 |

**Table - 2**

| t=1.2, M→ | 0.25 | | | 0.75 | | | 1.25 | | | 1.75 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\theta_r$ | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh |
| -12 | -6.4629 | 3.6885 | -0.4636 | -6.0067 | 3.6515 | -0.4648 | -5.5707 | 3.6184 | -0.4659 | -5.1541 | 3.5887 | -0.4669 |
| -10 | -6.4323 | 3.7064 | -0.4631 | -5.9774 | 3.6694 | -0.4644 | -5.5427 | 3.6362 | -0.4655 | -5.1272 | 3.6064 | -0.4664 |
| -8 | -6.3873 | 3.7327 | -0.4625 | -5.9343 | 3.6956 | -0.4637 | -5.5014 | 3.6624 | -0.4648 | -5.0876 | 3.6326 | -0.4658 |
| -6 | -6.3148 | 3.7752 | -0.4614 | -5.8649 | 3.7381 | -0.4626 | -5.4349 | 3.7048 | -0.4637 | -5.0238 | 3.6749 | -0.4647 |
| -4 | -6.1779 | 3.8557 | -0.4595 | -5.7339 | 3.8185 | -0.4607 | -5.3093 | 3.7851 | -0.4617 | -4.9033 | 3.7551 | -0.4627 |
| -2 | -5.8213 | 4.0677 | -0.4547 | -5.3922 | 4.0303 | -0.4558 | -4.9817 | 3.9966 | -0.4568 | -4.5889 | 3.9663 | -0.4577 |

**Table - 3**

| t=0.6, M→0.25 | | | | 0.75 | | | 1.25 | | | 1.75 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\theta_k$ | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh |
| -12 | 2.1105 | 1.9268 | -0.1844 | 2.2981 | 1.9184 | -0.1842 | 2.4773 | 1.9107 | -0.1841 | 2.6487 | 1.9037 | -0.1839 |
| -10 | 2.0548 | 1.9266 | -0.1863 | 2.2448 | 1.9181 | -0.1861 | 2.4263 | 1.9103 | -0.1860 | 2.5998 | 1.9033 | -0.1858 |
| -8 | 1.9710 | 1.9263 | -0.1891 | 2.1647 | 1.9177 | -0.1890 | 2.3497 | 1.9098 | -0.1888 | 2.5265 | 1.9027 | -0.1887 |
| -6 | 1.8310 | 1.9258 | -0.1939 | 2.0309 | 1.9169 | -0.1938 | 2.2218 | 1.9089 | -0.1937 | 2.4041 | 1.9016 | -0.1936 |
| -4 | 1.5496 | 1.9248 | -0.2039 | 1.7624 | 1.9154 | -0.2039 | 1.9652 | 1.9070 | -0.2038 | 2.1588 | 1.8994 | -0.2038 |
| -2 | 0.6941 | 1.9215 | -0.2366 | 0.9476 | 1.9107 | -0.2367 | 1.1886 | 1.9010 | -0.2369 | 1.4179 | 1.8923 | -0.2370 |

**Table - 4**

| t=1.2, M→ | 0.25 | | | 0.75 | | | 1.25 | | | 1.75 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\theta_k$ | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh |
| -12 | -3.7172 | 2.7920 | -0.3103 | -3.3901 | 2.7693 | -0.3099 | -3.0772 | 2.7487 | -0.3096 | -2.7776 | 2.7300 | -0.3094 |
| -10 | -3.8865 | 2.7911 | -0.3164 | -3.5522 | 2.7680 | -0.3161 | -3.2325 | 2.7470 | -0.3158 | -2.9265 | 2.7280 | -0.3156 |
| -8 | -4.1413 | 2.7898 | -0.3257 | -3.7960 | 2.7660 | -0.3255 | -3.4659 | 2.7444 | -0.3253 | -3.1502 | 2.7250 | -0.3251 |
| -6 | -4.5681 | 2.7875 | -0.3417 | -4.2042 | 2.7626 | -0.3416 | -3.8566 | 2.7401 | -0.3416 | -3.5242 | 2.7198 | -0.3415 |
| -4 | -5.4303 | 2.7827 | -0.3755 | -5.0279 | 2.7555 | -0.3758 | -4.6439 | 2.7311 | -0.3760 | -4.2771 | 2.7091 | -0.3762 |
| -2 | -8.0955 | 2.7668 | -0.4905 | -7.5662 | 2.7318 | -0.4920 | -7.0622 | 2.7008 | -0.4934 | -6.5821 | 2.6733 | -0.4947 |

**Table - 5**

| t=0.6, K→ | 1 | | | 3 | | | 5 | | | 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\theta_r$ | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh |
| -12 | 2.4689 | 1.9266 | 0.3294 | 2.6242 | 1.9261 | 0.5387 | 2.7621 | 1.9256 | 0.7237 | 2.8855 | 1.9252 | 0.8884 |
| -10 | 2.4180 | 1.9264 | 0.3305 | 2.5753 | 1.9259 | 0.5409 | 2.7150 | 1.9254 | 0.7267 | 2.8398 | 1.9250 | 0.8921 |
| -8 | 2.3416 | 1.9261 | 0.3321 | 2.5020 | 1.9256 | 0.5441 | 2.6442 | 1.9251 | 0.7312 | 2.7712 | 1.9247 | 0.8977 |
| -6 | 2.2141 | 1.9256 | 0.3348 | 2.3795 | 1.9251 | 0.5494 | 2.5261 | 1.9246 | 0.7387 | 2.6569 | 1.9242 | 0.9068 |
| -4 | 1.9583 | 1.9246 | 0.3397 | 2.1341 | 1.9240 | 0.5596 | 2.2896 | 1.9236 | 0.7530 | 2.4280 | 1.9232 | 0.9246 |
| -2 | 1.1844 | 1.9214 | 0.3518 | 1.3929 | 1.9208 | 0.5872 | 1.5761 | 1.9204 | 0.7930 | 1.7384 | 1.9200 | 0.9744 |

**Table - 6**

| t=1.2, K→ | 1 | | | 3 | | | 5 | | | 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\theta_r$ | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh |
| -12 | -3.0897 | 2.7916 | 0.5644 | -2.8186 | 2.7904 | 0.9198 | -2.5783 | 2.7893 | 1.2333 | -2.3637 | 2.7883 | 1.5119 |
| -10 | -3.2442 | 2.7907 | 0.5672 | -2.9670 | 2.7895 | 0.9257 | -2.7216 | 2.7884 | 1.2417 | -2.5026 | 2.7874 | 1.5223 |
| -8 | -3.4764 | 2.7894 | 0.5712 | -3.1902 | 2.7882 | 0.9344 | -2.9369 | 2.7871 | 1.2541 | -2.7112 | 2.7861 | 1.5377 |
| -6 | -3.8647 | 2.7872 | 0.5773 | -3.5630 | 2.7859 | 0.9483 | -3.2966 | 2.7848 | 1.2741 | -3.0596 | 2.7838 | 1.5628 |
| -4 | -4.6468 | 2.7825 | 0.5879 | -4.3130 | 2.7812 | 0.9742 | -4.0194 | 2.7801 | 1.3123 | -3.7590 | 2.7791 | 1.6108 |
| -2 | -7.0423 | 2.7673 | 0.6079 | -6.6027 | 2.7660 | 1.0396 | -6.2201 | 2.7650 | 1.4132 | -5.8843 | 2.7641 | 1.7399 |

**Table- 7**

| t=0.6, K→ | 1 | | | 3 | | | 5 | | | 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\theta_k$ | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh |
| -12 | 1.5529 | 2.2092 | 0.3464 | 1.7568 | 2.2086 | 0.5797 | 1.9361 | 2.2080 | 0.7839 | 2.0951 | 2.2076 | 0.9642 |
| -10 | 1.5613 | 2.2158 | 0.3463 | 1.7651 | 2.2152 | 0.5795 | 1.9444 | 2.2147 | 0.7837 | 2.1033 | 2.2143 | 0.9639 |
| -8 | 1.5738 | 2.2257 | 0.3461 | 1.7774 | 2.2251 | 0.5793 | 1.9566 | 2.2246 | 0.7834 | 2.1154 | 2.2241 | 0.9636 |
| -6 | 1.5942 | 2.2419 | 0.3457 | 1.7976 | 2.2413 | 0.5788 | 1.9765 | 2.2407 | 0.7829 | 2.1351 | 2.2403 | 0.9630 |
| -4 | 1.6335 | 2.2731 | 0.3451 | 1.8364 | 2.2725 | 0.5780 | 2.0149 | 2.2719 | 0.7818 | 2.1731 | 2.2715 | 0.9618 |
| -2 | 1.7410 | 2.3589 | 0.3434 | 1.9425 | 2.3583 | 0.5756 | 2.1199 | 2.3577 | 0.7790 | 2.2772 | 2.3572 | 0.9586 |

**Table - 8**

| t=1.2, K→ | 1 | | | 3 | | | 5 | | | 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\theta_k$ | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh | $C_f$ | Nu | Sh |
| -12 | -5.4802 | 3.6885 | 0.5979 | -5.0690 | 3.6869 | 1.0178 | -4.7099 | 3.6856 | 1.3826 | -4.3938 | 3.6845 | 1.7025 |
| -10 | -5.4509 | 3.7063 | 0.5976 | -5.0402 | 3.7047 | 1.0173 | -4.6816 | 3.7034 | 1.3820 | -4.3658 | 3.7023 | 1.7017 |
| -8 | -5.4079 | 3.7326 | 0.5973 | -4.9980 | 3.7310 | 1.0166 | -4.6401 | 3.7297 | 1.3810 | -4.3248 | 3.7286 | 1.7006 |
| -6 | -5.3385 | 3.7750 | 0.5966 | -4.9299 | 3.7734 | 1.0155 | -4.5731 | 3.7721 | 1.3795 | -4.2587 | 3.7710 | 1.6987 |
| -4 | -5.2077 | 3.8555 | 0.5954 | -4.8016 | 3.8538 | 1.0133 | -4.4467 | 3.8525 | 1.3765 | -4.1341 | 3.8513 | 1.6951 |
| -2 | -4.8668 | 4.0673 | 0.5921 | -4.4670 | 4.0655 | 1.0072 | -4.1175 | 4.0641 | 1.3684 | -3.8093 | 4.0629 | 1.6855 |

Nomenclature

| Symbol | Description | Symbol | Description |
|---|---|---|---|
| $\vec{B}$ | Magnetic induction vector | $D_M$ | Mass diffusivity |
| $B_0$ | Strength of the applied magnetic field $\left(y - \text{component of } \vec{B}\right)$ | $D_T$ | Thermal diffusion ratio |
| $C'$ | Concentration | $e^{b\lambda}$ | Plank function |
| $C_p$ | Specific heat at constant pressure | $\vec{E}$ | Electric Field |
| $C'_w$ | Concentration at the plate | $\vec{g}$ | Acceleration vector |
| $C'_\infty$ | Concentration far away from the plate | $g$ | Acceleration due to gravity |
| Ec | Eckert Number | $t$ | Non-dimensional time |
| Gr | Grashof number for heat transfer | $t'$ | Time |
| Gm | Grashof number for mass transfer | $t_0$ | Characteristic time |
| $\vec{J}$ | Current Density vector | $T'$ | Fluid temperature |
| $k_w$ | Mean absorption coefficient | $T'_w$ | Reference temperature |
| K | Chemical Reaction Parameter | $T'_\infty$ | Temperature far away from the plate |
| $K_T$ | Thermal conductivity | $u$ | Non-dimensional velocity profile |
| M | Hartmann number | $u'$ | X component of $\vec{q}$ |
| Nu | Nusselt number | $U_0$ | Plate velocity |
| P | Pressure | $(x', y', z')$ | Cartesian coordinates |
| Pr | Prandtl number | $y$ | Non-dimensional normal coordinate |
| $\vec{q}$ | Fluid velocity vector | $\rho$ | Fluid density |
| Q | Radiation parameter | $\tau$ | Coefficient of Skin friction |
| $q_r$ | Radiative flux in magnitude | $\mu$ | Co-efficient of viscosity |
| Re | Reynolds number | $\lambda$ | Wave length |
| Sc | Schmidt number | $\sigma$ | Electrical conductivity |
| Sh | Sherwood number | $\varphi$ | Dissipation of energy |

| | | | |
|---|---|---|---|
| Sr | Soret number | $\beta^*$ | Volumetric co-efficient of expansion with concentration |
| $\beta$ | Volumetric co-efficient of thermal expansion | $\phi$ | Non-dimensional concentration |
| $\upsilon$ | Kinematic viscosity | Subscript $_w$ | Refers to the values of physical quantities at the plate |
| $\theta$ | Non-dimensional temperature | Subscript $_\infty$ | Refers to the values of the physical quantities away from the plate |

## 6. ACKNOWLEDGMENTS

Authors are thankful to the reviewers for their valuable suggestions to enhance the quality of the article.

## 7. REFERENCES

[1] Cowling, T.G. (1957): Magnetohydrodynamics, Wiley Inter Science, New York.
[2] Shercliff J.A. (1965): A text book of Magnetohydrodynamics, Pergomon Press, London.
[3] Ferraro V.C.A. and Plumpton C. (1966): An Introduction to Magnetic Fluid Mechanics, Clarandon Press, Oxford.
[4] Crammer K.P. and Pai S.L. (1978): Magneto Fluid Dynamics for Engineers and Applied Physics; Mc. Craw Hill book Co. New York.
[5] F.C. Lai and F.A.Kulacki,*Int. J.Heat Mass Transfer*,(1990),vol.33,No.5P.1028-1031.
[6] Mansour M.A. (1990): Astrophysics and Science, 166, 269-275. DOI: 10.1007/ BF01094898.
[7] Raptis A. and Perdikis C. (1999): Radiation and free convection flow past a moving plate, Applied Mechanics and Engineering, 4, 817-821.
[8] Ganesan P. and Loganathan P. (2002): Radiation and mass transfer effects on flow of an incompressible viscous fluid past a moving vertical cylinder, Int. J. Heat and Mass Transfer, 45, 4281-4288.
[9] Mbeledogu I.U., Amakiri A.R.C. and Ogulu A. (2007): Unsteady MHD free convective flow of a compressible fluid past a moving vertical plate in the presence of radiative heat transfer, Int. J. Heat and Mass Transfer, 50, 1668- 1674.
[10] Makinde O.D. (2005): Free convection flow with thermal radiation and mass transfer past a moving vertical porous plate, Int. Communications in Heat and Mass Transfer, 32, 1411-1419.
[11] Sattar M.A. and Meleque M.A. (2000): Unsteady MHD natural convection flow along an accelerated porous plate with hall current and mass transfer in a rotating porous medium, Journal of Energy, Heat and Mass Transfer, 22, 67-72.
[12] Sattar M.A. and Kalim H. (1996): Unsteady free convection interaction with thermal radiation in a boundary layer flow past a vertical porous plate, Journal of Mathematical Physics, 30, 25-37.
[13] Samad M.A. and Rahman M.M. (2006): Thermal radiation interaction with unsteady MHD flow past a vertical porous plate immersed in a Porous medium, Journal of Naval Architecture and Marine Engineering, 3, 7-14.
[14] Prasad V.R., Reddy, N.B. and Muthucumaraswamy R. (2006): Transient radiative hydromagnetic free convection flow past an impulsively started vertical plate with uniform heat and mass flux, Theoret. Appl. Mech., 33, 31-63.
[15] Takhar H.S., Gorla R.S.R. and Sundalgekar V.M. (1996): Short communication radiation effects on MHD free convection flow of a gas past a semi—infinite vertical plate, Int. J. Numerical Methods Heat Fluid Flow, 6, 77-83.
[16] Ahmed N. and Sarmah H.K. (2009): Thermal radiation effect on a transient MHD flow with mass transfer past an impulsively fixed infinite vertical plate, Int. J. of Appl. Math and Mech., 5(5), 87-98.
[17] Ahmed N. (2012): Soret and Radiation effects on transient MHD free convection from an impulsively started infinite vertical plate, Journal of Heat Transfer, 134/062701-1-9, DOI: 10. 1115/1.4005749.
[18] Seth G.S., Nandkeolyan R. and Ansari M.S. (2011): Effect of Rotation on unsteady hydromagnetic natural convection flow past an impulsively moving vertical plate with ramped temperature in a porous medium with thermal diffusion and heat absorption, Int. J. of Appl. Math and Mech., 7, 52-69.
[19] Apelblat A. (1982): Mass transfer with a chemical reaction of the first order, effect of axial diffusion, The chemical Engineering Journal, 23, 193-203.
[20] Anderson H.I., Hansen O.R. and Holmedal B. (1994): Diffusion of a chemically reactive species from a stretching sheet, International Journal of Heat and Mass Transfer, 37, 659-664.
[21] Chambre P.L. and Young J.D. (1958): On the diffusion of a chemically reacting species in a laminar boundary layer flow, Phys. Fluids Flow, 1, 48-54.
[22] Muthukumaraswami R. (2002): Effect of a chemical reaction on a moving isothermal surface with suction, Acta Mechanica, 155, 65-72.
[23] Muthecumaraswamy R. and Meenakshisundaram S. (2006): Theoretical study of chemical reaction effects on vertical oscillating plate with variable temperature, Theoret. Appl. Mech., 339, 245-257.
[24] Ahmed N., and Sinha S., Effect of Chemical Reaction on a Transient MHD Flow Past an Impulsively Started Vertical Plate with Ramped Temperature and Concentration, Journal of Energy, Heat and Mass Transfer 35 (2013), 252-273
[25] Hazarika G.C. Chemical Reaction on a Transient MHD Flow Past an Impulsively Started Vertical Plate with Ramped Temperature and Concentration with viscous dissipation. International Journal of Fluid Engineering, ISSN-0974-3138.Vol.-6. No.1(2014) pp-39-51
[26] Cogley A.C.L., Vincenti W.G. and Gilles E.S. (1968): Differential approximation for radiative heat transfer in a Grey gas near equilibrium, American Institute of Aeronautics and Astronautics, 6(3), 551-553.