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Unsteady Parabolic MHD Flow past an Infinite Vertical Plate with Variable Temperature in the Presence of Thermal Radiation and Chemical Reaction

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***Abstract*—In this paper we analyse the effect of chemical reaction and thermal radiation on parabolic MHD flow past an infinite vertical plate with variable temperature a uniform magnetic field with variable temperature The non-dimensional equations governing the above flow characteristics are solved by using Laplace Transformation and the effect of different physical parameters on the velocity profile, temperature profile and concentration profile are illustrated graphically**

***Index Terms*— MHD, Chemical reaction, vertical plate, radiation, heat transfer, mass transfer, temperature, velocity Laplace transform method,**

NOMENCLATURE

A	Constants
C'	Species concentration in the fluid $kg\,m^{-3}$
C	Dimensionless concentration
C_p	Specific heat at constant pressure $J.kg^{-1}.k$
D	Mass diffusion coefficient $m^2.s^{-1}$
Gc	Mass Grashof number
Gr	Thermal Grashof number
g	Acceleration due to gravity $m.s^{-2}$
k	Thermal conductivity $W.m^{-1}.K^{-1}$
Pr	Prandtl number
Sc	Schmidt number
T	Temperature of the fluid near the plate K
t'	Time s
u	Velocity of the fluid in the x'-direction $m.s^{-1}$
u_0	Velocity of the plate $m.s^{-1}$
u	Dimensionless velocity
y	Coordinate axis normal to the plate m
Y	Dimensionless coordinate axis normal to the plate

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Greek symbols

β	Volumetric coefficient of thermal expansion K^{-1}
β^*	Volumetric coefficient of expansion with concentration K^{-1}
μ	Coefficient of viscosity $Ra.s$
ν	Kinematic viscosity $m^2.s^{-1}$
ρ	Density of the fluid $kg.m^{-3}$
τ	Dimensionless skin-friction $kg.m^{-1}.s^2$
θ	Dimensionless temperature
η	Similarity parameter
$erfc$	Complementary error function

Subscripts

w	Conditions at the wall
∞	Free stream conditions

I. INTRODUCTION

Flow of electrically conducting fluid past a vertical plate is a widely studied problem in fluid dynamics. The fact that magnetic field has profound influence on boundary layer flow of an electrically conducting fluid, has attracted the attention of researchers due to its various applications in plasma physics, nuclear science, engineering design and space dynamics. Such flows are termed as MHD flows in the broader sense and abundant literature reviews are available concerning MHD convective flow of fluid past a vertical plate. Convective flows with simultaneous heat and mass transfer under the influence of a magnetic field and chemical reaction arise in many transport processes both naturally and artificially in many branches of science and engineering applications. This phenomenon plays an important role in the chemical industry, power and cooling industry for drying, chemical vapour deposition on surfaces, cooling of nuclear reactors and petroleum industries. The study of heat and mass transfer with chemical reaction is of great practical importance in many branches of science and engineering. Chemical reactions can be modeled as either homogeneous or heterogeneous processes. This depends on whether they occur at an interface or as a single phase volume reaction.

A homogeneous reaction is one that occurs uniformly throughout a given phase. On the other hand, a heterogeneous reaction takes place in a restricted area or within the boundary of a phase. Chemical reactions can be modeled as either homogeneous or heterogeneous processes. This depends on whether they occur at an interface or as a single phase volume reaction. A homogeneous reaction is one that occurs uniformly throughout a given phase.

On the other hand, a heterogeneous reaction takes place in a restricted area or within the boundary of a phase. In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself. A reaction is said to be of first order, if the rate of reaction is directly proportional to the concentration itself. In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself. A reaction is said to be of first order, if the rate of reaction is directly proportional to the concentration itself. For example, the formation of smog is a first order homogeneous reaction. Consider the emission of nitrogen dioxide from automobiles and other smoke-stacks. This nitrogen dioxide reacts chemically in the atmosphere with unburned hydrocarbons (aided by sunlight) and produces peroxyacetylnitrate, which forms an envelope which is termed photo-chemical smog.

In several biological and in engineering systems - flow through a channel plays an important role. Some examples in living organisms are fluid transport mechanisms is blood flow in human body, air flow in lungs, flow system for transporting lymph using circulatory system and transpiration of cooling in internal combustion engines. The applications are many and are diversified in their nature. However, the basic concept of fluid transport phenomena remains unchanged. A classical example is in nuclear power station where the separation of Uranium U235 from U238 by gases diffusion. In many chemical and pharmaceutical industries, generally the slurry adheres to the reactor vessels and gets consolidated. As a result of this, the chemical compounds within the reactor vessel percolates through the boundaries causing loss of production and then consuming more reaction time.

Gupta [1] studied free convection on flow past a linearly accelerated vertical plate in the presence of viscous dissipative heat using perturbation method. Kafousias and Raptis [2] extended this problem to include mass transfer effects subjected to variable suction or injection. Free convection effects on flow past an exponentially accelerated vertical plate was studied by Singh and Naveen kumar [3]. The skin friction for accelerated vertical plate has been studied analytically by Hossain and Shayo [4]. Basant kumar Jha [5] studied MHD free convection and mass transform flow through a porous medium. Later Basant kumar Jha et al. [6] analyzed mass transfer effects on exponentially accelerated infinite vertical plate with constant heat flux and uniform mass diffusion. Recently Muthucumaraswamy et al. [7] studied mass transfer effects on exponentially accelerated isothermal vertical plate.

MHD effects on impulsively started vertical infinite plate with variable temperature in the presence of transverse magnetic field were studied by Soundalgekar et al. [8]. The effects of transversely applied magnetic field, on the flow of an electrically conducting fluid past an impulsively started infinite isothermal vertical plate were also studied by Soundalgekar et al. [9]. The radiative free convection flow of an optically thin gray-gas past semi-infinite vertical plate studied by Soundalgekar and Takhar.[10]. Hossain and Takhar have considered radiation effects on mixed convection along an isothermal vertical plate [11]. In all above studies the stationary vertical plate considered. Raptis and Perdikis [12] studied the effects of thermal-radiation and free convection flow past a moving vertical plate. The governing equations were solved analytically. Das et al [13] have considered radiation effects on flow past an impulsively started infinite isothermal vertical plate. The governing equations were solved by the Laplace transform technique. Muthucumaraswamy and Janakiraman [14] have studied MHD and radiation effects on moving isothermal vertical plate with variable mass diffusion.

It is proposed to study the effects of MHD flow past a parabolic flow past a starting motion of the infinite vertical plate in the presence of thermal radiation and chemical reaction. The dimensionless governing equations are solved using the Laplace transform technique. The solutions are in terms of exponential and complementary error function. Graphical results for the velocity, temperature and concentration profiles based on the numerical solutions are presented and discussed.

II. MATHEMATICAL ANALYSIS

In this paper, we consider a homogeneous first order chemical reaction between the fluid and species concentration to study radiation effects on unsteady parabolic MHD free convection flow of a viscous incompressible, electrically, conducting, radiating fluid past an infinite vertical plate with variable temperature in the presence of transverse applied magnetic field. The x' -axis is taken along the plate in the vertically upward direction and the y -axis is taken normal to the plate. At time $t' \leq 0$, the plate and fluid are at the same temperature T_∞ and concentration C'_∞ .At time $t' > 0$, the plate is started with a velocity $u = u_0 t'^2$ in its own plane against gravitational field. The temperature from the plate is raised to T_w and the concentration level near the plate are also raised to C'_w. A chemically reactive species which transforms according to a simple reaction involving the concentration is emitted from the plate and diffuses into the fluid. The plate is also subjected to a uniform magnetic field of strength B_0 is assumed to be applied normal to the plate. The reaction is assumed to take place entirely in the stream.

i. The induced magnetic field is assumed to be negligible as the magnetic Reynolds number of the flow is taken to be very small.
ii. The viscous dissipation is neglected in the energy equation.

iii. The effects of variation in density (ρ) with temperature and species concentration are considered only on the body force term, in accordance with usual Boussinesq approximation

iv. The fluid considered here is gray, absorbing / emitting radiation but a non-scattering medium.

v. Since the flow of the fluid is assumed to be in the direction of *x*- axis, so the physical quantities are functions of the space co-ordinate *y* and t' only.

Then under usual Boussinesq's approximation for unsteady parabolic starting motion is governed by the following equations:

$$\frac{\partial u}{\partial t'} = g\beta(T - T_\infty) + g\beta^*(C' - C'_\infty) + \nu\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}u \qquad (1)$$

$$\rho C_p \frac{\partial T}{\partial t'} = k\frac{\partial^2 T}{\partial y^2} - \frac{\partial q_r}{\partial y} \qquad (2)$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y^2} - k_l(C' - C'_\infty) \qquad (3)$$

With the following initial and boundary conditions:

$$\left.\begin{array}{l} u = 0,\ T = T_\infty,\quad C' = C'_\infty \ \text{ for all } \ y, t' \le 0 \\ t' > 0: u = u_0 t'^2, T = T_w, C' = C'_\infty + (C'_w - C'_\infty)At' \ \text{ at } y = 0 \\ u \to 0, T \to T_\infty,\ C' \to C'_\infty \quad \text{as} \quad y \to \infty \end{array}\right\} \qquad (4)$$

Where, $A = \left(\frac{u_0^2}{\nu}\right)^{\frac{1}{3}}$

The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial y} = -4a^*\sigma(T_\infty^4 - T^4) \qquad (5)$$

It is assumed that the temperature differences within the flow are sufficiently small such that T^4 may be expressed as a linear function of the temperature. This is accomplished by expanding T^4 in a Taylor series about T_∞ and neglecting higher-order terms, thus

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \qquad (6)$$

By using equations (5) and (6), equation (2) reduces to

$$\rho C_p \frac{\partial T}{\partial t'} = k\frac{\partial^2 T}{\partial y^2} + 16a^*\sigma T_\infty^3 (T_\infty - T) \qquad (7)$$

On introducing the following non-dimensional quantities:

$$\left.\begin{array}{l} U = u\left(\frac{u_0}{\nu^2}\right)^{1/3},\quad t = \left(\frac{u_0^2}{\nu}\right)^{1/3} t',\quad Y = y\left(\frac{u_0}{\nu^2}\right)^{1/3}, \\ \theta = \frac{T - T_\infty}{T_w - T_\infty}, C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, Gr = \frac{g\beta(T_w - T_\infty)}{(\nu . u_0)^{1/3}}, \\ Gc = \frac{g\beta(C'_w - C'_\infty)}{(\nu . u_0)^{1/3}},\ R = \frac{16a^*\sigma . T_\infty^3}{k}\left(\frac{\nu^2}{u_0}\right)^{\frac{2}{3}}, \\ K = K_l\left(\frac{\nu}{u_0^2}\right)^{\frac{1}{3}}, M = \frac{\sigma B_0^2}{\rho}\left(\frac{\nu}{u_0^2}\right)^{\frac{1}{3}}, \Pr = \frac{\mu C_p}{k}, Sc = \frac{\nu}{D} \end{array}\right\} \qquad (8)$$

The equations (1), (3) and (7) reduces to the following dimensionless form

$$\frac{\partial U}{\partial t} = Gr\theta + GcC + \frac{\partial^2 U}{\partial Y^2} - MU \qquad (9)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial Y^2} - \frac{R}{\Pr}\theta \qquad (10)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial Y^2} - KC \qquad (11)$$

The corresponding initial and boundary conditions in non-dimension quantities are

$$\left.\begin{array}{l} U = 0, \theta = 0, C = 0 \ \text{ for all } \ Y, t \le 0 \\ t > 0:\ U = t^2, \theta = 1,\ C = t \ \text{ at } \ Y = 0 \\ U \to 0, \theta \to 0,\ C \to 0 \ \text{ as } \ Y \to \infty \end{array}\right\} \qquad (12)$$

III. SOLUTION PROCEDURE

The solutions are in terms of exponential and complementary error function. The relation connecting error function and its complementary error function is as follows

$$erfc(x) = 1 - erf(x)$$

The dimensionless governing equations (9) to (11) and the corresponding initial and boundary conditions (12) are solved by using Laplace transform technique and the solutions are derived as follows

$$\theta = \frac{1}{2}\left[\begin{array}{l} \exp\left(2\eta\sqrt{\Pr at}\right)erfc\left(\eta\sqrt{\Pr} + \sqrt{at}\right) \\ + \exp\left(-2\eta\sqrt{\Pr at}\right)erfc\left(\eta\sqrt{\Pr} - \sqrt{at}\right) \end{array}\right]$$

$$C = \frac{t}{2}\left[\begin{array}{l} \exp\left(2\eta\sqrt{Sc\,K\,t}\right)erfc\left(\eta\sqrt{Sc} + \sqrt{Kt}\right) \\ + \exp\left(-2\eta\sqrt{Sc\,K\,t}\right)erfc\left(\eta\sqrt{Sc} - \sqrt{Kt}\right) \end{array}\right] - \frac{\eta\sqrt{Sc}\sqrt{t}}{2\sqrt{K}}\left[\begin{array}{l} \exp\left(-2\eta\sqrt{Sc\,K\,t}\right)erfc\left(\eta\sqrt{Sc} - \sqrt{Kt}\right) \\ - \exp\left(2\eta\sqrt{Sc\,K\,t}\right)erfc\left(\eta\sqrt{Sc} + \sqrt{Kt}\right) \end{array}\right]$$

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$$
\begin{aligned}
U = 2\Bigg(& \frac{(\eta^2 + M\,t)t}{4M}\left[\begin{array}{l}\exp\left(2\eta\sqrt{M\,t}\right) erfc\left(\eta+\sqrt{M\,t}\right)\\ +\exp\left(-2\eta\sqrt{M\,t}\right) erfc\left(\eta-\sqrt{M\,t}\right)\end{array}\right] + \frac{\eta\sqrt{t}\,(1-4M\,t)}{8M^{3/2}} \\
& \left[\begin{array}{l}\exp\left(-2\eta\sqrt{M\,t}\right) erfc\left(\eta-\sqrt{M\,t}\right)\\ -\exp\left(2\eta\sqrt{M\,t}\right) erfc\left(\eta+\sqrt{M\,t}\right)\end{array}\right] - \frac{\eta t}{2M\sqrt{\pi}}\exp(-(\eta^2 + M\,t)) \Bigg) \\
& +\mathrm{d}\Bigg(\frac{1}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{Mt}\right) erfc\left(\eta+\sqrt{Mt}\right)\\ +\exp\left(-2\eta\sqrt{Mt}\right) erfc\left(\eta-\sqrt{Mt}\right)\end{array}\right] \\
& -\frac{\exp(bt)}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{(M+b)t}\right) erfc\left(\eta+\sqrt{(M+b)t}\right)\\ +\exp\left(-2\eta\sqrt{(M+b)t}\right) erfc\left(\eta-\sqrt{(M+b)t}\right)\end{array}\right] \\
& -\frac{1}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{\Pr a\,t}\right) erfc\left(\eta\sqrt{\Pr}+\sqrt{a\,t}\right)\\ +\exp\left(-2\eta\sqrt{\Pr a\,t}\right) erfc\left(\eta\sqrt{\Pr}-\sqrt{a\,t}\right)\end{array}\right] \\
& +\frac{\exp(bt)}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{\Pr(a+b)t}\right) erfc\left(\eta\sqrt{\Pr}+\sqrt{(a+b)t}\right)\\ +\exp\left(-2\eta\sqrt{\Pr(a+b)t}\right) erfc\left(\eta\sqrt{\Pr}-\sqrt{(a+b)t}\right)\end{array}\right]\Bigg) \\
& +\mathrm{e}\Bigg(\frac{1}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{Mt}\right) erfc\left(\eta+\sqrt{Mt}\right)\\ +\exp\left(-2\eta\sqrt{Mt}\right) erfc\left(\eta-\sqrt{Mt}\right)\end{array}\right] \\
& -\frac{\exp(ct)}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{(M+c)t}\right) erfc\left(\eta+\sqrt{(M+c)t}\right)\\ +\exp\left(-2\eta\sqrt{(M+c)t}\right) erfc\left(\eta-\sqrt{(M+c)t}\right)\end{array}\right] \\
& -\frac{1}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{Sc\,K\,t}\right) erfc\left(\eta\sqrt{Sc}+\sqrt{Kt}\right)\\ +\exp\left(-2\eta\sqrt{Sc\,K\,t}\right) erfc\left(\eta\sqrt{Sc}-\sqrt{Kt}\right)\end{array}\right] \\
& +\frac{\exp(ct)}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{Sc(K+c)t}\right) erfc\left(\eta\sqrt{Sc}+\sqrt{(K+c)t}\right)\\ +\exp\left(-2\eta\sqrt{Sc(K+c)t}\right) erfc\left(\eta\sqrt{Sc}-\sqrt{(K+c)t}\right)\end{array}\right]\Bigg) \\
& +e\Bigg(c\Bigg(\frac{t}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{M\,t}\right) erfc\left(\eta+\sqrt{M\,t}\right)\\ +\exp\left(-2\eta\sqrt{M\,t}\right) erfc\left(\eta-\sqrt{M\,t}\right)\end{array}\right] \\
& -\frac{\eta\sqrt{t}}{2\sqrt{M}}\left[\begin{array}{l}\exp\left(-2\eta\sqrt{M\,t}\right) erfc\left(\eta-\sqrt{M\,t}\right)\\ -\exp\left(2\eta\sqrt{M\,t}\right) erfc\left(\eta+\sqrt{M\,t}\right)\end{array}\right] \\
& -\frac{t}{2}\left[\begin{array}{l}\exp\left(2\eta\sqrt{Sc\,K\,t}\right) erfc\left(\eta\sqrt{Sc}+\sqrt{Kt}\right)\\ +\exp\left(-2\eta\sqrt{Sc\,K\,t}\right) erfc\left(\eta\sqrt{Sc}-\sqrt{Kt}\right)\end{array}\right] \\
& +\frac{\eta\sqrt{Sc}\sqrt{t}}{2\sqrt{K}}\left[\begin{array}{l}\exp\left(-2\eta\sqrt{Sc\,K\,t}\right) erfc\left(\eta\sqrt{Sc}-\sqrt{Kt}\right)\\ -\exp\left(2\eta\sqrt{Sc\,K\,t}\right) erfc\left(\eta\sqrt{Sc}+\sqrt{Kt}\right)\end{array}\right]\Bigg)\Bigg)
\end{aligned}
$$

Where $a = \dfrac{R}{\Pr}$, $b = \dfrac{R-M}{1-\Pr}$, $c = \dfrac{ScK-M}{1-Sc}$,

$d = \dfrac{Gr}{b(1-\Pr)}$, $e = \dfrac{Gc}{c^2(1-Sc)}$ and $\eta = \dfrac{y}{2\sqrt{t}}$

IV. RESULTS AND DISCUSSION

The numerical values of the velocity, temperature and concentration are computed for different physical parameters like magnetic field parameter, thermal radiation parameter, chemical reaction parameter, Schmidt number, thermal Grashof number and mass Grashof number and *t*. The value of the Schmidt number *Sc* is taken to be 0.6 which corresponds to water-vapor. Also, the value of Prandtl number *Pr* are chosen such that they represent air (*Pr* =0.71). The solutions are in terms of exponential and complementary error function. Figure.1 illustrates the effects of the magnetic field parameter on velocity when (M = 2, 4, 7,) R=K=10, Gr=2, Gc =5 and t=0.2. It is observed that velocity increases with decreasing values of the magnetic field parameter. This shows that the increase in the magnetic field parameter leads to a fall in velocity. Figure.2 illustrates the effect of the velocity for different values of the chemical reaction parameter (K=2, 10, 20), R=4, M=2, Gr=2, Gc =5 and t=0.4. The trend shows that the velocity increases with decreasing chemical reaction parameter. The effect of velocity for different values of the radiation parameter (R=5, 10, 15), Gc=5,Gr=5,K=2 M=2 and t=0.4 are shown in figure 3. The trend shows that the velocity increases with decreasing radiation parameter. It is observed that the velocity decreases in the presence of high thermal radiation. Figure.4 demonstrates the effects of different thermal Grashof number (Gr = 2, 5), mass Grashof number (Gc = 5,10), K=2 , M=2 and R=4, on the velocity at t = 0.4. It is observed that the velocity increases with increasing values of the thermal Grashof number or mass Grashof number. Figure.5 represents the effect of velocity profiles for different Schmidt number (Sc = 0.16, 0.3, 0.6,), Gr = 2, Gc= 5, K = 2, K=2, M=2, R=4, and t = 0.4. The trend shows that the velocity increases with decreasing Schmidt number. It is observed that the relative variation of the velocity with the magnitude of the Schmidt number. Figure.6 demonstrates the velocity profiles for different values of time(t = 0.4,0.6,0.8), K= 2,Gr = 2,Gc=5,R=4 and M=2 are studied and presented in. It is observed that velocity increases with increasing values of time t. Figure.7 illustrates concentration profiles calculated for different values of Schmidt number (Sc=0.16, 0.3, 0.6), *K=2* and t=0.4. The profiles have the common feature that the concentration decreases in a monotone fashion from the surface to a zero value far away in the free stream. It is observed that the concentration increases with the decreasing Schmidt number. It is observed that the wall concentration increases with decreasing values of the Schmidt number. The temperature profiles calculated for different values of time (t = 0.2, 0.4, 0.6 and 1) are shown in Figure 8. The effect of a thermal radiation parameter is important in temperature profiles. It is observed that the temperature increases with increasing the time t.

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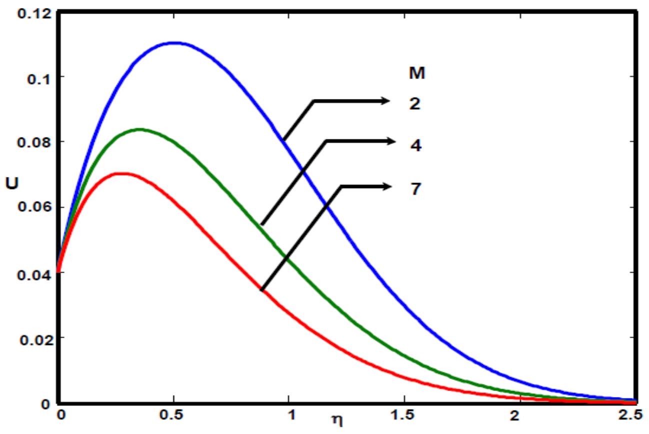

Figure 1. Velocity profiles for different M

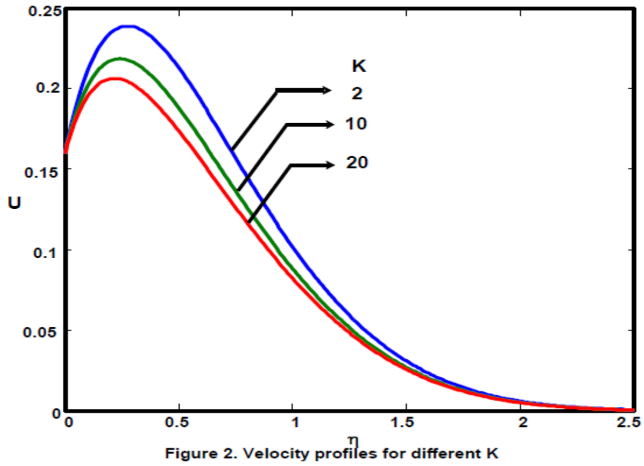

Figure 2. Velocity profiles for different K

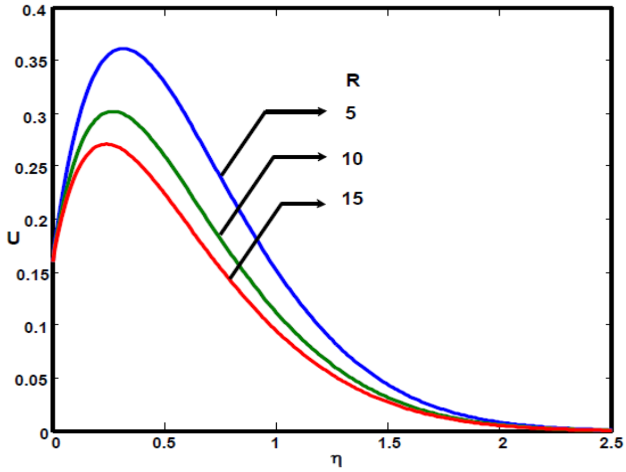

Figure 3. Velocity profiles for different R

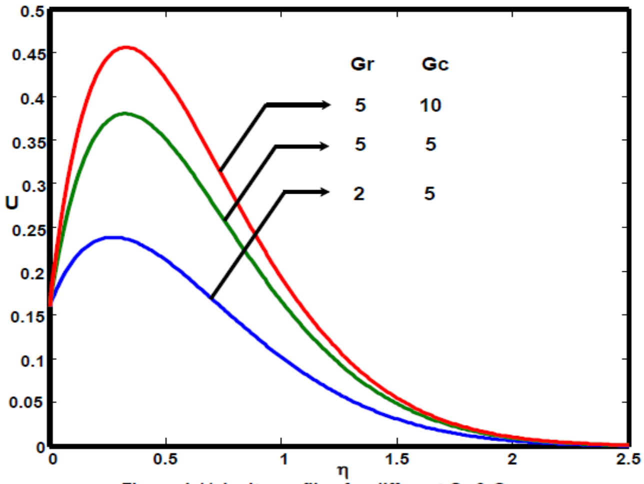

Figure 4. Velocity profiles for different Gr & Gc

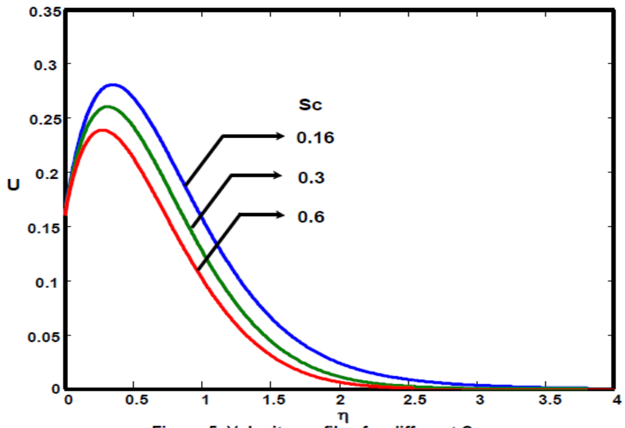

Figure 5. Velocity profiles for different Sc

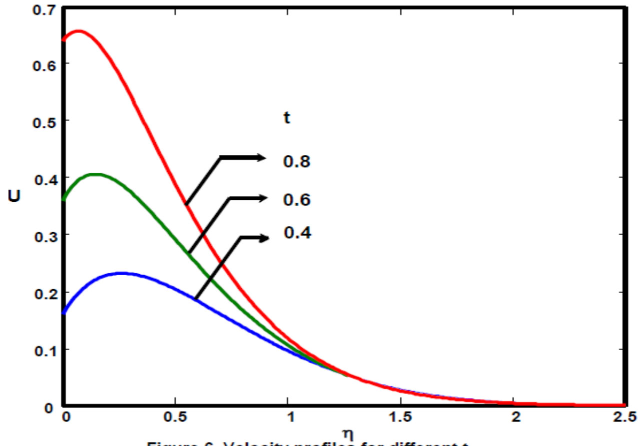

Figure 6. Velocity profiles for different t

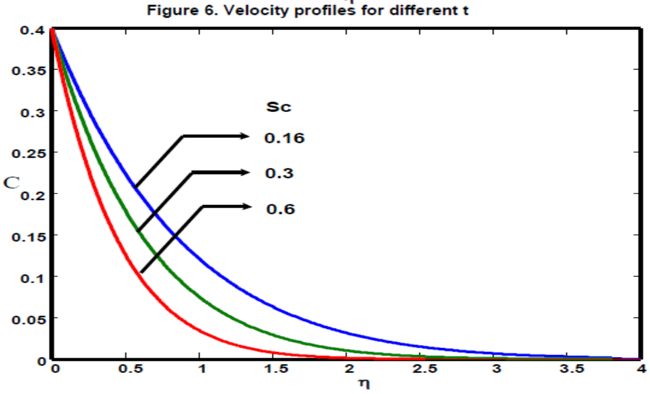

Figure 7.Concentration profiles for several Sc

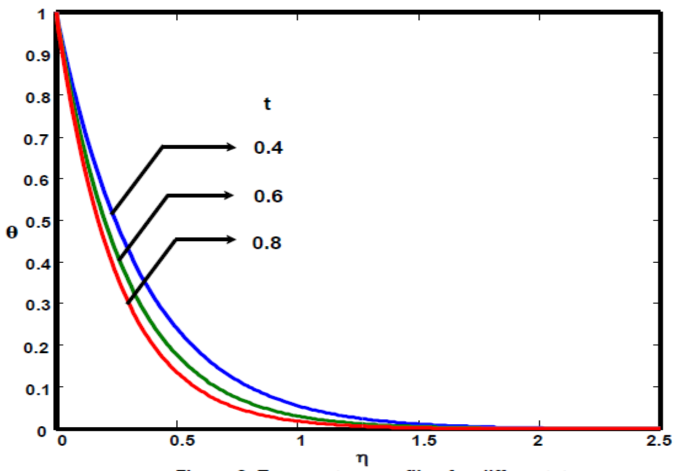

Figure 8. Temperature profiles for different t

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V. CONCLUSION

Theoretical solution of hydro magnetic thermal radiation and chemical reaction effects on unsteady parabolic flow past an infinite vertical plate with variable temperature has been studied in detail. The dimensionless equations are solved using Laplace transform technique. The effect of velocity, temperature and concentration for different parameters like M, R. K, Sc, Gr, Gc and t are studied. The study concludes that the velocity increases with decreasing magnetic field parameter or radiation parameter. It is also observed that the velocity increases with increasing thermal Grashof number or mass Grashof number.

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