

ROTATION EFFECTS ON FLOW PAST AN ACCELERATED ISOTHERMAL  
VERTICAL PLATE WITH CHEMICAL REACTION OF FIRST ORDER

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ABSTRACT

An exact analysis of rotation effects on unsteady flow of an incompressible and electrically conducting fluid past a uniformly accelerated infinite isothermal vertical plate, under the action of transversely applied magnetic field has been presented. The plate temperature is raised to  $T_w$  and the concentration level near the plate is also raised to  $C'_w$ . The dimensionless governing equations are solved using Laplace-transform technique. The velocity profiles, temperature and concentration are studied for different physical parameters like magnetic field parameter, chemical reaction parameter, thermal Grashof number, mass Grashof number, Schmidt number, Prandtl number and time. It is observed that the velocity increases with increasing values of thermal Grashof number or mass Grashof number. It is also observed that the velocity increases with decreasing magnetic field parameter or rotation parameter  $\Omega$ .

**Keywords:** Rotation, accelerated, isothermal, vertical plate, heat transfer, mass diffusion, magnetic field, chemical reaction

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1. INTRODUCTION

The influence of magnetic field on viscous incompressible flow of electrically conducting fluid has its importance in many applications such as extrusion of plastics in the manufacture of rayon and nylon, purification of crude oil, pulp, paper industry, textile industry and in different geophysical cases etc. In many process industries, the cooling of threads or sheets of some polymer materials is of importance in the production line. The rate of cooling can be controlled effectively to achieve final products of desired characteristics by drawing threads, etc. in the presence of an electrically conducting fluid subject to a magnetic field.

MHD plays an important role in agriculture, petroleum industries, geophysics and in astrophysics. Important applications in the study of geological formations, in exploration and thermal recovery of oil, and in the assessment of aquifers, geothermal reservoirs and underground nuclear waste storage sites. MHD flow has application in metrology, solar physics and in motion of earth's core. Also it has applications in the field of stellar and planetary magnetospheres, aeronautics, chemical engineering and electronics. In the field of power generation, MHD is receiving considerable attention due to the possibilities it offers for much higher thermal efficiencies in power plants.

Gupta et al [5] studied free convection on flow past a linearly accelerated vertical plate in the presence of viscous dissipative heat using perturbation method. Kafousias and Raptis [6] extended the above problem to include mass transfer effects subjected to variable suction or injection. Free convection effects on flow past an accelerated vertical plate with variable suction and uniform heat flux in the presence of magnetic field was studied by Raptis al [9].

MHD effects on flow past an infinite vertical plate for both the classes of impulse as well as accelerated motion of the plate was studied by Raptis and Singh [7]. Mass transfer effects on flow past a uniformly accelerated vertical plate was studied by Soundalgekar [11]. Basant Kumar Jha and Ravindra Prasad [1] analyzed mass transfer effects on the flow past an accelerated infinite vertical plate with heat sources. Singh [10] studied MHD flow past an impulsively started vertical plate in a rotating fluid. Rotation effects on hydromagnetic free convective flow past an accelerated isothermal vertical plate was studied by Raptis and Singh [8]. Recently, the rotation effects on flow past a vertical plate in the presence of thermal radiation was analyzed by Vijayalakshmi [12].

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Chemical reactions can be codified as either heterogeneous or homogeneous processes. This depends on whether they occur at an interface or as a single phase volume reaction. In well-mixed systems, the reaction is heterogeneous, if it takes place at an interface and homogeneous, if it takes place in solution. 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. Chambre and Young [2] have analyzed a first order chemical reaction in the neighborhood of a horizontal plate. Das et al[3] have studied the effect of homogeneous first order chemical reaction on the flow past an impulsively started infinite vertical plate with uniform heat flux and mass transfer. Again, mass transfer effects on moving isothermal vertical plate in the presence of chemical reaction studied by Das et al [4]. The dimensionless governing equations were solved by the usual Laplace-transform technique.

Hence, it is proposed to study the effects of rotation on the hydromagnetic free-convection flow of an incompressible viscous and electrically conducting fluid past a uniformly accelerated infinite isothermal vertical plate with uniform mass diffusion, in the presence of chemical reaction of first order. The dimensionless governing equations are solved using the Laplace-transform technique. The solutions are in terms of exponential and complementary error function. Such a study is found useful in magnetic control of molten iron flow in the steel industry, liquid metal cooling in nuclear reactors, magnetic suppression of molten semi-conducting materials and meteorology.

## 2. GOVERNING EQUATIONS

Consider the unsteady hydromagnetic flow of an electrically conducting fluid induced by viscous incompressible fluid past a uniformly accelerated motion of an isothermal vertical infinite plate when the fluid and the plate rotate as a rigid body with a uniform angular velocity  $\Omega'$  about  $z'$ -axis in the presence of an imposed uniform magnetic field  $B_0$  normal to the plate. Initially, the temperature of the plate and concentration near the plate are assumed to be  $T_\infty$  and  $C'_\infty$ . At time  $t' > 0$ , the plate starts moving with a velocity  $u = u_0 t'$  in its own plane and the temperature from the plate is raised to  $T_w$  and the concentration level near the plate are also raised to  $C'_w$ . Since the plate occupying the plane  $z' = 0$  is of infinite extent, all the physical quantities depend only on  $z'$  and  $t'$ . It is assumed that the induced magnetic field is negligible so that  $\vec{B} = (0, 0, B_0)$ . Then the unsteady flow is governed by free-convective flow of an electrically conducting fluid in a rotating system under the usual Boussinesq's approximation in dimensionless form are as follows:

$$\frac{\partial U}{\partial t} - 2\Omega V = Gr\theta + GcC + \frac{\partial^2 U}{\partial Z^2} - MU \quad (1)$$

$$\frac{\partial V}{\partial t} + 2\Omega U = \frac{\partial^2 V}{\partial Z^2} - MV \quad (2)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr} \frac{\partial^2 \theta}{\partial Z^2} \quad (3)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc} \frac{\partial^2 C}{\partial Z^2} - KC \quad (4)$$

With the following initial and boundary conditions:

$$\begin{aligned} u = 0, \quad T = T_\infty, \quad C' = C'_\infty \quad \text{for all } y, t' \leq 0 \\ t' > 0: \quad u = u_0 t', \quad T = T_w, \quad C' = C'_w \quad \text{at } y = 0 \\ u \rightarrow 0, \quad T \rightarrow T_\infty, \quad C' \rightarrow C'_\infty \quad \text{as } y \rightarrow \infty \end{aligned} \quad (5)$$

On introducing the following non-dimensional quantities:

$$U = \frac{u}{(vu_0)^{1/3}}, \quad V = \frac{v}{(vu_0)^{1/3}}, \quad t = t' \left( \frac{u_0^2}{v} \right)^{1/3}, \quad Z = z' \left( \frac{u_0}{v^2} \right)^{1/3}, \quad (6)$$

$$\theta = \frac{T - T_\infty}{T_w - T_\infty}, \quad Gr = \frac{g\beta(T_w - T_\infty)}{u_0}, \quad C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \quad Gc = \frac{g\beta^* (C'_w - C'_\infty)}{u_0}$$

$$M = \frac{\sigma B_0^2}{\rho} \left( \frac{v}{u_0^2} \right)^{1/3}, \quad Pr = \frac{\mu C_p}{k}, \quad Sc = \frac{v}{D}, \quad K = K_l \left( \frac{v}{u_0^2} \right)^{1/3}$$

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

The hydromagnetic rotating free-convection flow past an accelerated vertical plate is described by coupled partial differential equations (1) to (4) with the prescribed boundary conditions (5). To solve the equations (1) and (2), we introduce a complex velocity  $q = U + iV$ , equations (1) and (2) can be combined into a single equation:

$$\frac{\partial q}{\partial t} = Gr\theta + GcC + \frac{\partial^2 q}{\partial Z^2} - mq \tag{7}$$

The initial and boundary conditions in non-dimensional quantities are

$$\begin{aligned} q = 0, \quad \theta = 0, \quad C = 0 \quad \text{for all } Z, t \leq 0 \\ t > 0: \quad q = t, \quad \theta = 1, \quad C = 1 \quad \text{at } Z = 0 \\ q \rightarrow 0, \quad \theta \rightarrow 0, \quad C \rightarrow 0 \quad \text{as } Z \rightarrow \infty \end{aligned} \tag{8}$$

Where,  $m = M + 2i\Omega$ .

### 3. METHOD OF SOLUTION

The dimensionless governing equations (3),(4) and (7), subject to the initial and boundary conditions (8), are solved by the usual Laplace-transform technique and the solutions are derived as follows:

$$\begin{aligned} q = & \left( \frac{t}{2} + c + d \right) \left[ \exp(2\eta\sqrt{mt}) \operatorname{erfc}(\eta + \sqrt{mt}) + \exp(-2\eta\sqrt{mt}) \operatorname{erfc}(\eta - \sqrt{mt}) \right] \\ & - \frac{\eta\sqrt{t}}{2\sqrt{m}} \left[ \exp(-2\eta\sqrt{mt}) \operatorname{erfc}(\eta - \sqrt{mt}) - \exp(2\eta\sqrt{mt}) \operatorname{erfc}(\eta + \sqrt{mt}) \right] \\ & - 2c \operatorname{erfc}(\eta\sqrt{\operatorname{Pr}}) - c \exp(at) \left[ \exp(2\eta\sqrt{(m+a)t}) \operatorname{erfc}(\eta + \sqrt{(m+a)t}) + \exp(-2\eta\sqrt{(m+a)t}) \operatorname{erfc}(\eta - \sqrt{(m+a)t}) \right] \\ & - d \exp(bt) \left[ \exp(2\eta\sqrt{(m+b)t}) \operatorname{erfc}(\eta + \sqrt{(m+b)t}) + \exp(-2\eta\sqrt{(m+b)t}) \operatorname{erfc}(\eta - \sqrt{(m+b)t}) \right] \\ & + c \exp(at) \left[ \exp(2\eta\sqrt{a\operatorname{Pr}t}) \operatorname{erfc}(\eta\sqrt{\operatorname{Pr}} + \sqrt{at}) + \exp(-2\eta\sqrt{a\operatorname{Pr}t}) \operatorname{erfc}(\eta\sqrt{\operatorname{Pr}} - \sqrt{at}) \right] \\ & + d \exp(bt) \left[ \exp(2\eta\sqrt{Sc(K+b)t}) \operatorname{erfc}(\eta\sqrt{Sc} + \sqrt{(K+b)t}) + \exp(-2\eta\sqrt{Sc(K+b)t}) \operatorname{erfc}(\eta\sqrt{Sc} - \sqrt{(K+b)t}) \right] \\ & - d \left[ \exp(2\eta\sqrt{KtSc}) \operatorname{erfc}(\eta\sqrt{Sc} + \sqrt{Kt}) + \exp(-2\eta\sqrt{KtSc}) \operatorname{erfc}(\eta\sqrt{Sc} - \sqrt{Kt}) \right] \end{aligned} \tag{9}$$

$$\theta = \operatorname{erfc}(\eta\sqrt{\operatorname{Pr}}) \tag{10}$$

$$C = \frac{1}{2} \left[ \exp(2\eta\sqrt{KtSc}) \operatorname{erfc}(\eta\sqrt{Sc} + \sqrt{Kt}) + \exp(-2\eta\sqrt{KtSc}) \operatorname{erfc}(\eta\sqrt{Sc} - \sqrt{Kt}) \right] \tag{11}$$

where  $a = \frac{m}{\operatorname{Pr}-1}$ ,  $b = \frac{m-KSc}{Sc-1}$ ,  $c = \frac{Gr}{2a(1-\operatorname{Pr})}$ ,  $d = \frac{Gc}{2b(1-Sc)}$  and  $\eta = \frac{Z}{2\sqrt{t}}$

In order to get the physical insight into the problem, the numerical values of  $q$  have been computed from (9). While evaluating this expression, it is observed that the argument of the error function is complex and, hence, we have separated it into real and imaginary parts by using the following formula:

$$\operatorname{erf}(a+ib) = \operatorname{erf}(a) + \frac{\exp(-a^2)}{2a\pi} [1 - \cos(2ab) + i \sin(2ab)] + \frac{2 \exp(-a^2)}{\pi} \sum_{n=1}^{\infty} \frac{\exp(-n^2/4)}{n^2 + 4a^2} [f_n(a,b) + i g_n(a,b)] + \epsilon(a,b)$$

Where,  $f_n = 2a - 2a \cosh(nb) \cos(2ab) + n \sinh(nb) \sin(2ab)$

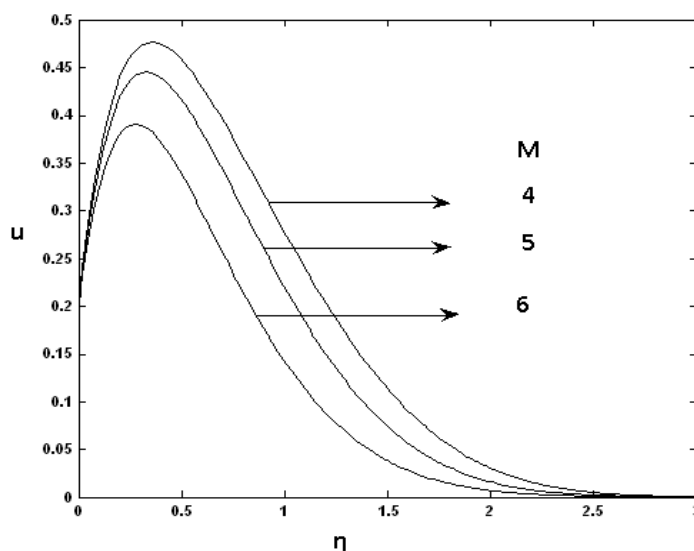
$g_n = 2a \cosh(nb) \sin(2ab) + n \sinh(nb) \cos(2ab)$

$|\epsilon(a,b)| \approx 10^{-16} |\operatorname{erf}(a+ib)|$

## RESULTS AND DISCUSSION

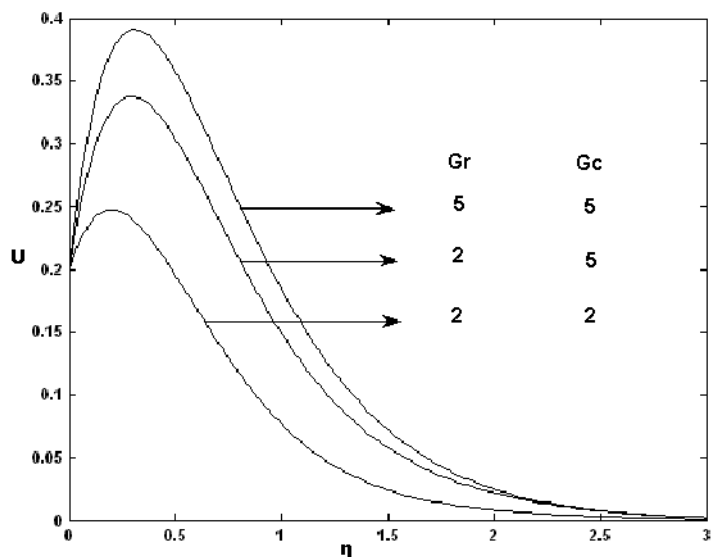
For physical understanding of the problem, numerical computations are carried out for different physical parameters Gr, Gc, Sc, Pr, m and t upon the nature of the flow and transport. The value of the Schmidt number Sc is taken to be 0.6 which correspond to water-vapor. Also, the values of Prandtl number Pr are chosen such that they represent air (Pr = 0.71) and water (Pr = 7.0). The numerical values of the velocity, temperature and concentration fields are computed for different physical parameters like Prandtl number, rotation parameter, magnetic field parameter, thermal Grashof number, mass Grashof number, Schmidt number and time.

Figure 1. Illustrates the effects of the magnetic field parameter on the velocity when (M = 4, 5, 6), Gr = Gc = 5,  $\Omega = 0.2$ , K=8, Pr = 7 and t = 0.2. It is observed that the 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 the velocity. This agrees with the expectations, since the magnetic field exerts a retarding force on the free convective flow.



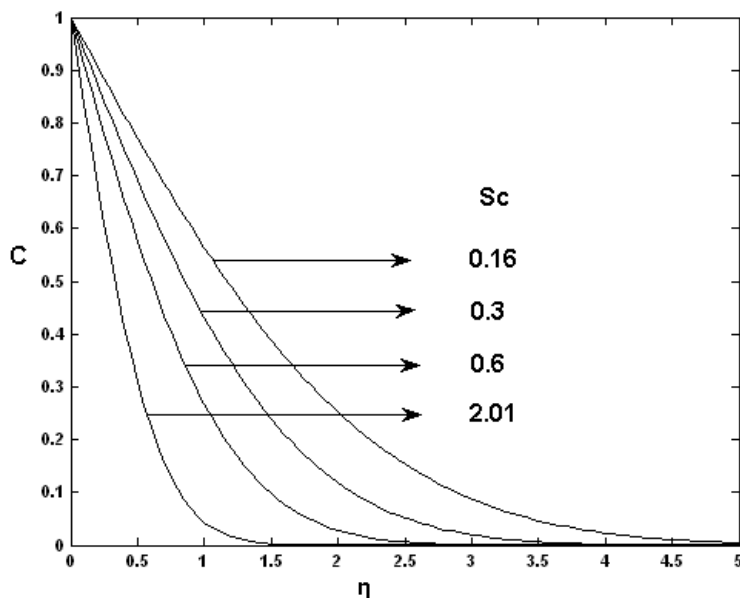
**Figure1. Primary Velocity Profiles for different M**

Figure 2. Demonstrates the effects of different thermal Grashof number (Gr = 2, 5), mass Grashof number (Gc = 2, 5), M = 1, K=8,  $\Omega = 0.1$ , Pr = 7 on the primary velocity at time t = 0.2. It is observed that the velocity increases with increasing values of the thermal Grashof number or mass Grashof number.



**Figure 2. Primary Velocity Profiles for different Gr and Gc**

Figure 3 represents the effect of concentration profiles for different Schmidt number ( $Sc = 0.16, 0.3, 0.6, 2.01$ ),  $K=0.2$  and  $t=0.2$ . The effect of concentration is important in concentration field. 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 wall concentration increases with decreasing values of the Schmidt number.



**Figure 3. Concentration Profiles for different Sc**

The temperature profiles are calculated for water and air from equation (10) and these are shown in Figure 4. The effect of the Prandtl number plays an important role in temperature field. It is observed that the temperature increases with decreasing Prandtl number. This shows that the heat transfer is more in air than in water.

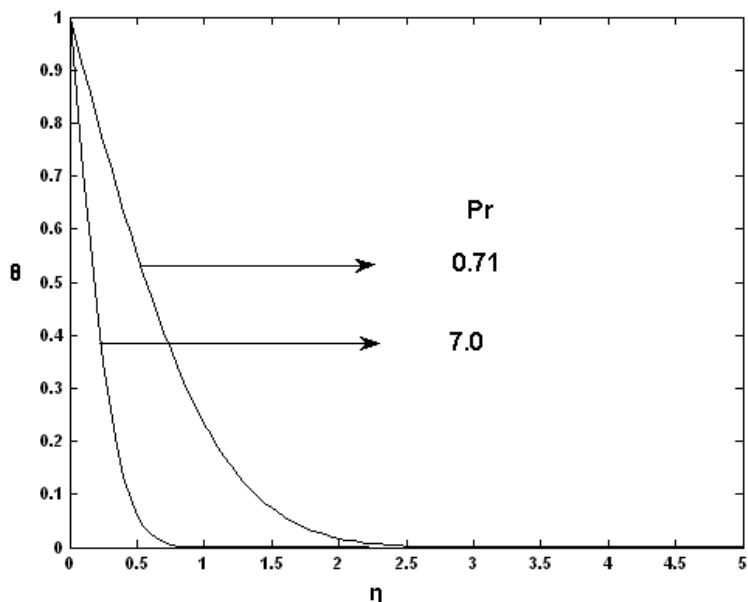


Figure 4. Temperature Profiles for different Pr

The concentration field for different values of chemical reaction parameter ( $K=0.2, 2, 5$ ) and  $t=0.6$  are shown in Figure 5. The trend shows that the wall concentration increases with decreasing values of the chemical reaction parameter  $K$ .

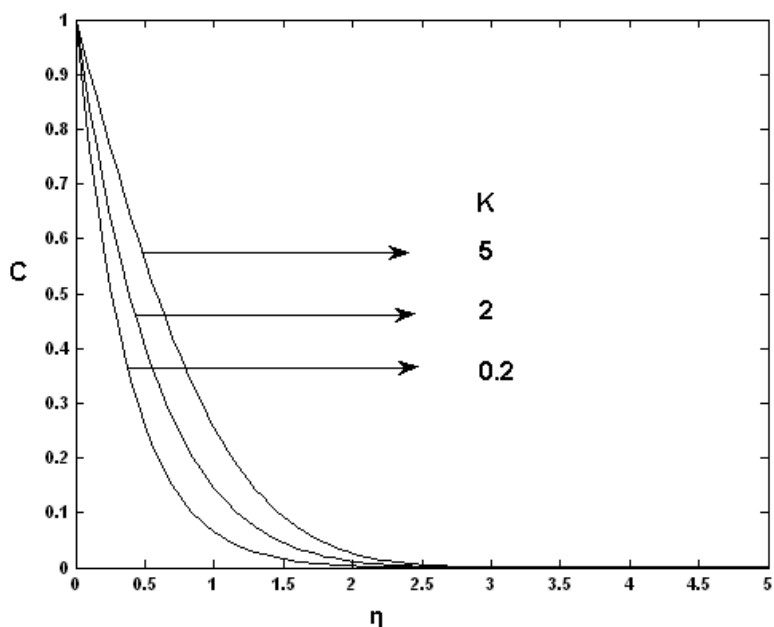


Figure 5. Concentration Profiles for different K

The secondary velocity profiles for different thermal Grashof number ( $Gr = 2, 5$ ), mass Grashof number ( $Gc = 2, 5$ ),  $\Omega = 0.3$ ,  $M = 2$ ,  $Pr = 7$  and  $t = 0.1$  are presented in figure 6. The trend shows that the velocity decreases with increasing values of thermal Grashof number or mass Grashof number.

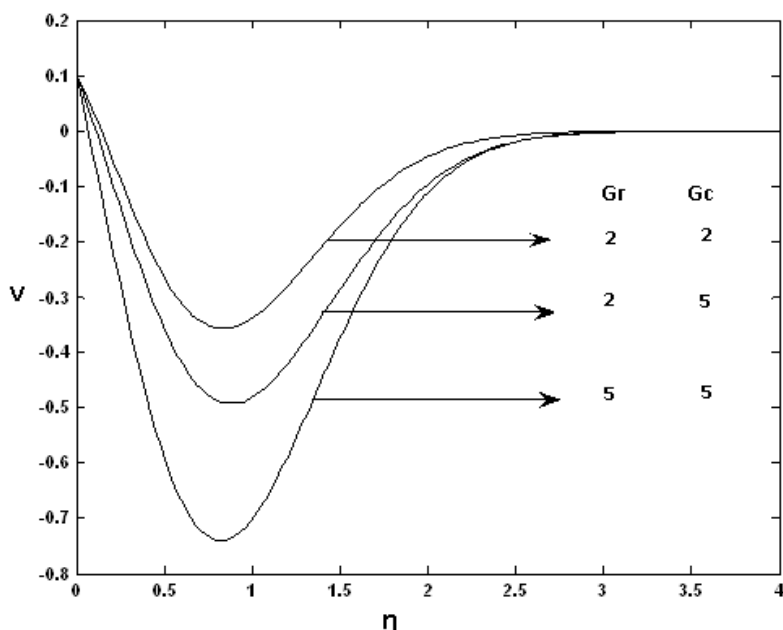


Figure 6. Secondary Velocity Profiles for different Gr and Gc

The secondary velocity profiles for different rotation parameter ( $\Omega = 0.5, 1$ ),  $Gr = Gc = 5$ ,  $Pr = 7$ ,  $M = 3$  and  $t = 0.2$  are shown in figure 7. It is observed that the velocity decreases with increasing values of the rotation parameter  $\Omega$ .

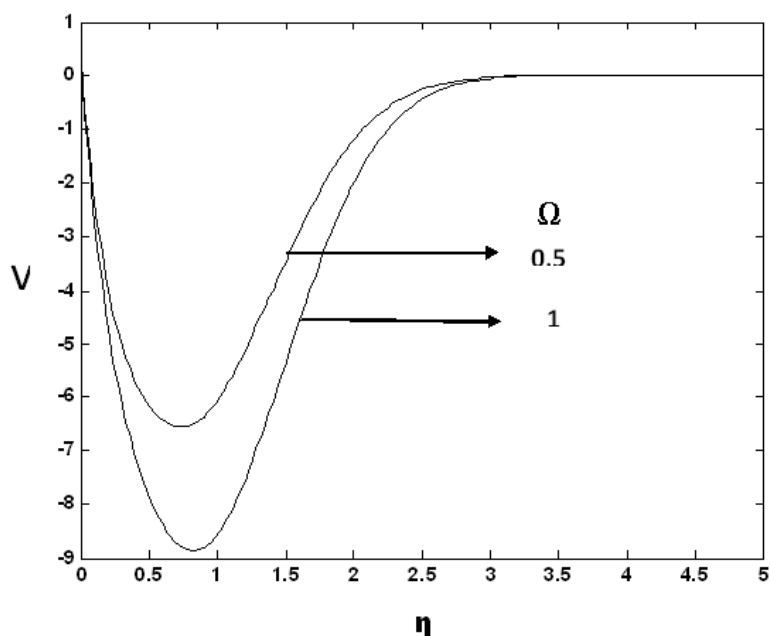


Figure 7. Secondary Velocity Profiles for different  $\Omega$

#### 4. CONCLUSIONS

The theoretical solution of flow past a uniformly accelerated infinite isothermal vertical plate in the presence of variable mass diffusion has been studied. The dimensionless governing equations are solved by the usual Laplace transform technique. The effect of different parameters like thermal Grashof number, mass Grashof number and  $t$  are studied graphically. It is observed that the velocity increases with increasing values of  $Gr$ ,  $Gc$  and  $t$ . But the trend is just reversed with respect to the rotation parameter or magnetic field parameter  $M$ .

#### NOMENCLATURE

- |   |  |
|---|--|
| A - constant                              | $C_\infty$ - concentration far away from the plate |
| $C'$ - species concentration in the fluid | $C_p$ - specific heat at constant pressure         |
| $C$ - dimensionless concentration         | $D$ - mass diffusion coefficient                   |
| $C_w$ - wall concentration                | $Gc$ - mass Grashof number                         |

Gr - thermal Grashof number	$x'$ - spatial coordinate along the plate
g - accelerated due to gravity	$y'$ - coordinate axis normal to the plate
k - thermal conductivity	$Z$ - dimensionless coordinate axis normal to the plate
K - chemical reaction parameter	$\beta$ - volumetric coefficient of thermal expansion
M - magnetic field parameter	$\beta^*$ - volumetric coefficient of expansion with concentration
Pr - Prandtl number	$\Omega$ - rotation parameter
Sc - Schmidt number	$\mu$ - coefficient of viscosity
T - temperature of the fluid near the plate	$\nu$ - kinematic viscosity
$T_w$ - temperature of the plate	$\rho$ - density of the fluid
$T_\infty$ - temperature of the fluid far away from the plate	$\tau$ - dimensionless skin-friction kg.
$t'$ - time	$\theta$ - dimensionless temperature
t - dimensionless time	$\eta$ - similarity parameter
u - velocity of the fluid in the x-direction	erfc - complementary error function
$u_0$ - velocity of the plate	
q - dimensionless velocity	

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