First Order Chemical Reaction and Hall Effect on MHD Flow past an Infinite Vertical Plate in the Presence of Rotating Fluid with Variable Mass

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Abstract— *Combined study of first order chemical reaction and Hall current on MHD flow past an accelerated infinite vertical plate in the presence of rotating fluid with variable mass diffusion has been analyzed. The effects of Hall parameter (m), Hartmann number (M), an imposed rotation parameter (Ω non-dimensional angular velocity),Thermal Grashof's number(Gr) and mass Grashof's number (Gc) on axial and transverse velocity profiles are presented graphically. It is found that when* $\Omega = M^2 m/(1+m^2)$*, the transverse velocity component vanishes and axial velocity attains a maximum value.*

Keywords— Hall parameter, MHD flows, Rotation, Chemical reaction, variable mass diffusion.

Nomenclature

A	Constant acceleration
$\vec{B}$	Magnetic induced vector
B_0	Imposed magnetic field
J_z	Component of current density J
μ_e	Magnetic permeability
m	Hall parameter
M	Hartman number
Y	Kinematic viscosity
Ω_z	Component of angular viscosity
Ω	Non-dimensional angular velocity
ρ	Fluid density
Gr	Thermal Grashof's number
Gc	Mass Grashof's number
Pr	Thermal Prandtl number
t'	Time
K	Chemical reaction parameter
k	Thermal conductivity
μ	Coefficient of viscosity
t	Non-dimensional time
θ	Dimensionless temperature
T	Temperature of the fluid near the plate
T_w	Temperature of the plate
T_∞	Temperature of the fluid for away from the Plate
β	Volumetric coefficient of thermal expansion
β^*	Volumetric coefficient of expansion with concentration
C'	Species concentration in the fluid
C	Dimensionless concentration
C_w	Wall concentration
C_∞	Concentration for away from the plate
(u, v, w)	- Components of velocity field F
(U,V,W)	- Non-dimensional velocity components
(x, y, z)	Cartesian co-ordinates
Z	Non-dimensional coordinate normal to the Plate

I. INTRODUCTION

Magneto hydro-dynamic has attracted the attention of a large number of scholars due to its diverse applications. In astrophysics and geophysics, it is applied to study the stellar and solar structures, interstellar matter, radio propagation through the ionosphere etc. In engineering it finds its applications in MHD pumps, MHD bearings etc. Comprehensive studies have also been carried out on MHD free convection and mass transfer flows in a rotating medium by many works. Some of them are Debnath[1]studied exact solutions of the unsteady hydrodynamic and hydro magnetic boundary layer equations in a rotating fluid system.

The application of Hydro magnetic incompressible viscous flow in science and engineering involving heat and mass transfer under the influence of chemical reaction is of great importance to many areas of science and engineering. This frequently occurs in petro-chemical industry, power and cooling system, cooling of nuclear reactors, heat exchanger design, forest fire dynamics and geophysics as well as in magneto hydrodynamic power generation systems. Dulal Pal[2] investigated the influence of Hall current and thermal radiation on MHD convective heat and mass transfer in a rotating porous channel with chemical reaction. Ahmed [3] analized the MHD transient flow past an impulsively started infinite horizontal porous plate in a rotating system with Hall current. Barik et al [4] discussed the Hall effects on unsteady MHD flow between two rotating disc with Non coincident parallel axes. Chaudhary [5] studied Hall Effect on MHD mixed convection flow of a viscoelastic fluid past an infinite vertical porous plate with mass transfer and radiation.

Diffusion rates can be altered tremendously by chemical reactions. The effect of a chemical reaction depend whether the reaction is homogeneous or heterogeneous. 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 the order n, if the reaction rate is proportional to the n^{th} power of the concentration. In particular, a reaction is said to be first order, if the rate of reaction is directly proportional to the concentration itself. Muthucumaraswamy et al [6] discussed the effects on first order chemical reaction on flow past an accelerated isothermal vertical plate in a rotating fluid with variable mass diffusion. Chambre[7] studied on the diffusion of a chemically reactive species in a laminar boundary layer flow. Das et al[8] investigated the Effects of mass transfer on flow past an impulsively started infinite vertical plate with chemical reaction. Ibrahim[9] analyzed the Radiation effects on chemically reacting magneto hydrodynamics (MHD) boundary layer flow of heat and mass transfer through a porous vertical flat plate.

In an ionized gas where the density is low and/or the magnetic field is very strong, the conductivity normal to the magnetic field is reduced due to the free spiraling of electrons and ions about the magnetic lines of force suffering collisions; also, a current is induced in a direction normal to both the electric and magnetic fields. This phenomenon, well known in the literature, is called the Hall Effect. The study of magneto hydrodynamic viscous flows with Hall currents has important engineering applications in problems of magneto hydrodynamic generators and of Hall accelerators as well as in flight magneto hydrodynamics. Many papers in this field have been published. Pop[10], studied Hall Effect on magneto hydrodynamic free convection about a semi-infinite vertical flat plate. Deka[11], investigated Hall effects on MHD flow past an accelerated plate. Chaudhary [12] discussed the Hall Effect on MHD Mixed convection flow of a viscoelastic fluid past an infinite vertical porous plate with mass transfer and Radiation.

In this paper we study and investigate the simultaneous effects of Hall current and rotation on MHD flow past on an infinite vertical plate relative to a rotating fluid with chemical reactions and variable mass diffusion. The dimensionless governing equations are solved by using 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.

II. MATHEMATICAL FORMULATION

Here x-axis is taken to be along the infinite vertical plate, in upward direction. The z-axis is taken as being normal to the plate and a strong magnetic field B_0 is considered along the z-axis. The leading edge of the plate should be taken as coincident with y-axis. The flow configuration together with the coordinate system used is shown in figure.

The effect of Hall current give rise to a force in the z-direction, which induces a cross flow in that direction, and hence the flow becomes three dimensional. To simplify the problem, we assume that there is no variation of flow, temperature and concentration quantities in z-direction.

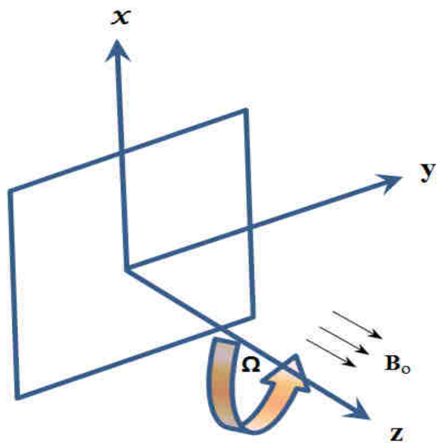

Fig.1: Mathematical model of the problem

The initial temperature of the plate and the fluid is assumed to be T_∞. After a time $t'>0$, the temperature of the plate increases to T_w, and is regarded to be constant. Also the pressure is assumed to be uniform in the flow. Let u, v, w be the components of velocity vector F.

The equation of conservation of electric charge *div J= 0* gives J_z is a constant. This constant is zero. Since $J_z = 0$ at the plate, which is electrically non-conducting. Thus $J_z = 0$ everywhere in the flow. From all these assumptions, in rotating frame of reference and using modifications of Ohm's law, the momentum equations for the unsteady flow with heat transfer are given by,

$$\frac{\partial u}{\partial t'}=\upsilon\frac{\partial^2 u}{\partial z^2}+2\Omega_z v-\frac{\sigma\mu_e^2 H_0^2}{\rho(1+m^2)}(u+mv)+g\beta(T-T_\infty)+g\beta^*(C'-C'_\infty) \quad (1)$$

$$\frac{\partial v}{\partial t'}=\upsilon\frac{\partial^2 v}{\partial z^2}-2\Omega_z u+\frac{\sigma\mu_e^2 H_0^2}{\rho(1+m^2)}(mu-v) \quad (2)$$

$$\rho C_p\frac{\partial T}{\partial t'}=k\frac{\partial^2 T}{\partial z^2} \quad (3)$$

$$\frac{\partial C'}{\partial t'}=D\frac{\partial^2 C'}{\partial z^2}-K_l(C'-C'_\infty) \quad (4)$$

Here the second term on the right hand side of the equations (1) & (2) are due to small Coriolis force. The boundary conditions are given by,

$$u=0, T=T_\infty, C'=C'_\infty \;\; v=0 \;\; \text{for all } z,\; t'\le 0 \quad (5)$$

$$u=At',\, T=T_w,\, C'=C'_\infty+(C'_w-C'_\infty)At' \;\; v=0 \text{ at } z=0 \;\; \text{for all } t'>0$$
$$u\to 0,\, T\to T_\infty,\, C'\to C'_\infty \text{ as } z\to\infty \;\; \text{for all } t'>0 \quad (6)$$

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

The dimensionless quantities are introduced as follows.

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

$$\Omega=\Omega_z\left(\frac{\upsilon}{u_0^2}\right)^{\frac{1}{3}},\, M^2=\frac{\sigma\mu_e^2H_0^2\upsilon^{\frac{1}{3}}}{2\rho\, u_0^{2/3}},\, \Pr=\frac{\mu C_p}{k},$$

$$K=K_l\left(\frac{\upsilon}{u_0^2}\right)^{\frac{1}{3}}\;\theta=\frac{T-T_\infty}{T_\omega-T_\infty},\, C=\frac{C'-C'_\infty}{C'_\omega-C'_\infty},$$

$$Gr=\frac{g\beta(T_\omega-T_\infty)}{u_0},\, Gc=\frac{g\beta^*(C'_\omega-C'_\infty)}{u_0}, \quad (7)$$

Together with the equations (1), (2), (3) and (4), boundary conditions (5), (6) using (7), we have

$$\frac{\partial U}{\partial t}=\frac{\partial^2 U}{\partial Z^2}+2V\left(\Omega-\frac{M^2m}{1+m^2}\right)-2\frac{M^2}{1+m^2}U+\theta Gr+CGc \quad (8)$$

$$\frac{\partial V}{\partial t}=\frac{\partial^2 V}{\partial Z^2}-2U\left(\Omega-\frac{M^2m}{1+m^2}\right)-2\frac{M^2}{1+m^2}V \quad (9)$$

With the boundary conditions

$$U=0, \theta=0, C=0, V=0 \;\; \text{for all } Z,\; t\le 0 \quad (10)$$

$$U=t, \theta=1, C=t, V=0 \;\text{at } Z=0 \;\; \text{for all } t>0$$
$$U\to 0, \theta\to 0, C\to 0, V\to 0 \text{ as } Z\to\infty \;\; \text{for all } t>0 \quad (11)$$

Now equations (8), (9) and boundary conditions (10), (11) can be combined to give

$$\frac{\partial F}{\partial t}=\frac{\partial^2 F}{\partial Z^2}-2F\left[\frac{M^2}{1+m^2}+i\left(\Omega-\frac{M^2m}{1+m^2}\right)\right]+\theta Gr+CGc$$

$$\frac{\partial F}{\partial t}=\frac{\partial^2 F}{\partial Z^2}-Fa+\theta Gr+CGc \quad (12)$$

Where $F=U+iV$ and $a=2\left[\frac{M^2}{1+m^2}+i\left(\Omega-\frac{M^2m}{1+m^2}\right)\right]$

$$\frac{\partial\theta}{\partial t}=\frac{1}{\Pr}\frac{\partial^2\theta}{\partial Z^2}$$

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

with boundary conditions

$$F=0, \theta=0, C=0 \;\; \text{for all } Z,\; t\le 0$$
$$F=t, \theta=1, C=t \;\text{at } Z=0 \;\; \text{for all } t>0 \quad (13)$$
$$F\to 0, \theta\to 0, C\to 0 \text{ as } Z\to\infty \;\; \text{for all } t>0$$

III. METHOD OF SOLUTION

The dimensionless governing equations (3), (4) and (12) subject to the initial and boundary conditions (13) are solved by the usual Laplace transform technique and the solutions are derived as follows.

$$F=\Big\{\left(\frac{t}{2}+x+y+cyt\right)\left[e^{2\eta\sqrt{at}}erfc\left(\eta+\sqrt{at}\right)+e^{-2\eta\sqrt{at}}erfc\left(\eta-\sqrt{at}\right)\right]$$
$$-\frac{\eta\sqrt{t}}{\sqrt{a}}\left[\frac{1}{2}+cy\right]\left[e^{-2\eta\sqrt{at}}erfc\left(\eta-\sqrt{at}\right)-e^{2\eta\sqrt{at}}erfc\left(\eta+\sqrt{at}\right)\right]$$
$$-2x\,erfc(\eta\sqrt{\Pr})$$
$$-xe^{bt}\left[e^{2\eta\sqrt{(a+b)t}}erfc\left(\eta+\sqrt{(a+b)t}\right)+e^{-2\eta\sqrt{(a+b)t}}erfc\left(\eta-\sqrt{(a+b)t}\right)\right]$$
$$-ye^{ct}\left[e^{2\eta\sqrt{(a+c)t}}erfc\left(\eta+\sqrt{(a+c)t}\right)+e^{-2\eta\sqrt{(a+c)t}}erfc\left(\eta-\sqrt{(a+c)t}\right)\right]$$
$$+xe^{bt}\left[e^{2\eta\sqrt{b\Pr t}}erfc\left(\eta\sqrt{\Pr}+\sqrt{bt}\right)+e^{-2\eta\sqrt{b\Pr t}}erfc\left(\eta\sqrt{\Pr}-\sqrt{bt}\right)\right]$$
$$+ye^{ct}\left[e^{2\eta\sqrt{Sc(K+c)t}}erfc\left(\eta\sqrt{Sc}+\sqrt{(K+c)t}\right)+e^{-2\eta\sqrt{Sc(K+c)t}}erfc\left(\eta\sqrt{Sc}-\sqrt{(K+c)t}\right)\right]$$
$$+\frac{cy\eta\sqrt{Sct}}{\sqrt{K}}\left[e^{-2\eta\sqrt{ScKt}}erfc(\eta\sqrt{Sc}-\sqrt{Kt})-e^{2\eta\sqrt{ScKt}}erfc(\eta\sqrt{Sc}+\sqrt{Kt})\right]$$
$$-y(1+ct)\left[e^{2\eta\sqrt{ScKt}}erfc\left(\eta\sqrt{Sc}+\sqrt{Kt}\right)+e^{-2\eta\sqrt{ScKt}}erfc\left(\eta\sqrt{Sc}-\sqrt{Kt}\right)\right]\Big\} \quad (14)$$

$$\theta=erfc(\eta\sqrt{\Pr}) \quad (15)$$

$$C=\frac{t}{2}\left[e^{2\eta\sqrt{Sc\,K\,t}}erfc\left(\eta\sqrt{Sc}+\sqrt{K\,t}\right)+e^{-2\eta\sqrt{Sc\,K\,t}}erfc\left(\eta\sqrt{Sc}-\sqrt{K\,t}\right)\right]$$
$$-\frac{\eta\sqrt{Sc\,t}}{2\sqrt{K}}\left[e^{-2\eta\sqrt{Sc\,K\,t}}erfc(\eta\sqrt{Sc}-\sqrt{K\,t})-e^{2\eta\sqrt{Sc\,K\,t}}erfc(\eta\sqrt{Sc}+\sqrt{K\,t})\right] \quad (16)$$

Where $b=\frac{a}{\Pr-1}$, $c=\frac{a-KSc}{Sc-1}$, $x=\frac{Gr}{2b(1-\Pr)}$, $y=\frac{Gc}{2c^2(1-Sc)}$, $\eta=\frac{z}{2\sqrt{t}}$

In order to get the physical insight in to the problem, the numerical values of F have been computed from (14), while evaluating this expression, it is observed that the argument of the error function is complex and hence we have separated it in to real and imaginary parts by using the following formula.

$$erf\,(a+ib)=erf\,(a)+\frac{\exp\left(-a^2\right)}{2a\pi}[(1-\cos(2ab)+i\sin(2ab)]$$
$$+\frac{2\exp(-a^2)}{\pi}\sum_{n=1}^{\infty}\frac{\exp\left(\frac{-n^2}{4}\right)}{n^2+4a^2}\left[f_n(a,b)+ig_n(a,b)\right]+\varepsilon(a,b)$$

Where

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

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

$$\left|\varepsilon(a,b)\right|\approx10^{-16}\left|erf\,(a+ib)\right|$$

The Rate of Heat Transfer

The rate of heat transfer (Nusselt number) from temperature field in non-dimensional form is given by

$$Nu=-\frac{1}{2\sqrt{t}}\left(\frac{\partial\theta}{\partial\eta}\right)_{\eta=0}=\frac{\sqrt{\Pr}}{\sqrt{t}\sqrt{\pi}}$$

The Rate of Mass Transfer

The rate of mass transfer (Sherwood Number) from concentration field in non-dimensional form is given by

$$Sh=-\frac{1}{2\sqrt{t}}\left(\frac{\partial C}{\partial\eta}\right)_{\eta=0}$$

$$=\frac{\sqrt{t}\sqrt{Sc}}{\sqrt{\pi}}\exp(-Kt)+t\sqrt{Sc\,K}\,erf\,(\sqrt{K\,t})+\frac{\sqrt{Sc}}{2\sqrt{K}}\,erf\,(\sqrt{K\,t})$$

IV. RESULTS AND DISCUSION

For physical understanding of the problem, numerical computations are carried out for different physical parameters Gr, Gc, Sc, Pr, m, 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 value of the Prandtl number Pr is taken to be 7 that represents water and time t=0.2.

Figure 2 shows the variation of primary velocity with rotation parameter (Ω=1, 3, 5), Gr=Gc=5, m=0.5, M=0.5, K=8 and t=0.2. It is observed that the primary velocity decreases with the increase in rotation parameter Ω. Figure 3 shows the variation of secondary velocity with rotation parameter (Ω=2, 3, 5), Gr=Gc=5, m=0.5, M=0.5, K=8 and t=0.2. The negative sign indicates that this component is transverse to the main flow direction in clockwise sense. It is observed that the secondary velocity decreases with the increase in rotation parameter Ω.

The effect of Hall parameter (m=1, 3, 5) on the primary velocity is shown in figure 4 for Ω =0.1, Gr=Gc=5, M=3, K=8 and t=0.2. It is observed that due to increase in Hall Parameter, there is decrease in the primary velocity. The effect of Hall parameter (m=1, 2, 3) on the transverse velocity is shown in figures 5 for Ω =0.1, Gr=Gc=5, M=0.8, K=8 and t=0.2. It is observed that due to increase in Hall Parameter, there is decrease in the secondary velocity component.

The effect of magnetic field parameter (M=2, 2.5, 3) on the primary velocity is shown in figure 6 for Ω =0.1, Gr=Gc=5, m=0.5, K=8 and t=0.2.It is observed that with the increase in Hartmann number primary velocity component decreases. The effect of magnetic field parameter (M=0.5, 2, 2.5) on the secondary velocity is shown in figure 7 for Ω =0.1, Gr=Gc=5, m=0.5, K=8 and t=0.2.It is observed that with the increase in Hartmann number secondary velocity component increases.

The effect of thermal Grashof number (Gr=2, 5) and mass Grashof number (Gc=2, 5), on the primary velocity is shown in figure 8 for Ω =0.1, m=0.1, M=0.5, K=8, Pr=0.71 and t=0.2. The primary velocity increases with increasing value of Gr and Gc.

The effect of chemical reaction parameter (K=2, 4, 6) on the primary velocity is shown in figure 9 for Ω =0.1, Gr=Gc=5, m=0.5, M=0.8 and t=0.2.The primary velocity decreases with increasing value of the chemical parameter K. The effect of chemical reaction parameter (K=6, 8, 12) on the secondary velocity is shown in figure 10 for Ω =0.1, Gr=Gc=5, m=0.5, M=0.8 and t=0.2.The the secondary velocity also decreases with increasing value of the chemical parameter K.

Table.1: Nusselt number for several t and Pr

t	Pr=.1	Pr=.71	Pr=7
0.2	0.3989	1.063	3.3378
0.3	0.3257	0.8679	2.7253

0.4	0.2821	0.7517	2.3602
0.6	0.2303	0.6137	1.9271

Table.2: Sherwood Number for several time parameter t and chemical parameter K

t	K=2	K=4	K=6	K=8
0.2	0.3157	0.4089	0.4872	0.5546
0.3	0.3958	0.5101	0.603	0.682
0.4	0.4605	0.5902	0.694	0.7831
0.6	0.5619	0.7151	0.8392	0.9467

Table.3: Sherwood Number for several t and Sc

t	Sc=.16	Sc=.3	Sc=.6	Sc=2.01
0.2	0.5546	0.7594	1.074	1.9657
0.3	0.682	0.9338	1.3206	2.4171
0.4	0.7831	1.0723	1.5165	2.7756
0.6	0.9467	1.2963	1.8332	3.3553

From table.1 the Nusselt number is increasing with increasing value of Prandtl number and the trend is reverse for time t.

From table.2 and 3, the Sherwood number is increasing with increasing value of the chemical parameter K , Schmidt number Sc and time parameter t.

V. CONCLUSION

The simultaneous effects of Hall current and rotation on MHD flow past an accelerated infinite vertical plate relative to a rotating fluid, with heat transfer characteristics has been studied. The effects of Hall parameter, Hartmann number, rotation parameter, Grashof's number and Prandtl number on transient axial velocity and transverse velocity is presented graphically. It is observed that, due to increase in K, the axial velocity decreases whereas the transient velocity increases. Axial velocity decreases with increasing value of Hartmann number *M* but the transverse velocity increases. There is a decrease in both velocity components with increasing values of Hall parameter *m* and Ω.

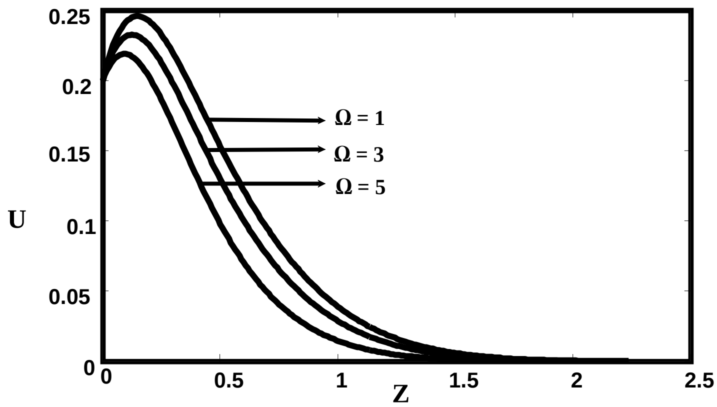

Fig.2: Primary velocity for several Omega

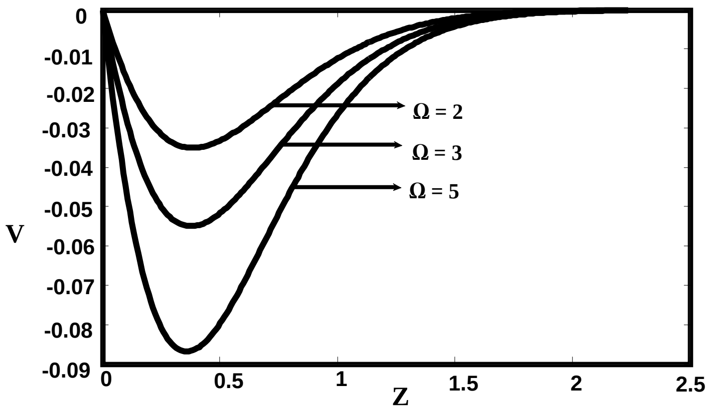

Fig.3: Secondary velocity for several Omega

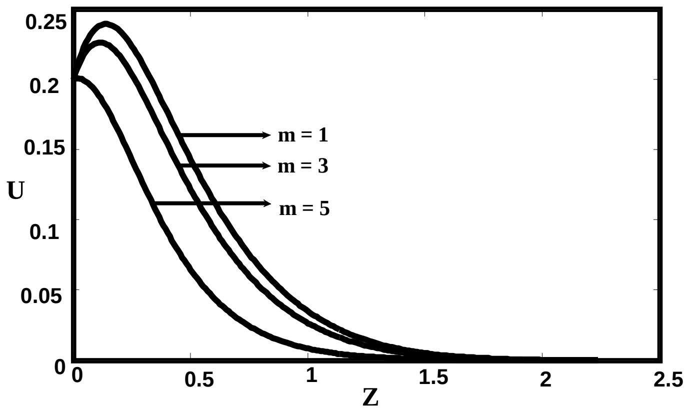

Fig.4: Primary velocity for several m

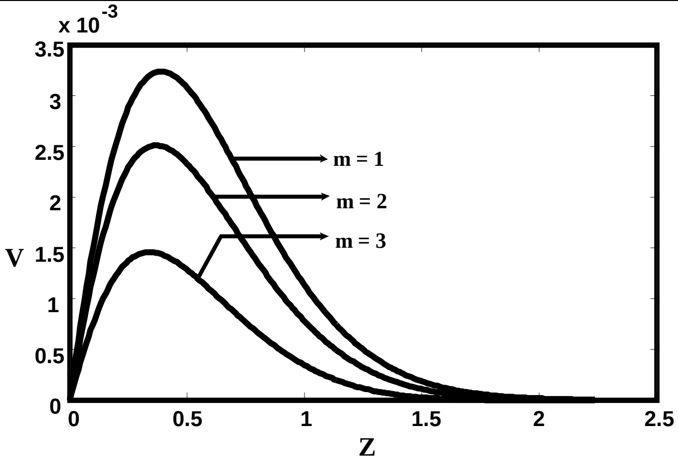

Fig.5 : Secondary velocity for several m

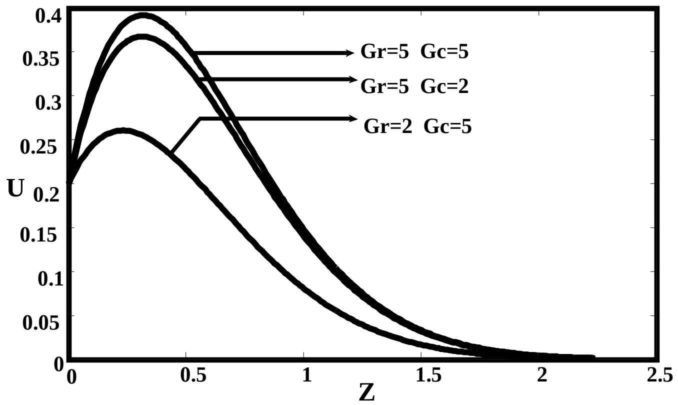

Fig.8: Primary velocity for several Gr, Gc

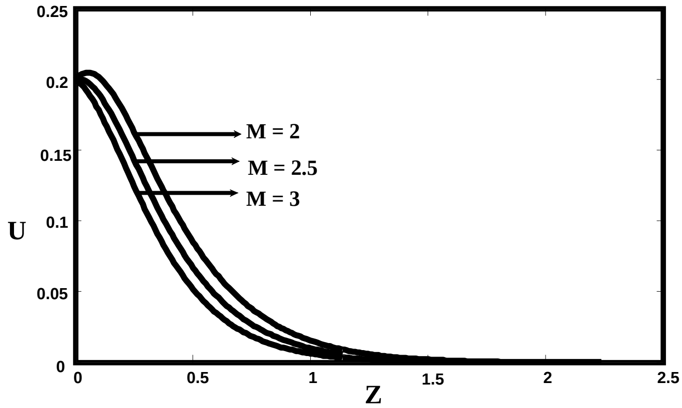

Fig.6: Primary velocity for several M

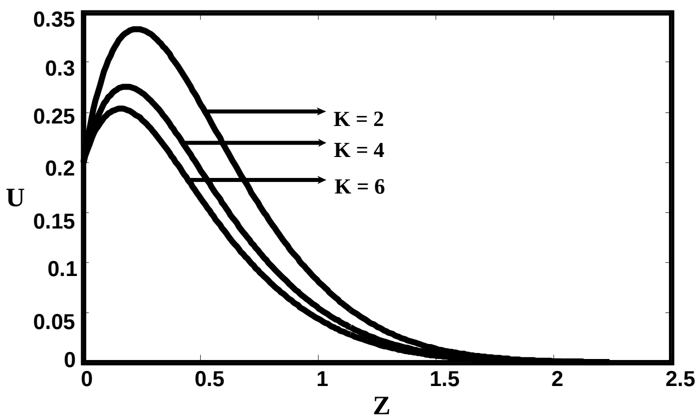

Fig. 9: Primary velocity for several K

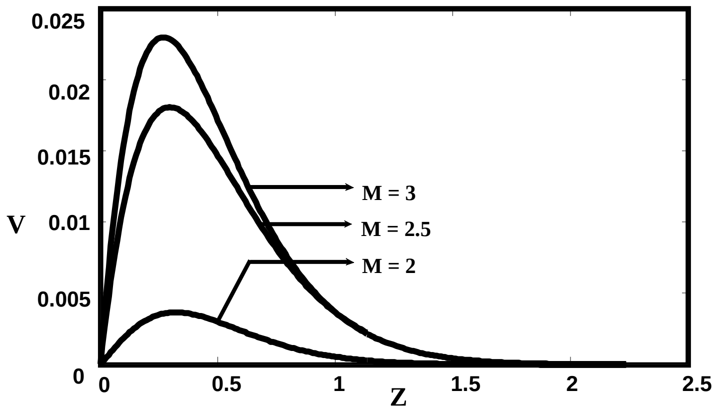

Fig.7: Secondary velocity for several M

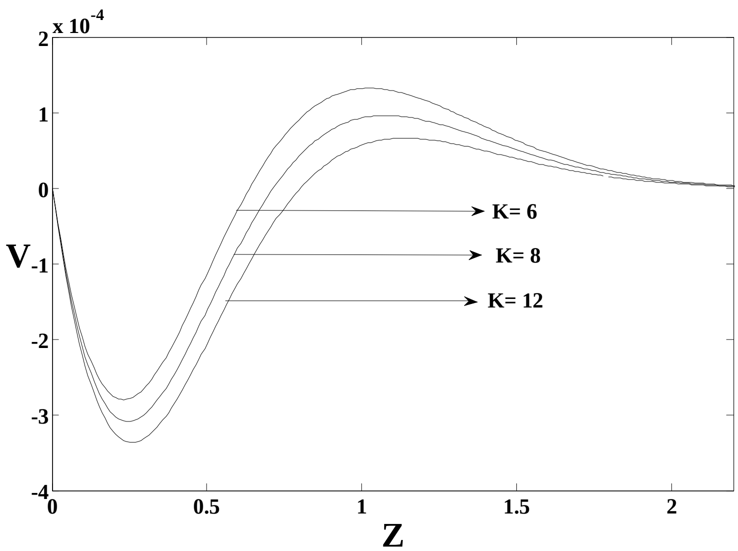

Fig.10: Secondary velocity for several K

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