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HALL EFFECTS ON MHD FLOW PAST AN INFINITE VERTICAL PLATE IN THE PRESENCE OF ROTATING FLUID OF VARIABLE TEMPERATURE AND MASS DIFFUSION WITH FIRST ORDER CHEMICAL REACTION

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ABSTRACT

Combined study of Hall current and rotation on MHD flow past an accelerated infinite vertical plate in the presence of rotating fluid of variable temperature and mass diffusion with first order chemical reaction has been analyzed. The effects of Hall parameter, Hartmann number, an imposed rotation parameter, thermal Grashof number and mass Grashof number 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 flow, rotation, chemical reaction.

INTRODUCTION

The phenomenon of MHD flow with heat and mass transfer with chemical reaction have been a subject of interest of many researchers because if its varied applications in science and technology. Heat and Mass transfer problems with chemical reaction are important in many processes such as drying, energy transfer in a wet cooling tower etc., when the strength of the magnetic field is strong; the effect of hall current is negligible.

It is of considerable importance and interest to study how the results of the hydro dynamical problems get modified by the effect of hall currents. Dulal Pal [1] has discussed the effect of chemical reaction in a porous medium. Pop [2] studied the effect of Hall currents on hydromagnetic flow near an accelerated plate. Deka [3] investigated Hall effects on MHD flow past an accelerated plate. Watanbe and Pop [4] studied the effect of Hall current on the steady MHD flow over a continuously moving flat plat when the liquid is permeated by a uniform transverse magnetic field. Kulandaivel *et al* [5] studied chemical reaction on moving vertical plate with constant mass flux in the presence of thermal radiation. Mansour *et al* [6] has considered coupled heat and mass transfer in darcy free convection from a heated vertical plate embedded in a porous medium under the effect of chemical reaction. Mahmoud and Mostafa [7] have analyzed variable viscosity and chemical reaction effects on mixed convection heat and mass transfer along a semi-infinite vertical plate.

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*. [8] 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 [9] studied on the diffusion of a chemically reactive species in a laminar boundary layer flow. Das *et al*. [10] investigated the Effects of mass transfer on flow past an impulsively started infinite vertical plate with chemical reaction. Ibrahim 11] 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 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 of variable temperature and mass diffusion with chemical reactions. 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.

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MATHEMATICAL FORMULATION

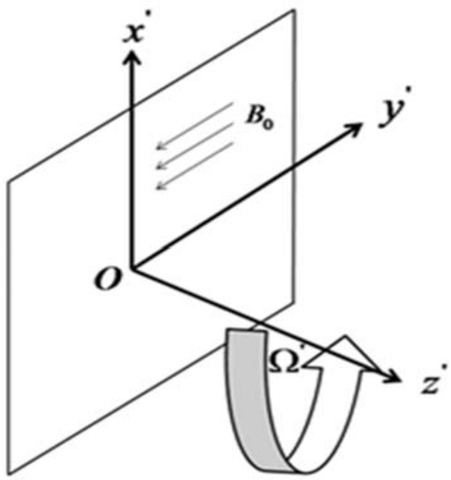

Figure-1. Mathematical model of the problem.

Here x-axis is taken to be along the infinite vertical plate, in upward direction. The y-axis is taken as being normal to the plate and a strong magnetic field B_0 is considered along the y-axis. The leading edge of the plate should be taken as coincident with z-axis. The flow configuration together with the coordinate system used is shown in figure1.

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.

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. By the equation of continuity, we have $\nabla . F = 0$.

The equation of conservation of electric charge *div J= 0* gives J_y is a constant. This constant is zero. Since $J_y = 0$ at the plate, which is electrically non-conducting. Thus $J_y = 0$ 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

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

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

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

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

Here the second term on the right hand side of the equations (1) and (2) are due to small

Coriolis force. The boundary conditions are given by,

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

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

where $A = \left(\frac{u_0^2}{\nu}\right)^{\frac{1}{3}} (> 0)$ is a constant.

The dimensionless quantities are introduced as follows.

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

$$\Omega = \Omega_z\left(\frac{\upsilon}{u_0^2}\right)^{\frac{1}{3}}, M^2 = \frac{\sigma\mu_e^2 H_0^2 \upsilon^{\frac{1}{3}}}{2\rho\ u_0^{2/3}}, C = \frac{C' - C'_\infty}{C'_\omega - C'_\infty},$$

$$Gr = \frac{g\beta(T_\omega - T_\infty)}{u_0},\ Gc = \frac{g\beta^*(C'_\omega - C'_\infty)}{u_0},\ \Pr = \frac{\mu C_p}{k},$$

$$K = K_l\left(\frac{\nu}{u_0^2}\right)^{\frac{1}{3}},\ \theta = \frac{T - T_\infty}{T_w - T_\infty} \quad (7)$$

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

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

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

With the boundary conditions

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

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$$\begin{aligned} &U=t\,,\theta=t, C=t, V=0 \;\; at\; Z=0 \;\;\; for\; all\;\; t>0 \\ &U\to 0,\theta\to 0\,, C\to 0\,, V\to 0\, as\;\; Z\to\infty \;\;\; for\; all\;\; t>0 \end{aligned} \tag{11}$$

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

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

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

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

$$\frac{\partial \theta}{\partial t}=\frac{1}{\Pr}\frac{\partial^2 \theta}{\partial Z^2} \tag{13}$$

$$\frac{\partial C}{\partial t}=\frac{1}{Sc}\frac{\partial^2 C}{\partial Z^2}-K\,C \tag{14}$$

With boundary conditions

$$\begin{aligned} &F=0,\theta=0, C=0 \;\; for\; all\; Z,\; t\le 0 \\ &F=t\,,\theta=t, C=t \;\; at\; Z=0 \;\;\; for\; all\;\; t>0 \\ &F\to 0,\theta\to 0\,, C\to 0 \;\; as\;\; Z\to\infty \;\;\; for\; all\;\; t>0 \end{aligned} \tag{15}$$

METHOD OF SOLUTION

The dimensionless governing equations (12), (13) and (14) subject to the initial and boundary conditions (15) are solved by the usual Laplace transform technique and the solutions are derived as follows:

$$\begin{aligned} F=&\Bigg\{\left[\frac{t}{2}+x+y+(bx+cy)\,t\right]\left[\exp(2n\sqrt{a\,t})erfc(n+\sqrt{a\,t})+\exp(-2n\sqrt{a\,t})erfc(n-\sqrt{a\,t})\right] \\ &-n\sqrt{\frac{t}{a}}\left[\frac{1}{2}+bx+cy\right]\left[\exp(-2n\sqrt{a\,t})erfc(n-\sqrt{a\,t})-\exp(2n\sqrt{a\,t})erfc(n+\sqrt{a\,t})\right]-2x\;erfc(n\sqrt{\Pr}) \\ &-x\exp(b\,t)\left[\exp(2n\sqrt{(a+b)\,t})erfc\left(n+\sqrt{(a+b)t}\right)+\exp(-2n\sqrt{(a+b)\,t})erfc\left(n-\sqrt{(a+b)t}\right)\right] \\ &+x\exp(bt)\left[\exp(2n\sqrt{\Pr b\,t})erfc(n\sqrt{\Pr}+\sqrt{bt})+\exp(-2n\sqrt{\Pr b\,t})erfc(n\sqrt{\Pr}-\sqrt{bt})\right] \\ &-2bxt\left[(1+2n^2\Pr)\;erfc\left(n\sqrt{\Pr}\right)-\frac{2n\sqrt{\Pr}}{\sqrt{\pi}}\exp(-n^2\Pr)\right] \\ &-y\exp(c\,t)\left[\exp(2n\sqrt{(a+c)\,t})erfc\left(n+\sqrt{(a+c)t}\right)+\exp(-2n\sqrt{(a+c)\,t})erfc\left(n-\sqrt{(a+c)t}\right)\right] \\ &+y\exp(c\,t)\left[\exp(2n\sqrt{Sc(K+c)\,t})erfc\left(n\sqrt{Sc}+\sqrt{(K+c)t}\right)+\exp(-2n\sqrt{Sc(K+c)\,t})erfc\left(n\sqrt{Sc}-\sqrt{(K+c)t}\right)\right] \\ &-y(1+c\,t)\left[\exp(2n\sqrt{Sc\,K\,t})erfc\left(n\sqrt{Sc}+\sqrt{Kt}\right)+\exp(-2n\sqrt{Sc\,K\,t})erfc\left(n\sqrt{Sc}-\sqrt{Kt}\right)\right] \\ &+c\,y\frac{n\sqrt{Sc\,t}}{\sqrt{K}}\left[\exp(-2n\sqrt{Sc\,K\,t})erfc\left(n\sqrt{Sc}-\sqrt{K\,t}\right)-\exp(2n\sqrt{Sc\,K\,t})erfc\left(n\sqrt{Sc}+\sqrt{K\,t}\right)\right]\Bigg\} \end{aligned} \tag{16}$$

$$\theta=t\left[(1+2n^2\Pr)erfc(n\sqrt{\Pr})-\frac{2n\sqrt{\Pr}}{\sqrt{\pi}}\exp(-n^2\Pr)\right] \tag{17}$$

$$\begin{aligned} C=&\Bigg\{\frac{t}{2}\left[\exp(2\eta\sqrt{Sc\;K\;t})erfc\left(\eta\sqrt{Sc}+\sqrt{K\;t}\right)+\exp(-2\eta\sqrt{Sc\;K\;t})erfc\left(\eta\sqrt{Sc}-\sqrt{K\;t}\right)\right] \\ &-\frac{\eta\sqrt{Sc\,t}}{2\sqrt{K}}\left[\exp(-2\eta\sqrt{Sc\;K\;t})erfc(\eta\sqrt{Sc}-\sqrt{K\;t})-\exp(2\eta\sqrt{Sc\;K\;t})erfc(\eta\sqrt{Sc}+\sqrt{K\;t})\right]\Bigg\} \end{aligned} \tag{18}$$

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

In order to get the physical insight in to the problem, the numerical values of F have been computed from (16), 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.

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

Where,

$$f_n=2a-2a\cosh(nb)\cos(2ab)+n\sinh(nb)\sin(2ab),$$
$$g_n=2a\cosh(nb)\sin(2ab)+n\sinh(nb)\cos(2ab)$$
$$\left|\varepsilon(a,b)\right|\approx10^{-16}\left|erf(a+ib)\right|$$

RESULTS AND DISCUSSIONS

For physical understanding of the problem, numerical computations are carried out for different physical parameters Gr, Gc, Sc, Pr, m, M, Ω, K 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, 0.71 and time t=0.2. The numerical values of the velocity, temperature and concentration fields are computed for different physical parameters like chemical parameter, rotation parameter, magnetic field parameter, Hall parameter, thermal Grashof number, mass Grashof number, Schmidt number and time.

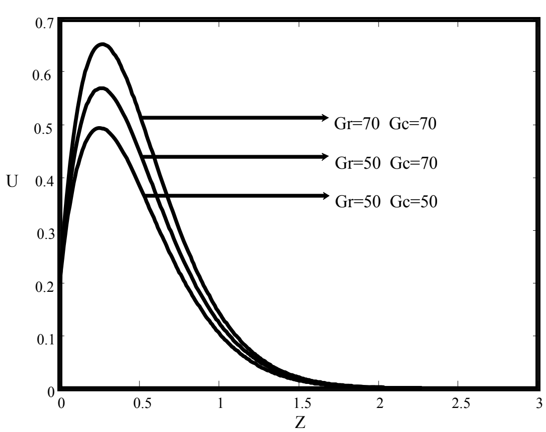

Figure-2. Primary velocity for several Gr, Gc.

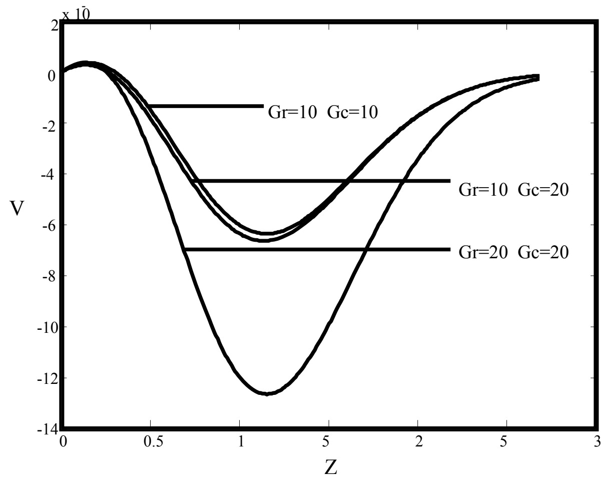

Figure-3. Secondary velocity for several Gr, Gc.

The effect of thermal Grashof number (Gr=50, 70) and mass Grashof number (Gc=50, 70), on the primary velocity is shown in Figure-2 for Ω =0.1, m=0.5, M=1, K=8, Pr=0.71 and t=0.2. The primary velocity increases with increasing value of thermal Grashof number Gr and mass Grashof number Gc.

The effect of thermal Grashof number (Gr=10, 20) and mass Grashof number (Gc=10, 20), on the secondary velocity is shown in Figure-3 for Ω =0.1, m=0.7, M=0.6, K=6, Pr=0.71 and t=0.2. The secondary velocity decreases with increasing value of thermal Grashof number Gr and mass Grashof number Gc.

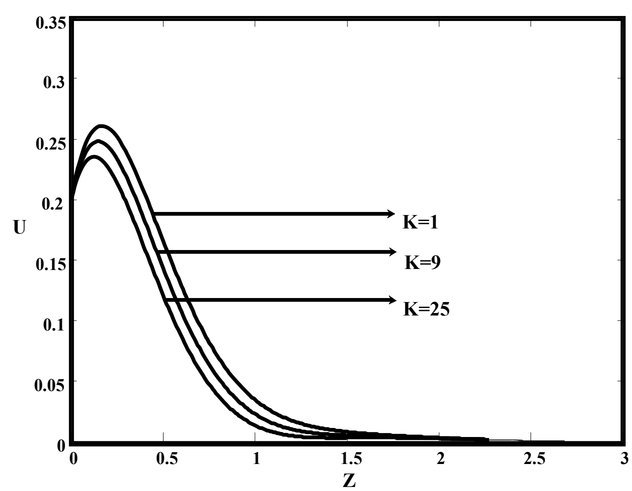

Figure-4. Primary velocity for several K.

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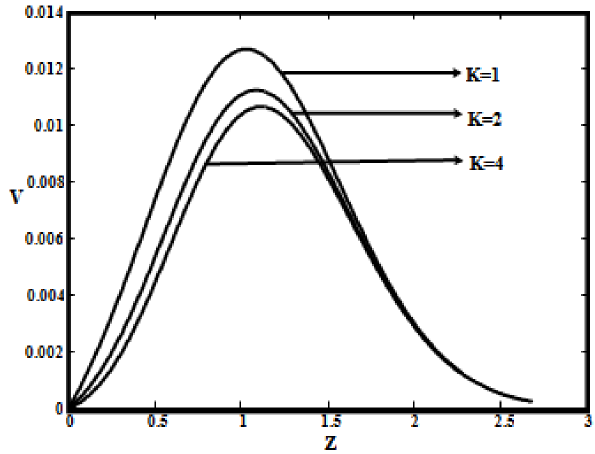

Figure-5. Secondary velocity for several K.

The effect of chemical reaction parameter (K= 1, 9, 25) on the primary velocity is shown in Figure-4 for Ω =0.1, Gr=Gc=20, m=0.8, M=0.3, Pr=0.71 and t=0.2.The primary velocity decreases with increasing value of the chemical parameter K.

The effect of chemical reaction parameter (K=1, 2, 4) on the secondary velocity is shown in Figure-5 for Ω =0.1, Gr=Gc=5, m=0.2, M=0.5, Pr=0.71 and t=0.2.The secondary velocity decreases with increasing value of the chemical parameter K.

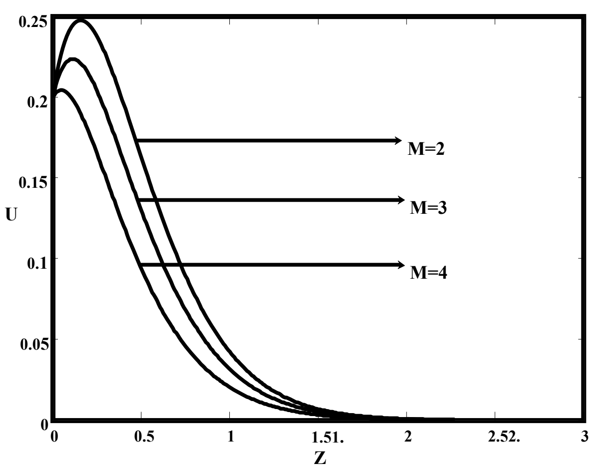

Figure-6. Primary velocity for several M.

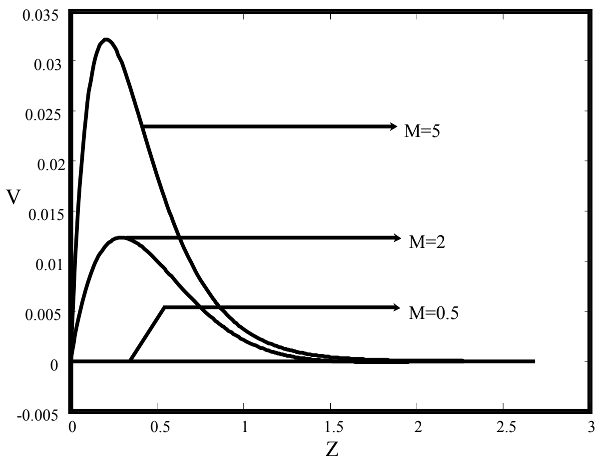

Figure-7. Secondary velocity for several M.

The effect of magnetic field parameter (M=2, 3, 4) on the primary velocity is shown in Figure-6 for Ω =0.1, Gr=Gc=20, m=0.5, K=8, Pr=0.71 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, 5) on the secondary velocity is shown in Figure-7 for Ω =0.1, Gr=Gc=5, m=0.5, K=8, Pr=.71 and t=0.2. It is observed that with the increase in Hartmann number secondary velocity component increases. The graph corresponding to M=0.5 satisfying the identity $\Omega = \frac{M^2 m}{1+m^2}$, showing a vanishing component.

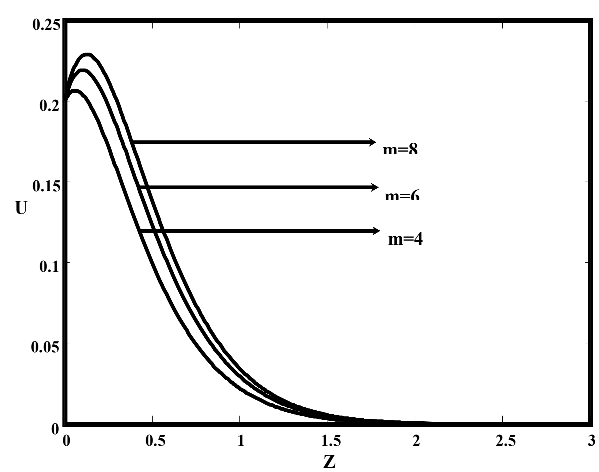

Figure-8. Primary velocity for several m.

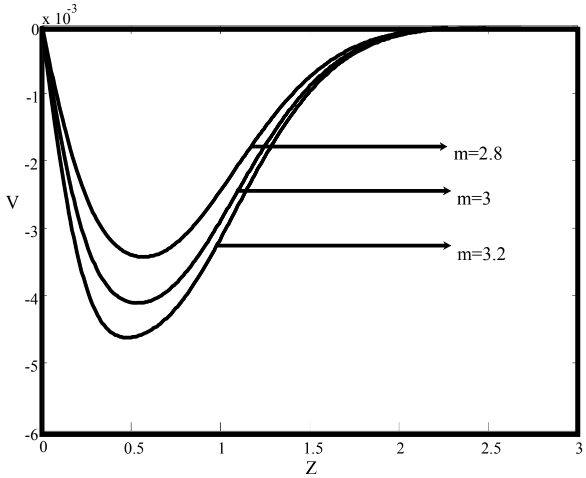

Figure-9. Secondary velocity for several m.

The effect of Hall parameter (m=4, 6, 8) on the primary velocity is shown in Figure-8 for Ω =0.1, Gr=Gc=20, M=5, K=8, Pr=0.71 and t=0.2. It is observed that due to increase in Hall Parameter, there is increase in the primary velocity.

The effect of Hall parameter (m=2.8, 3, 3.2) on the transverse velocity is shown in Figure-9 for Ω =0.1, Gr=Gc=5, M=0.5, K=8, Pr=7 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 due to increase in Hall Parameter, there is decrease in the secondary velocity component.

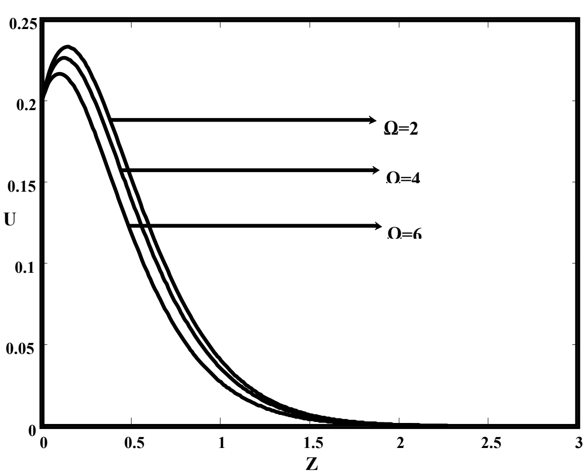

Figure-10. Primary velocity for several Omega.

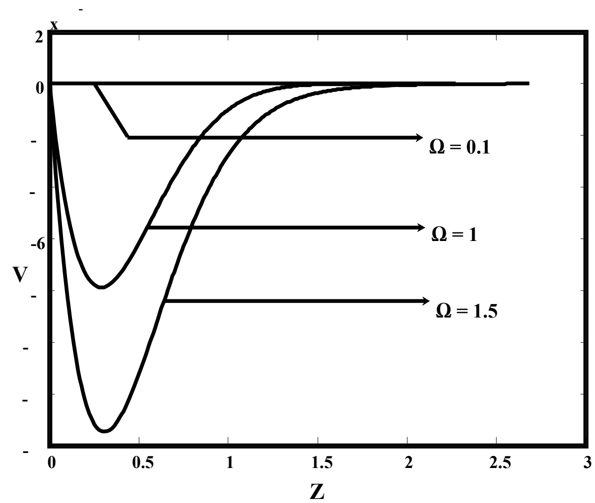

Figure-11. Secondary velocity for several Omega.

Figure-10 shows the variation of primary velocity with rotation parameter (Ω=2, 4, 6), Gr=Gc=15, m=0.5, M=0.5, K=8, Pr=0.71 and t=0.2. It is observed that the primary velocity decreases with the increase in rotation parameter Ω.

Figure-11 shows the variation of secondary velocity with rotation parameter (Ω=0.1, 1, 1.5), Gr=Gc=5, m=0.5, M=0.5, K=8, Pr=0.71 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 graph corresponding to Ω =0.1 satisfying the identity $\Omega = \frac{M^2 m}{1 + m^2}$ for M=0.5 and m=0.5, showing a vanishing component.

CONCLUSIONS

The simultaneous effects of Hall current and rotation on MHD flow past an infinite plate relative to a rotating fluid, with first order chemical reaction of variable temperature and mass diffusion has been studied. The effects of Hall parameter, Hartmann number, rotation parameter, Grashof's number and chemical parameter on axial velocity and transverse velocity is presented graphically. The study of rotating flow of an electrically conducting fluid in the presence of Hall effect relates the innovative phenomenon of reducing the two-dimensional flow to a one-dimensional one, which do not occur in the absence of rotation.It is also found that, when the rotation parameter equals the value $M^2 m / (1 + m^2)$ for the given Hartmann number M and Hall parameter m, the transverse component of velocity $V = 0$ everywhere in the flow field so that the fluid moves in the direction of the plate only, which is the case in the absence of heat transfer . It is also observed that, with an increase in the Hartmann

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number M, the primary velocity decreases while the secondary velocity increases, with an increase in the Hall parameter m, the primary velocity increases while the secondary velocity decreases. Due to increase in chemical parameter K and rotation parameter Ω, both velocities are decreases.

Nomenclature

A	Constant acceleration
$\vec{B}$	Magnetic induced vector
B_0	Imposed magnetic field
Jz	Component of current density J
μ_e	Magnetic permeability
m	Hall parameter
M	Hartman number
ν	Kinematic viscosity
Ω_z	Component of angular viscosity
Ω	Non-dimensional angular velocity
ρ	Fluid density
σ	Electrical conductivity
Gr	Thermal Grashof's number
Gc	Mass Grashof's number
Pr	Thermal Prandtl number
t'	Time
T	Temperature of the fluid near the plate
T_w	Temperature of the plate
T_∞	Temperature of the fluid for away from the plate
K	Chemical reaction parameter
k	Thermal conductivity
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
μ	Coefficient of viscosity
t	Non-dimensional time
θ	Dimensionless temperature
(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

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