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THERMAL-DIFFUSION EFFECT ON ROTATING HYDROMAGNETIC FLOW IN POROUS MEDIA

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ABSTRACT

Effects of thermal-diffusion on the rotating hydromagnetic two dimensional flow of an electrically conducting incompressible viscous fluid through porous medium are analyzed. The flow considered is past an infinite non-conducting moving plate. A complete analytical solution is obtained for the temperature, the concentration and the velocity field using Laplace transformation and the method of direct integration by means of the matrix exponential (state space approach) in the case when the plate oscillates in its plane. The influence of various parameters involved is discussed with the help of illustrative graphs.

KEYWORDS: MHD Flow, Heat and Mass Transfer, State Space, Rotating Systems.

1. INTRODUCTION

Thermal convection in rotating systems exhibits a rich variety of phenomena not only because of the interaction of rotation and convection, but also due to the interesting results which could be achieved. Study of the effects of rotation of an electrically conducting fluid in porous media with heat and mass transfer has received considerable attention due to its numerous application in geophysics and energy related engineering problems. Such type of applications include natural circulation in isothermal reservoirs, aquifers, porous insulation, heat storage bed, grain storage, extraction of geothermal energy and thermal insulation design. Newal et al [1] investigated the problem of the rotation of an incompressible, homogeneous , viscous fluid over a porous plate. Both the plate and the fluid were in a state of solid body rotation with a constant angular velocity about z-axis normal to the plate.

Laplace transform method was applied to obtain the complex velocity. Busse [2] studied the problem of of thermal convection in rotating system. He assumed the existence of a static state of heat conduction in a homogeneous fluid to prove that the basic state became unstable when the temperature exceeded a critical value. Several buoyancy driven boundary layer flows have been studied by Raptis et al. [3,4]. Oscillatory flow through porous medium has been analyzed by Raptis et al [5] , for small amplitude of oscillation only. To overcome this restriction, Singh et al [6] studied oscillatory flow in porous medium by employing two asymptotic expansions in powers of the frequency parameter. Hamid et al [7] studied the unsteady free convection flow due to heat and mass transfer through a porous medium bounded by an infinite vertical porous plate when the temperature and concentration at the plate is oscillatory with time about a constant non-zero mean and the problem is solved by using a regular expansion method for small value of frequency parameter.

The MHD convective flow in a rotating fluid has been investigated by many researchers, Ram et al. [8], studied the MHD free convection fluid flow past an impulsivly started vertical infinite plate in the presence of a uniform transverse magnetic field when the fluid and the plate are in a state of rigid rotation with a uniform angular velocity about an axis normal to the plate using an explicit finite difference method. Ezzat [9] and Ezzat et al. [10-11] applied the state space approach technique to solve a heated vertical plate problem and carried out the inverse Laplace numerically also formulated the state space approach for one dimensional viscoelastic magnetohydrodynamic unsteady free convection flow with the effects of a viscoelastic boundary layer flow with one relaxation time.

In most of the above applications, the method of solution was either numerical in time domain or in s domain. Helal [12], has solved the unsteady free convection flow due to heat and mass transfer through a porous medium bounded by an infinite vertical porous plate under the action of an external transverse magnetic field of uniform strength B_o. An analytical solution is obtained for the temperature , concentration and velocity fields as functions of time and space using the state space method and Laplace transform techniques.

The motivation of the present study is to solve the MHD fluid flow past a nonconductive moving horizontal impulsive started infinite plate in the presence of a uniform transverse magnetic field when the fluid and the plate are in a state of rigid rotation with a uniform angular velocity about an axis normal to the plate. A complete analytical solution is introduced for the temperature, concentration and velocity as functions of time and height using Laplace transformation and the method of direct integration by means of the matrix exponential (state space approach) which is applicable to a wide range of problems in the field of magneto-hydrodynamics.

2. MATHEMATICAL ANALYSIS

Consider the unsteady flow of an incompressible viscous fluid through a porous medium bounded by an infinite moving horizontal plate under the action of a transverse magnetic field. Both the fluid and the plate are in a state of rigid rotation with uniform angular velocity Ω' about the z'- axis. A uniform magnetic field B'_o is acting along the z'- axis. Initially $(t' \leq 0)$, the plate and the fluid are at rest and have the same temperature T'_∞ and the same concentration C'_∞ every where. At time $t' \succ 0$, the plate starts to move on its own plane with a velocity $U_o f(t')$ along the x'- axis.

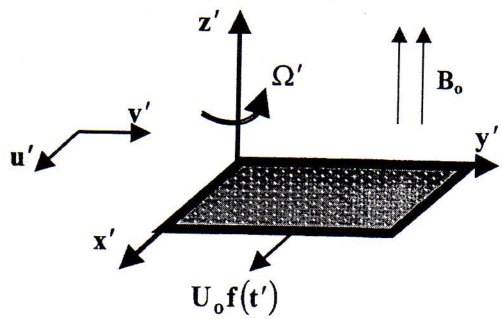

Figure 1: Definition Sketch

The governing equations for such a case are

$$\frac{\partial u'}{\partial t'} - 2\Omega' v' = \nu \frac{\partial^2 u'}{\partial z'^2} + g\beta(T' - T'_\infty) + g\beta^\bullet(C' - C'_\infty) - \left(\frac{\sigma B_o^2}{\rho} + \frac{\nu}{K}\right)u' \quad (1)$$

$$\frac{\partial v'}{\partial t'} + 2\Omega' u' = \nu \frac{\partial^2 v'}{\partial z'^2} - \left(\frac{\sigma B_o^2}{\rho} + \frac{\nu}{K}\right)v' \quad (2)$$

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

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial z'^2} + D_1 \frac{\partial^2 T'}{\partial z'^2} \quad (4)$$

Where u' and v' are the components of the velocity in x' and y' directions respectively, , the pressure gradient is neglected here with respect to the other forces and this is a reasonable assumption in rotating systems, g is the acceleration due to gravity , β and $\beta^\bullet$ are the coefficients of volume expansion and the coefficient of expansion with concentration respectively, ν is the kinematic viscosity of the fluid, D is the molecular diffusivity, D_1 is the modified molecular, diffusivity α is the thermal diffusivity , k is the thermal conductivity, c_p is the specific heat at constant pressure, σ is the electrical conductivity of the fluid, ρ is the density of the fluid, K is the permeability of the porous medium , T' and T'_∞ are the temperatures of the fluid in the plate boundary layer and away from the plate respectively , C' and C'_∞ are the concentration in the boundary layer and away from the plate respectively , and t' is the time.

The initial conditions are

$$V'(z',t') = 0, \quad T'(z',t') = T'_\infty, \quad C'(z',t') = C'_\infty \qquad \text{for } t' \le 0 \quad (5)$$

where $V' = (u', v', 0)$ is the velocity vector

The boundary conditions are

$$\begin{aligned} &V'(0,t') = (U_o f(t'), 0, 0), \qquad &T'(0,t') = T'_w,\ C'(0,t') = C'_w \\ &V'(\infty,t') = (0,0,0) \qquad &T'(\infty,t') = T'_\infty,\ C'(\infty,t') = C'_\infty \end{aligned} \quad (6)$$

where T'_w and C'_w are the mean temperature of the plate and the species concentration near the plate respectively and $f(t')$ is an arbitrary function .

Introducing the following non-dimensional parameters

$$u=\frac{u'}{U_o},\quad v=\frac{v'}{U_o},\quad z=z'\frac{U_o}{\nu},\quad t=t'\frac{U_o^2}{\nu},\quad p=\frac{\rho c_p \nu}{k},\quad S_c=\frac{\nu}{D},$$

$$\theta=\frac{T'-T'_\infty}{T'_w-T'_\infty},\quad C=\frac{C'-C'_\infty}{C'_w-C'_\infty},\quad M=\frac{\sigma B_o^2\nu}{\rho U_o^2},\quad N=\frac{\nu^2}{KU_o^2},\quad E=\Omega'\frac{\nu}{U_o^2},$$

$$G_r=\frac{\nu g\beta(T'_w-T'_\infty)}{U_o^3},\quad G_m=\frac{\nu g\beta^\bullet(C'_w-C'_\infty)}{U_o^3},\quad S_o=\frac{D_1(T'_w-T'_\infty)}{\nu(C'_w-C'_\infty)}$$

Where G_r and G_m are the Grashof number and the modified Grashof number respectively, p is the Prandtl number, Sc is the Schmidt number K is the permeability parameter , 1/N is the dimensionless permeability, M is the magnetic number and E is Ekman number. Equations (1)-(4) are converted to

$$\frac{\partial q}{\partial t}+2iEq=\frac{\partial^2 q}{\partial z^2}+G_r\theta+G_mC-(M+N)q \tag{7}$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{p}\frac{\partial^2\theta}{\partial z^2} \tag{8}$$

$$\frac{\partial C}{\partial t}=\frac{1}{S_c}\frac{\partial^2 C}{\partial z^2}+S_o\frac{\partial^2\theta}{\partial z^2} \tag{9}$$

with the following initial conditions

$$q(z,t)=0,\quad \theta(z,t)=0,\quad C(z,t)=0 \qquad \text{for } t\le 0 \tag{10}$$

where $q=u+iv$ and $i=\sqrt{-1}$

and the boundary conditions are

$$\begin{aligned} &q(0,t)=(f(t),0), && \theta(0,t)=1,\ C(0,t)=1\\ &q(\infty,t)=0, && \theta(\infty,t)=0,\ C(\infty,t)=0 \end{aligned} \tag{11}$$

3. TEMPERATURE SOLUTION

Taking the Laplace transform for Eq. (8) with the initial conditions (10) we get

$$\frac{d^2\tilde{\theta}}{dz^2} - sp\tilde{\theta} = 0 \tag{12}$$

where $\tilde{\theta} = \int_0^\infty e^{-st}\theta(z,t)\,dt$

Using the boundary conditions (11), Eq. (12) has the solution

$$\tilde{\theta}(z,s) = \frac{1}{s}e^{-z\sqrt{sp}} \tag{13}$$

Equation (13) has the inverse Laplace transform

$$\theta(z,t) = \operatorname{erfc}\left(\frac{z}{2}\sqrt{\frac{p}{t}}\right) \tag{14}$$

where *erfc* is the complementary error function.

4. CONCENTRATION SOLUTION

Taking the Laplace transform for Eq. (9) with the initial conditions (10) we get,

$$s\tilde{C} = \frac{1}{S_c}\frac{d^2\tilde{C}}{dz^2} + S_o\frac{d^2\tilde{\theta}}{dz^2} \tag{15}$$

where $\tilde{C} = \int_0^\infty e^{-st}C(z,t)dt$

and $\frac{d^2\tilde{\theta}}{dz^2}$ can be deduced from Eq. (13).

Using the boundary conditions (11), and following the same steps, the solution of Eq. (15) is given by

$$\tilde{C}(z,s) = \frac{1}{s}\left(1 - \frac{S_oS_cp}{S_c - p}\right)e^{-z\sqrt{sS_c}} + \frac{1}{s}\left(\frac{S_oS_cp}{S_c - p}\right)e^{-z\sqrt{sp}} \tag{16}$$

Equation (16) has the inverse Laplace transform

$$C(z,t) = \left(1 - \frac{S_oS_cp}{S_c - p}\right)\operatorname{erfc}\left(\frac{z}{2}\sqrt{\frac{S_c}{t}}\right) + \left(\frac{S_oS_cp}{S_c - p}\right)\operatorname{erfc}\left(\frac{z}{2}\sqrt{\frac{p}{t}}\right) \tag{17}$$

5. THE FLUID VELOCITY SOLUTION

Taking the Laplace transform for Eq. (7) and using the initial conditions (10) for the complex velocity q we get

$$\frac{d^2\tilde{q}}{dz^2} = L\tilde{q} + R(z,s) \tag{18}$$

where L and $R(z,s)$ are $L = s + M + N + i2E$ and $R(z,s) = -G_r\tilde{\theta}(z,s) - G_m\tilde{C}(z,s)$. $\tilde{\theta}(z,s)$ and $\tilde{C}(z,s)$ are given in equations (13) and (16) respectively.

$$R(z,s) = -G_r\frac{1}{s}e^{-z\sqrt{ps}} - G_m\frac{1}{s}\left(1 - \frac{S_oS_cp}{S_c - p}\right)e^{-z\sqrt{sS_c}} + \frac{1}{s}\left(\frac{S_oS_cp}{S_c - p}\right)e^{-z\sqrt{sp}}$$

Substituting

$$\frac{d\tilde{q}}{dz} = \tilde{q}_1 \tag{19}$$

Eq. (18) takes the form

$$\frac{d\tilde{q}_1}{dz} = L\tilde{q} + R(z,s) \tag{20}$$

The above equations, (19) and (20) can be written in matrix form as

$$\frac{d}{dz}\begin{bmatrix}\tilde{q}\\ \tilde{q}_1\end{bmatrix} = \begin{bmatrix}0 & 1\\ L & 0\end{bmatrix}\begin{bmatrix}\tilde{q}\\ \tilde{q}_1\end{bmatrix} + \begin{bmatrix}0\\ R(z,s)\end{bmatrix} \tag{21}$$

The formal solution of Eq. (21) can be expressed as

$$\begin{bmatrix}\tilde{q}\\ \tilde{q}_1\end{bmatrix} = e^{A(s)z}\begin{bmatrix}\tilde{q}(s,0)\\ \tilde{q}_1(s,0)\end{bmatrix} + e^{A(s)z}\int_0^z e^{-A(s)\tau}\begin{bmatrix}0\\ R(\tau,s)\end{bmatrix}d\tau \tag{22}$$

where $A(s) = \begin{bmatrix}0 & 1\\ L & 0\end{bmatrix}$

Determining the matrix exponential, using the Cayley-Hamilton theorem we get

$$e^{A(s)z} = a_oI + a_1A(s)$$

where I is the unit matrix, a_o and a_1 are given by

$$a_o = \frac{\lambda_2}{\lambda_2 - \lambda_1}e^{\lambda_1 z} - \frac{\lambda_1}{\lambda_2 - \lambda_1}e^{\lambda_2 z} \quad \text{and} \quad a_1 = \frac{-1}{\lambda_2 - \lambda_1}e^{\lambda_1 z} + \frac{1}{\lambda_2 - \lambda_1}e^{\lambda_2 z}$$

where λ_1 and λ_2 are the roots of the characteristic equation given by

$\lambda_1 = -\sqrt{L}$ and $\lambda_2 = \sqrt{L}$, the matrix will be

$$e^{A(s)z} = \begin{bmatrix} \cosh z\sqrt{L} & \frac{1}{\sqrt{L}}\sinh z\sqrt{L} \\ \sqrt{L}\sinh z\sqrt{L} & \cosh z\sqrt{L} \end{bmatrix}$$

Substituting into Eq. (22), the solution takes the form,

$$\tilde{q}(z,s) = e^{-z\sqrt{L}}\left[\tilde{q}(0,s) - \frac{\gamma}{2s\sqrt{L}\left(\sqrt{L}-\sqrt{ps}\right)} - \frac{\alpha G_m}{2s\sqrt{L}\left(\sqrt{L}-\sqrt{S_c s}\right)}\right]$$
$$+ e^{-z\sqrt{ps}}\left[\frac{\gamma}{2s\sqrt{L}\left(\sqrt{L}+\sqrt{ps}\right)} + \frac{\gamma}{2s\sqrt{L}\left(\sqrt{L}-\sqrt{ps}\right)}\right]$$
$$+ e^{-z\sqrt{S_c s}}\left[\frac{G_m\alpha}{2s\sqrt{L}\left(\sqrt{L}+\sqrt{S_c s}\right)} + \frac{G_m\alpha}{2s\sqrt{L}\left(\sqrt{L}-\sqrt{S_c s}\right)}\right] \tag{23}$$

where $\gamma = G_r + G_m \frac{S_o S_c p}{S_c - p}$, $\alpha = 1 - \frac{S_o S_c p}{S_c - p}$ and

$$\tilde{q}(0,s) = \int_0^\infty e^{-st} f(t)\,dt$$

Consider the case when the plate oscillates with the frequency ω, i.e ($f(t) = Ae^{i\omega t}$), where A and ω are constants.

The inverse Laplace Transform of Eq. (23) is given by:

$$q(t,z) = A.CF(a+i\omega, z, t) - \frac{\gamma}{2}\int_0^t \frac{1}{(1-p)\sqrt{a}} SF(a,z,t-\tau)\frac{e^{-a\tau}}{\sqrt{\pi\tau}}\,d\tau$$
$$-\frac{\gamma}{2}\int_0^t \frac{\sqrt{a-b}}{(1-p)\sqrt{a}} SF(a,z,t-\tau)\operatorname{erf}\left(\sqrt{(a-b)\tau}\right)e^{-b\tau}\,d\tau$$
$$-\frac{\gamma}{2}\int_0^t \frac{\sqrt{p}}{(1-p)\sqrt{a}} SF(a,z,t-\tau)\frac{1}{\sqrt{\pi\tau}}\,d\tau$$
$$-\frac{\gamma}{2}\int_0^t \frac{i\sqrt{bp}}{(1-p)\sqrt{a}} SF(a,z,t-\tau)\operatorname{erf}\left(i\sqrt{b\tau}\right)e^{-b\tau}\,d\tau$$

$$-\frac{G_m\alpha}{2}\int_0^t \frac{1}{(1-S_c)\sqrt{a}} SF(a,z,t-\tau)\frac{e^{-a\tau}}{\sqrt{\pi\tau}}\, d\tau$$

$$-\frac{G_m\alpha}{2}\int_0^t \frac{\sqrt{a-c}}{(1-S_c)\sqrt{a}} SF(a,z,t-\tau)\,\mathrm{erf}\left(\sqrt{(a-c)\tau}\right)e^{-c\tau}\, d\tau$$

$$-\frac{G_m\alpha}{2}\int_0^t \frac{\sqrt{S_c}}{(1-S_c)\sqrt{a}} SF(a,z,t-\tau)\frac{1}{\sqrt{\pi\tau}}\, d\tau$$

$$-\frac{G_m\alpha}{2}\int_0^t \frac{i\sqrt{cS_c}}{(1-S_c)\sqrt{a}} SF(a,z,t-\tau)\,\mathrm{erf}\left(i\sqrt{c\tau}\right)e^{-c\tau}\, d\tau$$

$$+\frac{\gamma}{1-p}\int_0^t \mathrm{erfc}\left(\frac{z\sqrt{p}}{2\sqrt{t-\tau}}\right)e^{-b\tau}d\tau + \frac{G_m\alpha}{1-S_c}\int_0^t \mathrm{erfc}\left(\frac{z\sqrt{S_c}}{2\sqrt{t-\tau}}\right)e^{-c\tau}d\tau \qquad (24)$$

where $a = M + N + i(2E),\quad b = \dfrac{a}{1-p},\quad c = \dfrac{a}{1-S_c},$

$$\left.\begin{matrix} SF(a,z,t) \\ CF(a,z,t)\end{matrix}\right\} = \frac{1}{2}\left[F_-(a,z,t) \pm F_+(a,z,t)\right]$$

and $F_\pm(a,z,t) = \mathrm{erfc}\left(\dfrac{z}{2\sqrt{t}} \pm \sqrt{at}\right)e^{\pm z\sqrt{t}}$

Equation (24) represents the exact solution of the complex velocity field.

6. RESULTS AND CONCLUSIONS

Equations (14), (17) and (24) represent the complete solution of the presented problem. To examine the effect of the various parameters on the temperature distribution, from Eq. (14), the variation of temperature with the vertical distance z is calculated at different values of the the Prandtle number p is shown in Fig. 2.

The temperature is calculated at time level 0.2, it is clear that the increase of the Prandtle number p makes the temperature distribution concentrates near the boundary layer. Figure 3 represents the transient behavior of the temperature at z=0.5. It shows that the steady state distribution comes at t=3.0 .

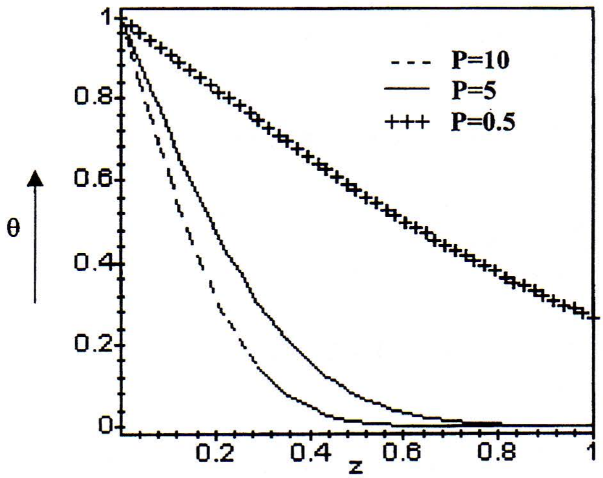

Fig. 2. Variation of Temperature with z at time=0.2

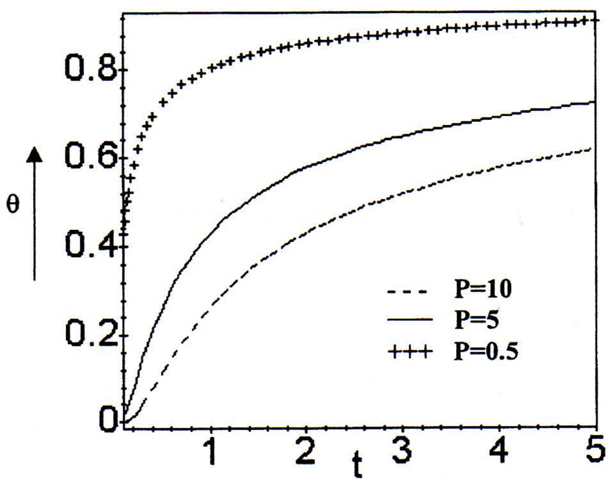

Fig. 3. Variation of Temperature with time at z=0.5.

To examine the effect of the various parameters on the concentration distribution, from Eq. (17), the variation of concentration with the vertical distance z is calculated at different values of the Schmidt number S_c is shown in Fig. 4.

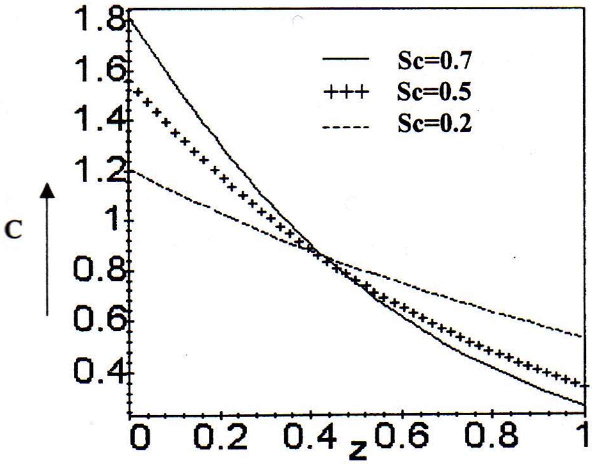

Fig. 4. Variation of Concentration with z at time=0.2.

The concentration is calculated at time level 0.2 and p=5.0, it is clear that the increase of the Schmidt number S_c makes the temperature distribution concentrates near the boundary layer and the concentration is approximately the same at z=0.4 for all values of S_c .

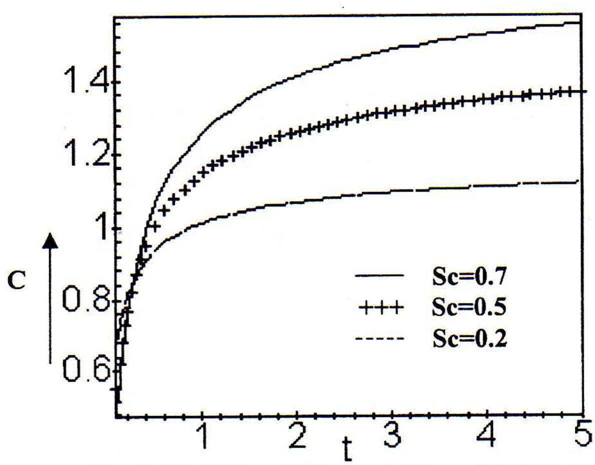

Fig. 5. Variation of Concentration with time at z=0.5.

Figure 5 represents the transient behavior of the concentration at z=0.5 . It shows that the steady state distribution comes at t=3.0 .

The behavior of the velocity components u and v with different parameters is examined from Eq. (24) with G_r and G_m =2.0 ,as follows:

Figure 6 shows the change of u and v with z for different values of the rotating parameter E at t=0.1. It is clear from the figure that the flow field is greatly affected by the variation of E near the plate (small values of z).

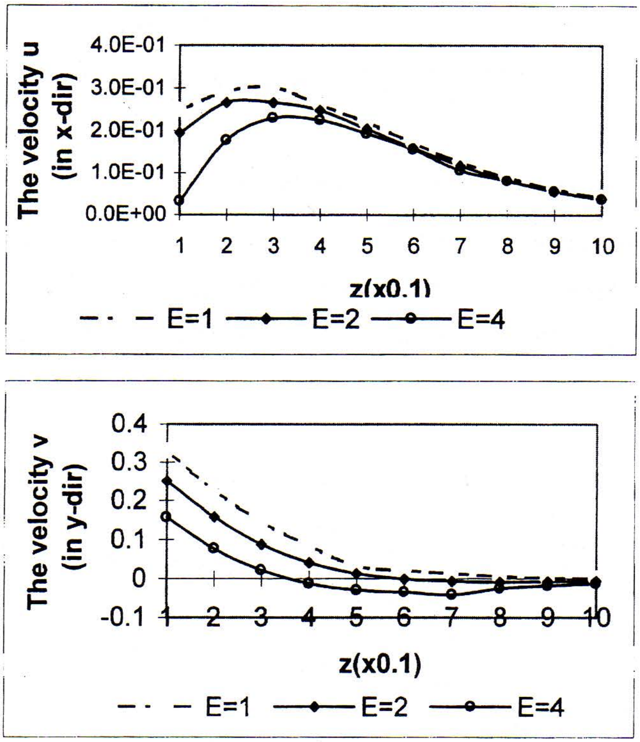

Fig. 6. Variation of Velocity Components u and v with z at different values of the rotating parameters E at t=0.1

Figure 7 shows the change of the velocity component u with z for different values of the the magnetic number M and the porosity N which representing a resistance to the flow field at t=0.1,E=1.0, p=5.0 and Sc=0.5. It is clear from the figure that the increase of M+N decreases the flow field.

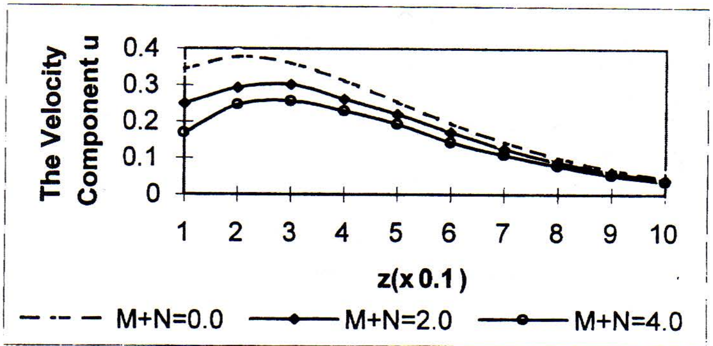

Fig. 7. Variation of The Velocity Component u with z at different values of the the magnetic number M and the porosity N at t=0.1.

Figure 8 shows the change of the velocity component v with z for different values of the modified Grashof number at t=0.1, p=5.0 and Sc=0.5, E=1.0. It is clear from the figure that the flow field is greatly affected by the variation of E near the plate (small values of z).

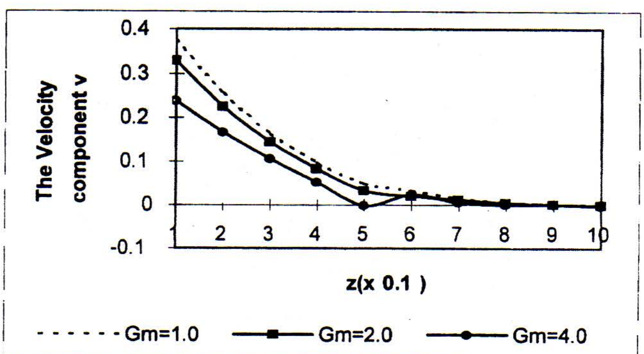

Fig. 8. Variation of The Velocity Component v with z at different values of the modified Grashof number at t=0.1

The temporal variation of the velocity components is shown in Fig. 9 at $z=0.5, p=5.0$, $S_c=0.5$, $A=G_m=G_r=1.0$ and $M+N=2.0$.

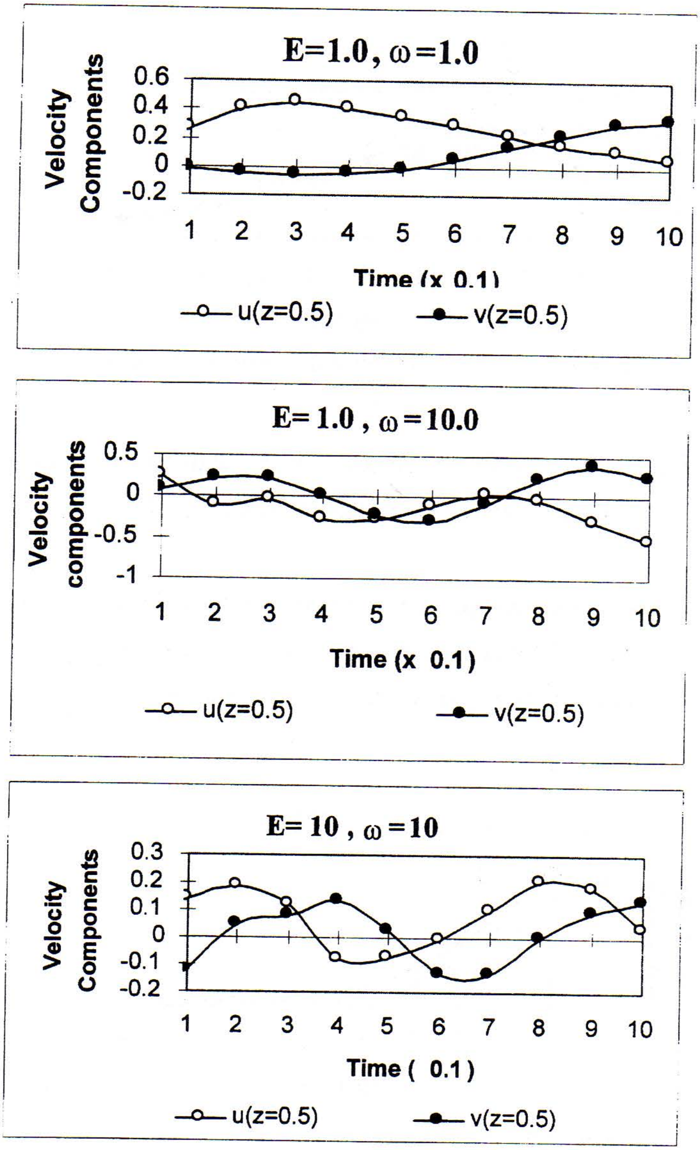

Fig. 9. Variation of Velocity Components u and v with time at different values of **E** and ω .

The effect of the different parameters on the flow velocity hodograph.

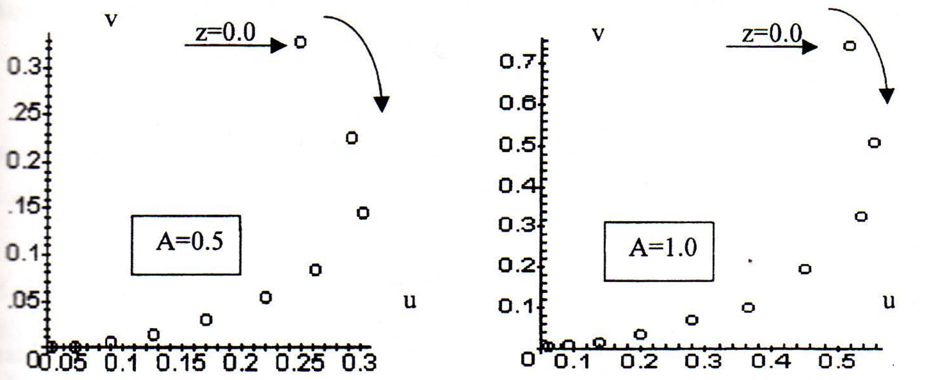

Fig. 10 Effect of A on the flow velocity hodograph. (G_m=2., E=1., M+N=2., ω =10.)

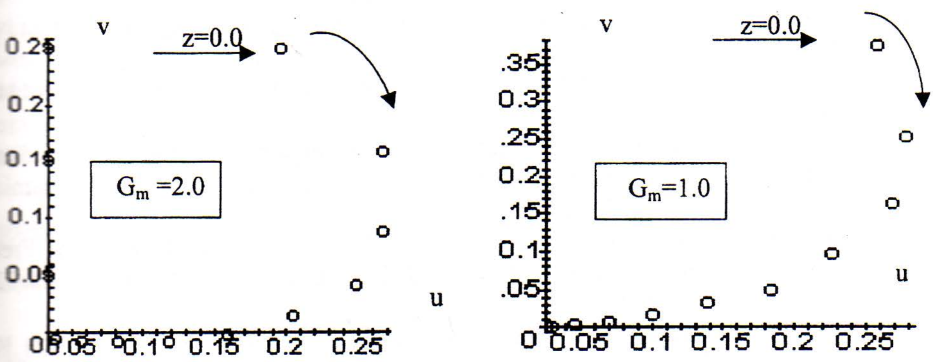

Fig. 11 Effect of G_m on the flow velocity hodograph. (A=.5., E=1., M+N=2., ω .)

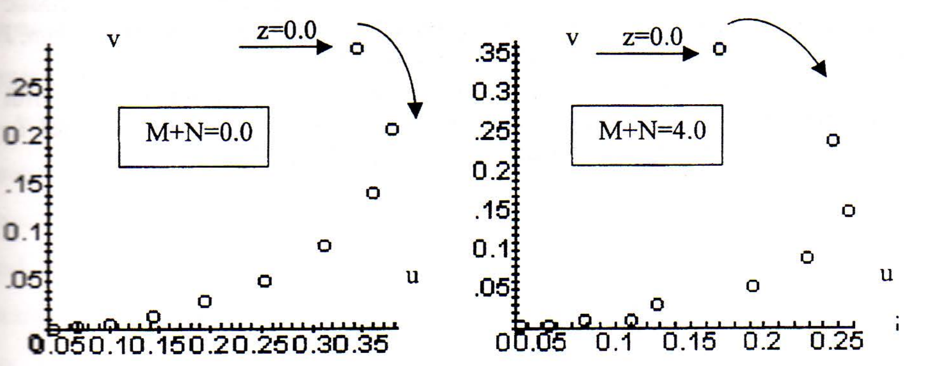

Fig. 12 Effect of M+N on the flow velocity hodograph. (A=.5., E=1., G_m =2., ω =10.)

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