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EFFECTS OF VISCOUS DISSIPATIVE MHD FLUID FLOW PAST A MOVING VERTICAL PLATE WITH ROTATING SYSTEM EMBEDDED IN POROUS MEDIUM

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An incompressible unsteady free convective viscous MHD rotating flow past a moving plate embedded in a porous medium is considered with the influence of viscous dissipation, heat source effects. It is assumed that the flow rotates with angular velocity which is normal to the plate and also that a transverse magnetic field is applied along the normal to the plate. Appropriate dimensionless quantities are applied to change the governing equations into dimensionless form. Then the equations are solved numerically using the Galerkin finite element method. Some important characteristics of the fluid are studied. The results are in good agreement with the available literature.

Key words: rotation, chemical reaction, heat source, viscous dissipation, porous medium.

1. Introduction

Solutal and thermal forces acting on a fluid in a porous medium have been investigated by many authors. They were considered in a rotating system. In this rotating system two forces are produced. Those are viscous force and Coriolis force at the end points. In some investigations, viscous dissipation is neglected with the usual circumstances.

Effects of viscous dissipation on micropolar fluids were investigated by Khonsari *et al.* [1]. The problem generated with the both primary and secondary flow which causes a rotation was described in Iynger *et al.* [2]. In the heat transfer phenomena the impact of viscous dissipation has an important role. In particular, viscous flows are regardless of mild velocities. Here the viscous dissipation transforms the kinetic energy to inner energy and because of this fluid motion increases. Different devices are designed in streambeds to decrease the kinetic energy of flow of water. Muthucumaraswamy *et al.* [3] discussed the consequences of MHD flow with rotation beyond an elevated isothermal plate. Muthucumaraswamy *et al.* [4] discussed a fluid rotating on a vertical plate. It was found that with time the temperature and concentration increase and that velocity increases with a reduction in radiation. Kendoush [5] studied the effect on magneto-hydrodynamic flow past an exponentially accelerated plate. The effect of radiation on an MHD flow is important in manufacturing processes like steel rolling, casting, the design of fins and elevations. Kishore *et al.* [6]

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discussed the importance of various effects of a free convection magneto hydrodynamic unsteady flow past a vertical plate. The viscous dissipation leads to temperature decrease. Muthucumaraswamy *et al.* [7] investigated transverse velocity. Ananda Reddy *et al.* [8] discussed the rotating fluid with ramped wall temperature. It is observed that the temperature and velocity are lower at the ramped temperature plate than the isothermal plate. Hussain *et al.* [9] discussed the effects of heat absorption, Hall current and chemical reaction. Prabhakar Reddy [10] studied the radiation and thermal diffusion of a hydro-magnetic free convection unsteady flow of a rotating fluid past an infinite vertical flat plate with heat absorption.

2. Mathematical model

Consider an unsteady MHD flow of a conducting fluid past an infinite vertical plate embedded in a porous medium in a rotating system. Here, the flow is three dimensional because of the Hall current. The flow is assumed along the x'-axis. Here, the z'- axis is perpendicular to the plate. A transverse magnetic field is applied parallel to the z'- axis. Here we assume a rotating system along the z'-axis with angular velocity in an anticlockwise direction. At $t' \le 0$ the fluid and the plate are at rest and uniform temperature T'_∞. Let the vector component of the velocity be $\left(u', v', 0\right)$ along the y' axis and x' axis. At time $t' > 0$, the plate starts moving along the x' direction with a velocity $u' = u_0$ in its own plane. Now the temperature is raised to a uniform temperature T'_w and concentration is raised to a uniform concentration C'_w. It is assumed that the plate is infinite in extent, hence all physical quantities depend only on z' and t'.Under these assumptions the equations that govern the flow are given:

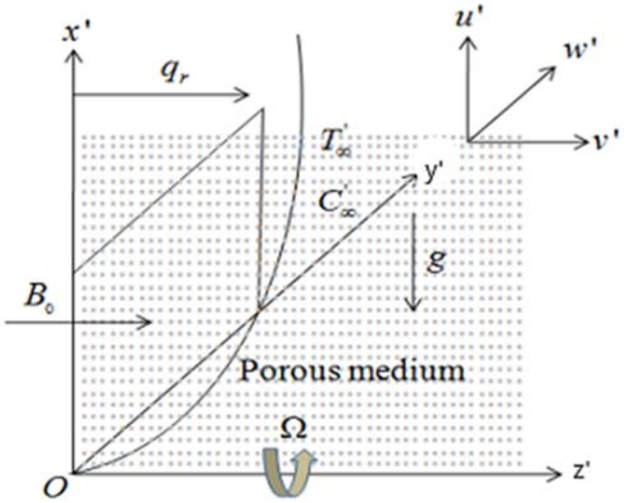

Fig.1. Flow geometry and coordinate system.

Equation of momentum:

$$\frac{\partial u'}{\partial t'} = \upsilon \frac{\partial^2 u'}{\partial z'^2} + g\beta\left(T' - T'_\infty\right) - \left(\frac{u' + mv'}{1+m^2}\right)\frac{\sigma B_0^2 \mu_e^2}{\rho} + 2\Omega'_z v' + g\beta^*\left(C' - C'_\infty\right) - \frac{\upsilon u'}{K_1}, \tag{2.1}$$

$$\frac{\partial v'}{\partial t'} = \upsilon \frac{\partial^2 v'}{\partial z'^2} - \left(\frac{v' - mu'}{1+m^2}\right)\frac{\sigma B_0^2 \mu_e^2}{\rho} - 2\Omega'_z u' - \frac{\upsilon v'}{K_1}. \tag{2.2}$$

Equation of energy:

$$\frac{\partial T'}{\partial t'}=\frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial z'^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial z'}-\frac{Q_0}{\rho c_p}\left(T'-T'_\infty\right)+\frac{\mu}{\rho c_p}\left(\frac{\partial u'}{\partial z'}\right)^2 . \tag{2.3}$$

Equation of diffusion:

$$\frac{\partial C'}{\partial t'}=D\frac{\partial^2 C'}{\partial z'^2}-\gamma'_r\left(C'-C'_\infty\right). \tag{2.4}$$

Here u' and v' are axial and transverse velocities of the flow. Here $\Omega=\dfrac{mM^2}{1+m^2}$.

The initial value and boundary conditions are given as below:

$$t'\le 0,\quad u'=v'=0,\quad C'=C'_\infty \quad \text{and} \quad T'=T''_\infty,\quad \forall \quad z'. \tag{2.5}$$

$$\forall \quad t'>0,\quad T'=T''_w,\quad u'=u'_0,\quad v'=0,\quad C'=C'_w \quad \text{at} \quad z'=0. \tag{2.6}$$

$$T'\to T''_\infty,\quad u'\to 0,\quad v'\to 0,\quad C'\to C'_\infty \quad \text{as} \quad z\to\infty. \tag{2.7}$$

The local radioactive heat flux is given below:

$$\frac{\partial q_r}{\partial z'}=-4a^*\left(T'^4_\infty-T'^4\right)\sigma^* \tag{2.8}$$

where the mean absorption coefficient a^* and the Stefan-Boltzmann constant is σ^*. It is assumed that temperature difference within the flow is small. After using the Taylor's series about T'_∞, after neglecting higher-order terms, we get:

$$T'^4\cong 4T'^3_\infty T'-3T'^4_\infty . \tag{2.9}$$

Equations (2.5), (2.6), (2.7) and (2.8), Eq.(2.3) reduce to:

$$\rho C_P\frac{\partial T'}{\partial t'}=k\frac{\partial^2 T'}{\partial y'^2}+16a^*\sigma^* T'^4_\infty\left(T'-T'_\infty\right)+\mu\left(\frac{\partial u'}{\partial y'}\right)^2-Q_0\left(T'-T'_\infty\right). \tag{2.10}$$

We introduce the non-dimensional quantities:

$$u=\frac{u'}{u_0},\quad v=\frac{v'}{v_0},\quad z=\frac{z'u_0}{v},\quad t=\frac{t'u_0^2}{v},\quad \Omega=\Omega'\frac{\upsilon}{u_0^2},\quad \theta=\frac{T'-T'_\infty}{T'_w-T'_\infty},$$

$$S_c=\frac{v}{D},\quad P_r=\frac{\mu C_p}{k},\quad M^2=\frac{\sigma\mu_e^2 B_0^2 v}{2\rho u_0^2},\quad R=\frac{16\,\sigma^* a^* T'^3_\infty \upsilon^2}{k\,P_r u_0^2}, \tag{2.11}$$

$$G_c = \frac{g\beta v\left(C_w^{'} - C_\infty^{'}\right)}{u_0^3}, \quad \varphi = \frac{C^{'} - C_\infty^{'}}{C_w^{'} - C_\infty^{'}}, \quad G_r = \frac{v\, g\, \beta\left(T_w^{'} - T_\infty^{'}\right)}{u_0^3},$$

cont. (2.11)

$$S = \frac{Q_0 v}{\rho\, C_P\, u_o^2}, \quad E_c = \frac{u_0^2}{C_P\left(T_w^{'} - T_\infty^{'}\right)}, \quad K_r = K_t \frac{\upsilon}{u_0^2}.$$

We put Eq.(2.10) into Eqs (2.1)-(2.3) and (2.9) and as a result the transformed governing non-dimensional equations of the flow become:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial z^2} - M^*\left(u + mv\right) + Gr\theta + Gm\varphi - \frac{u}{K} + 2\Omega v, \tag{2.12}$$

$$\frac{\partial v}{\partial t} + 2\Omega u = \frac{\partial^2 v}{\partial z^2} + M^*\left(mu - v\right) - \frac{v}{K}, \tag{2.13}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial z^2} + R\theta + Ec\left(\frac{\partial u}{\partial z}\right)^2 - S\theta, \tag{2.14}$$

$$\frac{\partial \varphi}{\partial t} + K_r\varphi = \frac{1}{Sc}\frac{\partial^2 \varphi}{\partial z^2}. \tag{2.15}$$

Boundary conditions:

$$\text{at} \quad t \le 0 \quad u = 0, \quad v = 0, \quad \theta = 0, \quad \varphi = 0 \quad \text{for all } z, \tag{2.16}$$

$$\text{when} \quad t > 0 \quad u = 1, \quad v = 0, \quad \theta = t, \quad \varphi = 1 \quad \text{at } z = 0,$$

$$u \to 0, \quad v \to 0, \quad \theta \to 0, \quad \varphi \to 0 \quad \text{as } z \to \infty. \tag{2.17}$$

When $\Omega = \dfrac{mM^2}{1+m^2}$ the transverse velocity vanishes.

3. Solution of the problem

Over the a typical element (e), $z_i \le z \le z_j$, the FEM approach to the linear function (2.12) is implemented.

$$\int_{z_j}^{z_k} \left\{ N^T \left[\frac{\partial^2 u^{(e)}}{\partial y^2} - M^*\left(u + mv\right) - \frac{\partial u^{(e)}}{\partial t} + P - \frac{u}{K} \right] \right\} dz = 0 \tag{3.1}$$

where

$$N^T = \begin{bmatrix} N_j \\ N_k \end{bmatrix},$$

$$P = (Gr)\theta + (G_m)C + 2\Omega v.$$

Integrating

$$\left\{ N^{(e)T} \frac{\partial u^{(e)}}{\partial z} \right\}_{z_j}^{z_k} - \int_{z_j}^{z_k} N^{(e)T} \frac{\partial u^{(e)}}{\partial z} dz - \int_{z_j}^{z_k} N^{(e)^T} \left[M^* (u + mv) + \frac{\partial u^{(e)}}{\partial t} - P + \frac{u^{(e)}}{K} \right] dz = 0 .$$

By ignoring the initial term in the preceding equation, we can get the following outcome:

$$\int_{z_j}^{z_k} N^{(e)T} \frac{\partial u^{(e)}}{\partial z} dz - \int_{z_j}^{z_k} N^{(e)^T} \left[M^* (u + mv) + \frac{\partial u^{(e)}}{\partial t} - P + \frac{u^{(e)}}{K} \right] dz = 0 . \tag{3.2}$$

On integrating, we get:

$$\frac{1}{l^{(e)^2}} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} u_j \\ u_k \end{bmatrix} + \frac{1}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} \dot{u}_j \\ \dot{u}_k \end{bmatrix} + \frac{M^*}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} u_j \\ u_k \end{bmatrix} + \frac{1}{6K} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} u_j \\ u_k \end{bmatrix} = \frac{P}{2} \begin{bmatrix} 1 \\ 1 \end{bmatrix} .$$

$$l^{(e)} = z_k - z_j = h .$$

Taking $z_{i-1} \le z \le z_i$ and $z_i \le z \le z_{i+1}$;

$$\frac{1}{l^{(e)^2}} \begin{bmatrix} 1 & -1 & 0 \\ -1 & 2 & -1 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} u_{i-1} \\ u_i \\ u_{i+1} \end{bmatrix} + \frac{1}{6} \begin{bmatrix} 2 & 1 & 0 \\ 1 & 4 & 1 \\ 0 & 1 & 2 \end{bmatrix} \begin{bmatrix} \dot{u}_{i-1} \\ \dot{u}_i \\ \dot{u}_{i+1} \end{bmatrix} + \frac{\left(M^* + \frac{1}{K} \right)}{6} \begin{bmatrix} 2 & 1 & 0 \\ 1 & 4 & 1 \\ 0 & 1 & 2 \end{bmatrix} \begin{bmatrix} u_{i-1} \\ u_i \\ u_{i+1} \end{bmatrix} = \frac{P}{2} \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} .$$

We get:

$$\frac{1}{l^{(e)^2}} \left[-u_{i-1} + 2u_i - u_{i+1} \right] + \frac{1}{6} \left[\dot{u}_{i-1} + 4\dot{u}_i + \dot{u}_{i+1} \right] + \frac{\left(M^* + \frac{1}{K} \right)}{6} \left[u_{i-1} + 4u_i + u_{i+1} \right] = P .$$

By the trapezoidal rule, the equations are obtained via the Crank-Nicholson method.

$$A_1 u_{i-1}^{n+1} + A_2 u_i^{n+1} + A_3 u_{i+1}^{n+1} = A_4 u_{i-1}^n + A_5 u_i^n + A_6 u_{i+1}^n + 6Pk$$

where

$$A_1 = -3r + \left(M^* + \frac{1}{K}\right)\frac{1}{2}rh^2 + 1, \quad A_4 = 3r - \left(M^* + \frac{1}{K}\right)\frac{1}{2}rh^2 + 1,$$

$$A_2 = 6r + \left(M^* + \frac{1}{K}\right)2rh^2 + 4, \quad A_5 = -6r - \left(M^* + \frac{1}{K}\right)2rh^2 + 4,$$

$$A_3 = -3r + \left(M^* + \frac{1}{K}\right)\frac{1}{2}rh^2 + 1, \quad A_6 = 3r - \left(M^* + \frac{1}{K}\right)\frac{1}{2}rh^2 + 1.$$

By applying the FEM to Eqs (2.13)-(2.15), we get:

$$B_1 v_{i-1}^{n+1} + B_2 v_i^{n+1} + B_3 v_{i+1}^{n+1} = B_4 v_{i-1}^n + B_5 v_i^n + B_6 v_{i+1}^n + 6k\left(M^* mu - 2\Omega u\right)$$

where

$$B_1 = -3r + \left(M^* + \frac{1}{K}\right)\frac{1}{2}rh^2 + 1, \quad B_4 = 3r - \left(M^* + \frac{1}{K}\right)\frac{1}{2}rh^2 + 1,$$

$$B_2 = 6r + \left(M^* + \frac{1}{K}\right)2rh^2 + 4, \quad B_5 = -6r - \left(M^* + \frac{1}{K}\right)2rh^2 + 4,$$

$$B_3 = -3r + \left(M^* + \frac{1}{K}\right)\frac{1}{2}rh^2 + 1, \quad B_6 = 3r - \left(M^* + \frac{1}{K}\right)\frac{1}{2}rh^2 + 1.$$

$$C_1\theta_{i-1}^{n+1} + C_2\theta_i^{n+1} + C_3\theta_{i+1}^{n+1} = C_4\theta_{i-1}^n + C_5\theta_i^n + C_6\theta_{i+1}^n + 6kQP_r$$

where

$$Q = E_c\left(\frac{\partial u}{\partial y}\right)^2$$

where

$$C_1 = -3r + (S-R)P_r\frac{1}{2}rh^2 + P_r, \quad C_4 = 3r - (S-R)P_r\frac{1}{2}rh^2 + P_r,$$

$$C_2 = 6r + (S-R)P_r 2rh^2 + 4P_r, \quad C_5 = -6r - (S-R)P_r 2rh^2 + 4P_r,$$

$$C_3 = -3r + (S-R)P_r\frac{1}{2}rh^2 + P_r, \quad C_6 = 3r - (S-R)P_r\frac{1}{2}rh^2 + P_r.$$

$$D_1\varphi_{i-1}^{n+1} + D_2\varphi_i^{n+1} + D_3\varphi_{i+1}^{n+1} = D_4\varphi_{i-1}^n + D_5\varphi_i^n + D_6\varphi_{i+1}^n$$

where

$$D_1 = -3r + \frac{1}{2}K_r S_c rh^2 + S_c, \qquad D_4 = 3r - \frac{1}{2}K_r S_c rh^2 + S_c,$$

$$D_2 = 6r + 2K_r S_c rh^2 + 4S_c, \qquad D_5 = -6r - 2K_r S_c rh^2 + 4S_c,$$

$$D_3 = -3r + \frac{1}{2}K_r S_c rh^2 + S_c, \qquad D_6 = 3r - \frac{1}{2}K_r S_c rh^2 + S_c.$$

Here

$$r = \frac{k}{h^2},$$

k, h are mesh sizes. Here i is space and j is time. Taking $k = 0.001$ and $h = 0.1$.
In Eqs (2.13)-(2.15) $i = 1$ in Eq.(2.1) and using boundary conditions (2.16) and (2.17), we get:

$$A_i X_i = B_i \quad \text{for} \quad i = 1(1)n.$$

A_i are the matrices of order n range and X_i, B_i are the column matrices of n range. By using Thomas algorithm we obtain the solutions for velocity, temperature and concentration. Through the MATLAB we get the numerical solution for equations. Convergence and stability of the FEM the MATLAB is implemented. So there is no important change in concentration, temperature, secondary velocity and primary velocity. The method is convergent and stable.

4. Result and discussion

The parameters like M, R, m, Kr, Ω, P_r, S_c, G_r, Ec, S, K are shown in graphs $Kr = 0.2$, $\Omega = 2$, $Gr = 5$, $Gm = 10$, $M = 2$, $m = 0.5$, $R = 2$, $t = 2$, $P_r = 7$, $Sc = 2.01$, $S = 2$, $K = 0.5$, $Ec = 0.1$.

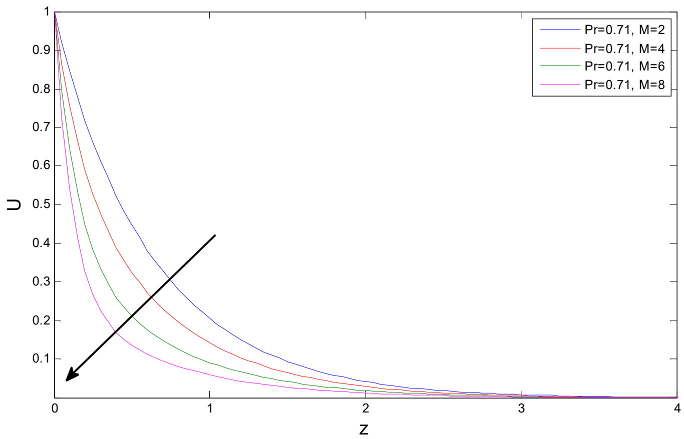

Fig.2. Variation of *u* for different *M*.

The primary velocity decreases with an increasing magnetic parameter. Since the Lorenz force performs normal to the field.

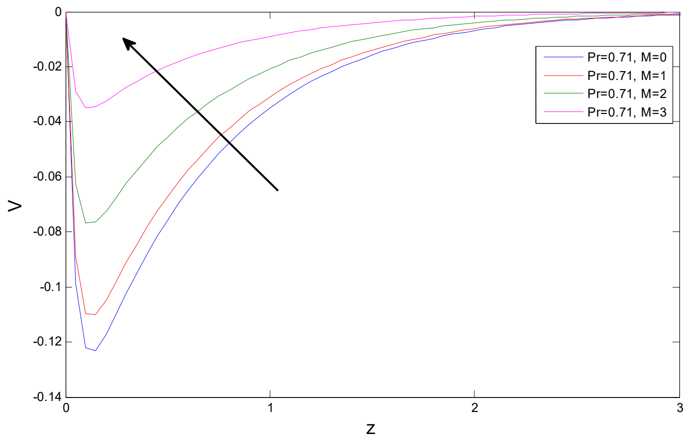

Fig.3. Variation of v for different M.

The secondary velocity increases when the magnetic parameter increases.

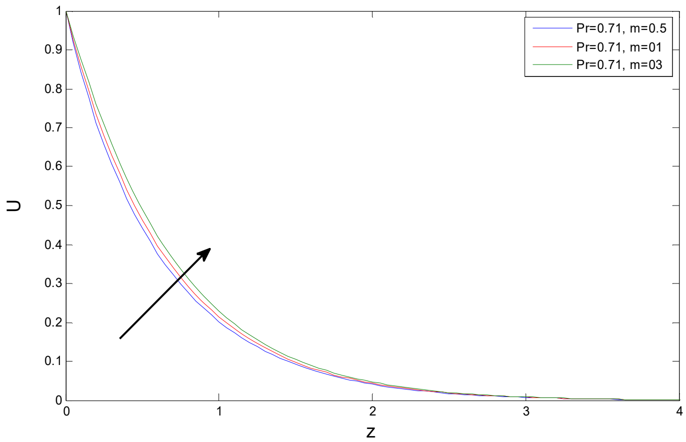

Fig.4. Variation of u for different m.

The primary velocity increases due to an increase in the Hall parameter. Since an increase of m results in a decrease in conductivity and a decrease in the effect of magnetic field resistance. The fluid velocity increases in both directions.

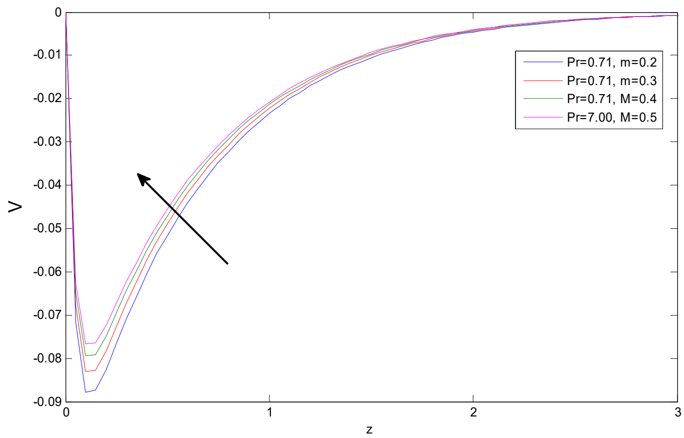

Fig.5. Variation of v for different m.

The secondary velocity increases with higher values of the Hall parameter. So the secondary velocity is consistent throughout the boundary layer.

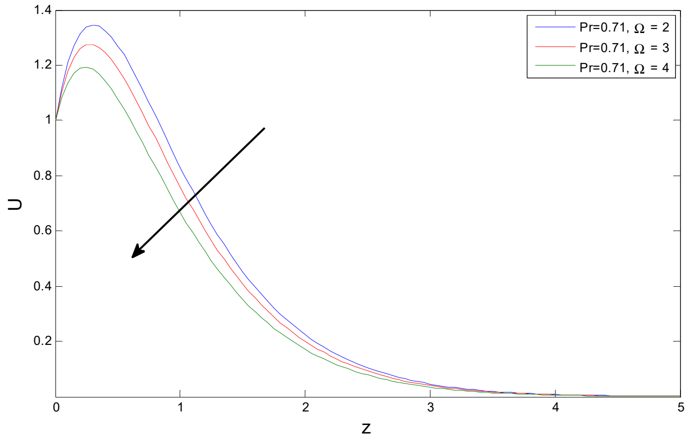

Fig.6. Variation of u for different Ω.

By increasing the rotation parameter, primary velocity gets decreased because rotation has a tendency to retard the fluid flow.

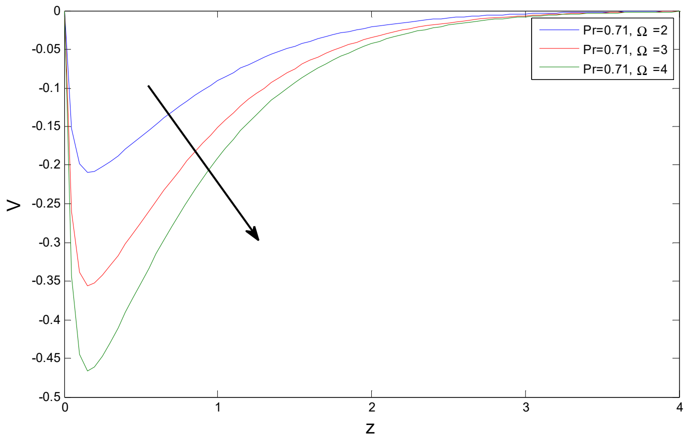

Fig.7. Variation of v for different Ω.

The Coriolis force has a tendency to suppress the flow of fluid. So the secondary velocity decreases with an increases in the rotation parameter.

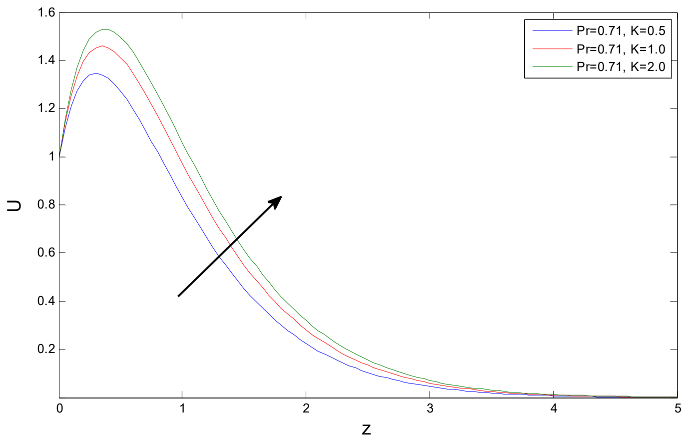

Fig.8. Variation of u for different K.

Here the primary velocity increases with an increase in the permeability parameter. Since there is a decrease in resistance of the porous medium.

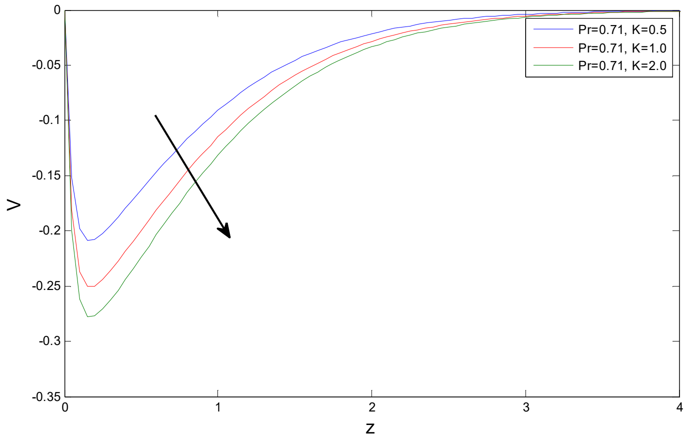

Fig.9. Variation of v for different K.

The secondary velocity decreases with the increase in permeability.

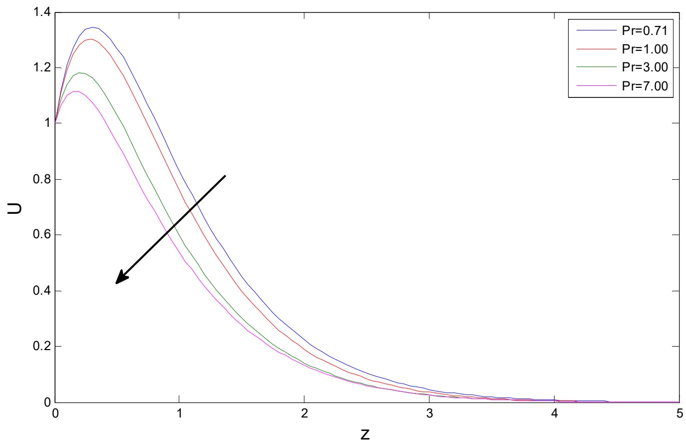

Fig.10. Variation of u for different P_r .

The primary velocity decreases as the Prandtl number increases.

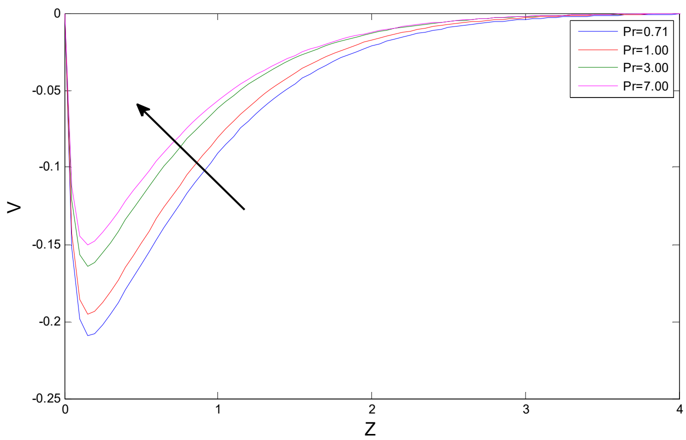

Fig.11. Variation of v for different P_r .

The secondary velocity increases throughout the boundary layer as the Prandtl number increases.

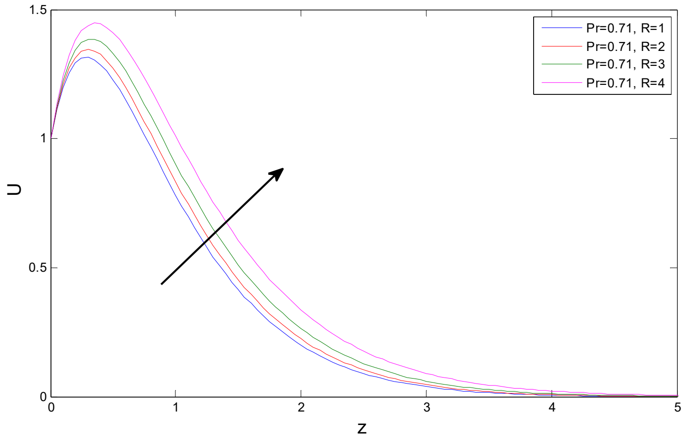

Fig.12. Variation of u for different R.

In the boundary layer there is additional scattered heat by the thermal radiation, so when the thermal radiation increases, velocity also increases.

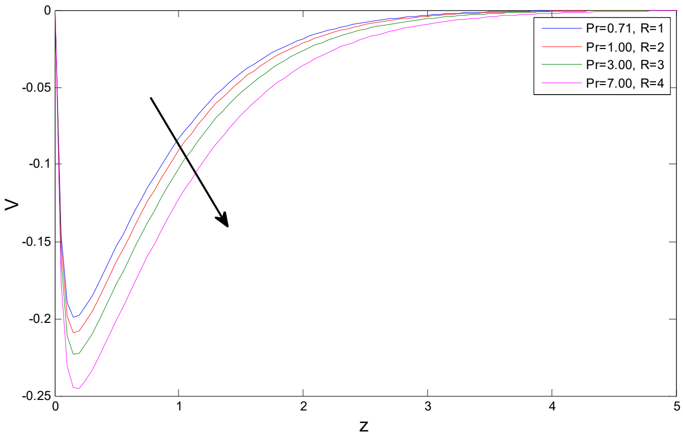

Fig.13. Variation of v for different R.

An increase of the radiation parameter causes an increase in the secondary velocity.

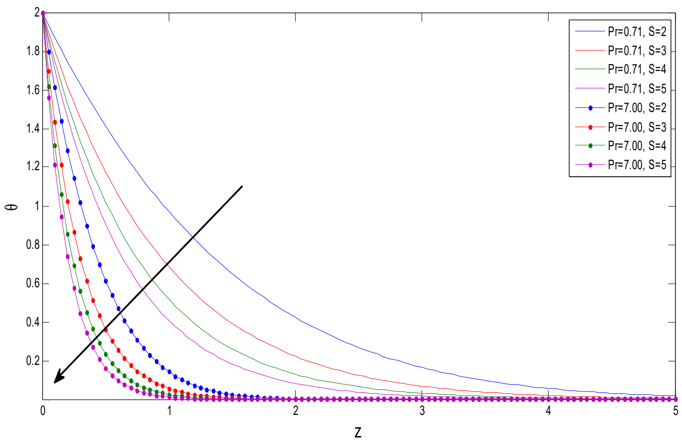

Fig.14. Variation of θ for different S.

Here the temperature of the fluid decreases with an increasing heat absorption. This is because is when heat absorbed in the boundary layer, it is thickened. So the fluid temperature in the boundary layer decreases.

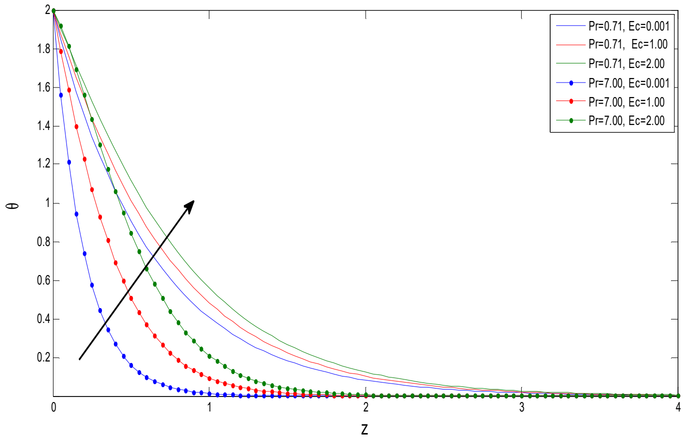

Fig.15. Variation of θ for different *Ec*.

Higher values of the Eckert number increase the temperature.

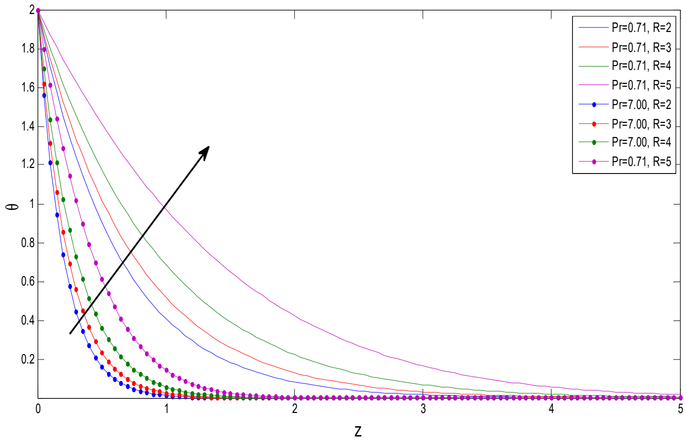

Fig.16. Variation of θ for different *R*.

Higher values of the radiation parameter cause an increase in temperature. Higher values of radiation increase the thermal boundary layer thickness.

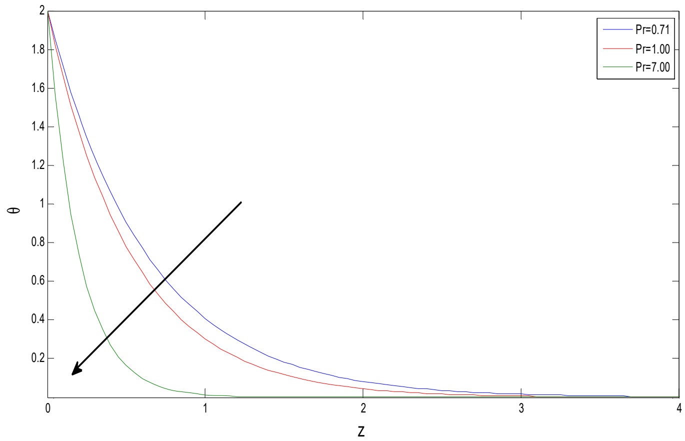

Fig.17. Variation of θ for different P_r .

For higher values of P_r, the temperature decreases. An increase in P_r can decrease the thermal diffusivity. So the capacity of a material to maintain thermal energy is decreased, so the temperature decreases.

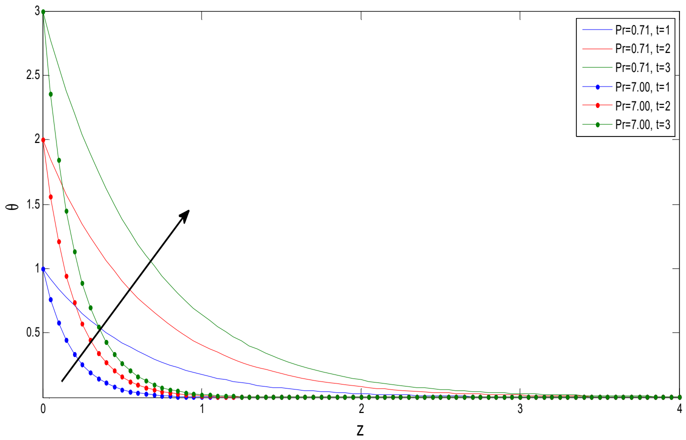

Fig.18. Variation of θ for different *t*.

Higher values of time increase the temperature of the fluid.

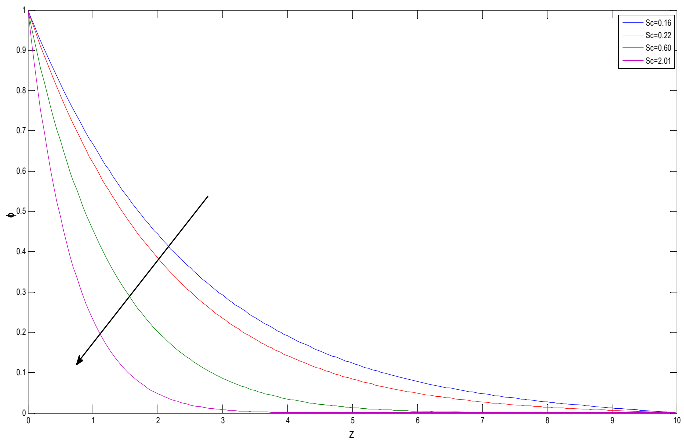

Fig.19. Variation of φ for different *Sc*.

At all points in the flow of the fluid, concentration profile decreases with increasing *Sc*.

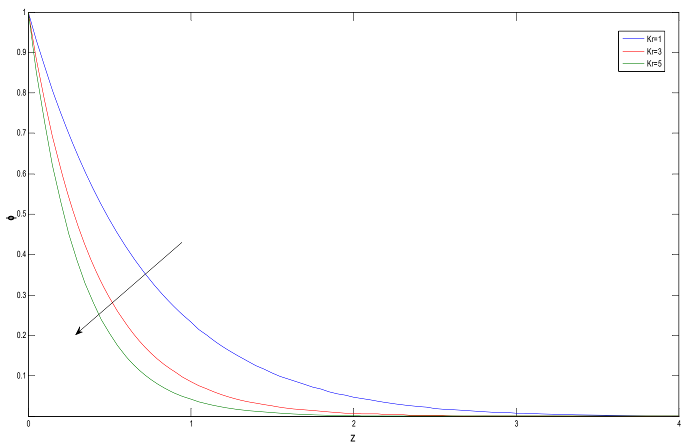

Fig.20. Variation of φ for different *Kr*.

Increasing the rate of chemical reaction causes a decrease in species concentration. Since growing chemical reaction in the fluid causes high molecular motion.

5. Conclusions

- When the radiation parameter, permeability parameter, rotation parameter increase, velocity also increases.
- When the magnetic parameter increases, there is a reduction in the primary velocity.
- With the increase of M, Ω and P_r, the primary velocity is reduced.
- With higher values of M and P_r, the secondary velocity decreases.
- The concentration decreases with increasing Kr.
- Rotation has a tendency to decelerate the flow in the x direction and accelerate it in the z- direction for both types of thermal conditions.
- A growing Eckert number is evident at all points of the flow field where the temperature increased.

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Nomenclature

B_0 – uniform magnetic field
C' – species concentration
c_w – wall concentration
Ec – Eckert number
G_c – mass Grashof number
G_r – thermal Grashof number
K_r – chemical reaction parameter
M – magnetic parameter
m – Hall current
P_r – Prandtl number
S – heat source
S_c – Schmidt number
T – temperature of the fluid near the plate
T_w – plate temperature
T_∞ – temperature of the fluid far away from the plate
t – dimensionless time
β – volumetric coefficient of thermal expansion
θ – dimensionless temperature
μ – viscosity coefficient
v – kinematic viscosity

ρ – density

σ – electrical conductivity

φ – dimensionless concentration

Ω – dimensionless angular velocity

Ω_z – uniform angular velocity

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