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Unsteady MHD Couette Flow Through A Porous Medium In A Rotating System

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Abstract:- In the present study an unsteady magneto-hydrodynamic flow through porous medium between two infinite parallel plates in a rotating system has been considered. The expressions for the velocity and stress fields have been obtained by solving the field equations with the help of Laplace transform technique. The effects of rotational, permeability and magnetic field parameters on the velocity components have been discussed with the help of figures. Further, the effects of magnetic field parameter on the stress fields due to the velocity components have been illustrated graphically.

Keywords:- MHD flow; Porous medium; Permeability; Laplace transform, Shear stress; Visco-elastic flow.

I. INTRODUCTION

The fluid flow problems between two infinite parallel plates in rotating system has drawn considerable attention during recent years due to its wide range of application in designing thermo siphon tubes, in cooling turbine blades etc. Further the flow through porous medium has much importance in oil refinery, crude oil purification, fluid droplets and sprays etc. Jana *et al*. [2] studied unsteady flow of viscous fluid through a porous medium bounded by a porous plate in a rotating system. Seth *et al*. [3] investigated steady hydrodynamic Couette flow in a rotating system with non-conducting walls. Das *et al*. [4] discussed unsteady MHD Couette flow in a rotating system. Das *et al.* [5] studied Hall effects on unsteady rotating MHD flow through porous channel with variable pressure gradient. Das *et al*. [6] investigated on unsteady Couette flow in a Rotating System. Singh *et al*. [7] studied three dimensional Couette Flow through Porous Medium. Mazumder [8] discussed an exact solution of an oscillatory Couette flow through porous medium in a rotating system. Seth *et al.* [9] discussed effects of rotation and magnetic field on unsteady Couette flow in a porous channel.

This paper is devoted to study an unsteady magneto-hydrodynamic flow through porous medium between two infinite parallel plates in a rotating system. The velocity and stress fields are obtained by solving the governing equation with the help of Laplace transform technique. The results are discussed with the help of figures and tables. The velocity component in x-coordinate direction decreases with increase in rotational parameter K. The velocity components in x- and y-coordinate directions increase with increase in permeability parameter K_p and they decrease in magnitude with increase in magnetic field parameter M. As time τ takes higher values, the velocity components increase in magnitude. The stress field T_x due to velocity field in x-coordinate direction, decreases in magnitude with increase in M and the stress field T_y due to velocity component in the y-coordinate direction, increases with increase in M.

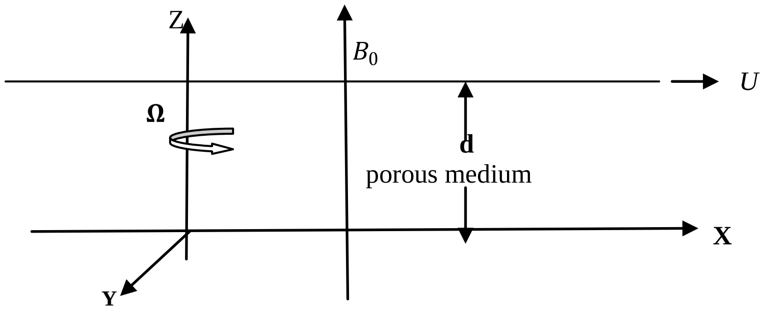

FIG. 1: GEOMETRY OF THE PROBLEM

II. FORMULATION OF THE PROBLEM

Let us consider the unsteady flow of an incompressible fluid through porous medium between two infinite parallel plates separated at a distance 'd' in presence of transverse magnetic field B_0. The fluid and the plates rotate in unison about an axis normal to the plane of the plates with angular velocity $\mathbf{\Omega}$. Let the distance 'd' between the plates is small in comparison with the characteristic length of the plates. The upper plate moves with a uniform velocity U along the plane of the plate itself where x-axis is taken along the plane of the lower plate. The z-axis is taken along the normal direction of the lower plate and y axis is taken in the direction normal to the xz-plane. Since the flow created is due to movement of the upper plate there is no applied pressure gradient. Since the plates are infinite dimensional in x-and y-directions, all the physical quantities must be functions of z and t only. Let us assume the velocity field of the form

$\vec{\mathbf{V}} = (u, v, 0)$ where u and v are velocity components in x- and y-coordinate directions.

The Navier-Stokes equations of motion are given by

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial z^2} + 2\Omega v - \frac{\sigma B_0^2 u}{\rho} - \frac{\nu u}{K_p} \tag{1}$$

$$\frac{\partial v}{\partial t} = \nu \frac{\partial^2 v}{\partial z^2} - 2\Omega u - \frac{\sigma B_0^2 v}{\rho} - \frac{\nu v}{K_p} \tag{2}$$

Where $\nu = \frac{\mu}{\rho}$ is kinematic viscosity, σ is the conductivity of the fluid, ρ is the density of the fluid, μ is the viscosity of the fluid, K_p is the permeability of the porous medium, B_0 is the intensity of the magnetic field.

The initial and boundary conditions are

$$u(z,0) = 0, v(z,0) = 0 \text{ for } 0 \le z \le d \tag{3}$$

$$u(0,t) = 0, v(0,t) = 0 \text{ for } t > 0$$

$$u(d,t) = U, v(d,t) = 0 \text{ for } t > 0 \tag{4}$$

Let us introduce non-dimensional variables

$$\eta = \frac{z}{d}, \tau = \frac{\nu t}{d^2}, u' = \frac{u}{U}, v' = \frac{v}{U}, K_p' = \frac{K_p}{d^2}$$

Then the equation (1) and equation (2) becomes respectively (On dropping the $'$ sign for convenience)

$$\frac{\partial u}{\partial \tau} = \frac{\partial^2 u}{\partial \eta^2} + 2K^2 v - M^2 u - \frac{u}{K_p} \tag{5}$$

$$\frac{\partial v}{\partial \tau} = \frac{\partial^2 v}{\partial \eta^2} - 2K^2 u - M^2 v - \frac{v}{K_p} \tag{6}$$

where $K^2 = \frac{\Omega d^2}{\nu}$ is the rotational parameter, $M^2 = \frac{\sigma B_0^2 d^2}{\rho \nu}$ is the magnetic field parameter, K_p is the parameter of permeability of the porous medium.

Combining the coupled differential equations (5) and (6) we obtain

$$\frac{\partial F}{\partial \tau} = \frac{\partial^2 F}{\partial \eta^2} - 2iK^2 F - M^2 F - \frac{F}{K_p} \tag{7}$$

Where $F = u + iv$, $i = \sqrt{-1}$

III. SOLUTION OF THE PROBLEM

The governing equation (7) in terms of new non-dimensional variables can be rewritten as

$$\frac{\partial^2 F}{\partial \eta^2} - \left(2iK^2 + M^2 + \frac{1}{K_p}\right)F - \frac{\partial F}{\partial \tau} = 0 \tag{8}$$

The initial and boundary conditions (3) and (4) yield

$$F(\eta, 0) = 0, 0 \le \eta \le 1 \tag{9}$$

$$F(0,\tau) = 0, \tau > 0$$

$$F(1,\tau) = 1, \tau > 0 \tag{10}$$

Applying Laplace Transformation we obtain from equation (8)

$$\left[\frac{d^2}{d\eta^2} - \left(M^2 + 2iK^2 + \frac{1}{K_p} + p\right)\right]\bar{F}(\eta, p) = 0 \tag{11}$$

Where $\bar{F}(\eta, p)$ is Laplace Transformation of $F(\eta, \tau)$ and p is Laplace transform parameter.

The solution of the equation (11) can be written as

$$\bar{F}(\eta, p) = A \exp\left(\left(M^2 + 2iK^2 + \frac{1}{K_p} + p\right)\eta\right) + B \exp\left(-\left(M^2 + 2iK^2 + \frac{1}{K_p} + p\right)\eta\right) \tag{12}$$

Where A, B are arbitrary constants to be determined by the equations below

$$\bar{F}(0,p) = 0, \bar{F}(1,p) = \frac{1}{p}$$

Using the above equations the solution of the equation (11) can be written as

$$\bar{F}(\eta,p) = \frac{1}{p}\frac{\sinh(\sqrt{p+a}\,\eta)}{\sinh(\sqrt{p+a})} \tag{13}$$

where $a = M^2 + 2iK^2 + \frac{1}{K_p}$

Taking inverse Laplace transformation we obtain from equation (13)

$$F(\eta,\tau) = \frac{1}{2\pi i}\int_{\gamma-i\infty}^{\gamma+i\infty} e^{pt}\,\bar{F}(\eta,p)dp \quad ,\gamma \text{ is a positive constant.}$$

The poles of the integrand of the above integral are $p = 0, (-n^2\pi^2 - a)$ $(n = 0,1,2,3, \ )$

By residue theorem of complex integrals as given in [1],

$$F(\eta,\tau) = \frac{\sinh(\sqrt{a}\,\eta)}{\sinh(\sqrt{a})} + \sum_{n=1}^{\infty}\frac{2n\pi(-1)^n}{n^2\pi^2 + a}\exp(-(n^2\pi^2 + a)\tau)\sin n\pi\eta \tag{14}$$

Let $\sqrt{a} = \sqrt{M^2 + \frac{1}{K_p} + 2iK^2} = \gamma + i\delta$ where $\gamma = \frac{1}{\sqrt{2}}\sqrt{\sqrt{\left(M^2 + \frac{1}{K_p}\right)^2 + 4K^4} + \left(M^2 + \frac{1}{K_p}\right)}$

And $\delta = \frac{1}{\sqrt{2}}\sqrt{\sqrt{\left(M^2 + \frac{1}{K_p}\right)^2 + 4K^4} - \left(M^2 + \frac{1}{K_p}\right)}$

Then from equation (14)

$$F(\eta,\tau) = \frac{\sinh(\gamma + i\delta)\eta}{\sinh(\gamma + i\delta)} + \sum_{n=1}^{\infty}\frac{2n\pi(-1)^n}{n^2\pi^2 + (\gamma + i\delta)^2}\exp(-(n^2\pi^2 + (\gamma + i\delta)^2)\tau)\sin n\pi\eta \tag{15}$$

The equation (15) can be rewritten as

$$F(\eta,\tau) = \frac{S(\gamma\eta) + iC(\gamma\eta)}{S(\gamma) + iC(\gamma)} + \sum_{n=1}^{\infty}\frac{2n\pi(-1)^n(n^2\pi^2 + \gamma^2 - \delta^2 - 2i\gamma\delta)}{\{(n^2\pi^2 + \gamma^2 - \delta^2)^2 + 4\gamma^2\delta^2\}}e^{-(n^2\pi^2+\gamma^2-\delta^2)\tau} \times (\cos 2\gamma\delta\tau - i\sin 2\gamma\delta\tau)\sin n\pi\eta \tag{16}$$

Where $S(\gamma\eta) = \sinh\eta\gamma\cos\delta\eta$, $C(\gamma\eta) = \cosh\eta\gamma\sin\eta\delta$, $S(\gamma) = \sinh\gamma\cos\delta$, $C(\gamma) = \cosh\gamma\sin\delta$

Separating real and imaginary parts we obtain from equation (16)

$$u(\eta,\tau) = \frac{S(\gamma\eta)S(\gamma) + C(\gamma\eta)C(\gamma)}{S^2(\gamma) + C^2(\gamma)} + \sum_{n=1}^{\infty}\frac{2n\pi(-1)^n}{\{(n^2\pi^2 + \gamma^2 - \delta^2)^2 + 4\gamma^2\delta^2\}}e^{-(n^2\pi^2+\gamma^2-\delta^2)\tau}\sin n\pi\eta \times \{(n^2\pi^2 + \gamma^2 - \delta^2)\cos 2\gamma\delta\tau - 2\gamma\delta\sin 2\gamma\delta\tau\} \tag{17}$$

$$v(\eta,\tau) = \frac{C(\gamma\eta)S(\gamma) - S(\gamma\eta)C(\gamma)}{S^2(\gamma) + C^2(\gamma)} - \sum_{n=1}^{\infty}\frac{2n\pi(-1)^n}{\{(n^2\pi^2 + \gamma^2 - \delta^2)^2 + 4\gamma^2\delta^2\}}e^{-(n^2\pi^2+\gamma^2-\delta^2)\tau}\sin n\pi\eta \left((n^2\pi^2 + \gamma^2 - \delta^2)\sin 2\gamma\delta\tau + 2\gamma\delta\cos 2\gamma\delta\tau\right) \tag{18}$$

For $K_p \to \infty$ the equations (17) and (18) coincides with the equations (26) and (27) of Das *et al.* [5].

The magnitude and direction of the velocity field vector $\vec{\mathbf{V}} = (u, v, 0)$ are respectively given by

$$\mathrm{V} = \sqrt{u^2 + v^2} \text{ and } \theta = \tan^{-1}\left(\frac{v}{u}\right)$$

where u and v are given by equations (17) and (18) respectively.

A. Shear Stress at the Stationary Plate

The non-dimensional shear stress components due to velocities at the stationary plate $(\eta = 0)$ is given by

$$T_x + iT_y = \left(\frac{\partial F(\eta,\tau)}{\partial\eta}\right)_{\eta=0} = \frac{\gamma + i\delta}{\sinh(\gamma + i\delta)} + \sum_{n=1}^{\infty}\frac{2(n\pi)^2(-1)^n}{n^2\pi^2 + (\gamma + i\delta)^2}exp(-(n^2\pi^2 + (\gamma + i\delta)^2)\tau) \tag{19}$$

Separating the real and imaginary parts of both sides of equation (19) we get the shear stress due to velocity components u and v at the stationary plate $(\eta = 0)$ respectively as

$$T_x = \frac{\gamma \sinh \gamma \cos \delta + \delta \cosh \gamma \sin \delta}{\sinh^2\gamma \cos^2\delta + \cosh^2\gamma \sin^2\delta} + \sum_{n=1}^{\infty} \frac{2(n\pi)^2(-1)^n}{\{(n^2\pi^2 + \gamma^2 - \delta^2)^2 + 4\gamma^2\delta^2\}} e^{-(n^2\pi^2+\gamma^2-\delta^2)\tau} \times \{(n^2\pi^2 + \gamma^2 - \delta^2)\cos 2\gamma\delta\tau - 2\gamma\delta \sin 2\gamma\delta\tau\} \quad (20)$$

$$T_y = \frac{\delta \sinh \gamma \cos \delta - \gamma \cosh \gamma \sin \delta}{\sinh^2\gamma \cos^2\delta + \cosh^2\gamma \sin^2\delta} - \sum_{n=1}^{\infty} \frac{2(n\pi)^2(-1)^n}{\{(n^2\pi^2 + \gamma^2 - \delta^2)^2 + 4\gamma^2\delta^2\}} e^{-(n^2\pi^2+\gamma^2-\delta^2)\tau} \times \left((n^2\pi^2 + \gamma^2 - \delta^2)\sin 2\gamma\delta\tau + 2\gamma\delta \cos 2\gamma\delta\tau\right) \quad (21)$$

B. Steady State Solution

It is evident from the equations (17) and (18) that the transient effects die out as time $\boldsymbol{\tau} \to \infty$ and the ultimate steady state is reached.

Hence from equation (15) we obtain the steady state velocity as follows

$$F(\eta, \tau) = \frac{\sinh(\gamma + i\delta)\eta}{\sinh(\gamma + i\delta)} \quad (22)$$

Then the steady state velocity components assume the following forms

$$u(\eta, \tau) = \frac{S(\gamma\eta)S(\gamma) + C(\gamma\eta)C(\gamma)}{S^2(\gamma) + C^2(\gamma)} \quad (23)$$

$$v(\eta, \tau) = \frac{C(\gamma\eta)S(\gamma) - S(\gamma\eta)C(\gamma)}{S^2(\gamma) + C^2(\gamma)} \quad (24)$$

C. Two Different Cases

Case I: When $K^2 \ll 1$ and $M \gg 1$ i.e. when M is large and K^2 small order of magnitude the flow becomes boundary layer type. For the boundary layer near the upper plate $\eta = 1$, introducing the boundary layer coordinate $\zeta = 1 - \eta$,we obtain the velocity distributions

$$u = e^{-\gamma_1\zeta} \cos \delta_1\zeta \quad (25)$$

$$v = -e^{-\gamma_1\zeta} \sin\delta_1 \zeta \quad (26)$$

$$\text{Where } \gamma_1 = M\left(1 + \frac{1}{2M^2K_p}\right), \delta_1 = \frac{K^2}{M} \quad (27)$$

Solutions (25) and (26) reveal that there arises a thin boundary layer of thickness $O({\gamma_1}^{-1})$ near the moving plate of the channel. The exponential terms in equations (25) and (26) die out quickly as ζ increases. The thickness of the boundary layer decreases with an increase in the permeability parameter K_p since γ_1 decreases with increase in K_p. When $\zeta \geq \frac{1}{\gamma_1}$ i.e. outside the boundary layer velocity components assume the forms $u \approx 0$ and $v \approx 0$. Thus we can conclude that the fluid flow confine in boundary region only in a rapidly rotating system.

Case II: When $K^2 \gg 1$ and $M \ll 1$ the velocity distributions obtained from equation (22) are

$$u = e^{-\gamma_2\zeta} \cos \delta_2\zeta \quad (28)$$

$$v = -e^{-\gamma_2\zeta} \sin\delta_2 \zeta \quad (29)$$

$$\text{Where } \gamma_2 = K\left[1 + \frac{1}{4K^2}\left(M^2 + \frac{1}{K_p}\right)\right] \quad (30)$$

$$\delta_2 = K\left[1 - \frac{1}{4K^2}\left(M^2 + \frac{1}{K_p}\right)\right] \quad (31)$$

The expression of the velocity distribution given by equations (28) and (29) demonstrate the existence of a thin boundary layer of thickness $O(\gamma_2^{-1})$ adjacent to the moving plate of the channel where γ_2 is given by equation (30).

IV. RESULTS AND DISCUSSION

Fig. 2 reveals that an increase in rotational parameter K leads to decrease in velocity component u near the moving plate but near the lower plate increase in K leads to increase in aforesaid field. It can also be observed from the figure that near the upper plate the magnitude of the velocity component v decreases with an increase in K but at very near to upper plate v increases with an increase in K and for large values of K, there is an incipient flow reversal near the stationary plate. **Fig. 3** shows that an increase in the parameter of permeability K_p results in increase in velocity component u whereas an increase in K_p leads to decrease in velocity component v. In **Fig.4** velocity components u and v are plotted against η for different values of magnetic parameter M. It is evident from the figure that an increase in M results in decrease in the magnitude of both velocities and it is expected as the magnetic field has a retarding influence on the velocity components. Velocity components u and v are depicted against η for different values of time τ in **Fig. 5**. The figure shows that as τ increases the velocity component u increases and same is the case for the velocity component v. **Fig. 6** shows how the shear stresses T_x and T_y due to the velocities u and v change with time $\boldsymbol{\tau}$ for different values of magnetic field parameter M. The figure shows that the stress field T_x at the lower plate $(\eta = 0)$decreases with increase in M while the stress field T_y at the lower plate increases with increase in M. In **Fig. 7** exhibits the variation pattern of T_x and T_y with regard to the rotational parameter K with time $\boldsymbol{\tau}$. It can be seen that T_x decreases with increase in K and there is negative stress for $K = 15$ while T_y increases with increase in K. **Fig. 8** shows the variations of T_x and T_y with time $\boldsymbol{\tau}$ for different values of permeability parameter K_p. It can be concluded from the figure that there is no significant effects of K_p on T_x and T_y . **Fig. 9** shows the variation pattern of the magnitude of the velocity field with regard to the permeability parameter K_p. Increase in K_p leads to decrease in the magnitude of the velocity field. From **Fig. 10** it can be noticed that the magnitude of the velocity field increases with increase in the rotational parameter K.

In **Table I** numerical values of shear stress due to velocity component u at the stationary plate $(\eta = 0)$ are computed for different values of M and $\boldsymbol{\tau}$ with $K = 5, K_p = 0.2$. From the table it is evident that for fixed $\boldsymbol{\tau}$ the shear stress T_x decreases with increase in M and for fixed M, T_x decreases with increase in time $\boldsymbol{\tau}$ and this is supported by the results in **Fig. 6**. In **Table II** numerical values of shear stress due to velocity component v at the stationary plate $(\eta = 0)$ are computed for different values of M and $\boldsymbol{\tau}$ with $K = 5, K_p = 0.2$. The table shows that for fixed M the shear stress T_y increases with increase in $\boldsymbol{\tau}$ and also for fixed time $\boldsymbol{\tau}$, T_y increases with M and this is the real fact supported by the results in **Fig. 6.** In **Table III** shear stress T_x is computed for different values of K and $\boldsymbol{\tau}$ with $K = 5, K_p = 0.2$. From the table it can be seen that for $K = 5, 10$ the shear stress T_x decreases with $\boldsymbol{\tau}$ whereas for $K = 15, 20$ there is negative stress and this is the case illustrated in **Fig.7.** From **Table IV** it is evident that for increasing values of K, the stress T_y increases with time $\boldsymbol{\tau}$ which is the case shown in **Fig.7.**

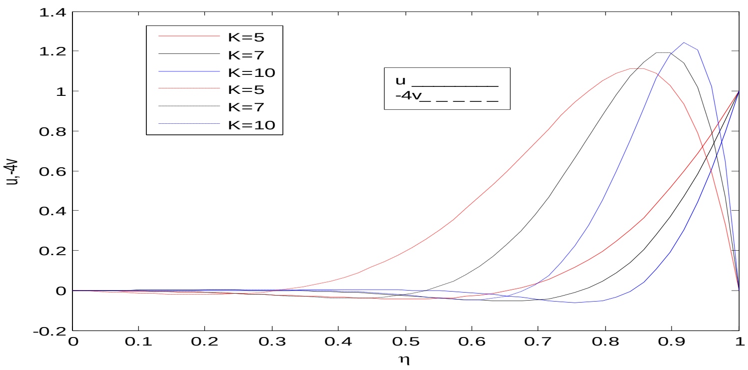

Fig. 2: Velocity components u and v are plotted against η for different values of rotational parameter K with $M = 2, K_p = 0.2, \tau = 5$

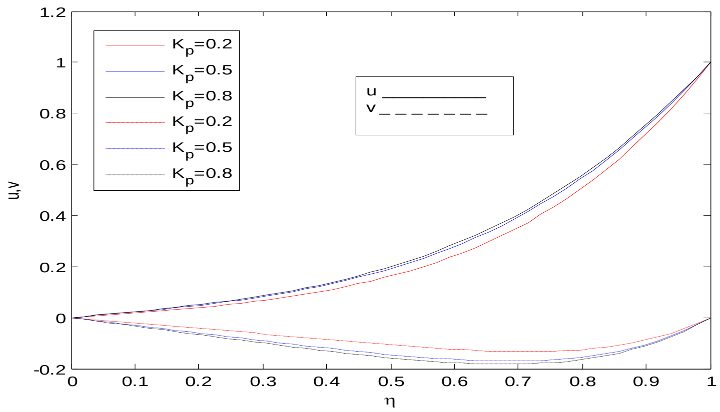

Fig. 3: Velocity components u and v are plotted against η for different values of Permeability parameter K_p with $M = 2, K = 2.0, \tau = 5$

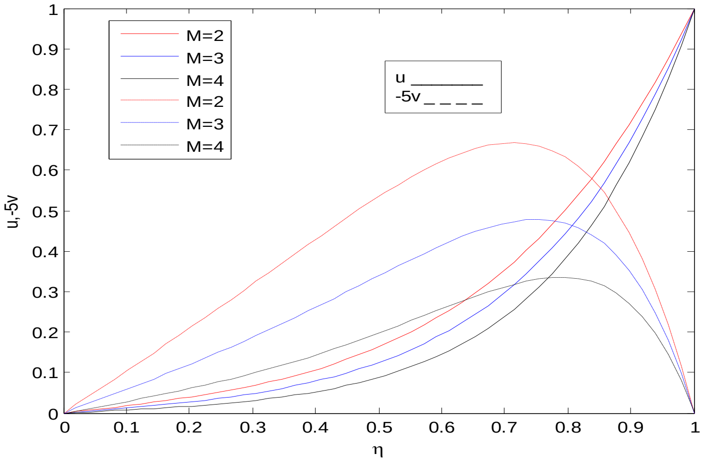

Fig. 4: velocity components u and v are plotted against η for different values of magnetic field parameter M with $K_p = 0.2, K = 2.0, \tau = 5$

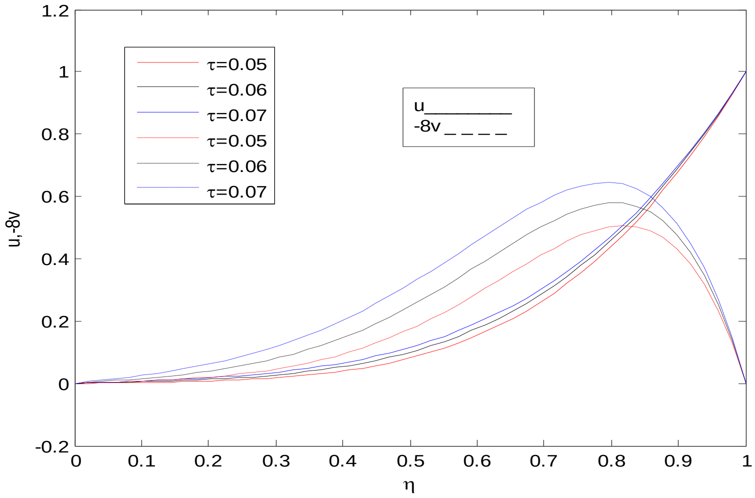

Fig. 5: velocity components u and v are plotted against η for different values of τ with $K_p = 0.2, K = 2.0, M = 2$

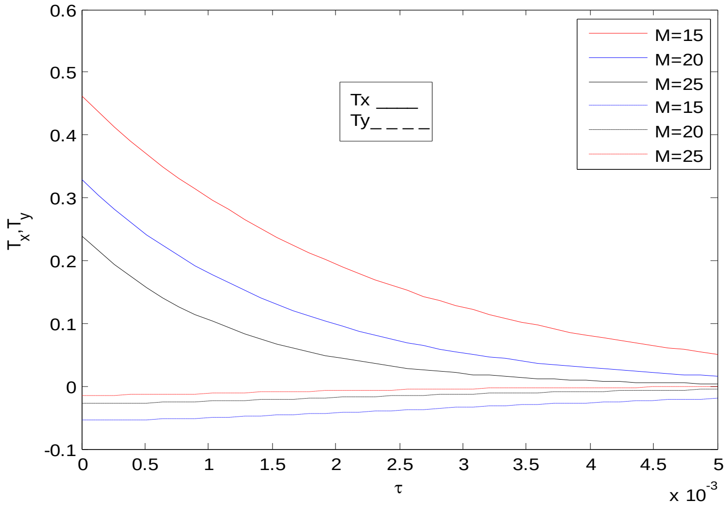

Fig. 6: Shear stress T_x and T_y due to velocity components u and v are depicted against time τ for different values of magnetic field parameter M with $K_p = 0.2, K = 5$.

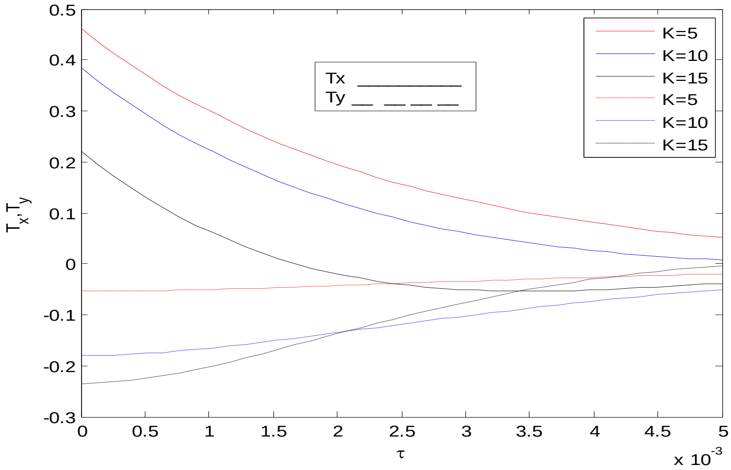

Fig. 7: Shear stress T_x and T_y due to velocity components u and v are depicted against time τ for different values of rotational parameter M with $K_p = 0.2, M = 5$.

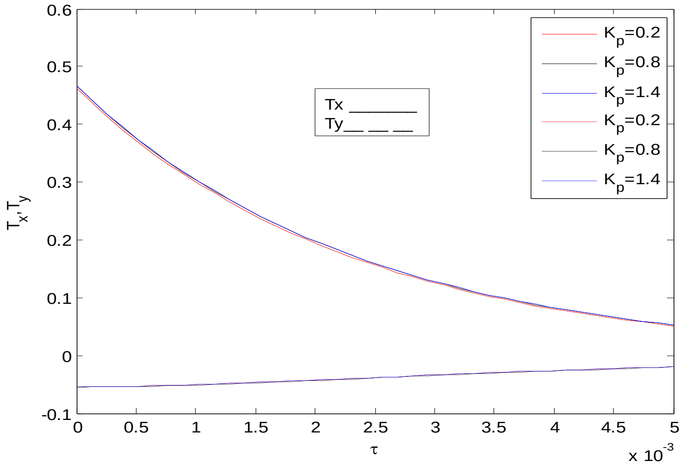

Fig. 8: Shear stress T_x and T_y due to velocity components u and v are depicted against time τ for different values of permeability parameter K_p with $K = 5, M = 5$.

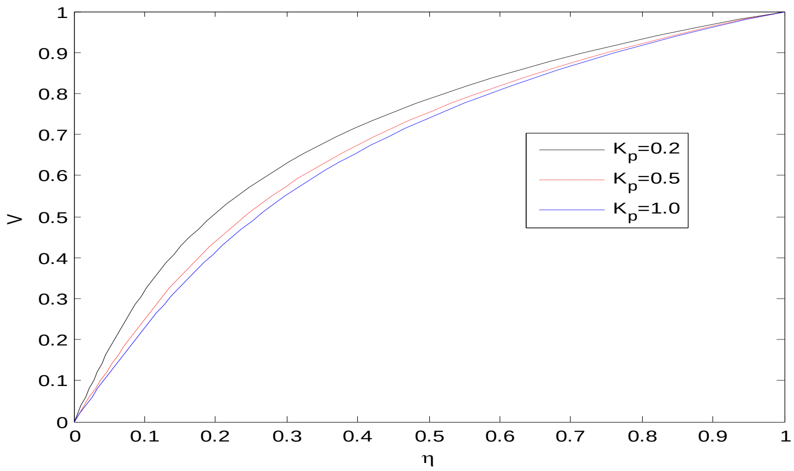

Fig. 9: The magnitude of the velocity field is depicted against η for different values of K_p with $M = 2, K = 2.0, \tau = 5.0$

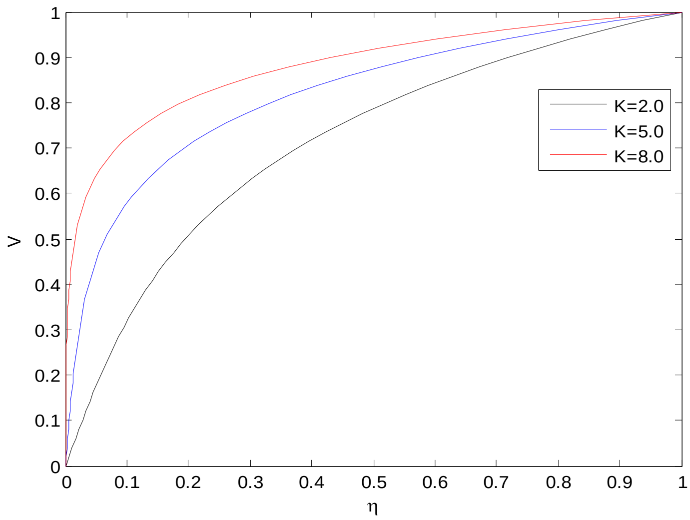

Fig.10: The magnitude of the velocity field is depicted against η for different values of K with $K_p = 0.2, M = 2, \tau = 5.0$

Table I: Shear stress T_x at the plate $(\eta = 0)$ due to velocity component u with $K = 5, K_p = 0.2$

$M\backslash\tau$	**0.001**	**0.002**	**0.003**	**0.004**	**0.005**
5	0.6586	0.5166	0.4033	0.3134	0.2423
10	0.4722	0.3451	0.2510	0.1817	0.1309
15	0.3001	0.1944	0.1253	0.0804	0.0513
20	0.1802	0.0983	0.0533	0.0288	0.0155

Table II: Shear stress T_y at the plate $(\eta = 0)$ due to velocity component v with $K = 5, K_p = 0.2$

$M\backslash\tau$	**0.001**	**0.002**	**0.003**	**0.004**	**0.005**
5	-0.1743	-0.1637	-0.1496	-0.1338	-0.1176
10	-0.1012	-0.0918	-0.0801	-0.0680	-0.0564
15	-0.0503	-0.0425	-0.0340	-0.0261	-0.0195
20	-0.0241	-0.0182	-0.0126	-0.0084	-0.0053

Table III: Shear stress T_x at the plate $(\eta = 0)$ due to velocity component u with $M = 5, K_p = 0.2$

$K\backslash\tau$	**0.001**	**0.002**	**0.003**	**0.004**	**0.005**
5	0.6586	0.5166	0.4033	0.3134	0.2423
10	0.3248	0.1888	0.0886	0.0186	-0.0268
15	0.0030	-0.1080	-0.1577	-0.1581	-0.1269
20	-0.0971	-0.1493	-0.1045	-0.0212	0.0429

Table IV: Shear stress T_y at the plate $(\eta = 0)$ due to velocity component v with $M = 5, K_p = 0.2$

$K\backslash\tau$	0.001	0.002	0.003	0.004	0.005
5	-0.0241	-0.0182	-0.0126	-0.0084	-0.0053
10	-0.0863	-0.0628	-0.0416	-0.0257	-0.0151
15	-0.1299	-0.0804	-0.0403	-0.0156	-0.0033
20	-0.1081	-0.0347	0.0061	0.0151	0.0097

V. CONCLUSIONS

An investigation on unsteady MHD flow through a porous medium between two infinite parallel plates in a rotating system has been considered. The effects of rotation parameter K, permeability parameter K_p, magnetic field parameter M and time τ on velocity components u and v have been discussed. The effects of M on the shear stresses T_x and T_y due to velocities u and v respectively with time τ have been illustrated graphically. On the basis of the above study the following conclusions can be made:

1. The velocity components u and v decrease with increase in K and for large values of K. It can be seen that there is an incipient flow reversal near the stationary plate.
2. For growing values of permeability parameter K_p, the velocity component u increases with η whereas the velocity component v decreases with η.
3. Increase in M results in decrease in the magnitudes in the velocities u and v.
4. As time τ takes higher values the velocity components u and v increase.
5. The shear stress T_x due to velocity component u decreases with time τ for increasing values of M. But the shear stress T_y due to velocity component v increases with time τ for increasing values of M.
6. The magnitude V of the velocity field decreases with increasing values of permeability parameter K_p.
7. The magnitude V of the velocity field increases with increase in rotational parameter K.

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