MHD FLOW THROUGH POROUS MEDIUM IN A PARALLEL PLATE CHANNEL TAKING HALL CURRENT INTO ACCOUNT

P.Sulochana
Associate Professor, Dept of Mathematics,
Intel Engineering College, Anantapuramu, A.P., India

ABSTRACT

In this paper we discussed the steady hydro magnetic flow of a couple stress fluid in a parallel plate channel through a porous medium under the influence of a uniform inclined magnetic field of strength Ho inclined at an angle of inclination α with the normal to the boundaries and taking into hall current. The perturbations are created by a constant pressure gradient along the plates. The equations for the couple stress fluid flow in the porous medium are based on Brinkman's model. The exact solution of the velocity in the porous medium is analytically derived, its behaviour computationally discussed with reference to the various governing parameters. The shear stresses on the boundaries and the discharge between the plates are also obtained analytically and their behaviour is computationally discussed with different variations in governing parameters.

KEYWORDS: *couple stress fluid, porous medium, inclined magnetic field, MHD flows, hall current effects*.

I. INTRODUCTION

In recently years the hydro magnetic flow in a rotating channel in the presence of an applied uniform magnetic field as well as constant pressure gradient has been considered by a number of research workers, taking into account the various aspects of the problem. The channel flow problems where the flow is maintained by torsional or non-torsional oscillations of one or both the boundaries, threw some light in finding out the growth and development of boundary layers associated with the flows occurring in geothermal phenomena. D.V. Krishna *et. al* [4] studied the hydro magnetic convection flow of a viscous electrically conducting fluid through a porous medium in a rotating parallel plate channel. Later M. Guria *et. al* [3] studied the unsteady couette flow of a viscous incompressible fluid confined between parallel plates, rotating with an uniform angular velocity about an axis normal to the plates, here the flow was induced by the motion of the upper plate and the fluid and plates rotate in unison with the same angular velocity. Claire Jacobs [1] studied the transient effects considering the small amplitude torsional oscillations of disks. This problem had been extended to the hydro magnetic case by Vidyanidhi [10], who discussed torsional oscillations of the disks maintained at different temperatures. Debnath [2] considered an unsteady hydrodynamic and hydro magnetic boundary flow in a rotating viscous fluid due to oscillations of plates including the effects of uniform pressure gradients and uniform suction. The structure of the velocity field and the associated Stokes, Ekman and Rayleigh boundary layers on the plates are determined for the resonant and non-resonant cases. Rao.D.R.V., Krishna.D.V. & Debanath, Rao *et. al* [6] have made an initial value investigation of the combined free and forced convection effects in an unsteady hydro magnetic viscous incompressible rotating fluid between two disks under a uniform transverse magnetic field. This analysis has been extended to porous boundaries by Sarojamma and Krishna [7], and later by Siva Prasad [8] to include the Hall current effects. Veera Krishna *et.al* [9] discussed the steady hydro magnetic flow of a couple stress fluid through a porous medium in a rotating parallel plate channel under the influence of a uniform transverse magnetic field making use of Brinkman's model. Recently, Alsaedi.A. et.al [11] discussed peristaltic flow of couple stress fluid through a uniform porous medium in planar channel. Peristaltic hemodynamic flow of couple stress fluids through a porous medium under the influence of slip effect was discussed by D.Tripathi [12]. Some important studies on peristaltic flow of Newtonian fluid with constant viscosity/variable viscosity and non-Newtonian fluids through the porous medium have been presented by El-Shehawey and Husseny [13], Afifi and Gad [14], and Srinivas and Kothandapani 15]. The features of Newtonian, non-Newtonian, and porosity on flow pattern have been discussed.

In this paper we discuss the steady hydro magnetic flow of a couple stress fluid in a parallel plate channel through a porous medium under the influence of a uniform inclined magnetic field of strength H_o inclined at an angle of inclination α with the normal to the boundaries and taking into hall current.

II. FORMULATION AND SOLUTION OF THE PROBLEM

We consider an incompressible viscous and electrically conducting couple stress fluid in a parallel plate channel bounded by a porous medium and taking hall current into account. The fluid is driven by a uniform pressure gradient parallel to the channel plates and the entire flow field is subjected to a uniform inclined magnetic field of strength H_o inclined at an angle of inclination α with the normal to the boundaries in the transverse *xy*-plane. In the equation of motion along x-direction the x-component current density $-\mu_e J_z H_o$ and the z-component current density $\mu_e J_x H_o$.

We choose a Cartesian system O(*x, y, z*) such that the boundary walls are at *z=0* and *z=l* and are assumed to be parallel to *xy*-plane. The steady flow through porous medium is governed by Brinkman's equations. At the interface the fluid satisfies the continuity condition of velocity and stress. The boundary plates are assumed to be parallel to *xy*-plane and the magnetic field of strength H_o inclined at an angle of inclination α to the *z*-axis in the transverse *xz*-plane. This inclined magnetic field on the axial flow along the *x*-direction gives rise to the current density along *y*-direction in view of Ohm's law. Also the inclined magnetic field in the presence of current density exerts a Lorentz force with components along O(*x, z*) direction, The component along *z*-direction induces a secondary flow in that direction while its *x*-components changes perturbation to the axial flow. The steady hydro magnetic equations governing the couple stress fluid under the influence of a uniform inclined magnetic field of strength H_o inclined at an angle of inclination α with reference to a frame are

$$\frac{\eta}{\rho}\frac{d^4u}{dz^4} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{d^2u}{dz^2} - \frac{\mu_e J_z H_o Sin\alpha}{\rho} - \frac{\nu}{k}u \tag{1}$$

$$\frac{\eta}{\rho}\frac{d^4w}{dz^4} = \nu\frac{d^2w}{dz^2} + \frac{\mu_e J_x H_o Sin\alpha}{\rho} - \frac{\nu}{k}w \tag{2}$$

Where, (*u*, *w*) are the velocity components along O(*x*, *z*) directions respectively. ρ is the density of the fluid, μ_e is the magnetic permeability, ν is the coefficient of kinematic viscosity, k is the permeability of the medium, H_o is the applied magnetic field. When the strength of the magnetic field is very large, the generalized Ohm's law is modified to include the Hall current, so that

$$J + \frac{\omega_e \tau_e}{H_0} J \times H = \sigma\,(E + \mu_e\, q \times H) \tag{3}$$

Where, q is the velocity vector, H is the magnetic field intensity vector, E is the electric field , J is the current density vector, ω_e is the cyclotron frequency, τ_e is the electron collision time, σ is the fluid conductivity and, μ_e is the magnetic permeability. In equation (2.3) the electron pressure gradient, the ion-slip and thermo-electric effects are neglected. We also assume that the electric field $E=0$ under assumptions reduces to

$$J_x - m\, J_z Sin\alpha = -\sigma\mu_e H_0 w\, Sin\alpha \tag{4}$$

$$J_z + m\, J_x Sin\alpha = -\sigma\mu_e H_0 u Sin\alpha \tag{5}$$

where $m = \omega_e \tau_e$ is the Hall parameter.

On solving equations (2.3) and (2.4) we obtain

$$J_x = \frac{\sigma\mu_e H_0 Sin\alpha}{1 + m^2 Sin^2\alpha}(umSin\alpha - w) \tag{6}$$

$$J_z = \frac{\sigma\mu_e H_0 Sin\alpha}{1+m^2 Sin^2\alpha}(u + wmSin\alpha) \tag{7}$$

Using the equations (6) and (7), the equations of the motion with reference to frame are given by

$$\frac{\eta}{\rho}\frac{d^4u}{dz^4} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{d^2u}{dz^2} - \frac{\sigma\mu_e^2 H_0^2 Sin\alpha}{\rho(1+m^2 Sin^2\alpha)}(u + wmSin\alpha) - \frac{\nu}{k}u \tag{8}$$

$$\frac{\eta}{\rho}\frac{d^4w}{dz^4} = \nu\frac{d^2w}{dz^2} + \frac{\sigma\mu_e^2 H_0^2 Sin\alpha}{\rho(1+m^2 Sin^2\alpha)}(umSin\alpha - w) - \frac{\nu}{k}w \tag{9}$$

Let $q = u + iw$

Now combining the equations (8) and (9), we obtain

$$\frac{\eta}{\rho}\frac{d^4q}{dz^4} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{d^2q}{dz^2} - \frac{\sigma\mu_e^2 H_0^2 Sin^2\alpha}{\rho(1+m^2 Sin^2\alpha)}(1 - imSin\alpha)q - \frac{\nu}{k}q \tag{10}$$

The boundary conditions are

$$q = 0 \quad , \quad at \quad z = 0 \tag{11}$$

$$q = 0 \quad , \quad at \quad z = l \tag{12}$$

$$\frac{d^2q}{dz^2} = 0, \quad at \quad z = 0 \tag{13}$$

$$\frac{d^2q}{dz^2} = 0, \quad at \quad z = l \tag{14}$$

We introduce the non-dimensional variables

$$z^* = \frac{z}{l}, \quad q^* = \frac{ql}{\nu}, \quad q_p^* = \frac{q_p l}{\nu}, \quad P^* = \frac{Pl^2}{\rho\nu^2}, \quad h^* = \frac{h}{l}, \quad \xi^* = \frac{\xi}{l}.$$

Using the non-dimensional variables, the governing non-dimensional equations are (dropping asterisks)

$$S\frac{d^4q}{dz^4} - \frac{d^2q}{dz^2} + \left(\frac{M^2 Sin^2\alpha(1 - imSin\alpha)}{1+m^2 Sin^2\alpha} + D^{-1}\right)q = P \tag{15}$$

where, $M^2 = \dfrac{\sigma\mu_e^2 H_0^2 l^2}{\rho\nu}$ is the Hartmann number, $m = \omega_e\tau_e$ is the Hall Parameter,

$D^{-1} = \dfrac{l^2}{k}$ is the inverse Darcy parameter, $S = \dfrac{\eta}{\rho l^2\nu}$ is the Couple stress parameter ,

$P = -\dfrac{\partial p}{\partial x}$ is the imposed pressure gradient.

Corresponding boundary conditions are

$$q = 0 \quad , \quad at \quad z = 0 \tag{16}$$

$$q = 0 \quad , \quad at \quad z = 1 \tag{17}$$

$$\frac{d^2q}{dz^2} = 0, \quad at \quad z = 0 \tag{18}$$

$$\frac{d^2q}{dz^2} = 0, \quad at \quad z = 1 \tag{19}$$

Solving the equation (15) making use of the boundary conditions, we obtain

$$q = Ae^{m_1 z} + Be^{m_2 z} + Ce^{-m_1 z} + De^{-m_2 z} + \frac{P}{\left(\frac{M^2 Sin^2\alpha(1-imSin\alpha)}{1+m^2 Sin^2\alpha}\right)} \qquad (20)$$

The shear stresses on the upper plate and lower plate are given by

$$\tau_U = \left(\frac{dq}{dz}\right)_{z=1} \quad and \quad \tau_L = \left(\frac{dq}{dz}\right)_{z=0}$$

where, the constants *A*, *B*, *C* and *D* are mentioned in below.

$$A = -B - C - D - \frac{P}{\frac{M^2 Sin^2\alpha}{(1+imSin\alpha)} + D^{-1}}$$

$$B = \frac{P(e^{m_1}-1)}{\left(\frac{M^2 Sin^2\alpha}{(1+imSin\alpha)} + D^{-1}\right)(e^{m_2}-e^{m_1})} - C\frac{(e^{-m_1}-e^{m_1})}{(e^{m_2}-e^{m_1})} - D\frac{(e^{-m_1}-e^{m_1})}{(e^{m_2}-e^{m_1})}$$

$$C = \frac{P\,m_1^2(e^{m_2}-1) - P\,m_2^2(e^{m_1}-1)}{\left(\frac{M^2 Sin^2\alpha}{(1+imSin\alpha)} + D^{-1}\right)(e^{m_1}-e^{-m_1})} - D\frac{(m_2^2-m_1^2)(e^{m_2}-e^{-m_2})}{(e^{m_1}-e^{-m_1})}$$

$$D = \frac{g_1}{g_2}$$

$$g_1 = [P(m_1^2-m_2^2)e^{m_1+m_2} + Pm_2^2 e^{m_2} - Pm_1^2 e^{m_1}](m_1^2-m_2^2)(e^{-m_1}-e^{m_1}) -$$

$$-(m_1^2-m_2^2)(-e^{m_1+m_2} + e^{-m_1+m_2})(Pm_1^2 e^{m_1} - Pm_2^2 e^{m_2} + Pm_2^2 - Pm_1^2)$$

$$g_2 = \left(\frac{M^2 Sin^2\alpha}{(1+imSin\alpha)} + D^{-1}\right)(e^{m_2}-e^{m_1})[(m_1^2-m_2^2)e^{-m_1} + (-m_1^2+m_2^2)e^{m_1}]^2$$

$$[(m_1^2-m_2^2)e^{m_1-m_2} - (m_1^2-m_2^2)e^{m_1+m_2}] - [(m_1^2-m_2^2)e^{-m_1+m_2} - (m_1^2-m_2^2)e^{m_1+m_2}]$$

$$[(m_1^2-m_2^2)e^{-m_2} + (-m_1^2+m_2^2)e^{m_2}]$$

$$m_1 = \sqrt{\frac{1+\sqrt{1-4S\left(\frac{M^2 Sin^2\alpha}{(1+imSin\alpha)} + D^{-1}\right)}}{2S}}, \qquad m_2 = \sqrt{\frac{1-\sqrt{1-4S\left(\frac{M^2 Sin^2\alpha}{(1+imSin\alpha)} + D^{-1}\right)}}{2S}}.$$

III. RESULTS AND DISCUSSION

The velocities representing the ultimate flow have been computed numerically for different sets of governing parameters namely viz. The Hartmann parameter *M*, the inverse Darcy parameter D^{-1}, couple stress parameter *S* and hall parameter *m*, and their profiles are plotted in figures (1-4) and (5-8) for the velocity components *u* and *v* respectively. For computational purpose we have assumed an angle of inclination α and the applied pressure gradient in the *x*-direction and are fixed. Since the thermal buoyancy balances the pressure gradient in the absence of any other applied force in the direction, the flow takes place in planes parallel to the boundary plates. However the flow is three dimensional and all the perturbed variables have been obtained using boundary layer type equations, which reduce to two coupled differential equations for a complex velocity.

We notice that the magnitude of the velocity component *u* reduces and *v* increases with increasing the intensity of the magnetic field *M* the other parameters being fixed, it is interesting to note that the resultant velocity experiences retardation with increasing *M* (Fig. 1 & 4). (Fig. 2 & 6) exhibit both the velocity components *u* and *v* reduces with increasing the inverse Darcy parameter D^{-1}. Lower the permeability of the porous medium lesser the fluid speed in the entire fluid region. The resultant velocity experiences retardation with increasing the inverse Darcy parameter D^{-1}. Here we observe that the retardation due to an increase in the porous parameter is more rapid than that due to increase in the Hartmann number *M*. In other words, the resistance offered by the porosity of the medium is much more than the resistance due to the magnetic lines of force. We notice that *u* exhibits a great enhancement in contrast to *v* which retards appreciably with increase in the couple stress parameter *S*, but the resultant velocity shows and appreciable enhancement with in *S* (Fig. 3 & 7). We also notice that the magnitude of the both velocity components *u* and *v* increase with increasing the hall parameter *m* the other parameters being fixed, it is interesting to note that the resultant velocity experiences maximum enhancement with increasing *m* (Fig. 4 & 8).

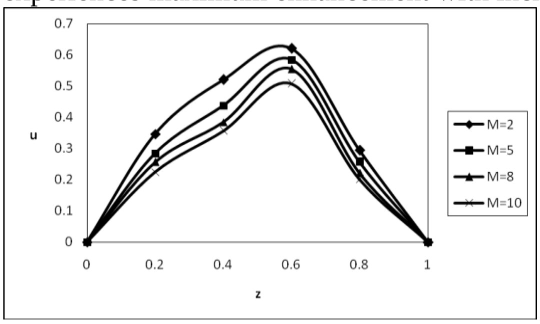

Fig. 1: The velocity profile *u* for different *M* with $D^{-1}=1000, S=1, m=1, \alpha=\frac{\pi}{4}$

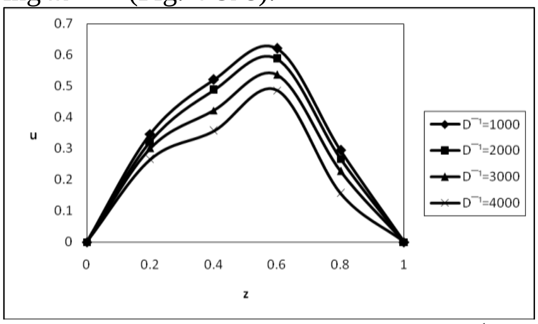

Fig. 2: The velocity profile *u* for different D^{-1} with $M=2, S=1, m=1, \alpha=\frac{\pi}{4}$

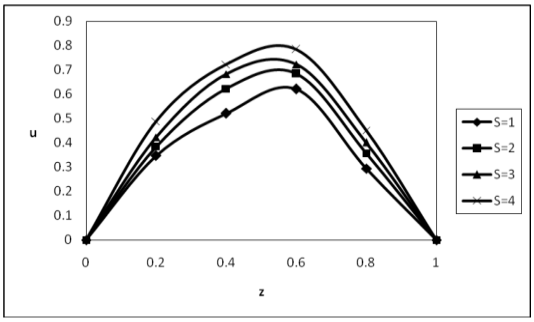

Fig. 3: The velocity profile *u* for different *S* with $D^{-1}=1000, M=2, m=1, \alpha=\frac{\pi}{4}$

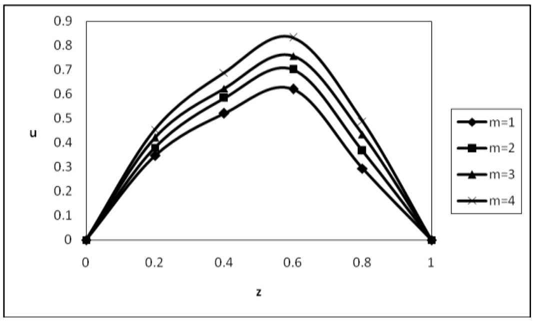

Fig. 4: The velocity profile *u* for different *m* with $D^{-1}=1000, M=2, S=1, \alpha=\frac{\pi}{4}$

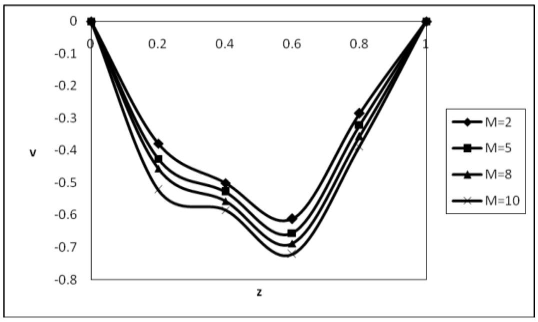

Fig. 5: The velocity profile *v* for different *M* with $D^{-1}=1000, S=1, m=1, \alpha=\frac{\pi}{4}$

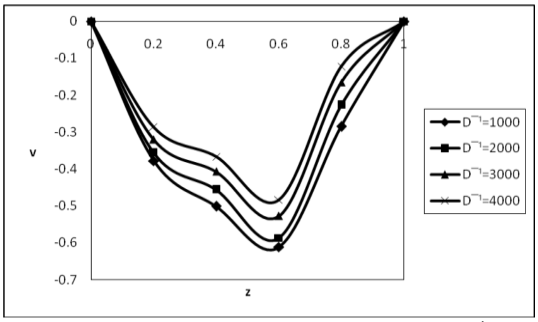

Fig. 6: The velocity profile *v* for different D^{-1} with $M=2, S=1, m=1, \alpha=\frac{\pi}{4}$

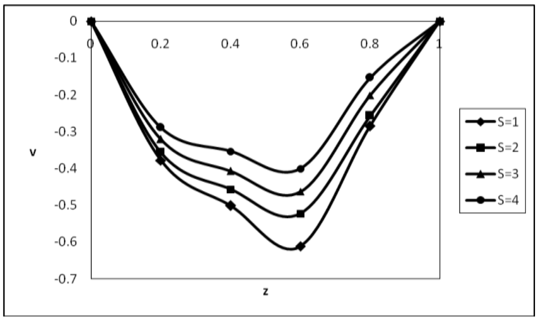

Fig. 7: The velocity profile v for different S with $D^{-1}=1000, M=2, m=1, \alpha=\frac{\pi}{4}$

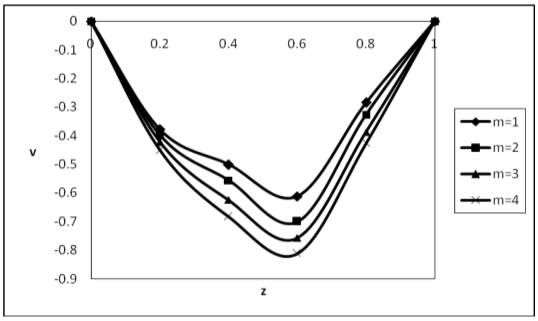

Fig. 8: The velocity profile v for different m with $D^{-1}=1000, M=2, S=1, \alpha=\frac{\pi}{4}$

Table I: The shear stresses (τ_x) on the upper plate.

M	I	II	III	IV	V	VI	VII
2	0.004275	0.003865	0.003211	0.004831	1.536526	0.036562	0.266859
5	0.005756	0.005211	0.004839	0.006875	1.836563	0.065326	0.726652
8	0.006336	0.006008	0.005315	0.008365	2.008832	0.073365	0.855682
10	0.006834	0.006331	0.005999	0.009445	5.008265	0.096652	0.911452
D^{-1}	1000	2000	3000	1000	1000	1000	1000
S	1	1	1	2	3	1	1
m	1	1	1	1	1	2	3

Table II: The shear stresses (τ_y) on the upper plate.

M	I	II	III	IV	V	VI	VII
2	-0.00665	-0.00633	-0.00608	-0.00831	-0.01652	-0.03657	-0.06536
5	-0.00746	-0.00708	-0.00633	-0.00953	-0.02365	-0.08326	-0.09652
8	-0.00836	-0.00766	-0.00683	-0.01834	-0.06536	-0.12085	-0.12652
10	-0.00911	-0.00833	-0.00783	-0.02008	-0.09336	-0.22653	-0.83115
D^{-1}	1000	2000	3000	1000	1000	1000	1000
S	1	1	1	2	3	1	1
m	1	1	1	1	1	2	3

Table III: The shear stresses (τ_x) on the lower plate.

M	I	II	III	IV	V	VI	VII
2	0.134521	0.226532	0.383669	0.180832	-2.46575	5.465245	8.366525
5	0.246532	0.300652	0.477682	0.468332	-3.66583	6.756839	9.666525
8	0.383665	0.400822	0.588362	0.836522	-4.66586	8.116535	10.11532
10	0.322656	0.433756	0.666832	0.999855	-4.88842	10.11586	11.20834
D^{-1}	1000	2000	3000	1000	1000	1000	1000
S	1	1	1	2	3	1	1
m	1	1	1	1	1	2	3

Table IV: The shear stresses (τ_y) on the lower plate.

M	I	II	III	IV	V	VI	VII
2	-0.26532	-0.03636	-0.00421	-0.45226	-1.00855	-4.32652	-8.66575
5	-0.36653	-0.04082	-0.00466	-0.83652	-1.24652	-5.26652	-10.0835
8	-0.42208	-0.05216	-0.00621	-0.94526	-1.85765	-7.33668	-10.9995
10	-0.48322	-0.05832	-0.00682	-0.99652	-2.32652	-9.44326	-12.0845
D^{-1}	1000	2000	3000	1000	1000	1000	1000
S	1	1	1	2	3	1	1
m	1	1	1	1	1	2	3

The shear stresses on the upper and lower plates and the discharge between the plates are calculated computationally and tabulated in the tables (I-V). The magnitude of these stresses at the upper plate is significantly high compared to the respective magnitudes at the lower plate. We notice that the magnitude of the both stresses τ_x and τ_y enhances in the upper plate and lower plates with increasing *M*, *S* and *m*, while on the upper plate τ_x and τ_y reduces and on the lower plate τ_x rapidly enhances and τ_y reduces with increase in the inverse Darcy parameter D^{-1}. The retardation at the upper plate is significantly low compared to enhancement at the lower plate (Tables. I-IV).

The discharge *Q* reduces in general with increase in the intensity of the magnetic field *M* and lower permeability of the porous medium (corresponding to an increase in D^{-1}) and enhances the couple stress parameter *S* and *m* (Table. V).

Table V: Discharge Q

M	I	II	III	IV	V	VI	VII
2	1.840014	1.514985	1.355847	2.001452	2.455145	2.825451	3.225655
5	1.588749	1.355466	1.144569	1.885469	2.000255	2.522413	2.887989
8	1.302254	1.144541	1.000546	1.665898	1.889872	2.002115	2.452244
10	1.225466	0.011451	0.002145	1.524465	1.622549	1.885474	2.000256
D^{-1}	1000	2000	3000	1000	1000	1000	1000
S	1	1	1	2	3	1	1
m	1	1	1	1	1	2	3

IV. CONCLUSIONS

- The magnitude of the velocity component *u* reduces and *v* increases with increasing the intensity of the magnetic field *M*, also the resultant velocity experiences retardation with increasing *M*.
- Both the velocity components *u* and *v* reduces with increasing the inverse Darcy parameter D^{-1}. Lower the permeability of the porous medium lesser the fluid speed in the entire fluid region. The resultant velocity experiences retardation with increasing the inverse Darcy parameter D^{-1}.
- We observe that the retardation due to an increase in the porous parameter is more rapid than that due to increase in the Hartmann number *M*. In other words, the resistance offered by the porosity of the medium is much more than the resistance due to the magnetic lines of force.
- We observed that *u* exhibits a great enhancement in contrast to *v* which retards appreciably with increase in the couple stress parameter *S*, but the resultant velocity shows and appreciable enhancement with in *S*.
- We observed that *u* and *v* exhibits a great enhancement appreciably with increase in the hall parameter *m*, likewise the resultant velocity shows enhancement with increase in *m*.
- The magnitude of these stresses at the upper plate is significantly high compared to the respective magnitudes at the lower plate.
- The discharge *Q* reduces in general with increase in the intensity of the magnetic field *M* and D^{-1} and enhances with the couple stress parameter *S* and *m*.

V. FUTURE WORK

Studies pertaining to the couple-stress fluid behaviour are very useful, such studies bear the potential to better explain the behaviour of rheological complex fluids, such as liquid crystals, polymeric suspensions that have long chain molecules, lubrication as well as human/sub-human blood. In future, being motivated by the observations given above, we have undertaken a study here that concerns peristaltic flow of couple-stress fluids through porous medium with different conditions. The problems will be carried out by using lubrication theory that means long wavelength and low Reynolds number approximations.

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AUTHOR'S BIOGRAPHY

P. Sulochana is working as Associate Professor of Mathematics in Intell Engg. College, Anantapuramu, A.P., India. She has 18 years of experience in teaching for B.Tech, M.C.A., M.Sc., and M.Tech students. She obtained Ph.D degree from Sri Krishnadevaraya University, Anantapuramu, A.P., India in 2006. She is a life member in many professional bodies.