RESEARCH ARTICLE OPEN ACCESS

Heat transfer on MHD flow of visco-elastic fluid through a rotating porous channel with Hall Effect

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ABSTRACT
In this paper, hydro magnetic convective flow of an electrically conducting visco-elastic fluid through a rotating porous channel has been considered taking hall current into account. The governing equations are formed using Brinkman model. The exact solutions of the velocity and the temperature distributions are obtained analytically, using Laplace transform technique, which consists of both the steady and transient states. The ultimate steady state velocity and temperature distributions are numerically discussed for various values of the flow parameters. The numerical values of the shear stresses and the Nusselt number are tabulated and discussed.
Keywords**:** Convective flow, heat source, heat transfer, porous medium and rotating channel

Date of Submission: 10-10-2017 Date of acceptance: 31-10-2017

Nomenclature

ρ	Density of the fluid	μ_e	Magnetic permeability
ν	Coefficient of kinematic viscosity	k	Permeability of the medium
H_0	Applied magnetic field	α_1	Normal stress modulus
T	Non- dimensional time	T_0	Characteristic temperature
α	Dimensional heat source parameter	g	Acceleration due to gravity
β	Coefficient of volume expansion	Q	Strength of the heat source
C_p	Specific heat at constant pressure	V	Velocity vector
E	Electric field J		Current density vector
ω_e	Cyclotron frequency	τ_e	Electron collision time
σ	Fluid conductivity	e	Electron charge
p_e	Electron pressure	$H(t)$	Heaviside's unit step function
M	Magnetic field parameter	E	Ekman number
m	Hall parameter	S	Second grade fluid parameter
D^{-1}	Inverse Darcy Parameter	P_r	Prandtl number
α	Heat source Parameter	R	Pressure gradient Parameter
Gr_1	Grashof number along *x* direction	Gr_2	Grashof number along *y* direction
u	Dimensionless axial velocity component		
v	Dimensionless transverse velocity component		
A	Gradient of the temperature along *x* direction		
B	Gradient of the temperature along *y* direction		

I. INTRODUCTION

The hydro magnetic rotating flow of non-Newtonian fluids between parallel plates has important applications in magneto hydrodynamic (MHD) power generators and pumps, accelerators etc. The flow through porous medium is very important particularly in the fields of agricultural engineering and technology for irrigation processes, especially in petroleum industry to study petroleum extraction process and transport, and also in chemical engineering and technology for filtration and purification processes. Successions of explorations were made by Raptis et al. [1-3] into the study of two-dimensional flow through porous medium past an infinite vertical wall. The MHD flow through a duct/planar channel has also been studied by various researchers [4-10]. Mazumder et al., [11] analyzed the hall effects on combined free and forced convection hydro magnetic flow through a channel. Singh [12] studied MHD effects on oscillatory flow between two parallel flat plates when the entire system rotates about an axis normal to the planes of the plates.

The hall current is very important and it has a marked effect on the magnitude and direction of the current density and consequently on the magnetic force. Debnath et al. [13] have studied the effects of hall current on unsteady hydro magnetic flow past a porous plate in a rotating fluid system. Veera Krishna and Suneetha [14] and Suneetha et al. [15] discussed the effects of hall current on the unsteady flow of Newtonian fluid between two rigid non-conducting rotating plates. Hall effects on an unsteady MHD flow of a viscous incompressible electrically conducting fluid in a horizontal porous channel with variable pressure gradient in a rotating system have been discussed by Das et al. [16].

The industrial applications include many transport processes where the simultaneous heat and mass transfer occurs as a result of combined buoyancy effects of thermal diffusion and diffusion of chemical species. The chemical reaction on an electrically conducting fluid through a porous medium with slip effects have been presented by Senapati et al.[17]. Gopal and Balamurugan [18] presented the theoretical and computational study of unsteady hydrodynamic flow of an electrically conducting Maxwell fluid through porous medium in a rotating parallel plate channel about an axis normal to the channel. VeeraKrishna and Prakash [19] discussed the effects of hall current on unsteady MHD flow in a rotating parallel plate channel bounded by porous bed on the lower half. Gopal et al. [20] investigated the effect of Maxwell fluid on the unsteady hydro magnetic flow of an electrically conducting fluid through porous medium in a rotating parallel plate channel about an axis normal to the channel. Dharmaiah et al. [21] examined the chemical reaction effect on MHD Casson fluid flow over an inclined moving plate with heat source/sink. Veera Krishna and Gangadhar Reddy [22] discussed MHD free convective rotating flow of a visco-elastic fluid past an infinite vertical oscillating plate. Veera Krishna and SubbaReddy [23] discussed the unsteady MHD convective flow of second grade fluid through a porous medium in a rotating parallel plate channel with temperature dependent source.

In this paper, we have considered the hall effects on the hydromagnetic convective flow of an electrically conducting visco-elastic fluid through a rotating porous channel using Brinkman model.

II. FORMULATION AND SOLUTION OF THE PROBLEM:

We have considered the unsteady hydro magnetic convective flow of an electrically conducting visco-elastic fluid through porous medium between two parallel non conducting plates under a uniform transverse magnetic field H_o taking hall current into account. At initial stage, both the plates and the fluid rotate with the same angular velocity Ω. At $t > 0$, the fluid is possessed by an invariable pressure gradient parallel to the plate and in addition the lower plate performs non-torsional oscillation in its individual plane. We stimulated the plates cooled or heated by aconsistent temperature gradient in same direction parallel to the plane at the plates. The physical configuration of the problem is shown in Figure. 1.

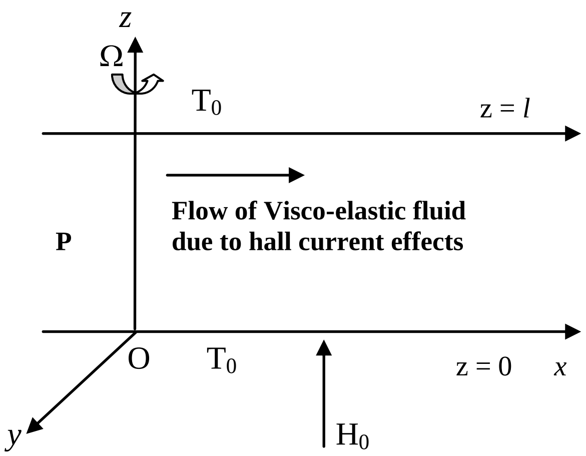

Figure1. Physical configuration of the Problem

We choose a Cartesian co-ordinate system O(*x*, *y*, *z*) such that the plates are at $z=0$ and $z=l$. The boundary layer equations of motion are given by

$$\frac{\partial u}{\partial t}-2\Omega v=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial z^2}+\frac{\alpha_1}{\rho}\frac{\partial^3 u}{\partial z^2\partial t}+\mu_e J_y H_0-\frac{\nu}{k}u \tag{1}$$

$$\frac{\partial v}{\partial t}+2\Omega u=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\frac{\partial^2 v}{\partial z^2}+\frac{\alpha_1}{\rho}\frac{\partial^3 v}{\partial z^2\partial t}-\mu_e J_x H_0-\frac{\nu}{k}v \tag{2}$$

$$-\frac{1}{\rho}\frac{\partial p}{\partial z}-g(1-\beta(T-T_0))=0 \tag{3}$$

The energy equation is

$$\left(\frac{\partial}{\partial t}+u\frac{\partial}{\partial x}+v\frac{\partial}{\partial y}\right)(T-T_0)=\alpha_1\frac{\partial}{\partial z^2}(T-T_0)+\frac{Q}{\rho c_p}(T-T_0) \tag{4}$$

Since the plates extend to infinity along *x* and *y* directions, all the physical quantities except the pressure depend on z and t alone. When the potency of the magnetic field is very hefty, the generalized Ohm's law is tailored to include the hall current, so that

$$J+\frac{\omega_e\tau_e}{B_0}J\times B=\sigma\ (E+V\times B+\frac{1}{en_e}\nabla p_e) \tag{5}$$

In equation (5) the electron pressure gradient, the ion-slip and thermo-electric effects are ignored and also the electric field $E=0$ and under these assumptions trim down to

$$J_x+m\ J_y=\sigma B_0 v \tag{6}$$

$$J_y+m\ J_x=-\sigma B_0 u \tag{7}$$

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

On solving equations (6) and (7), we obtain

$$J_x=\frac{\sigma B_0}{1+m^2}(v+mu) \tag{8}$$

$$J_y=\frac{\sigma B_0}{1+m^2}(mv-u) \tag{9}$$

Substituting the equations (8) and (9) in the equations (1) and (2), we obtain

$$\frac{\partial u}{\partial t}-2\Omega v=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial z^2}+\frac{\alpha_1}{\rho}\frac{\partial^3 u}{\partial z^2\partial t}+\frac{\sigma\mu_e^2H_0^2}{\rho\left(1+m^2\right)}\left(mv-u\right)-\frac{\nu}{k}u \tag{10}$$

$$\frac{\partial v}{\partial t}+2\Omega u=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\frac{\partial^2 v}{\partial z^2}+\frac{\alpha_1}{\rho}\frac{\partial^3 v}{\partial z^2\partial t}-\frac{\sigma\mu_e^2H_0^2}{\rho\left(1+m^2\right)}\left(v+mu\right)-\frac{\nu}{k}v \tag{11}$$

Combining equations (10) and (11), taking$q= u + iv$, we obtain

$$\left(\frac{\partial q}{\partial t}+2i\Omega q=-\frac{1}{\rho}\frac{\partial p}{\partial \xi}+\nu\frac{\partial^2 q}{\partial z^2}+\frac{\alpha_1}{\rho}\frac{\partial^3 q}{\partial z^2\partial t}-\frac{\sigma\mu_e^2H_0^2}{\rho(1-im)}q-\frac{\nu}{k}q\right) \tag{12}$$

Integrating (3) we get,

$$\frac{p}{\rho}=-gz+\beta g\int(T-T_0)\,dz+\phi(\xi,\bar{\xi})H(t)$$

where $\xi=x-iy,\ \bar{\xi}=x+iy$

We use (3) in equation (12) and obtain,

$$\frac{\partial}{\partial z}\left(\frac{\partial q}{\partial t}+2i\Omega q-\nu\frac{\partial^2 q}{\partial z^2}-\frac{\alpha_1}{\rho}\frac{\partial^3 q}{\partial z^2\partial t}+\left(\frac{\sigma\mu_e^2H_0^2}{\rho\left(1-im\right)}+\frac{\nu}{k}\right)q\right)=-2\beta g\frac{\partial}{\partial\xi}\left(T-T_0\right) \tag{13}$$

For the completeness of equation (13) we assume that

$$T - T_0 = (Ax + By)\,H(t) + \theta_1(z,t)$$

where $\theta_1(z,t)$ is an arbitrary function of *z* and *t*, taking $T_0 + Ax + By + \theta_1\omega_1$ as the dimensional temperature of the lower and upper plates, for $t > 0$, we obtain the equation.

$$\left(\frac{\partial}{\partial t} + 2i\Omega - \nu\frac{\partial^2}{\partial z^2} - \frac{\alpha_1}{\rho}\frac{\partial^3}{\partial z^2\partial t} + \frac{\sigma\mu_e^2H_0^2}{\rho(1-im)} + \frac{\nu}{k}\right)q = \beta g\left(A + iB\right)zH(t) + D \tag{14}$$

where $D = \frac{\partial}{\partial \xi}\left[\phi(\xi,\bar{\xi})\right]H(t)$

The initial and boundary conditions are

$$q\left(z,t\right) = ae^{i\omega t} + be^{-i\omega t} \text{ at } z = 0 \tag{15}$$

$$q\left(z,t\right) = 0 \text{ at } z = l \ \forall t \le 0 \text{ and } \forall z \tag{16}$$

$$q\left(z,t\right) = 0 \text{ at } z = 0 \ \forall t \le 0 \text{ and } \forall z \tag{17}$$

$$\theta\left(z,t\right) = \frac{\beta g l^3\left(\theta_1\omega_2 - \theta_1\omega_1\right)}{\nu^2} = \theta_0 \text{ at } z = l \tag{18}$$

Introducing the non-dimensional variables

$$z^* = \frac{z}{l}, q^* = \frac{ql}{\nu}, t^* = \frac{t\nu}{l^2}, \omega^* = \frac{\omega l^2}{\nu}, \theta^* = \frac{\beta g l^3\left(\theta_1 - \theta_1\omega_1\right)}{\nu^2}$$

and using the non-dimensionalization process, the unsteady governing equations reduce to (dropping asterisks),

$$\frac{\partial^2 q}{\partial z^2} + S\frac{\partial^3 q}{\partial z^2\partial t} - \left(\frac{M^2}{1-im} + 2iE^{-1} + D^{-2}\right)q - \frac{\partial q}{\partial t} = GrzH(t) + R \tag{19}$$

$$\frac{\partial^2\theta}{\partial z^2} - \alpha\theta - Pr\left(\frac{\partial\theta}{\partial t} + \left(Gr_1u + Gr_2v\right)H(t)\right) = 0 \tag{20}$$

where $M^2 = \frac{\sigma\mu_e^2H_0^2l^2}{\rho\nu}$ is the Hartmann number (Magnetic field parameter), $E = \frac{\nu}{\Omega l^2}$ is the Ekman number, $S = \frac{\alpha_1}{\rho l^2}$ is the visco-elastic fluid parameter, $D^{-1} = \frac{l^2}{k}$ is the inverse Darcy Parameter, $P_r = \frac{\mu C_p}{k_1}$ is the Prandtl number, $\alpha = \frac{Ql^2}{k_1}$ is the Heat source Parameter, $R = \left(-\frac{l^3}{\nu^3}\right)D$ is the Pressure gradient Parameter, and $Gr = Gr_1 + iGr_2$ is the Grashof number.

The corresponding initial and boundary conditions are

$$q\left(z,t\right) = ae^{i\omega t} + be^{-i\omega t} \text{ at } z = 0 \tag{21}$$

$$q\left(z,t\right) = 0 \text{ at } z = 1 \ \forall\, t \le 0, \forall\, z \tag{22}$$

$$\theta\left(z,t\right) = 0 \text{ at } z = 0 \ \forall\, t \le 0, \forall\, z \tag{23}$$

$$\theta\left(z,t\right) = \frac{\beta g l^3\left(\theta_1\omega_2 - \theta_1\omega_1\right)}{\nu^2} = \theta_0 \text{ at } z = 1 \tag{24}$$

Taking Laplace transforms of the equations (19) and (20), we obtain

$$\left(1 + sS\right)\frac{d^2\bar{q}}{dz^2} - \left(s + \frac{M^2}{1-im} + 2iE^{-1} + D^{-2}\right)\bar{q} = Gr\,z\,H(t) + R\,\frac{1}{s} \tag{25}$$

$$\frac{d^2\bar{\theta}}{dz^2}-\left(s\,Pr+\alpha\right)\bar{\theta}-Pr\left(Gr_1 u+Gr_2 v\right)H(t)=0 \tag{26}$$

Relevant transformed boundary conditions are

$$\bar{q}\left(z,s\right)=\frac{a}{s-i\omega}+\frac{b}{s+i\omega}\ \text{at}\ z=0 \tag{27}$$

$$\bar{q}\left(z,s\right)=0\ \text{at}\ z=1 \tag{28}$$

$$\bar{q}\left(z,s\right)=0\ \text{at}\ z=0 \tag{29}$$

$$\bar{\theta}\left(z,s\right)=\frac{\beta g l^3\left(\theta_1\omega_2-\theta_1\omega_1\right)}{\nu^2}=\theta_0\ \text{at}\ z=1 \tag{30}$$

The constants involved are evaluated and the transformed velocity and temperature are given by

$$\bar{q}=\left(\frac{a}{s-i\omega}+\frac{b}{s+i\omega}+\frac{R}{s(1+sS)\lambda_1^2}+\frac{Grz}{(1+sS)\lambda_1^2}\right)\cosh\lambda_1 z+$$
$$\left\{-\left[\frac{a}{s-i\omega}+\frac{b}{s+i\omega}+\frac{R}{s(1+sS)\lambda_1^2}+\frac{Grz}{(1+sS)\lambda_1^2}\right]\frac{\cosh\lambda_1}{\sinh\lambda_1}+\frac{R}{s(1+sS)\lambda_1^2\sinh\lambda_1}\right.$$
$$\left.+\frac{Gr}{(1+sS)\lambda_1^2\sinh\lambda_1}\right\}\sinh\lambda_1 z-\frac{R}{s(1+sS)\lambda_1^2}-\frac{Grz}{(1+sS)\lambda_1^2} \tag{31}$$

$$\bar{\theta}=-\frac{\Pr Gr}{\lambda_2^2 s}\cosh\lambda_2 z+\left\{\frac{\theta_0}{\sinh\lambda_2}+\frac{\Pr Gr}{\lambda_2^2 s}\frac{\cosh\lambda_2}{\sinh\lambda_2}-\frac{\Pr Gr}{\lambda_2^2 s}\frac{1}{\sinh\lambda_2}\right\}\sinh\lambda_2 z+\frac{\Pr Gr}{\lambda_2^2 s} \tag{32}$$

where $\lambda_1^2=\dfrac{s+\dfrac{M^2}{1-im}+2iE^{-1}+D^{-2}}{1+sS}$ and $\lambda_2^2=Prs+\alpha$

Taking inverse Laplace transforms (Bromwich contour integral formula) of the equations (31) and (32), we obtain the following expressions for the velocity and temperature:

$$q(z,t)=u+iv=-\frac{R\ \sinh\left(d_1\left(1-z\right)\right)}{d_1^2\ \sinh\left(d_1\right)}+\frac{\left(Gr-R\right)\ \sinh\left(d_1 z\right)}{d_1^2\ \sinh\left(d_1\right)}$$
$$+\frac{\left(RS+Gr\,z\right)\sinh\left(d_4(1-z)\right)}{d_4\sinh\left(d_4\right)}+\frac{\left(RS+Gr\,z\right)\sinh\left(d_4 z\right)}{d_4\sinh\left(d_4\right)}+$$
$$-\frac{(RS+Gr\,z)}{d_4}-\frac{(Grz-R)}{d_1^2}+\frac{a\sinh\left(d_2\left(1-z\right)\right)}{\sinh\left(d_2\right)}e^{i\omega t}+\frac{b\ \sinh\left(d_3\left(1-z\right)\right)}{\sinh\left(d_3\right)}e^{-i\omega t}+$$
$$+\sum_{n=1}^{\infty}\left(\frac{a}{d_6^2+i\omega}+\frac{b}{d_6^2-i\omega}+\frac{R}{n\pi d_6^2}\right)\sinh\left(n\pi\left(z-1\right)\right)\cdot e^{-d_6^2 t}-$$
$$-2\left(Gr-R\right)\sum_{n=1}^{\infty}\frac{(-1)^n}{n\pi d_4^2}\ \sin(n\pi z)\cdot e^{-d_4^2 t} \tag{33}$$

$$\theta(z,t)=\frac{\theta_0\ \sinh(\sqrt{\alpha}z)}{\sinh(\sqrt{\alpha})}+2\sum_{n=1}^{\infty}(-1)^n\sinh(n\pi z)\cdot e^{-\frac{(\alpha+n^2\pi^2)t}{Pr}}$$
$$+Pr\left\{Gr_1\operatorname{Re}\left\{q(z,t)\right\}+Gr_2\cdot\operatorname{Im}\left\{q(z,t)\right\}\right\} \tag{34}$$

The dimensional shear stresses τ_x and τ_y are obtained at the lower and upper plates from (33) and are given by

$$(\tau_x + i\tau_y)_{z=0} = \frac{R\cosh(d_1)}{d_1\sinh(d_1)} + \frac{(Gr - R)}{\sinh(d_1)} - \frac{RS\cosh(d_4)}{\sinh(d_4)} - \frac{RS}{\sinh(d_4)} - \frac{Gr}{d_1^2} - \frac{ad_2\cosh(d_2)}{\sinh(d_2)} e^{i\omega t}$$
$$-\frac{b\,d_3\cosh(d_3)}{\sinh(d_3)} e^{-i\omega t} + \sum_{n=1}^{\infty}\left(\frac{a}{d_6^2 + i\omega} + \frac{b}{d_6^2 - i\omega} + \frac{R}{n\pi d_6^2}\right) n\pi\cosh\left(n\pi\right) e^{-d_6^2 t} -$$
$$-2\left(Gr - R\right)\sum_{n=1}^{\infty}\frac{(-1)^n}{d_4^2}\, e^{-d_4^2 t}$$

$$(\tau_x + i\tau_y)_{z=1} = \frac{R}{d_1\sinh(d_1)} + \frac{(Gr - R)}{\sinh(d_1)} - \frac{RS + Gr}{\sinh(d_4)} + \frac{(RS + Gr)\cos(d_4)}{\sinh(d_4)} - \frac{Gr}{d_1^2} - \frac{ad_2}{\sinh(d_2)} e^{i\omega t}$$
$$-\frac{b\,d_3}{\sinh(d_3)} e^{-i\omega t} + \sum_{n=1}^{\infty}\left(\frac{a}{d_6^2 + i\omega} + \frac{b}{d_6^2 - i\omega} + \frac{R}{n\pi d_6^2}\right) n\pi\, e^{-d_6^2 t} - 2\left(Gr - R\right)\sum_{n=1}^{\infty}\frac{(-1)^n}{d_4^2}\, e^{-d_4^2 t}$$

The rate of heat transfer coefficient (Nusselt number) on the plates, using equation (34), are given by

$$(Nu)_{z=0} = \sqrt{\alpha}\,\cot(\sqrt{\alpha}) + Pr\,Gr\,a_8$$
$$(Nu)_{z=1} = \sqrt{\alpha}\,\mathrm{csch}(\sqrt{\alpha}) + Pr\,Gr\,a_9$$

III. RESULTS AND DISCUSSIONS:

We have considered hydromagnetic convective flow of an electrically conducting second grade fluid through a porous medium in a rotating parallel plate channel taking hall current into account and in the presence of a temperature dependent heat source. The perturbations in the flow are produced by a constant pressure gradient along the plates in addition to non-torsional oscillations of the lower plate. The governing equations are formed using Brinkman model. The exact solutions of the velocity and the temperature distributions are obtained analytically using Laplace transform technique. The analytical solution consists of both steady and transient states. The quasi-steady parts of the velocity and temperature representing the ultimate flow have been computed numerically for different sets of governing parameters viz. the Hartmann parameter M, the inverse Darcy parameter D^{-1}, the Ekman number E, the hall parameter *m*, the second grade fluid parameter S, the Grashof number Gr and the frequency of oscillation ω. Their profiles are plotted in Figures (2-8) for the oscillating lower plate and for plate in rest respectively. For computational purpose we have assumed Gr to be real so that the applied pressure gradient in the *y*-direction is zero, and Gr is positive or negative according as the plates are heated or cooled along the direction of the *x*-axis (non-zero pressure gradient $R = 10$). Also the Prandtl number Pr is chosen to be $Pr = 0.71$. Since the thermal buoyancy balances the vertical pressure gradient in the absence of any other applied force in the direction of rotation, 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 partial differential equations for a complex velocity and the real temperature.

It is evident from the figures (2-8) that the velocity profiles are parabolic in nature. We noticed that, the magnitude of the velocity component *u* enhances and that of *v* diminishes throughout the fluid region with increasing Ekman number E or second grade fluid parameter S or hall parameter *m*, the other parameters being fixed (Fig 2, 5, 6). The resultant velocity also increases with increasing E, S and *m*. Both the velocity components *u* and *v* experience retardation with increasing the intensity of the magnetic field (Hartmann number M).

The application of the transverse magnetic field plays an important role of a resistive type force (Lorentz force) similar to drag force (that acts in the opposite direction of the fluid motion) which tends to resist the flow thereby decreasing its velocity (Fig 3). Similar behaviour is observed for the resultant velocity. It is also noted from Fig 4 that magnitude of the velocity components *u* and v diminish throughout the fluid region with increasing inverse Darcy parameter D^{-1}. We observe that the lower the permeability of the porous medium the lesser the fluid speed in the entire fluid region. The resultant velocity is also trim down throughout the fluid region. It is observed that an increase in Grashof number leads to raise both the primary velocity *u* and the secondary velocity *v* as shown in Fig (7). This is because; increase in Grashof number Gr leads to more heating and less density. The resultant velocity also boosts up throughout the fluid region. It is observed from Fig. (8) that the magnitude of the velocity component *u* oscillates in the entire fluid region where as the velocity component *v* diminishes with increasing the frequency of oscillation ω. The resultant velocity also reduces throughout the fluid region.

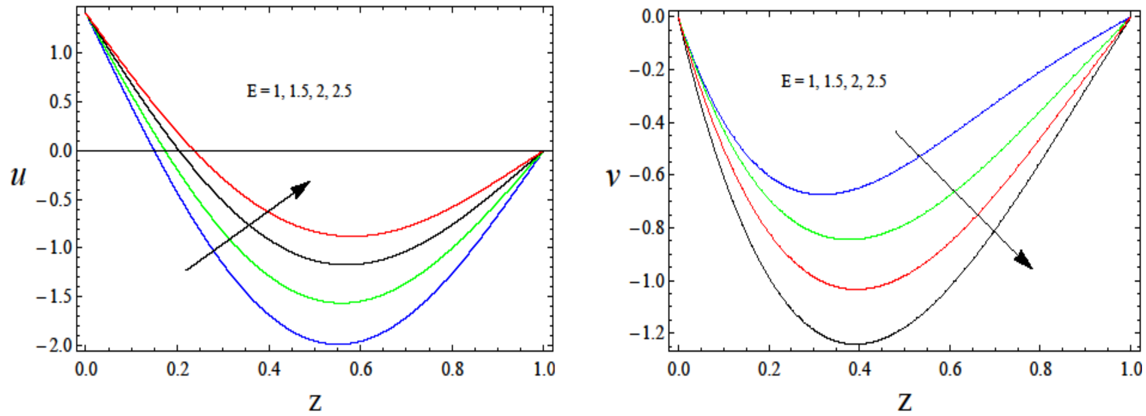

Figure2. The velocity profiles for *u* and *v* against E
$M = 1, m = 1, D^{-1} = 50, S = 1, \omega = \pi / 4, Gr = 2$

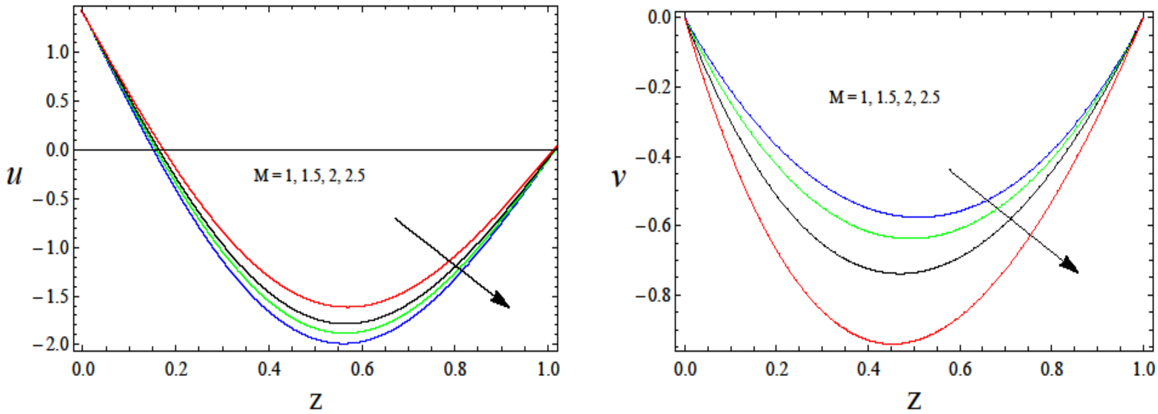

Figure3. The velocity profiles for *u* and *v* against M
$E = 1, m = 1, D^{-1} = 50, S = 1, \omega = \pi / 4, Gr = 2$

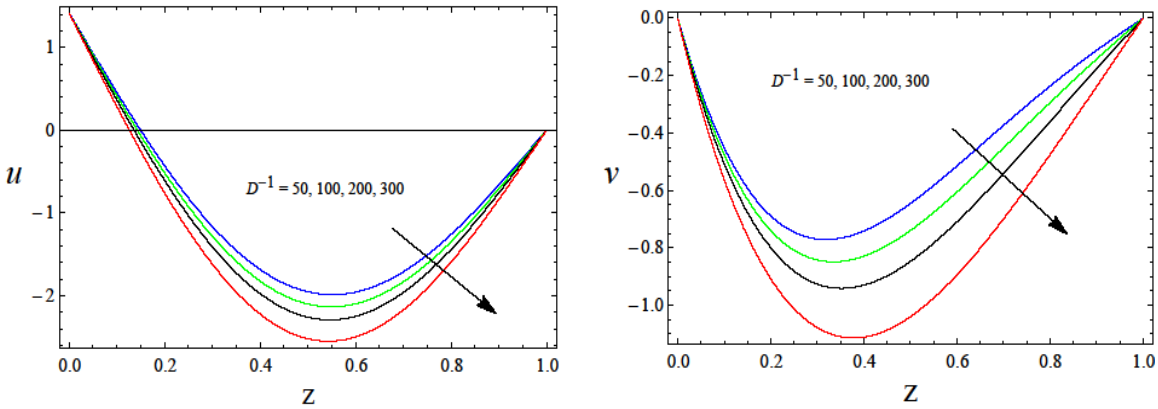

Figure4. The velocity profiles for *u* and *v* against D^{-1}
$E = 1, m = 1, M = 1, S = 1, \omega = \pi / 4, Gr = 2$

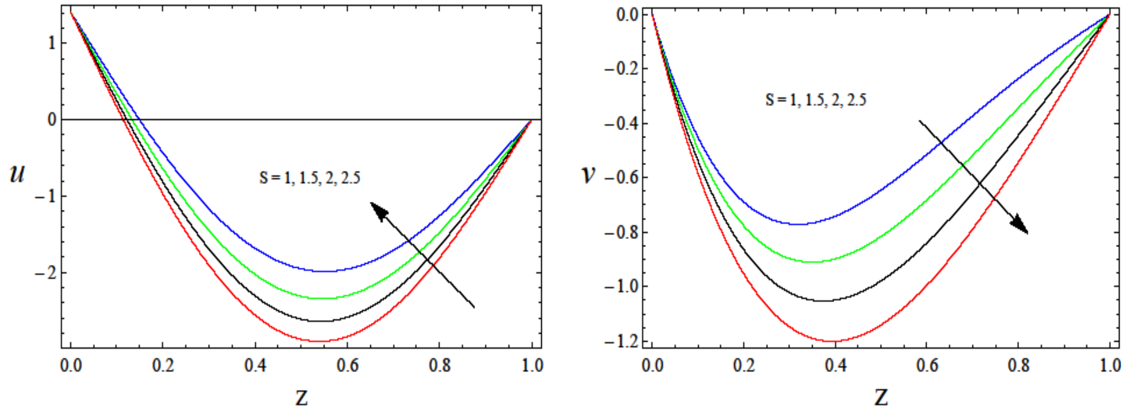

Figure5. The velocity profiles for u and v against S
$E = 1, m = 1, D^{-1} = 50, M = 1, \omega = \pi / 4, Gr = 2$

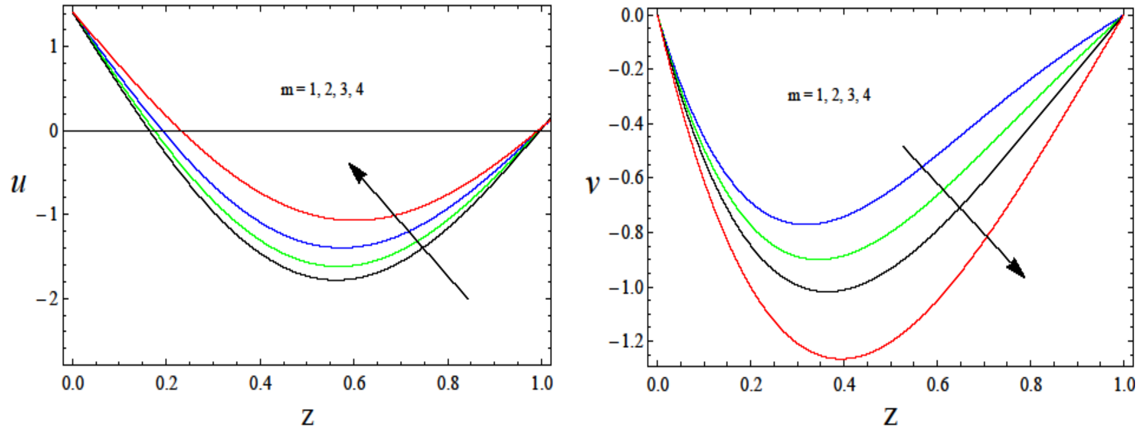

Figure6. The velocity profiles for u and v against m
$E = 1, M = 1, D^{-1} = 50, S = 1, \omega = \pi / 4, Gr = 2$

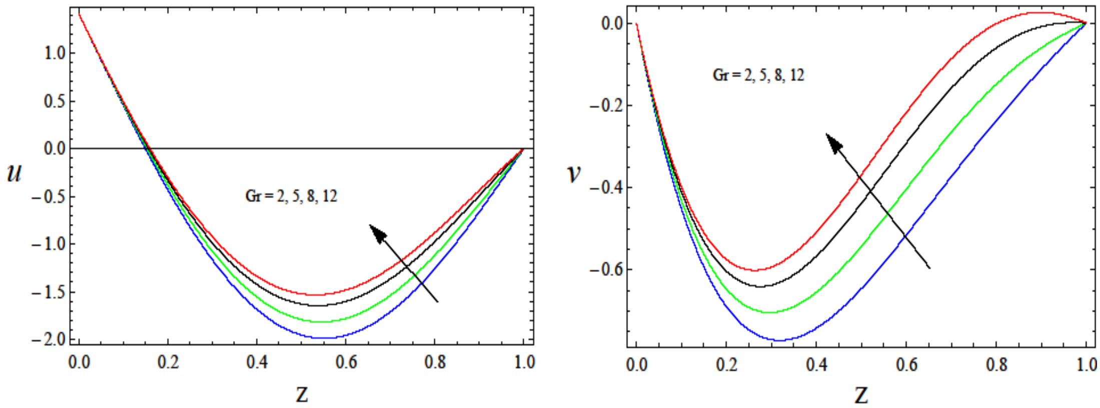

Figure7. The velocity profiles for u and v against Gr
$E = 1, m = 1, D^{-1} = 50, S = 1, \omega = \pi / 4, M = 1$

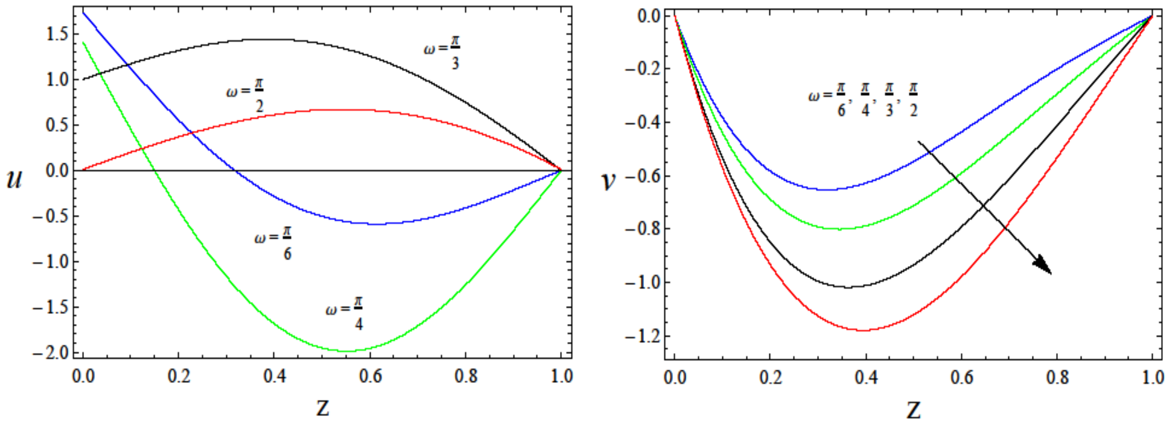

Figure8. The velocity profiles for *u* and *v* against ω
$E = 1, m = 1, D^{-1} = 50, S = 1, M = 1, Gr = 2$

IV. CONCLUSIONS:

From the above discussion the following conclusions are made:

1. The resultant velocity increases with increasing E, S and *m*.
2. The transverse magnetic field plays the role of a resistive type force similar to drag force which tends to resist the flow thereby decreasing its velocity. Similar behaviour is observed for the resultant velocity.
3. The Lower the permeability of the porous medium the lesser the fluid speed in the entire fluid region. The resultant velocity is also trim down throughout the fluid region with increasing D^{-1}.
4. An increase in Grashof number leads to a raise in both the primary velocity *u* and the secondary velocity *v*.
5. The resultant velocity also reduces throughout the fluid region with increasing ω.

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International Journal of Engineering Research and Applications (IJERA) is **UGC approved** Journal with Sl. No. 4525, Journal no. 47088. Indexed in Cross Ref, Index Copernicus (ICV 80.82), NASA, Ads, Researcher Id Thomson Reuters, DOAJ.

B.V. Padmavathi. “Heat transfer on MHD flow of visco-Elastic fluid through a rotating porous channel with Hall Effect.” International Journal of Engineering Research and Applications (IJERA) , vol. 7, no. 10, 2017, pp. 24–33.