Hall effects on Run-up flow of Rivlin-Ericksen fluid in a parallel plate channel Bounded by Porous bed on the Lower half

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Abstract: In this paper, we consider the unsteady MHD flow of Rivlin-Ericksen fluid in a parallel plate channel bounded by a densely packed porous bed abutting a lower plate taking hall current into account. The fluid flow is through a composite medium consists of two zones. The unsteady governing equations are solved as initial value problem. Zone - 1 consisting of Rivlin-Ericksen fluid in the non-porous region bounded above by an impermeable boundary plane. The flow in zone - 2 consists of flow through porous region bounded below by rigid plane. The flow in the non-porous region is governed by Navier-Stokes equation. The porous region although densely packed allows slip through the interface. Hence we choose Darcy-Lapwood model to govern through the flow through porous bed. At the interface the slip velocity satisfies the Beaver-Joseph condition. Also at the interface the continuity of the velocity is imposed so that the velocity of the fluid in the clean fluid region at the interface is equal to the slip velocity. The solutions for the velocity in both clean fluid and porous regions have been derived analytically and also its behaviour is computationally discussed with reference to different flow parameters. The shear stresses on the boundaries and the mass flux are also obtained analytically and their behaviour is computationally discussed.

Keywords: Darcy Lapwood Model, Hall Effects, MHD Flows, Parallel Plate Channels, Porous Bed, Run-up flows and Unsteady Flows.

I. INTRODUCTION

The study on run up flows of viscous fluid has its importance in the field of petroleum industry, chemical and bio-chemical industry, ceramic industry, paper technology, extraction of energy from geo-thermal regions etc. The mathematical modelling and simulation of the flow of fluids through porous media are important for designing and controlling a number of industrial processes including the production of fluids from underground reservoir and remediation of underground water resources. The simulation of flow is carried out using constitutive and conservative relations based on a macroscopic representation of porous media. There is a considerable interest in the recent years in the study of flow past a naturally permeable bed, with appropriate boundary conditions at a naturally permeable boundary. The usual conditions are, the normal flux is continuous and the tangential velocity is zero. The former is completely satisfactory but the latter is clearly only an approximation. The existence of the slip at the porous bed, due to the transfer of momentum from the free flow to Darcy flow which sets up the drag, is connected with presence of a very thin boundary layer of stream wise moving fluid just beneath the nominal surface of the permeable material. The fluid in this layer is pulled along by the flow in the channel. Many of the authors [1-3] studied in this area of flow through porous media. The unsteady flow of a dusty Rivlin-Ericksen fluid through circular and co-axial ducts has been discussed by Sisodia and Gupta [4]. The MHD transient flow of second order RivlinEricksen fluid through porous medium down an inclined channel was studied by Lal et al. [5]. M.V.Krishna *et al.* [6] discussed the unsteady flow of an incompressible viscous fluid in a rotating parallel plate channel bounded on one side by a porous bed under the influence of a uniform transverse magnetic field making use of Darcy Lapwood model. D. V. Krishna *et al.* [7] discussed the unsteady hydromagnetic flow of an incompressible viscous fluid in a rotating parallel plate channel with porous lining under the influence of uniform transverse magnetic field normal to the channel and it was extended by M.V. Krishna *et al*. [8]. M. V. Krishna *et al*. [9] studied the steady hydro magnetic flow of a couple stress fluid through a composite medium in a rotating parallel plate channel with porous bed on the lower half subjected to subjected to normal to the channel and extended the problem taking hall current into account by M. V. Krishna *et al*. [10]. M. V. Krishna and S. G. Malashetty [11] discussed the unsteady flow of an in compressible electrically conducting second grade fluid in rigidly rotating parallel plate channel bounded below by a sparsely packed porousbed subjected to normal to the channel and extended the problem taking hall current into account by M.Veera Krishna and S. G. Malashetty [12]. Recently, Krishna and Prakash [13] discussed the hall current effects on unsteady hydromagnetic flow in a parallel plate channel rotating bounded by porous bed at the lower half.

Motivated on the above studies, in this paper, we have considered the unsteady MHD flow of Rivlin-Ericksen fluid in a parallel plate channel bounded by a densely packed porous bed abutting a lower plate and taking hall current into account. The fluid flow is through a composite medium consists of two zones. The unsteady governing equations are solved as initial value problem making use of Laplace transform technique.

II. Formulation and Solution of the problem

We consider the unsteady flow of an the flow of visco-elastic Rivlin – Ericksen fluid through a planar channel in between z =0 and z = h. fluid in a rotating parallel plate channel bounded on one side by a porous bed subjected to a uniform transverse magnetic field normal to the channel taking hall current into account. At $t>0$ the fluid is driven by a constant pressure gradient parallel to the channel walls. We choose a Cartesian system O(x, y, z) such that the boundary walls are at $z=0$ and $z=l$. Z-axis being the axis of rotation of the plates. The fluid medium consists of two zones namely zone 1and zone 2. Zone 1 consists of clean fluid governed by Navier-Stokes equations and zone 2 corresponds to the flow through porous bed governed by Darcy-Lapwood equations. At the interface the fluid satisfies the continuity condition of velocity and shear stress. The unsteady hydro magnetic equations governing the incompressible viscous fluid in zone 1 under the influence of transverse magnetic field with reference to a frame are

$$\frac{\partial u}{\partial t} = -\frac{1}{\circ}\frac{\partial p}{\partial x} + \neg\frac{\partial^2 u}{\partial z^2} + \frac{\sim_1}{\circ}\frac{\partial^3 u}{\partial t \partial z^2} + \mu_e J_y H_0 \tag{1}$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\circ}\frac{\partial p}{\partial y} + \neg\frac{\partial^2 v}{\partial z^2} + \frac{\sim_1}{\circ}\frac{\partial^3 v}{\partial t \partial z^2} - \mu_e J_x H_0 \tag{2}$$

The Darcy – Lapwood equations governing the flow through porous medium in zone – 2 is

$$\frac{1}{¢}\frac{\partial u_p}{\partial t} = -\frac{1}{\circ}\frac{\partial p}{\partial x} + \mu_e J_y^P H_0 - \frac{\neg_{eff}}{K} u_p \tag{3}$$

$$\frac{1}{¢}\frac{\partial v_p}{\partial t} = -\frac{1}{\circ}\frac{\partial p}{\partial y} - \mu_e J_x^P H_0 - \frac{\neg_{eff}}{K} v_p \tag{4}$$

Where u and v is the velocity along the channel, u_p and v_p is the Darcy velocity, t is the time, ¢ is the density, p is the pressure, « is the coefficient of viscosity in the non-porous region, «$_{eff}$ is the coefficient of viscosity in the porous region, $\sim_1$ is the coefficient of visco-elasticity, ¢ is the prosity, K is the permeability, H_0 is the magnetic field, ± is the fluid conductivity, «$_e$ is the magnetic permeability. Since the plates extends to infinity along x and y directions, all the physical quantities except the pressure depend on z and t alone. Hence u, v and u_p, v_p are function of z and t alone and hence the respective equations of continuity are trivially satisfied. When the strength of the magnetic field is very large, the generalized Ohm's law is modified to include the Hall current, so that

$$J+\frac{\omega_e\tau_e}{H_0}J\times H=\sigma\,(E+\mu_e\,q\times H) \tag{5}$$

Where, q is the velocity vector, H is the magnetic field intensity vector, E is the electric field, J is the current density vector, μ_e is the cyclotron frequency, 2_e is the electron collision time, ± is the fluid conductivity and μ_e is the magnetic permeability. In equation (5) 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

$$J_x+m\,J_y=\sigma\mu_e H_0 v \tag{6}$$

$$J_y-m\,J_x=-\sigma\mu_e H_0 u \tag{7}$$

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

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

$$J_x=\frac{\sigma\mu_e H_0}{1+m^2}(v+mu) \tag{8}$$

$$J_y=\frac{\sigma\mu_e H_0}{1+m^2}(mv-u) \tag{9}$$

and

$$J_x^p=\frac{\sigma\mu_e H_0}{1+m^2}(v+mu) \tag{10}$$

$$J_y^p=\frac{\sigma\mu_e H_0}{1+m^2}(mv-u) \tag{11}$$

Using the equations (8) and (9) the equations of the motion with reference to frame zone 1 are given by

$$\frac{\partial u}{\partial t}=-\frac{1}{°}\frac{\partial p}{\partial x}+¬\frac{\partial^2 u}{\partial z^2}+\frac{\sim_1}{°}\frac{\partial^3 u}{\partial t\partial z^2}+\frac{\sigma\mu_e^2H_0^2}{\rho(1+m^2)}(mv-u) \tag{12}$$

$$\frac{\partial v}{\partial t}=-\frac{1}{°}\frac{\partial p}{\partial y}+¬\frac{\partial^2 v}{\partial z^2}+\frac{\sim_1}{°}\frac{\partial^3 v}{\partial t\partial z^2}-\frac{\pm\,\mu_e^2H_0^2}{\rho(1+m^2)}(v+mu) \tag{13}$$

The Darcy-Lapwood equations governing the flow through porous medium in zone – 2 is

$$\frac{1}{¢}\frac{\partial u_p}{\partial t}=-\frac{1}{°}\frac{\partial p}{\partial x}+\frac{\sigma\mu_e^2H_0^2}{\rho(1+m^2)}(mv_p-u_p)-\frac{¬_{eff}}{K}u_p \tag{14}$$

$$\frac{1}{¢}\frac{\partial v_p}{\partial t}=-\frac{1}{°}\frac{\partial p}{\partial y}-\frac{\pm\,\mu_e^2H_0^2}{\rho(1+m^2)}(v_p+mu_p)-\frac{¬_{eff}}{K}v_p \tag{15}$$

Let $q=u+iv$, $\xi=x-iy$, $q_p=u_p+iv_p$

Now combining equations (12) and (13), we obtain

$$\frac{\partial q}{\partial t}=-\frac{1}{°}\frac{\partial p}{\partial ¶}+¬\frac{\partial^2 q}{\partial z^2}+\frac{\sim_1}{°}\frac{\partial^3 q}{\partial t\partial z^2}-\frac{\sigma\mu_e^2H_0^2}{\rho(1-im)}q \tag{16}$$

Now combining equations (3) and (4), we obtain

$$\frac{1}{¢}\frac{\partial q_p}{\partial t}=-\frac{1}{°}\frac{\partial p}{\partial ¶}-\frac{\sigma\mu_e^2H_0^2}{\rho(1-im)}q_p-\frac{¬_{eff}}{K}q_p \tag{17}$$

The initial and boundary conditions are

$q = 0$ at $z = 0$ $(t < 0)$ (18)

$q = U$ at $z = h$ $(t \geq 0)$ (19)

At the interface $z = s_1$, the slip velocity is given by Beaver-Joseph condition

$$\frac{\partial q}{\partial z} = \frac{\sim}{\sqrt{K}}\left(q_B - q_P\right) \tag{20}$$

$$q = q_B \ at \ \ z = s_1 \tag{21}$$

Where, q_B is the slip velocity along the channel, $\sim$ is the non-dimensional number (slip parameter).
We introduce the following non-dimensional variables

$$(\text{¶}, z) = h(\text{¶}', z'),\ q = q'U,\ p = P°U^2,\ q_p = q_p'U,\ q_B = q_B'U,\ t = \frac{h}{U}t',\ s_1 = \frac{s_1'}{h}$$

The equation governing (dropping the dashes) initial flow in clean fluid region zone-1 in non-dimensional form is

$$\frac{d^2 q}{dz^2} - \left(\frac{M^2}{1 - im}\right) Rq = PR \tag{22}$$

The corresponding non-dimensional boundary condition is

$$q = 0 \qquad \text{at} \qquad z = 1 \tag{23}$$

The initial axial velocity in the porous bed (Zone-2) is given by

$$q_p = \frac{PD^2 R^{\text{ª}-1}}{1 + D^2 R^{\text{ª}-1}\left(\frac{M^2}{1 - im}\right)} \tag{24}$$

Where,

$M^2 = \frac{\pm «_e^2 H_0^2 h}{°U}$ is the Hartmann number, $R = \frac{°Uh}{«}$ is the Reynolds's number, $D^{-2} = \frac{h^2}{K}$ the inverse Darcy Parameter and $\text{ª} = \frac{«_{eff}}{«}$ is the ratio of the viscosities.

At $t \geq 0$, the momentum equations governing the flow in the non-dimensional form in Zone-1 and Zone 2 respectively are given by

$$\frac{\partial q}{\partial t} = -\frac{\partial p}{\partial \text{¶}} + \frac{1}{R}\frac{\partial^2 q}{\partial z^2} + S\frac{\partial^3 q}{\partial t \partial z^2} - \frac{M^2}{1 - im} q \tag{25}$$

$$\frac{1}{\text{¢}}\frac{\partial q_p}{\partial t} = -\frac{\partial p}{\partial \text{¶}} - \frac{M^2}{1 - im} q_p - D^{-1} R^{-1\text{ª}} q_p \tag{26}$$

Where $S = \frac{\sim_1}{°h^2}$ is the visco-elastic parameter.

The boundary and interfacial conditions in non- dimensional form are

$$q = 1 \quad \text{at} \quad z = 1 \tag{27}$$

$$q = q_B\ ;\ \ \frac{\partial q}{\partial z} = D^{-1}\sim\left(q_B - q_P\right) \text{ at } z = s_1 \tag{28}$$

Solving (22) subjected to the condition (23) the initial flow in the non-porous region is given by

$$q=\frac{C_1}{\sinh\sqrt{\frac{M^2R}{1+m^2}}}\left[\sinh\sqrt{\frac{M^2R}{1+m^2}}(1-z)\right]+\frac{PR}{\sqrt{\frac{M^2R}{1+m^2}}}\left[\frac{\sinh\sqrt{\frac{M^2R}{1+m^2}}\,z}{\sinh\sqrt{\frac{M^2R}{1+m^2}}}-1\right] \tag{29}$$

Where, C_1 is an arbitrary constant to be determined. We now solve (25) and (26) subjected to the conditions (27) and (28) using Laplace transform technique.
The shear stresses on the upper plate and lower plate are given by

$$\tau_U=\left(\frac{dq}{dz}\right)_{z=1} \quad \text{and} \quad \tau_L=\left(\frac{dq}{dz}\right)_{z=s_1}$$

We also determine the mass flux by the formula,

$$Q_x+iQ_y=\int_{s_1}^{1} q\,dz\,,\ \ i.e., \text{Mass flux } Q=\sqrt{Q_x^{\,2}+Q_y^{\,2}}$$

.

III. Results and Discussions

We have considered the unsteady MHD flow of Rivlin-Ericksen fluid in a parallel plate channel bounded by a densely packed porous bed abutting a lower plate taking Hall current into account. The fluid flow is through a composite medium consists of two zones. The governing Darcy-Lapwood model equation in the porous medium being linear cannot satisfy more than one condition. Hence for compatibility we introduce an interfacial condition namely the Beavers-Joseph condition (B-J Condition) which allows the fluid to slip with velocity q_B at the interface. We combine the equations in both clean fluid region as well as the porous region. The equation governing the flow in the clean fluid region (zone 1) reduced to a second order partial differential equation for the dependent variable $q=u+iv$, which is solved by using Laplace transform method. The equation governing the flow in porous bed (zone 2) is a first order differential equation for the dependent variable $q_p=u_p+iv_p$, which reduces to an algebraic equation on taking the Laplace transform. On taking the inverse Laplace transform the solution for the combined velocity q is obtained. The slip velocity q_B has been calculated using B-J condition and is governed by the expression.

The velocity profiles for u and v in the clean fluid region have been drawn for the different variations in the governing parameters like the Hartmann number M, the inverse Darcy parameter D^{-1}, the visco-elastic parameter S and the ratio of viscosities ª and also being the other parameters fixed (¢ = 0.3, ~ = 0.5, $R=1$). By using these values, the analytical expressions derived in the previous section have been computed by employing a suitable software, viz. MATHEMATICA. Figs. (1-5) corresponds to these profiles for the thickness of porous bed is small while Fig (6-10) corresponds to these profiles when the thickness of the porous bed is large.

We notice that magnitude of the velocity components u reduces and v enhances with increasing M or D^{-1} in either case of smaller and larger thickness of porous bed (Figs. 1-2 & 6-7). The resultant velocity however reduces with M and D^{-1} irrespective of the thickness of the porous bed. Lower the permeability lesser the fluid speed is viewed throughout the fluid region. The similar behaviour is observed for the variation in the ratio of viscosities ª **.** This is true in either case of smaller and larger thickness of porous bed (Fig. 4 & 9). From the Figs. (3 & 8), which depict, the magnitude of both the velocities u and v also the resultant velocity raise with increasing the visco-elastic parameter S. It is also interesting to note that for visco-elastic fluid, when we increase the Hall parameter m, both the velocities with its magnitude are boosting throughout the fluid region (Fig. 5 & 10)

The slip velocities u_B and v_B have been calculated using B-J condition and are tabulated for the different variations in the governing parameters. The slip velocity u_B reduces and v_B enhances in its magnitude with increasing in M, D^{-1} and α for the smaller and larger thickness of porous bed whereas u_B and v_B increases with increasing S or m (Table 1).

The shear stresses at the lower plate are evaluated and tabulated in the table (2). It indicates the stress τ_x and the magnitude of the stress τ_y enhances with increasing M and α and reduces with D^{-1} in case of smaller and larger thickness of the porous bed. For increasing the visco-elastic parameter S and m**,** both the stresses τ_x and τ_y enhances for smaller thickness and however continuously retardation for the thickness of the porous bed is large. The table (3) corresponds to the behaviour of mass flux and we notice that reduces with increase in M, D^{-1} or α and enhances with increasing in S or m for either case of the thickness of porous bed.

I. **Velocity Profiles for *u* & *v* when the thickness of the porous bed (s_1=0.2) is small**

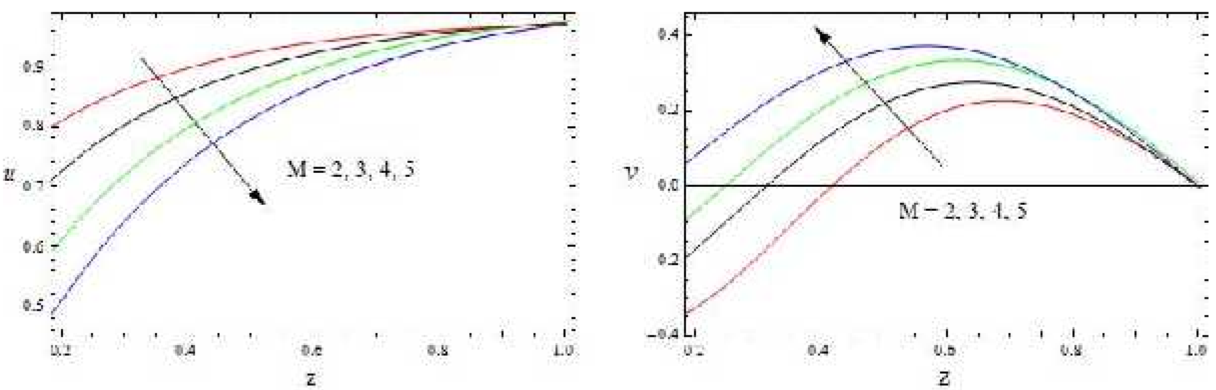

Fig 1. The velocity profiles for *u* & *v* against *M* with $D^{-1}=150, S=1, \alpha=1.2, m=1$

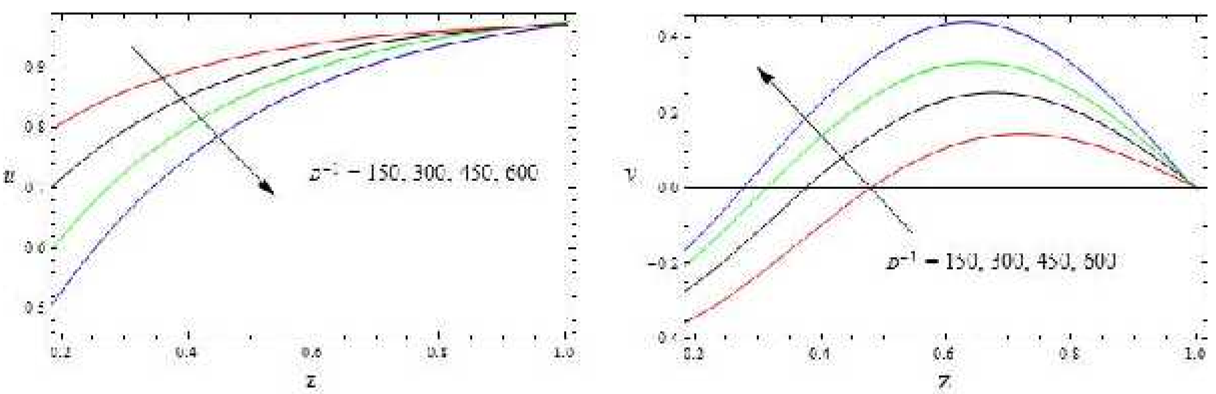

Fig 2. The velocity profiles for *u* & *v* against D^{-1} with $M=2, S=1, \alpha=1.2, m=1$

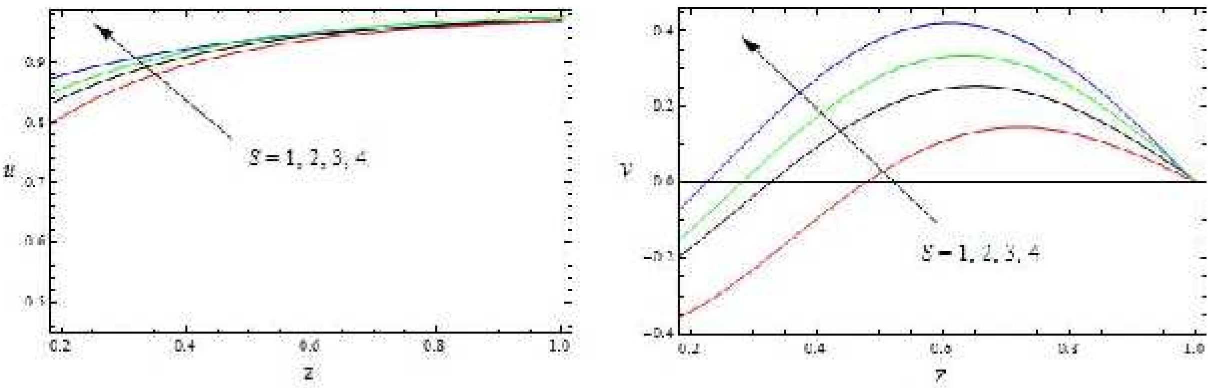

Fig 3. The velocity profiles for *u* & *v* against D^{-1} with $D^{-1}=150, M=2,$ ª $=1.2, m=1$

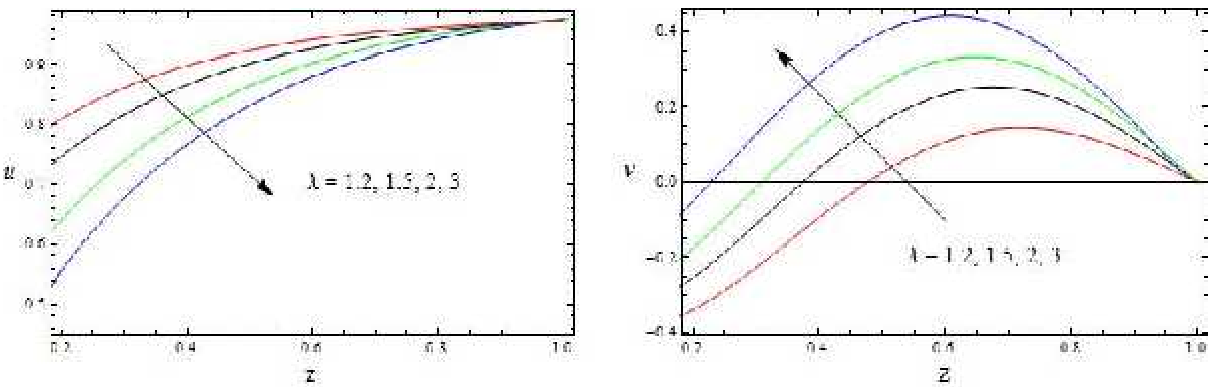

Fig 4. The velocity profiles for *u* & *v* against ª with $D^{-1}=150, M=2,$ ª $=1.2, m=1$

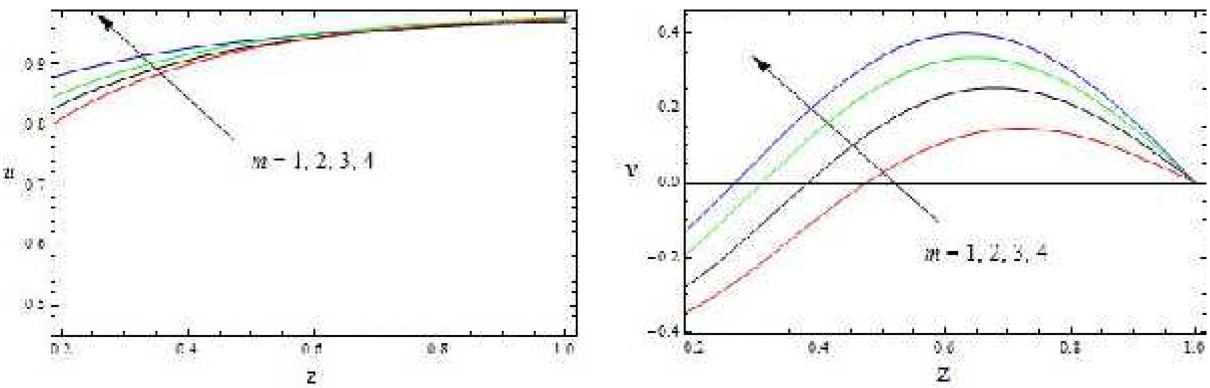

Fig 5. The velocity profiles for *u* & *v* against m with $D^{-1}=150, M=2,$ ª $=1.2, S=1$

II. Velocity Profiles for *u* & *v* when the thickness of the porous bed (s_1=0.5) is large

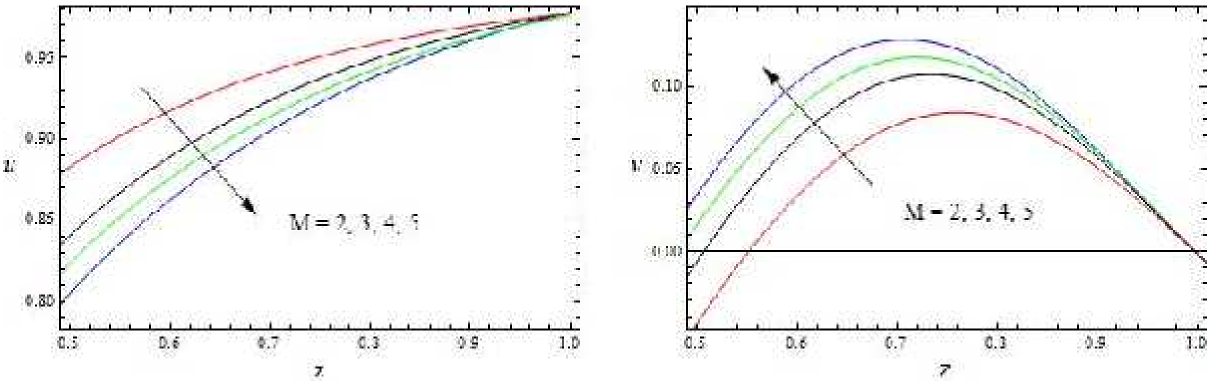

Fig 6. The velocity profiles for *u* & *v* against *M* with $D^{-1} = 150, S = 1,$ ª $= 1.2, m = 1$

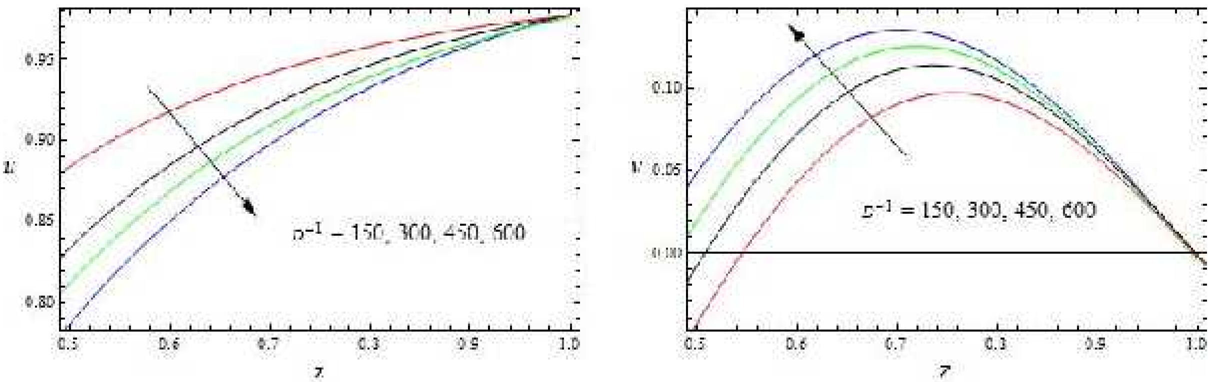

Fig 7. The velocity profiles for *u* & *v* against D^{-1} with $M = 2, S = 1,$ ª $= 1.2, m = 1$

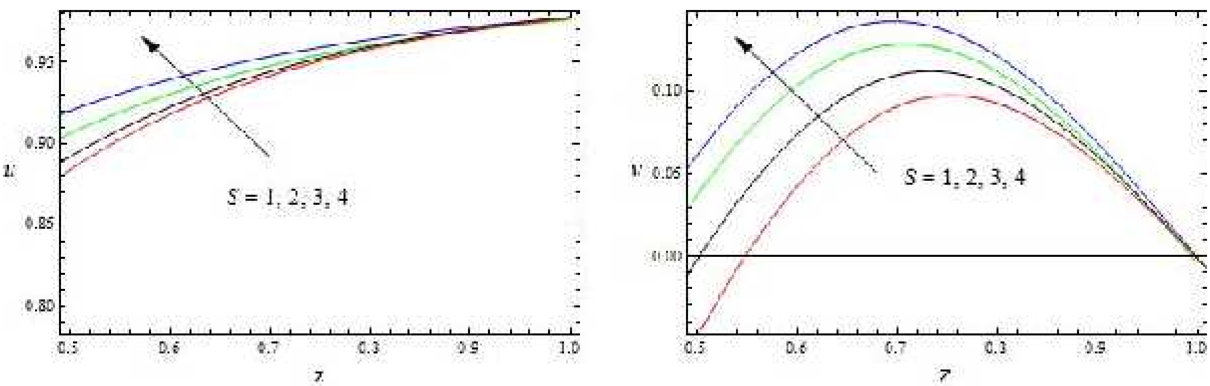

Fig 8. The velocity profiles for *u* & *v* against *S* with $D^{-1} = 150, M = 2,$ ª $= 1.2, m = 1$

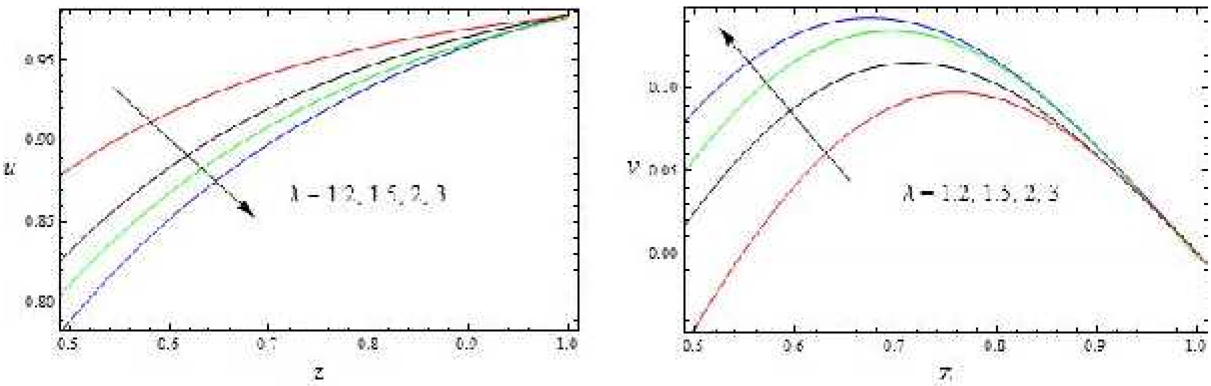

Fig 9. The velocity profiles for u & v against ª with $D^{-1} = 150, M = 2, S = 1, m = 1$

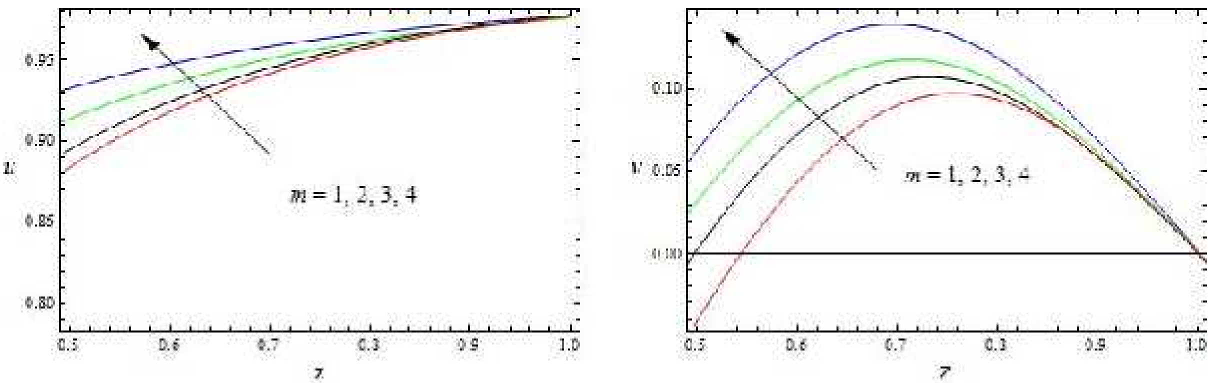

Fig 10. The velocity profiles for u & v against m with $D^{-1} = 150, M = 2,$ ª $= 1.2, S = 1$

Table - 1. The slip velocity

M	D^{-1}	S	ª	m	$s_1 = 0.2$		$s_1 = 0.5$	
					u_B	v_B	u_B	v_B
2	150	1	1.2	1	0.800124	-0.34623	0.881207	-0.05252
3	150	1	1.2	1	0.712359	-0.21338	0.844269	-0.01524
4	150	1	1.2	1	0.601238	-0.10814	0.822336	0.01254
2	250	1	1.2	1	0.700248	-0.27045	0.833328	-0.01589
2	350	1	1.2	1	0.610215	-0.20421	0.806258	0.01285
2	150	2	1.2	1	0.835221	-0.19002	0.896258	-0.01005
2	150	3	1.2	1	0.863245	-0.17526	0.905345	0.02396
2	150	1	1.5	1	0.743874	-0.19257	0.826556	0.01855
2	150	1	1.8	1	0.623845	-0.27889	0.808080	0.05018
2	150	1	1.2	2	0.825632	-0.24552	0.892588	-0.00584
2	150	1	1.2	3	0.844522	-0.19322	0.902565	0.02556

Table – 2: The Shear stress at the lower plate

M	D^{-1}	S	α	m	$s_1 = 0.2$		$s_1 = 0.5$	
					τ_x	τ_y	τ_x	τ_y
2	150	1	1.2	1	0.889855	-1.22546	1.655478	-3.55896
3	150	1	1.2	1	1.255628	-1.33565	1.884785	-3.85548
4	150	1	1.2	1	1.588479	-1.55847	2.332566	-4.11254
2	250	1	1.2	1	0.588475	-1.02546	1.366208	-3.14055
2	350	1	1.2	1	0.322565	-0.08564	1.254785	-2.54405
2	150	2	1.2	1	1.225696	-1.52256	1.144521	-2.95485
2	150	3	1.2	1	1.522646	-1.80477	0.988547	-1.22251
2	150	1	1.5	1	2.011452	-1.98554	2.744785	-5.45562
2	150	1	1.8	1	2.566545	-2.14526	3.225652	-6.95551
2	150	1	1.2	2	2.321450	-1.85525	0.852265	-2.22565
2	150	1	1.2	3	3.056695	-2.66585	0.254565	-0.98854

Table - 3. The mass flux

M	D^{-1}	S	α	m	$s_1 = 0.2$	$s_1 = 0.5$
2	150	1	1.2	1	1.854785	3.788542
3	150	1	1.2	1	1.455025	3.452162
4	150	1	1.2	1	1.020546	3.102541
2	250	1	1.2	1	1.622548	3.566582
2	350	1	1.2	1	1.366548	3.325562
2	150	2	1.2	1	2.114566	5.001450
2	150	3	1.2	1	2.566245	6.332569
2	150	1	1.5	1	1.552698	3.102025
2	150	1	1.8	1	1.202448	2.988546
2	150	1	1.2	2	2.322560	6.584452
2	150	1	1.2	3	2.884502	8.333256

IV. Conclusions

We have considered the unsteady MHD flow of Rivlin-Ericksen fluid in a parallel plate channel bounded by a densely packed porous bed abutting a lower plate and taking hall current into account. The fluid flow is through a composite medium consists of two zones. The unsteady governing equations are solved as initial value problem making use of Laplace transform technique.

1. The resultant velocity in the clean fluid region reduces with increasing M, D^{-1} or α and enhances with S for the irrespective of the thickness of porous bed.
2. The magnitude of the slip velocities u_B reduces and v_B improves with increasing in M, D^{-1} or α for the either of thickness of porous bed, whereas u_B and v_B increases with increasing S.
3. The stress τ_x and the magnitude of the stress τ_y enhances with increasing M and α and reduces with D^{-1} in case of smaller and larger thickness of the porous bed.
4. The mass flux reduces with increase in M, D^{-1} or α and enhances with increasing in S or m for either case of the thickness of porous bed.

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