Journal of Informatics and Mathematical Sciences
Vol. 10, No. 3, pp. 417–428, 2018
ISSN 0975-5748 (online); 0974-875X (print)
Published by RGN Publications
DOI: 10.26713/jims.v10i3.726

http://www.rgnpublications.com

Research Article

Influence of Hall Current on Hydromagnetic Flow Through a Uniform Channel Bounded by Porous Media of Finite Thickness

K. Ramakrishnan

Department of Mathematics, Karpagam College of Engineering, Othakkal Mandapam, Coimbatore 641 032, Tamilnadu, India
krkresearch@gmail.com

Abstract. A steady two dimensional hydromagnetic flow through a uniform channel covered by porous media having finite thickness is considered. A uniform magnetic field is applied in the perpendicular direction of the motion of the fluid. Since, it is assumed that the thickness of the porous media is smaller than the width of the flow channel, analytical solutions are obtained by using Beavers-Joseph-Rudraiah slip condition. Expressions for primary and secondary velocities and the shear stress are obtained. These expressions have been computed for different values of the Hartmann number, Hall parameter, Darcy velocity, the porous parameter and width of the porous medium. The effects of these parameters on both primary and secondary velocities and shear stress have been investigated.

Keywords. MHD flow; Porous media; BJR slip condition; Hall current

MSC. 76W05; 76S05

Received: December 4, 2017 **Accepted:** June 21, 2018

1. Introduction

The problem of flow through and past porous media was studied by many investigators, because of numerous applications in geophysical fluid mechanics. In mathematical description of any transport problem through porous media, the essential part is the correct specification of boundary conditions.

Beavers and Joseph [1] have shown that the no-slip condition is no longer valid and they have postulated that slip exists (hereafter called BJ slip condition) at the nominal surface because of the transfer of momentum. The BJ slip condition is independent of the thickness of the porous layer (H). Following the research work done by Beavers and Joseph, studies on the problem of the interface region between a porous layer and a fluid-filled channel using slip condition have received the most attention (Bhatt and Sacheti [3], Singh and Laurence [23], Pal *et al.* [14], Kharab [7], Vafai and Kim [25], Van Lankveld [26], Makinde and Osalusi [8], Mehmood and Ali [10], Jat and Chaudhary [6], Ramakrishnan and Shailendhra [17], and Srinivas and Ramana Murthy [24]).

In many industrial applications, the thickness of the porous layer is smaller than that of fluid layer. Rudraiah [22] derived the slip condition known as BJR slip condition involving the thickness of the layer (H). When $H \to \infty$, BJR slip condition reduces to BJ slip condition. It can be described by the Brinkman equation, when the boundary layer is very thin and depending on the value of slip parameter. Outside this layer, the velocity is almost constant and approaches the Darcy velocity.

Recently, numerous of research works have been carried out in the case of flow through porous media with finite thickness. Rudraiah and Ng [19] discussed various analytical and numerical techniques used to investigate instabilities and importance of Nano-size smart materials under different conditions. Rudraiah *et al.* [21] investigated the electrohydrodynamic dispersion of macromolecular components in biological bearing. Rudraiah and Ng [20] studied analytically, the dispersion in fluid-saturated deformable or non deformable porous media with or without chemical reaction. Ng *et al.* [12] analyzed electrohydrodynamic dispersion due to pulsatile flow in a channel bounded by porous layer of smart material using both the BJ and the BJR-slip conditions. Ramakrishnan and Shailendhra [16] studied the effect of BJR slip condition on hydromagnetic blood flow through a uniform channel covered by porous media of finite thickness.

The problem of effects of Hall current on hydromagnetic flow through porous media attracts many investigators (Pop and Soundalgekar [15], Mazumder *et al.* [9], Vidyanidhi and Narayana [27], Bhaskara Reddy and Bathaiah [2], Haroun [4], Hayat *et al.* [5], Mekheimer and El Kot [11] and Okongo *et al.* [13]) due to its applications in industrial and bio engineering related problems. Very recently Ramakrishnan [18] investigated the Hall effects on hydromagnetic flow through a channel bounded by porous media using Beavers-Joseph (BJ) slip condition.

Study on flow through porous media involving the thickness of the porous layer with Hall current effects may be relevant due to its applications in many scientific fields. With this motivation in mind, in the present work, hydromagnetic flow through a uniform channel covered by porous media is considered and it is assumed that the thickness of the porous layer is smaller than the width of the fluid layer. The required basic equations are derived and the slip condition developed by Rudraiah [22] is used. The combined effect of porous parameter, Hartmann number, width of the porous media and Hall parameter on the primary and secondary velocities and wall shear stress is discussed in detail.

2. Formulation and Solution of the Problem

Consider an infinitely long channel of uniform width $2h$ through which a laminar, steady and viscous hydromagnetic fluid flows. The channel is bounded externally on either side by densely packed saturated porous layers each of width H at $y = \pm h$. It is assumed that the fluid behaves like a homogeneous conducting Newtonian fluid with constant density ρ, viscosity μ and small electrical conductivity σ_e. The porous layer is assumed to be homogeneous, isotropic and densely packed. The channel is symmetrical about the x-axis. Since the channel is infinitely long, all the physical quantities (except pressure) depend only on y.

Let u and v be the velocity components of the fluid at a point (x, y) where x is measured along the channel and y normal to it. A uniform magnetic field H_0 is applied normal to the motion of the fluid. $B_0 = \mu_e H_0$, is the electromagnetic induction where μ_e is the magnetic permeability. Since, the magnetic Reynolds number is lesser than unity, the induced magnetic field can be neglected in comparison with the applied magnetic field.

The equation of continuity $\nabla \cdot \vec{q} = 0$ gives $v = 0$, where $\vec{q} = (u, v, w)$. When a strong magnetic field is applied, the Hall effect induces a secondary flow, and so there will be two components of the velocity u and w. The solinoidal relation $\nabla \cdot \vec{H} = 0$ for the magnetic field gives $H_y = H_0 =$ constant everywhere in the fluid. The conservation of electric charge $\nabla \cdot \vec{J} = 0$ gives $J_y =$ constant and this constant is zero, since $J_y = 0$ on the walls which are electrically non-conducting.

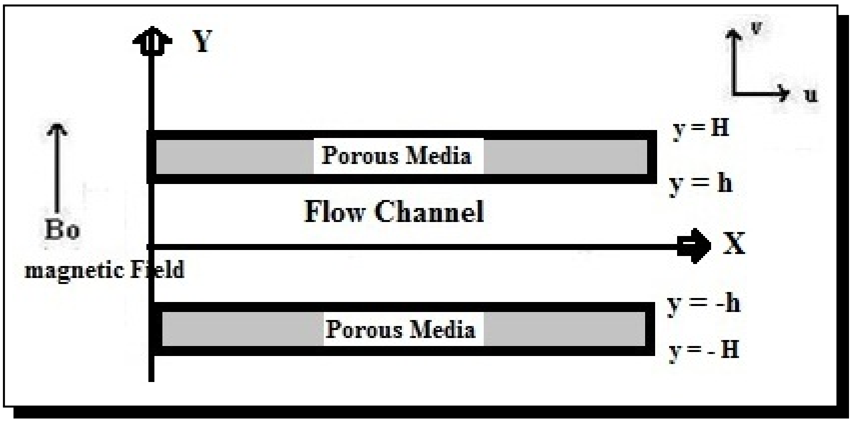

Figure 1. Physical configuration.

In the absence of an external electric field, the effect of polarization of the fluid is negligible. It can also be assumed that the applied electric filed $\vec{E} = 0$. Also, the ion slip, electron pressure and thermo-electric effects are neglected.

Under the above assumptions, the governing equations of the flow (after neglecting inertia effects) in the dimensionless form are:

$$R\frac{\partial p}{\partial x} = \frac{\partial^2 u}{\partial y^2} - \frac{M^2}{1+m^2}(u + mw), \tag{1}$$

$$v = 0, \tag{2}$$

$$R\frac{\partial p}{\partial y} = 0, \tag{3}$$

$$R\frac{\partial p}{\partial z} = \frac{\partial^2 w}{\partial y^2} + \frac{M^2}{1+m^2}(mu - w), \tag{4}$$

where

$$M^2 = \frac{\sigma_e \mu_e^2 H_0^2 h^2}{\mu_f}, \quad R = \frac{Uh}{\nu}.$$

These equations are solved using the BJR slip boundary conditions, which, in the dimensionless form (Rudraiah [22]) are given by,

$$\frac{du}{dy} = \delta_1 Q_1 + \delta_2(u_{b_1} - Q_1) \quad \text{at } y = -1, \tag{5}$$

$$\frac{du}{dy} = -\delta_1 Q_1 - \delta_2(u_{b_2} - Q_1) \quad \text{at } y = 1, \tag{6}$$

$$\int_{-1}^{1} u(y)dy = n_f, \tag{7}$$

$$v = \epsilon Q_y, \tag{8}$$

$$Q_1 = -\frac{k}{\mu}\frac{\partial p}{\partial x}, \tag{9}$$

$$w = 0 \qquad \text{at } y = \pm 1, \tag{10}$$

$$u = u_{b1} \qquad \text{at } y = 1, \tag{11}$$

$$u = u_{b2} \qquad \text{at } y = -1, \tag{12}$$

where

$$\delta_1 = \frac{\lambda\sqrt{\lambda}\sigma_p \epsilon}{\delta_0 \sinh\left(\frac{\sigma_p}{\sqrt{\lambda}}\right)}, \quad \delta_2 = \frac{\sqrt{\lambda}}{\delta_0}\sigma_p \coth\left(\frac{\sigma_p}{\sqrt{\lambda}}\right), \tag{13}$$

$$\sigma_p = \frac{H}{\sqrt{k}}, \quad \delta_0 = \frac{H}{h}. \tag{14}$$

Here, λ is a positive constant called viscosity factor, n_f is the net flux through the channel, u_{b1} and u_{b2} are the slip velocities, Q_1 is the Darcy velocity, k is the permeability of the porous material and σ_p is called the porous parameter.

Since the channel is of uniform width, use the approximation that the wall slope is everywhere negligible (Ramakrishnan [16]). Eliminating the pressure terms between (1), (3) and (4), the basic equations in non-dimensional form are as follows :

$$\frac{d^3 u}{dy^3} - H_R\frac{du}{dy} - mH_R\frac{dw}{dy} = 0, \tag{15}$$

$$\frac{d^3 w}{dy^3} + mH_R\frac{du}{dy} - H_R\frac{dw}{dy} = 0. \tag{16}$$

Since u and w are function of y alone. Here,

$$H_R = \frac{M^2}{m^2+1}$$

Solving the simultaneous equations (15) and (16) subject to the conditions from (5) to (12), the expressions for primary and secondary velocity components are given by,

$$u(y) = B_1 + 2B_2 f(y) + 2B_3 g(y), \tag{17}$$

$$\begin{aligned} w(y) = &\frac{1}{mrH_R^2}\left[\left(\chi_{17}B_2+\chi_{18}B_3\right)\left(\psi_1 f(y)+\psi_2 g(y)\right)\right] \\ &+\frac{1}{mrH_R^2}\left[\left(\chi_{17}B_3-\chi_{18}B_2\right)\left(\psi_1 g(y)-\psi_2 f(y)\right)\right] \\ &-\frac{1}{mrH_R^2}[\chi_{15}\left(\chi_{17}B_2+\chi_{18}B_3\right)]-\frac{1}{mrH_R^2}\left[\chi_{16}\left(\chi_{17}B_3-\chi_{18}B_2\right)\right]. \end{aligned} \tag{18}$$

The slip velocity and net flux through the channel are given by,

$$u_b = \frac{1}{2}\left[\frac{\left(\chi_3\chi_{12}-\chi_1\chi_9\right)n_f}{\chi_3\chi_{14}-\chi_1\chi_{11}+\delta_2}\right]+\left[\frac{\left(1+\chi_3\chi_{13}-\chi_1\chi_{10}\right)(\delta_2-\delta_1)Q_1}{\chi_3\chi_{14}-\chi_1\chi_{11}+\delta_2}\right], \tag{19}$$

$$\frac{n_f}{R} = \left[\frac{2rH_R+\frac{\delta_0^2}{\sigma_p^2}(\delta_2-\delta_1)[\zeta_1-2rH_R(\chi_{23}+\chi_{22}\chi_{25})]}{2[\zeta_2-2rH_R(\chi_{19}+\chi_{22}\chi_{24})]}\right]\frac{\partial p}{\partial x}. \tag{20}$$

The shear stress components in the lower wall are given by

$$\tau_x = -2\left[B_2\chi_3+B_3\chi_1\right], \tag{21}$$

$$\tau_z = -\frac{1}{rH_R}\left[B_2\zeta_3+B_3\zeta_4\right], \tag{22}$$

where

$$f(y) = \cosh(\psi_1 y)\cos(\psi_2 y),$$

$$g(y) = \sinh(\psi_1 y)\sin(\psi_2 y),$$

$$r = \sqrt{1+m^2},$$

$$\theta = \arctan(m),$$

$$\psi_1 = \sqrt{rH_R}\cos\left(\frac{\theta}{2}\right),$$

$$\psi_2 = \sqrt{rH_R}\sin\left(\frac{\theta}{2}\right),$$

$$\chi_1 = \psi_1\cosh(\psi_1)\sin(\psi_2)-\psi_2\sinh(\psi_1)\cos(\psi_2),$$

$$\chi_2 = \psi_1\cosh(\psi_1)\sin(\psi_2)+\psi_2\sinh(\psi_1)\cos(\psi_2),$$

$$\chi_3 = \psi_1\sinh(\psi_1)\cos(\psi_2)-\psi_2\cosh(\psi_1)\sin(\psi_2),$$

$$\chi_4 = \psi_1\sinh(\psi_1)\cos(\psi_2)+\psi_2\cosh(\psi_1)\sin(\psi_2),$$

$$\chi_5 = \psi_1 \sin(\psi_1)\cos(\psi_2) + \psi_2 \sinh(\psi_1)\cosh(\psi_2),$$

$$\chi_6 = \cosh^2(\psi_1) - \cos^2(\psi_2),$$

$$\chi_7 = \sinh(\psi_1)\sin(\psi_2),$$

$$\chi_8 = \cosh(\psi_1)\cos(\psi_2),$$

$$\chi_9 = \frac{\chi_3}{rH_R\chi_5 - 2\psi_1\psi_2\chi_6},$$

$$\chi_{10} = \frac{rH_R\chi_8 - \chi_4}{rH_R\chi_5 - 2\psi_1\psi_2\chi_6},$$

$$\chi_{11} = \frac{rH_R[\delta_2\chi_8 + \chi_3] - \delta_2\chi_4}{rH_R\chi_5 - 2\psi_1\psi_2\chi_6},$$

$$\chi_{12} = \frac{\chi_1}{rH_R\chi_5 - 2\psi_1\psi_2\chi_6},$$

$$\chi_{13} = \frac{rH_R\chi_7 - \chi_2}{rH_R\chi_5 - 2\psi_1\psi_2\chi_6},$$

$$\chi_{14} = \frac{rH_R[\delta_2\chi_7 + \chi_1] - \delta_2\chi_2}{rH_R\chi_5 - 2\psi_1\psi_2\chi_6},$$

$$\chi_{15} = \psi_1 \cosh(\psi_1)\cos(\psi_2) + \psi_2 \sinh(\psi_1)\sin(\psi_2),$$

$$\chi_{16} = \psi_1 \sinh(\psi_1)\sin(\psi_2) - \psi_2 \cosh(\psi_1)\cos(\psi_2),$$

$$\chi_{17} = 2\psi_1\left(\psi_1^2 - 3\psi_2^2 - F\right),$$

$$\chi_{18} = 2\psi_2\left(3\psi_1^2 - \psi_2^2 - F\right),$$

$$\chi_{19} = 1 + \chi_4\chi_{12} - \chi_2\chi_9,$$

$$\chi_{20} = \chi_{15}\chi_{17} - \chi_{16}\chi_{18},$$

$$\chi_{21} = \chi_{15}\chi_{18} + \chi_{16}\chi_{17},$$

$$\chi_{22} = \chi_2\chi_{11} - \chi_4\chi_{14},$$

$$\chi_{23} = \chi_4\chi_{13} - \chi_2\chi_{10},$$

$$\chi_{24} = \frac{\chi_3\chi_{12} - \chi_1\chi_9}{\chi_3\chi_{14} - \chi_1\chi_{11} + \overline{\alpha}\sigma},$$

$$\chi_{25} = \frac{1 + \chi_3\chi_{13} - \chi_1\chi_{10}}{\chi_3\chi_{14} - \chi_1\chi_{11} + \overline{\alpha}\sigma},$$

$$\zeta_1 = \chi_{20}\left(\chi_{14}\chi_{25} - \chi_{13}\right) + \chi_{21}\left(\chi_{10} - \chi_{11}\chi_{25}\right),$$

$$\zeta_2 = \chi_{20}\left(\chi_{14}\chi_{24} - \chi_{12}\right) + \chi_{21}\left(\chi_9 - \chi_{11}\chi_{24}\right),$$

$$\zeta_3 = \chi_{17}\sinh(\psi_1)\cos(\psi_2) - \chi_{18}\cosh(\psi_1)\sin(\psi_2),$$

$$\zeta_4 = \chi_{18}\sinh(\psi_1)\cos(\psi_2) + \chi_{17}\cosh(\psi_1)\sin(\psi_2),$$

and

$$B_1 = \frac{1}{2rH_R}\left[\left(1-\chi_2\chi_9+\chi_4\chi_{12}\right)N_f\right]+\frac{1}{2rH_R}\left[2\left(\chi_4\chi_{13}-\chi_2\chi_{10}\right)(\delta_2-\delta_1)Q_1\right]$$
$$+\frac{1}{2rH_R}\left[2\left(\chi_2\chi_{11}-\chi_4\chi_{14}\right)u_{b_1}\right],$$
$$B_2 = -\frac{1}{4}\chi_{12}N_f-\frac{1}{2}\chi_{13}(\delta_2-\delta_1)Q_1+\frac{1}{2}\chi_{14}u_{b_1},$$
$$B_3 = \frac{1}{4}\chi_9 N_f+\frac{1}{2}\chi_{10}(\delta_2-\delta_1)Q_1-\frac{1}{2}\chi_{11}u_{b_1}.$$

3. Results and Discussion

The purpose of the present discussion is to analyze and compare the effects of Hartmann number(M), porous parameter(σ_p), Hall parameter(m) and width of the porous layer(H) on the primary velocity(u), secondary velocity(w) and shear stress. In this case, it is considered that the thickness of the porous layer is smaller than the width of the fluid layer. The boundary condition at the clear fluid - porous medium interface suggested by Rudraiah [22] is taken.

To observe the quantitative effects of σ_p, M, m and H, numerical evaluations of the analytic results obtained for u, w, τ_x and τ_z for the values of the physical parameters $Q_1 = 0.001$, $\sigma_p = 10^2, 10^3$, $M = 2,3,4$ and $m = 1,2,3,4$ are carried out.

The effect of Hartmann number(M) on the primary velocity u is depicted in Figure 2 and Figure 3. A parabolic primary velocity profile is observed with the maximum value at the channel centerline and minimum value at the walls. However, a general decrease in the magnitude of primary velocity profile is noticed with an increase in Hartmann number(M). The occurrence of negative primary velocity near the channel walls due to large value of M indicates the possibility of flow reversal near the walls. Figure 4 and Figure 5 are drawn to find the effect of the Hall parameter m on the primary velocity. It is observed that the primary velocity is increasing with increasing m for a given value of M. It is seen that the distribution of primary velocity have more values in the case of flow through porous media with infinite thickness using BJ slip condition than in the case of finite thickness porous media (Ramakrishnan [18]).

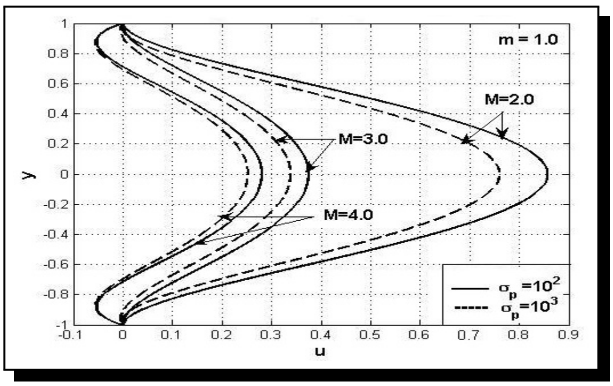

Figure 2. Primary velocity u for $m = 1.0$ and different values of M

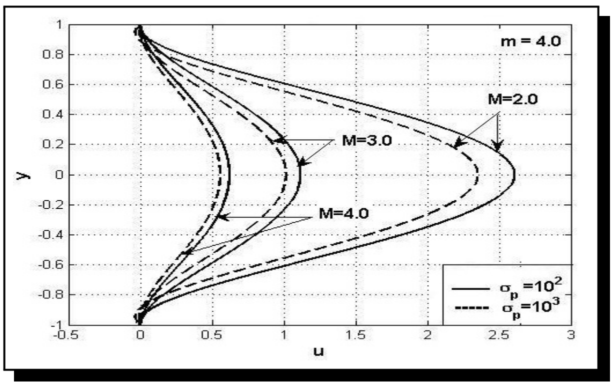

Figure 3. Primary velocity u for $m = 4.0$ and different values of M

From Figures 2-5, it is seen that the primary velocity decreases as the porous parameter increases. However, when the porous parameter(σ_p) is further increased beyond 10^5, there is no significant difference in the primary velocity (graphs are not shown), since, in this case, the walls behave like impermeable walls.

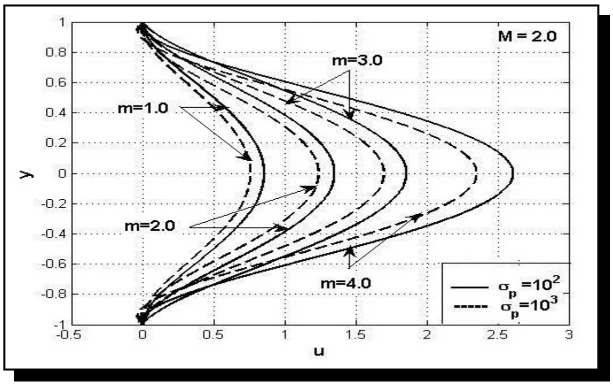

Figure 4. Primary velocity u for $M = 2.0$ and different values of m

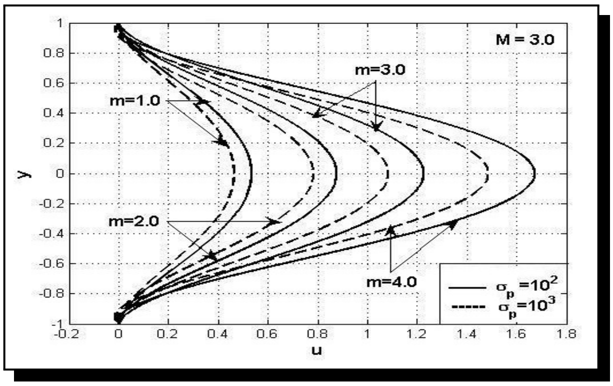

Figure 5. Primary velocity u for $M = 3.0$ and different values of m

The secondary velocity(w) profiles are plotted in Figure 6 and Figure 7 for different values of M and for a given value of m. It is found that the secondary flow velocity decreases in magnitude with the increase in Hartmann number(M). It is interesting to note that the secondary flow is decreased in magnitude as σ_p increases for $m = 1.0$ and it increases numerically through the channel by increasing σ_p for $m = 4.0$. This pattern of flow velocity distribution is not seen in the case of infinite thickness porous media (Ramakrishnan [18]).

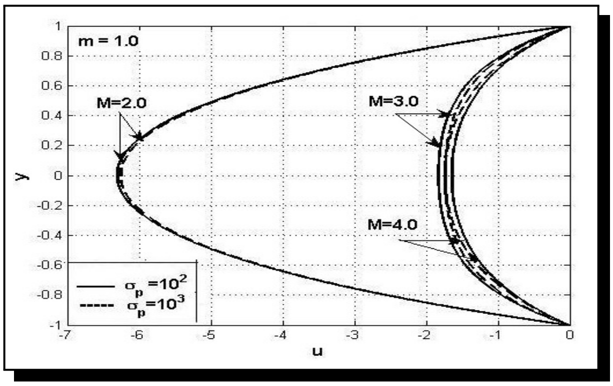

Figure 6. Secondary velocity w for $m = 1.0$ and different values of M

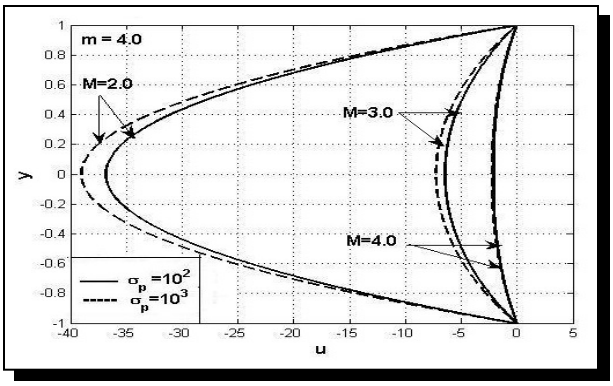

Figure 7. Secondary velocity w for $m = 4.0$ and different values of M

In Figure 8 and Figure 9, the effect of Hall parameter(m) on the secondary flow velocity for a given value of M is shown. It is observed that the secondary flow velocity increases in magnitude with the increase in Hall parameter m. This confirms the fact that the secondary velocity component is a result of the Hall effect; therefore it will respond positively to increases in m values. It is also noticed that for $M = 2.0$, the secondary velocity increases as σ_p increases. For large $M = 3.0$, the secondary velocity slightly decreases when σ_p increases.

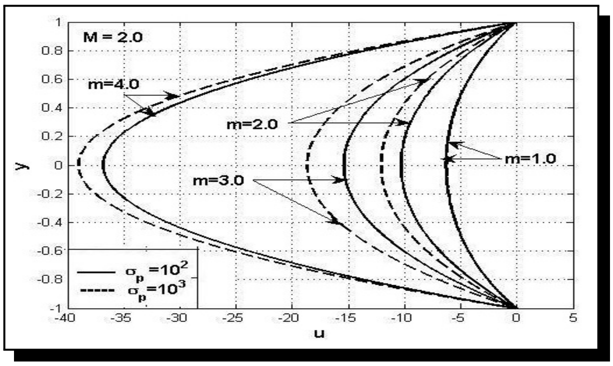

Figure 8. Secondary velocity w for $M = 2.0$ and different values of m

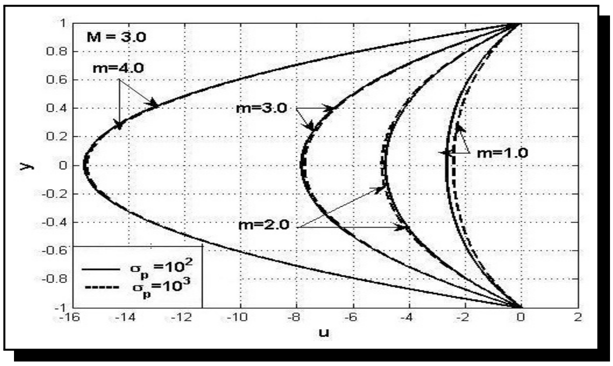

Figure 9. Secondary velocity w for $M = 3.0$ and different values of m

Figure 10 and Figure 11 indicate the development of the primary velocity for various width of the porous layer H for fixed values of M and m. It is clear from these figures that the primary velocity is increasing in the central region of the channel for increasing H and no significant changes in near the boundary of the channel. In general, primary velocity distribution decreases as σ_p increases. It is also noted that for large values of M, m and σ_p there is no significant difference in the distribution of the primary velocity.

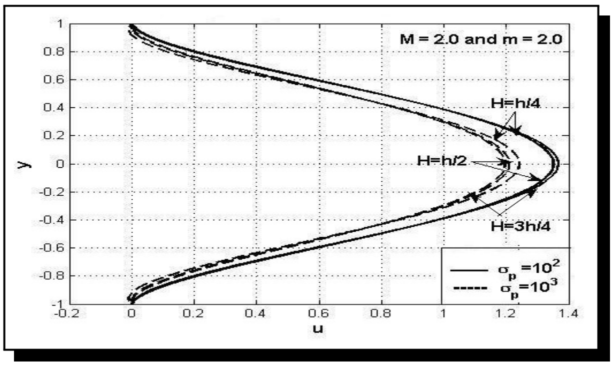

Figure 10. Primary velocity u for $M = 2.0$, $m = 1.0$ and different values of H

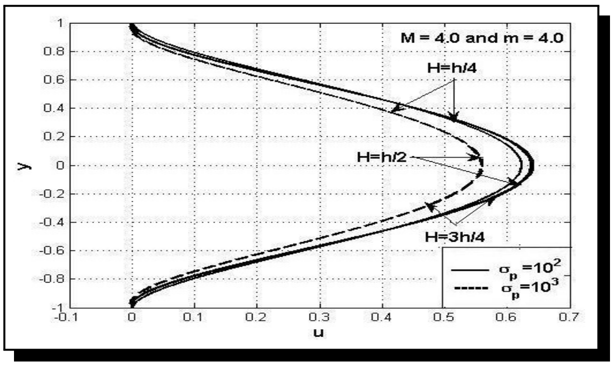

Figure 11. Primary velocity u for $M = 3.0$, $m = 4.0$ and different values of H

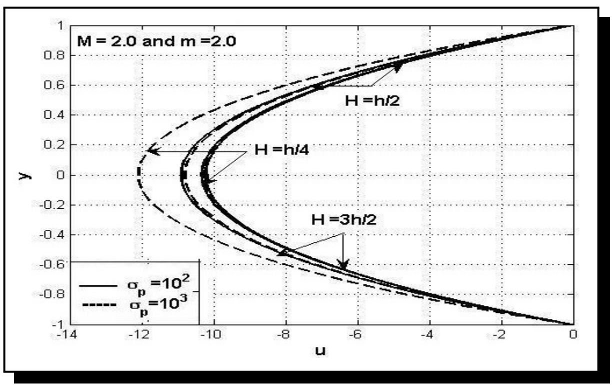

Figure 12. Secondary velocity w for $M = 2.0$, $m = 1.0$ and different values of H

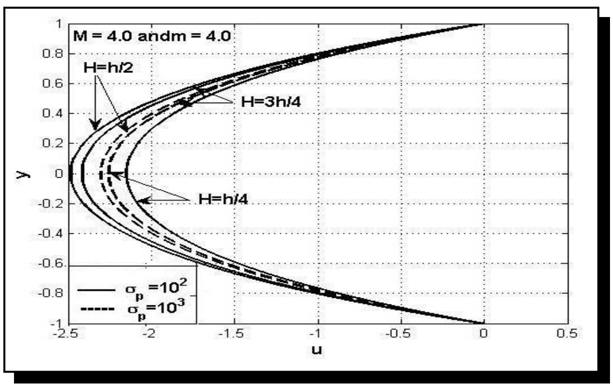

Figure 13. Secondary velocity w for $M = 3.0$, $m = 4.0$ and different values of H

Figure 12 and Figure 13 show the effect of width of the channel(H) on the secondary flow velocity at fixed values of M and m. It is observed that the secondary flow velocity decreases in magnitude as H increases. It is also noted that the secondary velocity has larger values in the central core region of the channel.

The values of shear stress at the lower wall for the primary and secondary flows are given in Table 1 and Table 2 respectively for different values of m and M and a particular value of $H = h/4$ and $\sigma = 10^2$. The value of shear stress at the lower walls for the primary and secondary flows decreases numerically as both M and m increases. It is also observed that the values of shear stress at the upper wall are equal and opposite to those at the lower wall.

Table 1. Shear Stress(τ_x) for primary velocity at different values of M and m ($H = h/4$ and $\sigma = 10^2$)

$m \rightarrow$	1	2
$M \downarrow$		
2.0	−0.9798	−0.2242
3.0	−0.4525	−0.0798
4.0	−0.1110	−0.0422

Table 2. Shear Stress(τ_z) for secondary velocity at different values of M and m ($H = h/4$ and $\sigma = 10^2$)

$m \rightarrow$	1	2
$M \downarrow$		
2.0	−5.4384	−1.7311
3.0	−2.8101	−1.4720
4.0	−2.7125	−0.9436

4. Conclusion

The effects σ_p, M, H and m on the steady flow of conducting viscous incompressible fluid in a uniform channel covered by porous media using the BJR slip condition were investigated. Results reveal that M produces a retarding effect on both the primary and secondary velocities, where the other parameter i.e., m has an accelerating effect on primary and secondary velocities. The porous parameter σ_p accelerates primary and secondary velocity for large value of m, whereas it decreases both the velocities when m is small. It is observed that when H increases, both the primary and secondary velocities decrease. The primary and secondary flow shear stress also decreases numerically when both the parameters M and m increases.

Competing Interests

The author declares that he has no competing interests.

Authors' Contributions

The author wrote, read and approved the final manuscript.

References

[1] G.S. Beavers and D.D. Joseph, Boundary conditions at a naturally permeable wall, *J. Fluid Mech.* **30** (1967), 197 – 207, DOI: 10.1017/S0022112067001375.

[2] N. Bhaskara Reddy and D. Bathaiah, Hall effects on MHD flow through a porous straight channel, *Def. Sci. J.* **32**(4) (1982), 313 – 326, DOI: 10.14429/dsj.32.6322.

[3] B.S. Bhatt and N.C. Sacheti, On the analogy in slip flows, *Indian J. Pure Appl. Math.* **10**(3) (1979), 303 – 306.

[4] M.H. Haroun, A mathematical study of Hall effects on peristaltic transport of hydromagnetic flow through a porous medium, *J. Porous Media* **10**(7) (2007), 1 – 13, DOI: 10.1615/jpormedia.v10.i7.40.

[5] T. Hayat, Z. Abbas and S. Asghar, Effects of Hall current and heat transfer on the flow in a porous medium with slip condition, *J. Porous Media* **10**(1) (2007), 35 – 50, DOI: 10.1615/jpormedia.v10.i1.30.

[6] R.N. Jat and S. Chaudhary, Magnetohydrodynamic boundary layer flow past a porous substrate with Beavers-Joseph boundary condition, *Indian J. Pure Appl. Phys.* **47** (2009), 624 – 630.

[7] A. Kharab, A Poiseuille flow past a permeable hill, *Computers Math. Appli.* **19**(2) (1990), 9 – 15.

[8] O.D. Makinde and E. Osalusi, MHD flow in a channel with slip at the permeable boundaries, *Rom. J. Phys.* **51** (3) (2006), 319 – 328.

[9] B.S. Mazumder, B.S. Gupta and N. Datta, Hall effects on combined free and forced convective hydromagnetic flow through a channel, *Int. J. Engg. Sci.* **14** (1976), 285 – 292, DOI: 10.1016/0020-7225(76)90045-8.

[10] A. Mehmood and A. Ali, The effect of slip condition on unsteady MHD oscillatory flow of a viscous fluid in a planer channel, *Rom. Journ. Phys.* **52**(1-4) (2007), 85 – 91.

[11] Kh.S. Mekheimer and M.A. EI Kot, Influence of magnetic field and Hall currents on blood flow through a stenotic artery, *Appl. Math. Mech. Engg. Ed.* **29**(8) (2008), 1093 – 1104.

[12] C.-O. Ng, N. Rudraiah and S. Nagaraj, Electrohydrodynamic pulsatile flow in a channel bounded by porous layer of smart material, *Int. J. Engg. Sci.* **47** (2009), 103 – 115, DOI: 10.1016/j.ijengsci.2008.07007.

[13] M.O. Okongo, G.P. Nderitu and J.M. Mugambi, Hall current effects on a flow in a variable magnetic field past an infinite vertical Porous flat plate, *International Journal of Recent Research and Applied Studies* **19**(1) (2014), 96 – 113.

[14] D. Pal, R. Veerabhadraiah, P.N. Shivakumar and N. Rudraiah, Longitudinal dispersion of tracer particles in a channel bounded by porous media using slip condition, *Int. J. Math. Math. Sci.* **7**(4) (1984), 755 – 764, DOI: 10.1155/50161171284000788.

[15] I. Pop and V.M. Soundalgekar, Effects of Hall current on hydromagnetic flow near a porous plate, *Acta Mechanica* **20** (1974), 315 – 318, DOI: 10.1007/BF01175933.

[16] K. Ramakrishnan and K. Shailendhra, Hydromagnetic blood flow through a uniform channel with permeable walls covered by porous media of finite thickness, *Journal of Applied Fluid Mechanics* **6**(1) (2013), 39 – 47.

[17] K. Ramakrishnan and K. Shailendhra, Hydromagnetic flow through uniform channel bounded by porous media, *Appl. Math. Mech.-Engl. Ed.* **32**(7) (2011), 837 – 846, DOI: 10.1007/s10483-011-1463-7.

[18] K. Ramakrishnan, Hall current effects on hydromagnetic flow through uniform channel bounded by porous media, *International Journal of Fluid Mechanics Research* **45**(1) (2017), 1 – 14.

[19] N. Rudraiah and C.-O. Ng, A model for manufacture of nano-sized smart materials free from impurities, *Current Science* **86** (8) (2004), 1076 – 1091.

[20] N. Rudraiah and C.-O. Ng, Dispersion in Porous media with and without reaction: A review, *Journal of Porous Media* **10** (3) (2007), 219 – 248 (2007), DOI: 10.1615/jpormedia.v10.i3.10.

[21] N. Rudraiah, C.-O. Ng, C. Nagaraj and H.N. Nagaraj, Electro hydrodynamic dispersion of Macromolecular components in biological bearing, *J. Ener. Heat Mass Transfer* **28** (2006), 261 – 280.

[22] N. Rudraiah, Coupled parallel flows in a channel and a bounding porous medium of finite thickness, *J. Fluids Engg.* **107** (1985), 322 – 329, DOI: 10.1115/1.3242486.

[23] R. Singh and L. Lawrence, Influence of slip velocity at a membrane surface on ultra-filtration performance-I (Channel flow system), *Int. J. Heat Mass Transfer* **12** (1979), 721 – 729, DOI: 10.1016/0017.9310(79)90119-4.

[24] J. Srinivas and J.V. Ramana Murthy, Flow of two immiscible couple stress fluids between two permeable beds, *Journal of Applied Fluid Mechanics* **9**(1) (2016), 501 – 507, DOI: 10.18869/acadpub.jafm.68.224.24013.

[25] K. Vafai and S.J. Kim, Fluid mechanics of the interface region between a porous medium and a fluid layer - An exact solution, *Int. J. Heat Fluid flow* **11** (1990), 254 – 256, DOI: 10.1016/0142-727X(90)90045-D.

[26] M.A.M. Van Lankveld, Validation of boundary conditions between a porous medium and a viscous fluid, *Report No. WFW 91.071*, August 1991, Eindhoven University of Technology (1991).

[27] V. Vidyanidhi and P.C.L. Narayana, The Hall effects on hydromagnetic flow over a permeable bed, *Acta Phys. Acad. Sci. Hung.* **46**(3) (1979), 137 – 152.