Magneto hydrodynamic flow past a rotating circular cylinder

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Abstract

In this paper, the effect of a uniform magnetic field on the viscous fluid past a rotating circular cylinder with constant angular velocity has been studied. A uniform magnetic field is applied transversely to the flow. In zone I, the equation is governed by Navier-Stokes equation. In zone II, the porous region is governed by Brinkman equation. The matching conditions at porous liquid interface suggested by Ochoa-Tapia are used to get the flow field. The flow through a porous medium of infinite extent and the flow through a porous medium bounded by a concentric cylinder, where the outer cylinder rotates and the inner one is stationary are also discussed for an electrically conducting fluid. The graph for various measures is drawn. The velocity of the flow field is observed for different magnetic field, Darcy number, slip coefficient and radius of the inner cylinder. The increase or decrease of velocity depends on the magnetic field.

1. Introduction:

The interest in MHD fluid flow is important because of its extensive application in MHD power generators, fluid droplet sprays, purification of crude oil, petroleum industry etc. Magnetic field has an important effect while studying viscous flow problems for the porous sphere involving Brinkman equation in the porous region $\mu\nabla^2 v - \frac{\mu}{k} v = \nabla p$ where μ is the coefficient of viscosity of the fluid, v is the velocity vector, k is the permeability of the porous medium and p is the pressure. Brinkman [1] analyzed the viscous force exerted by the flow in a fluid on a dense swarm of particles. Rajasekhara et al [2] discussed coquette flow over a permeable bed. Later on, Rudraiah et al [3] derived the temperature distribution in coquette flow. Chandrasekhara et al [4] analyzed the effect of slip on porous walled squeeze-films. Ochoa-Tapia and Whitaker [5] suggested the matching condition at the porous liquid interface. Presently, Srivastava et al [6, 7] discussed the effect of viscous fluid in a rotating disk with porous medium. Srivastava and others [8, 9, 10] also developed the torsional oscillation of a disk and rotation of a cylinder surrounded by a porous medium.

The present study is based on the effect of magnetic field on the flow past a circular cylinder surrounded by a porous medium of finite thickness and of infinite extent. The circular cylinder is rotated with a constant angular velocity. The viscous fluid through a porous medium is governed by Brinkman equation and the fluid in the free flow region is governed by Stokes equation. The graphs for velocity against various measures are considered and the results are obtained.

2. Mathematical Formulation:

Consider the rotation of an infinite circular cylinder $r = a$ with a constant angular velocity Ω and an arbitrary stokes flow of a viscous fluid past a cylinder between the region $a \le r \le \lambda_1 a$ which is called zone I. A uniform magnetic field is applied transversely to the flow of the fluid. The governing equation of the flow inside the region $(r \le \lambda_1 a)$ is given by Navier Stokes equation

$$\mu\left[\nabla^2 V_1 - \frac{\sigma B_0^2}{\mu}\right] = 0 \tag{1}$$

where μ is the coefficient of viscosity, V_1 is the velocity of the fluid flow, σ is the Darcy number, B_0 is the magnetic induction and $V_1 = V_1^* / a\Omega$, V_1^* is the non vanishing circumferential velocity. The flow in the porous region $r \ge \lambda_1 a$ is fully saturated with the viscous fluid. A magnetic field is applied to the fluid and this region is called zone II. The flow in the porous region is governed by the Brinkman's equation

$$\mu\left[\nabla^2 V_2 - \frac{\mu}{k} V_2 - \sigma B_0^2 V_2\right] = 0 \tag{2}$$

where $V_2 = V_2^* / a\Omega$, $k > 0$ is the permeability of the porous region. $y = r / a$ is used to transform the above physical quantities. Hence the governing equation in the free flow region is

$$\frac{d^2 V_1}{dy^2} + \frac{1}{y}\frac{dV_1}{dy} - \left(\frac{1}{y^2} + \delta^2\right)V_1 = 0 \tag{3}$$

where $\delta^2 = (aM)^2$ and $M^2 = \frac{\sigma B_0^2}{\mu}$

The solution of this equation is

$$V_1 = A_1 I_1(\delta y) + A_2 K_1(\delta y) \tag{4}$$

where I_1 and K_1 are modified Bessel functions of first and second kind respectively and of order one and A_1 and A_2 are constants.

In the porous region the governing equation is

$$\frac{d^2 V_2}{dy^2} + \frac{1}{y}\frac{dV_2}{dy} - \left(\frac{1}{y^2} + \xi^2\right)V_2 = 0 \tag{5}$$

where $\xi^2 = (\sigma\gamma)^2$, $\sigma^2 = \frac{a^2}{k}$ and $\gamma^2 = 1 + M^2 k$

The general solution of this equation is

$$V_2 = B_1 I_1(\xi y) + B_2 K_1(\xi y) \tag{6}$$

where B_1 and B_2 are constants.

3. Boundary conditions:

Ochoa-Tapia and Whitaker suggested the condition at the interface of the fluid, when the porous medium is governed by Brinkman's equation.

i)Continuity of the velocity components on $y = \lambda_1$

$$V_1(\lambda_1) = V_2(\lambda_1) = U \tag{7}$$

ii)Tangential stress on $y = \lambda_1$

$$\tau_{r\theta_1} - \tau_{r\theta_2} = \frac{\mu}{\sqrt{k}} \alpha V_1 \tag{8}$$

where $\tau_{r\theta}$ is the shearing stress on the interface $y = \lambda_1$ and α is a dimensionless constant depending upon the surface of the porous material. Equation (8) can also be written as

$$\frac{\partial V_1}{\partial y} - \frac{\partial V_2}{\partial y} = \alpha \sigma V_1 \text{ at } y = \lambda_1 \tag{9}$$

The boundary conditions of the problem are

i) $V_1 = 1$ at $y = 1$ (10)

ii)Condition at infinity: $V_2 = \infty$ as $y \to \infty$ (11)

4. Method of solution:

To solve the flow inside the porous region and the clear fluid region, we consider the solution of the equations (3) and (4) which satisfies the boundary conditions (10) and (11) with the matching condition (7) and (9) at the interface $y = \lambda_1$.

At $y = \lambda_1$,

$$V_1 = A_1 I_1(\delta y) + \left(\frac{1 - A_1 I_1(\delta)}{K_1(\delta)} \right) K_1(\delta y) \tag{12}$$

$$V_2 = B_2 K_1(\xi y) \tag{13}$$

where A_1 and B_2 are calculated by using the matching conditions at the interface $y = \lambda_1$

$$A_1=\left\{\frac{-\xi K_1(\delta\lambda_1)K_0(\xi\lambda_1)+K_1(\xi\lambda_1)\left(\alpha\sigma K_1(\delta\lambda_1)+\delta K_0(\delta\lambda_1)\right)}{\delta K_1(\xi\lambda_1)\left(I_0(\delta\lambda_1)K_1(\delta)+K_0(\delta\lambda_1)I_1(\delta)\right)+\left(I_1(\delta)K_1(\delta\lambda_1)-I_1(\delta\lambda_1)K_1(\delta)\right)\left(\alpha\sigma K_1(\xi\lambda_1)-\xi K_0(\xi\lambda_1)\right)}\right\}$$

(14)

$$B_2=\left\{\frac{A_1\left(I_1(\delta\lambda_1)K_1(\delta)-K_1(\delta\lambda_1)I_1(\delta)\right)+K_1(\delta\lambda_1)}{K_1(\xi\lambda_1)K_1(\delta)}\right\} \tag{15}$$

The values of the constants A_1 and B_2 are calculated for different values of σ,α and M by taking $\lambda_1=2$. The values of A_1 and B_2 are given in table I.

5. Bounded porous medium:

When the porous medium is bounded by an impervious concentric circular cylinder of radius $\lambda_2 a$, $(\lambda_2>\lambda_1)$ the boundary conditions of the problem are

i) $V_1=1$ at $y=1$ (16)

ii) $V_2=0$ at $y=\lambda_2$ (17)

The solutions of the equations (3) and (5) satisfying the boundary conditions (16) and (17) are

$$V_1=\frac{A_1}{K_1(\delta)}\left(I_1(\delta y)K_1(\delta)-I_1(\delta)K_1(\delta y)\right)+\left(\frac{K_1(\delta y)}{K_1(\delta)}\right) \tag{18}$$

$$V_2=\frac{B_1}{K_1(\xi\lambda_2)}\left(I_1(\xi y)K_1(\xi\lambda_2)-I_1(\xi\lambda_2)K_1(\xi y)\right) \tag{19}$$

Let $C=\dfrac{A_1}{K_1(\delta)}$ and $D=\dfrac{B_1}{K_1(\xi\lambda_2)}$

Using C and D equations (18) and (19) are given by

$$V_1=C\left(I_1(\delta y)K_1(\delta)-I_1(\delta)K_1(\delta y)\right)+\left(\frac{K_1(\delta y)}{K_1(\delta)}\right) \tag{20}$$

$$V_2=D\left(I_1(\xi y)K_1(\xi\lambda_2)-I_1(\xi\lambda_2)K_1(\xi y)\right) \tag{21}$$

where C and D are constants to be determined by using the matching conditions (7) and (8) at the interface.

$$C=\left\{\frac{D\left(I_1(\xi\lambda_1)K_1(\xi\lambda_2)-I_1(\xi\lambda_2)K_1(\xi\lambda_1)\right)-K_1(\delta\lambda_1)/K_1(\delta)}{\left(I_1(\delta\lambda_1)K_1(\delta)-I_1(\delta)K_1(\delta\lambda_1)\right)}\right\} \tag{22}$$

$$D = \frac{\delta\lambda_1\left(I_0(\delta\lambda_1)K_1(\delta\lambda_1) + I_1(\delta\lambda_1)K_0(\delta\lambda_1)\right)}{D_1} \tag{23}$$

$$\begin{aligned} D_1 = \{ & \left(I_1(\xi\lambda_1)K_1(\xi\lambda_2) - I_1(\xi\lambda_2)K_1(\xi\lambda_1)\right)[2I_1(\delta)K_1(\delta\lambda_1) + \delta\lambda_1(I_0(\delta\lambda_1)K_1(\delta) + I_1(\delta)K_0(\delta\lambda_1)) \\ & + \alpha\sigma\lambda_1(I_1(\delta)K_1(\delta\lambda_1) - I_1(\delta\lambda_1)K_1(\delta)] + \xi\lambda_1\left(I_1(\xi\lambda_2)K_0(\xi\lambda_1) - I_0(\xi\lambda_1)K_1(\xi\lambda_2)\right) \\ & (I_1(\delta\lambda_1)K_1(\delta) - I_1(\delta)K_1(\delta\lambda_1))\} \end{aligned}$$

The values of the constants C and D are given in table II.

6. Outer cylinder rotates and inner cylinder is stationary:

An impervious solid infinite circular cylinder is surrounded by a porous medium in the region $a \le r \le \lambda_1 a$ is called zone I and an arbitrary electrically conducting viscous fluid flows past this porous region. In this region the flow is governed by Brinkman equation. Viscous fluid in the outer impervious concentric circular cylinder in the region $\lambda_1 a \le r \le \lambda_2 a$ is called zone II. The flow in zone II is governed by Navier-Stokes equation. The outer cylinder with radius $r = \lambda_2 a$ rotates with a constant angular velocity Ω and the inner cylinder $r = a$ is at rest. This system acts as a viscometer using which the angular velocity of the outer cylinder and the torque on the inner cylinder are calculated.

In this case the boundary conditions are

$$V_1 = 0 \quad \text{at} \quad y = 1 \tag{24}$$

$$V_2 = 1 \quad \text{at} \quad y = \lambda_2 \tag{25}$$

The solutions of the equations (3) and (5) satisfying the boundary conditions (24) and (25) are

$$V_1 = \frac{A_1}{K_1(\delta)}\left(I_1(\delta y)K_1(\delta) - I_1(\delta)K_1(\delta y)\right) \tag{26}$$

$$V_2 = \frac{B_1}{K_1(\xi\lambda_2)}\left(I_1(\xi y)K_1(\xi\lambda_2) - I_1(\xi\lambda_2)K_1(\xi y)\right) + \frac{K_1(\xi y)}{K_1(\xi\lambda_2)} \tag{27}$$

Let $E = \frac{A_1}{K_1(\delta)}$ and $F = \frac{B_1}{K_1(\xi\lambda_2)}$

Using E and F equations (26) and (27) become

$$V_1 = E\left(I_1(\delta y)K_1(\delta) - I_1(\delta)K_1(\delta y)\right) \tag{28}$$

$$V_2 = F\left(I_1(\xi y)K_1(\xi\lambda_2) - I_1(\xi\lambda_2)K_1(\xi y)\right) + \frac{K_1(\xi y)}{K_1(\xi\lambda_2)} \tag{29}$$

where E and F are constants to be determined by using the matching conditions (7) and (8) at the interface

$$E = \left[\frac{F\left(I_1(\xi\lambda_1)K_1(\xi\lambda_2) - I_1(\xi\lambda_2)K_1(\xi\lambda_1)\right) + \dfrac{K_1(\xi\lambda_1)}{K_1(\xi\lambda_2)}}{\left(I_1(\delta\lambda_1)K_1(\delta) - I_1(\delta)K_1(\delta\lambda_1)\right)} \right] \tag{30}$$

$$F = \left[\frac{K_1(\xi\lambda_1)\left(\delta\lambda_1 I_0(\delta\lambda_1)K_1(\delta) + I_1(\delta)K_0(\delta\lambda_1)\right) + \left(I_1(\delta)K_1(\delta\lambda_1) - I_1(\delta\lambda_1)K_1(\delta)\right)\left(\alpha\sigma\lambda_1 K_1(\xi\lambda_1) - \xi\lambda_1 K_0(\xi\lambda_1)\right)}{K_1(\xi\lambda_2)D_2} \right] \tag{31}$$

where

$$D_2 = \{\left(\delta\lambda_1 K_1(\delta)I_0(\delta\lambda_1) + K_0(\delta\lambda_1)I_1(\delta)\right)\left(I_1(\xi\lambda_1)K_1(\xi\lambda_2) - I_1(\xi\lambda_2)K_1(\xi\lambda_1)\right) + (\alpha\sigma\lambda_1 + 2)$$
$$\left(I_1(\delta)K_1(\delta\lambda_1) - I_1(\delta\lambda_1)K_1(\delta)\right)\left(I_1(\xi\lambda_1)K_1(\xi\lambda_2) - I_1(\xi\lambda_2)K_1(\xi\lambda_1)\right) + \xi\lambda_1(I_1(\delta\lambda_1)K_1(\delta) -$$
$$I_1(\delta)K_1(\delta\lambda_1))\left(K_1(\xi\lambda_2)I_0(\xi\lambda_1) + I_1(\xi\lambda_1)K_0(\xi\lambda_1)\right)\}$$

The values of the constants E and F are given in table III for different values of σ and α by considering $\lambda_1 = 1.2$ and $\lambda_2 = 1.4$.

7. Results and Conclusion:

Fig.1 represents the variation of the fluid velocity with slip coefficient for different values of magnetic induction $(M = 1.5, 2, 2.5, 3)$ at constant σ and λ_1. The fluid velocity increases gradually with increase in slip coefficient. This velocity-slip coefficient curve lies higher for lower magnetic induction and vice versa. In fig.2, the variation of the velocity with slip coefficient for different values of $\lambda_1, (\lambda_1 = 2, 2.2, 2.4, 2.6)$ at constant magnetic induction (M) and Darcy number (σ) is shown. The fluid velocity increases gradually with increase in slip coefficient as seen in the previous case with the curve lying higher for lower λ_1 and vice versa. The variation of velocity against slip coefficient for different values of Darcy number $(\sigma = 3, 4, 5, 6)$ has been plotted in fig.3. Velocity increases as the slip coefficient increases due to the effect of magnetic field with the velocity dipping for increasing Darcy number.

In the case of a bounded porous medium, the variation of fluid velocity with slip coefficient for varying magnetic fluid $(M = 3, 4, 5, 6)$ is shown in fig.4 where σ and λ_1 are maintained constant. Here the velocity increases exponentially with increase in slip coefficient with the curve lying higher for lower magnetic field and vice versa. In fig.5, the variation of velocity with λ_1 is shown for constant σ, but for a varying magnetic field $(M = 3, 4, 5, 6)$. The velocity decreases with increase in radius of the cylinder λ_1 however there is a slight increment before this decline for higher values of M. While analysing the slip coefficient (α), it is observed from fig.6 that the velocity decreases as λ_1 increases and the rate of decrement of velocity depends on the slip coefficient (α). For negative slip coefficient $(\alpha = -0.1, -0.2, -0.3, -0.4)$ the velocity again decreases with increasing λ_1 due to the effect of magnetic field.

When the inner cylinder is stationary and the outer cylinder rotates, the velocity-slip coefficient graph is plotted for different values of Darcy number $(\sigma = 3,4,5,6)$ as in fig.7. This graph shows that the velocity increases for increasing Darcy number but the variation of velocity with respect to slip coefficient is very small. In fig.8, the graph of velocity against the distance from the inner cylinder (λ_1), when it is stationary, has been drawn. The velocity decreases for different values of M $(M = 2,3,4,5)$. The variation of velocity with the distance from the inner cylinder λ_1 for different Darcy number $(\sigma = 2,3,4,5)$ is plotted in figure 9. The velocity decreases for increasing radius of the inner cylinder (λ_1) and but it increases for increasing Darcy number (σ). Figure 10 shows the variation of velocity against the radius of the inner cylinder (λ_1) when it is stationary for different values of slip coefficient $(\alpha = 0.1,0.2,0.3,0.4)$. The velocity decreases for increasing radius and the varying slip-coefficient (α) does not affect the velocity graph.

The magneto hydrodynamic flow past a rotating circular cylinder with Navier-Stokes equation in the free flow region and Brinkman equation in the porous region was discussed. The flow through a porous medium of infinite extent and that bounded by a concentric cylinder where the outer cylinder rotates and the inner cylinder is stationary are also discussed. The values of the constants in the velocity flow field are tabulated for different Darcy numbers. In the case of a magnetic flow through the circular cylinder, the velocity increases for varying values of magnetic field, Darcy number and the radius of the cylinder. For a bounded porous medium the velocity increases with increase in magnetic field. If the outer cylinder rotates and the inner one remains stationary, the velocity decreases for varying magnetic field, Darcy number and the slip coefficient. A significant effect is obtained for the magneto hydrodynamic flow past a circular cylinder.

Table I

α	$\sigma = 2$			$\sigma = 3$			$\sigma = 4$		
	A_1	B_2	U	A_1	B_2	U	A_1	B_2	U
-0.5	-0.0021	9.429	0.0689	-0.0044	508.0	0.0471	-0.0049	1461.49	0.0416
-0.4	-0.0018	9.7918	0.0715	-0.0042	528.717	0.0489	-0.0048	15299	0.0435
-0.3	-0.0015	10.1837	0.0744	-0.0039	550.477	0.0509	-0.0045	1605.04	0.0456
-0.2	-0.0012	10.6083	0.0775	-0.0038	574.106	0.0532	-0.0043	1687.94	0.0479
-0.1	-0.0009	11.0698	0.0809	-0.0035	599.854	0.0556	-0.0040	1779.88	0.0506
0	-0.0005	11.5733	0.0845	-0.0032	628.02	0.0582	-0.0037	1882.4	0.0535
0.1	-0.0001	12.1247	0.0886	-0.0029	658.961	0.0610	-0.0034	1997.45	0.0568
0.2	0.0004	12.7314	0.0929	-0.0026	693.109	0.0642	-0.0029	2127.48	0.0605
0.3	0.0009	13.4019	0.0979	-0.0022	730.99	0.0678	-0.0026	2275.63	0.0647
0.4	0.0015	14.147	0.1033	-0.0018	773.25	0.0716	-0.0020	2445.95	0.0695
0.5	0.0021	14.9798	0.1094	-0.0014	820.697	0.0760	-0.0015	2643.82	0.0752

Table II

α	$\sigma=2$										
	-0.5	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5
C	0.6581	0.7803	0.9291	1.1142	1.3507	1.6637	2.0972	2.7375	3.7791	5.7710	11.106
D	-0.556	-0.611	-0.677	-0.759	-0.865	-1.005	-1.199	-1.485	-1.949	-2.839	-5.222
U	0.6089	0.6687	0.7415	0.8320	0.9477	1.1008	1.3138	1.6259	2.1353	3.1095	5.7185

Table III

α	$\sigma=2$			$\sigma=3$			$\sigma=4$		
	E	F	U	E	F	U	E	F	U
-0.5	9.0238	0.5374	1.6289	13.5184	0.0369	2.5397	15.1026	0.0195	2.8403
-0.4	9.0289	0.5052	1.6341	13.5189	0.0341	2.5402	15.1029	0.0176	2.8406
-0.3	9.0338	0.4753	1.6389	13.5194	0.0316	2.5406	15.1032	0.0159	2.8409
-0.2	9.0382	0.4474	1.6434	13.5198	0.0293	2.541	15.1035	0.0144	2.8412
-0.1	9.0424	0.04212	1.6476	13.5201	0.0272	2.5414	15.1037	0.0131	2.8414
0	9.0464	0.3967	1.6515	13.5205	0.0252	2.5417	15.1039	0.0119	2.8416
0.1	9.0500	0.3736	1.6552	13.5208	0.0234	2.5420	15.1041	0.0108	2.8418
0.2	9.0535	0.3519	1.6587	13.5211	0.0218	2.5423	15.1043	0.0099	2.8419
0.3	9.0568	0.3314	1.6619	13.5213	0.0202	2.5426	15.1044	0.0089	2.8422
0.4	9.0599	0.3121	1.6650	13.5216	0.0188	2.5428	14.1046	0.0082	2.8423
0.5	9.0628	0.2938	1.6679	13.5218	0.0174	2.5431	15.1047	0.0075	2.8424

Figures

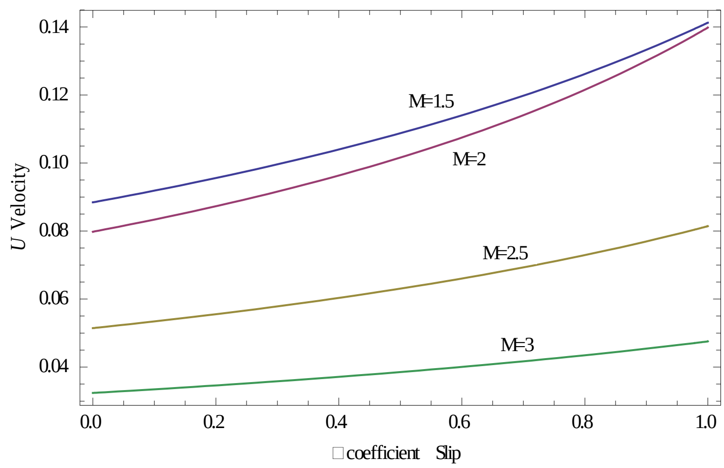

Fig.1. Variation of velocity with slip coefficient for different magnetic field $(M=1.5,2,2.5,3)$, $\sigma=2$ and $\lambda_1=2$.

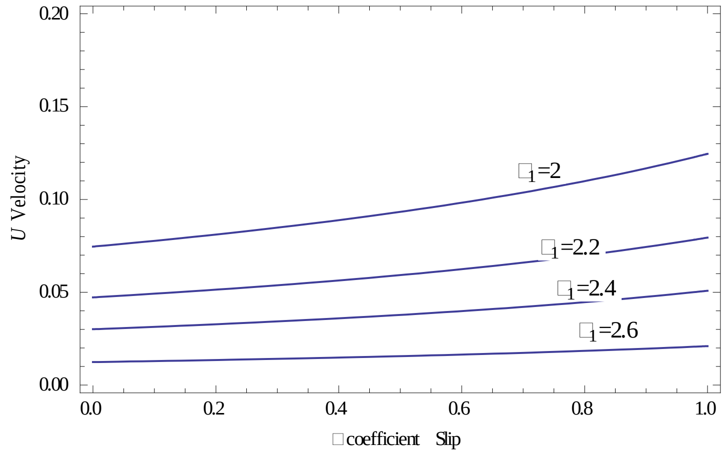

Fig.2. Variation of velocity with slip coefficient for different radius of the cylinder $(\lambda_1 = 2, 2.2, 2.4, 2.6)$, $\sigma = 2$ and $M = 2$.

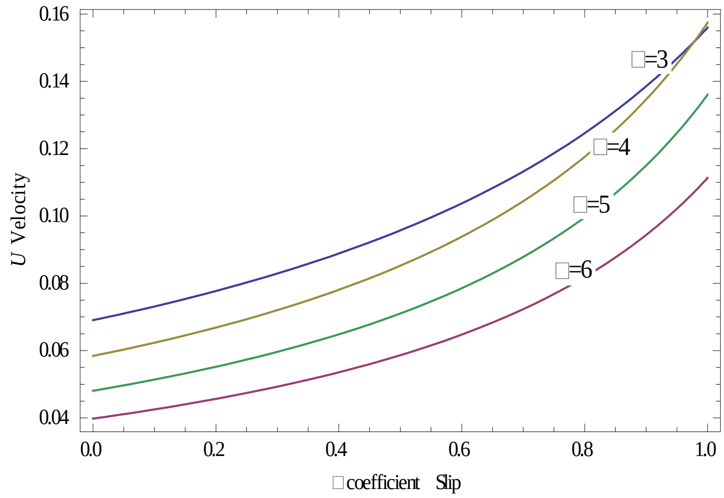

Fig.3. Variation of velocity with slip coefficient for different Darcy number $(\sigma = 3, 4, 5, 6)$, $M = 2$ and $\lambda_1 = 2$.

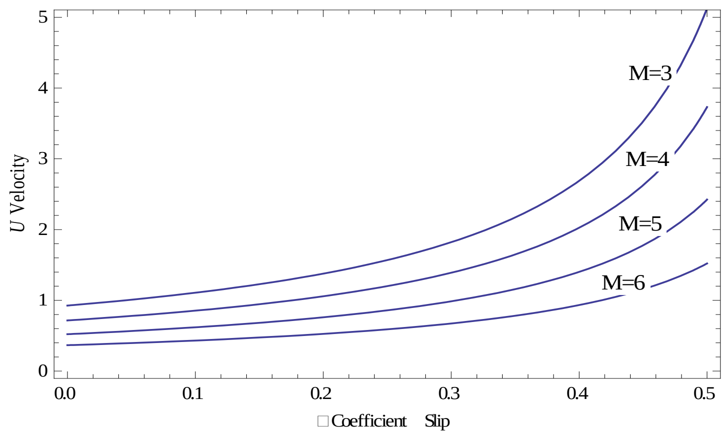

Fig.4. Variation of velocity with slip coefficient for different magnetic field $(M = 3, 4, 5, 6)$, $\lambda_1 = 1.5$, $\lambda_2 = 2.5$ and $\sigma = 2$ in the case of bounded porous medium.

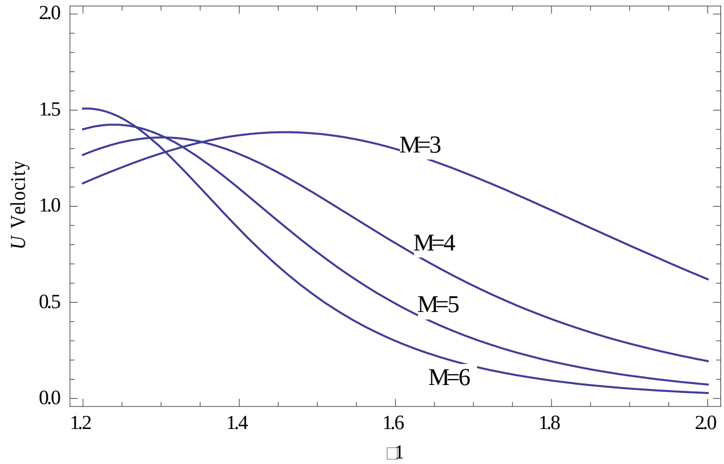

Fig.5. Variation of velocity with radius of inner cylinder for different magnetic field $(M = 3,4,5,6)$, $\alpha = 0.2$, $\lambda_2 = 2.5$ and $\sigma = 2$ in the case of bounded porous medium.

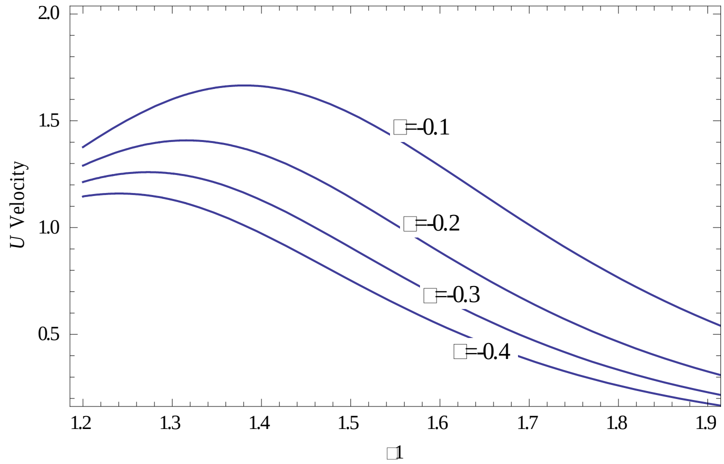

Fig.6. Variation of velocity with radius of inner cylinder for different slip coefficient $(\alpha = -0.1,-0.2,-0.3,-0.4)$, $M = 4$, $\lambda_2 = 2.5$ and $\sigma = 2$ in the case of bounded porous medium.

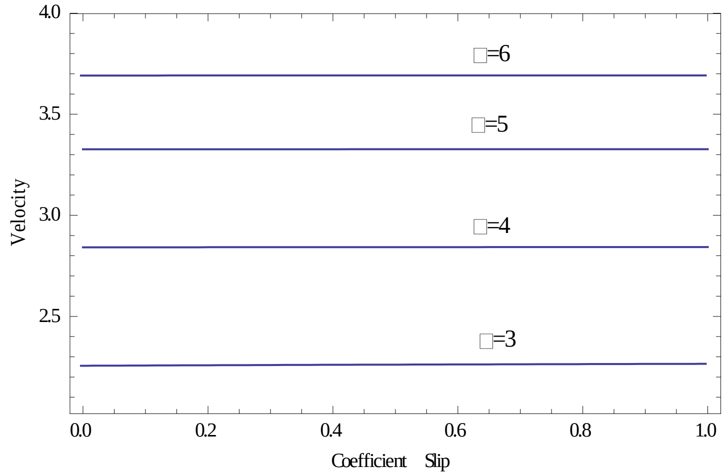

Fig.7. Variation of velocity with slip coefficient for different Darcy number $(\sigma = 3,4,5,6)$, $\lambda_1 = 1.2$, $\lambda_2 = 1.4$ and $M = 2$ in the case of inner cylinder is stationary and outer one is rotates.

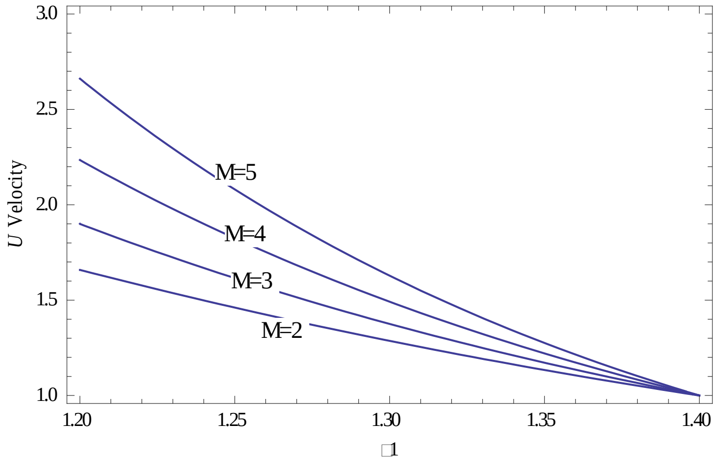

Fig.8. Variation of velocity with radius of the inner cylinder for different magnetic field $(M = 2,3,4,5)$, $\alpha = 0.2$, $\lambda_2 = 1.4$ and $\sigma = 2$ in the case of inner cylinder is stationary and outer one is rotates.

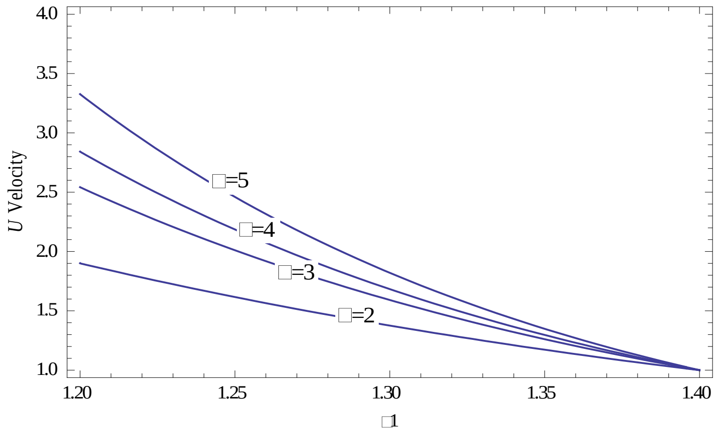

Fig.9. Variation of velocity with radius of inner cylinder for different Darcy number $(\sigma = 2,3,4,5)$, $\alpha = 0.2$, $\lambda_2 = 1.4$ and $M = 2$ in the case of inner cylinder is stationary and outer one is rotates.

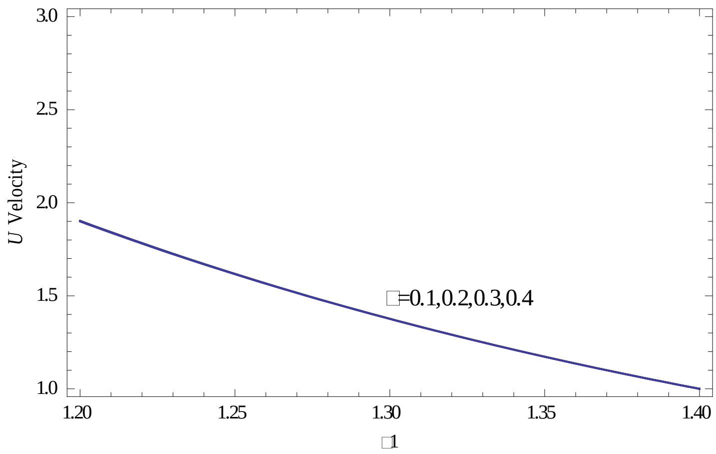

Fig.10. Variation of velocity with radius of inner cylinder for different slip coefficient $(\alpha = 0.1,0.2,0.3,0.4)$, $\sigma = 2$, $\lambda_2 = 1.4$ and $M = 2$ in the case of inner cylinder is stationary and outer one is rotates.

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