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STEADY MHD FLOW OF MICROPOLAR FLUID BETWEEN TWO ROTATING CYLINDERS WITH POROUS LINING

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ABSTRACT: The steady flow of an electrically conducting, incompressible micropolar fluid in a narrow gap between two concentric rotating vertical cylinders, with porous lining on inside of outer cylinder, under an imposed axial magnetic field is studied. Beavers and Joseph slip condition is taken at the porous lining boundary. The velocity profiles, coefficient of skin friction on the cylinders are calculated. The effects of Hartmann number, the porous lining thickness parameter, coupling number, couple stress parameters and Reynolds number on azimuthal velocity, micro-rotation component and coefficient of skin friction on cylinders are depicted through graphs.
KEYWORDS: Micropolar fluid; Magnetic field; porous lining; Skin friction; Angular velocity; micro-rotation vector

INTRODUCTION

Micropolar fluids are fluids with microstructures. They belong to a class of fluids with a non-symmetric stress tensor. Micropolar fluids consist of rigid, randomly oriented spherical particles with their own spins and micro-rotations, suspended in a viscous medium. The concept of micro-rotation was proposed by Cosserat and Cosserat in the theory of elasticity [1]. In the middle of the 1960s, Condiff and Dahler [2] and Eringen [3] applied the concept to describe fluids with microstructures. Recently, a comprehensive text book on micropolar fluids has been published [4]. Physical examples of micropolar fluids can be seen in ferrofluids [5], blood flows [6, 7], bubbly liquids [8], liquid crystals [9], and so on, all of them containing intrinsic polarities. Thus, micropolar fluid mechanics is not a useless generalization of the Navier-Stokes model, but is a physically relevant model that has many applications.

Flows through and past porous media with finite thickness are of relevance in many industrial applications like lubrication and tapping of solar energy. The control of shearing stress is important in the design of rotating machinery like totally enclosed fan cooled motors and lubrication industry in which centrifugal force plays a major role.

Channabasappa et al [10] have examined the effect of porous lining thickness on velocity vector and shear stresses at the wall of inner and outer cylinders for the flow between two rotating cylinders. Sai [11] has studied the steady motion of an electrically conducting, incompressible viscous liquid in a narrow gap between two concentric rotating vertical cylinders in presence of an imposed magnetic field and he has presented the velocity profiles graphically. Bathaiah et al [12] have studied the viscous incompressible, slightly conducting fluid flow between two concentric rotating cylinders with non-erodable and non conducting porous lining on the inner wall of the outer cylinder under the influence of radial magnetic field of the form given in Hughes and Young and they have shown the effect of magnetic parameter, porous lining thickness, the ratio of the velocities of the cylinders, the slip parameter on velocity and temperature distributions graphically. Beavers and Joseph [13] studied the flow of a viscous fluid in a channel bounded below by a naturally permeable wall. Ramamurthy [14] have obtained the velocity distribution and magnetic field for a viscous incompressible conducting fluid between two coaxial rotating cylinders under the influence of radial magnetic field. Singh et al [15] have investigated the impulsive motion of a viscous liquid contained between two concentric circular cylinders in the presence of radial magnetic field. Mahapatra [16] studied the unsteady motion of an incompressible viscous conducting liquid between two porous concentric circular cylinders in presence of a radial magnetic field. Subotic et al [17] have obtained the analytical solutions for the flow and temperature fields in an annulus with a porous sleeve between two rotating cylinders and they studied the effects of Darcy number, Brinkman number and porous sleeve thickness on the velocity profile and temperature distribution. Ranganna et al [18] have studied the stability analysis of laminar flow between two long concentric circular rotating cylinders with non-erodible porous lining on the outer wall of the inner cylinder and he has shown the effect of porous lining thickness on critical Taylor *number graphically. Kamel [19] has studied the creeping motion of a polar fluid in the annular region between the two eccentric rotating cylinders. He depicted the dependence of the velocity components and the spin on the coupling number and the length ratio graphically. Meena et al [20] have studied the flow of a viscous incompressible fluid between two eccentric rotating porous cylinders with small suction/injection at both the cylinders and they have presented stream lines and pressure plots graphically. Borkakati et al [21] have examined the steady flow of an incompressible electrically conducting fluid between two coaxial cylinders in presence of radial magnetic field and they plotted graphically the heat transfer rate from the cylinders against the Hartmann number.*

Srinivasacharya et al [22] have studied the steady flow of incompressible and electrically conducting micropolar fluid flow between two concentric porous cylinders and they have presented the profiles of velocity and micro-rotation components for different micropolar fluid parameters and magnetic parameter. Pontrelli et al [23] studied the steady flow of an Oldroyd-B fluid between two porous concentric circular cylinders. They found velocity by numerically solving a system of nonlinear ODEs obtained from the equation of motion and constitutive equations and the effects of non-Newtonian parameters on velocity and on shear stress are shown through graphs.

Fetecau et al [24] studied the velocity fields corresponding to the motion of an incompressible second grade fluid due to longitudinal and torsional oscillations of an infinite circular cylinder.

In this paper, we study the steady incompressible electrically conducting micropolar fluid flow between two concentric rotating cylinders with porous lining in the presence of an axial magnetic field.

FORMULATION AND SOLUTION OF THE PROBLEM

Consider an incompressible micropolar fluid between two concentric circular cylinders of radii a and b (a<b). The inner and outer cylinders are rotating with constant angular velocities Ω_1 and Ω_2 respectively.

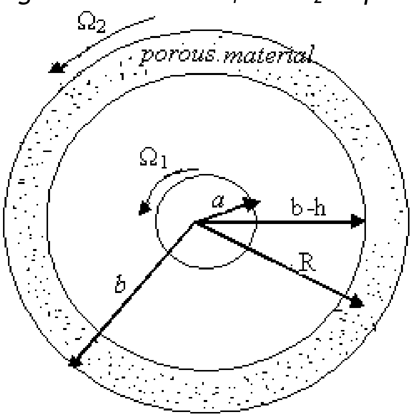

Figure 1. A section of the flow configuration

There is a non-erodible porous lining of thickness h on the inside of the outer cylinder. The flow is generated due to the rotation of these cylinders. The flow is subject to a constant magnetic field B_0 along the axis of the cylinders and no external electric field is applied. We assume that the induced magnetic field is much smaller than the externally applied magnetic field. Assume that the magnetic Reynolds number is very small, so that induced magnetic field and electric field produced by the motion of the electrically conducting fluid are negligible. The physical model of the problem is shown in Figure 1.

Choose the cylindrical polar coordinate system (R,θ, Z) with origin at the centre of the cylinder and Z axis along the axis of the cylinder and with (e_r, e_θ, e_z) as unit base vectors. Neglecting body forces and body couples, the field equations governing the micropolar fluid dynamics are:

$$\nabla_1 \cdot Q = 0 \qquad (1)$$

$$\rho Q.\nabla_1 Q = -\nabla_1 P + \kappa \nabla_1 \times l - (\mu+\kappa)\nabla_1 \times \nabla_1 \times Q + J \times B \qquad (2)$$

$$\rho j Q.\nabla_1 l = -2\kappa l + \kappa \nabla_1 \times Q - \gamma \nabla_1 \times \nabla_1 \times l + (\alpha+\beta+\gamma)\nabla_1(\nabla_1 \cdot l) \qquad (3)$$

where Q is velocity vector, l is micro rotation vector, P is the fluid pressure, ρ and j are the fluid density and micro-gyration parameter, and {μ, κ}and {α, β, γ}are viscosity and gyro viscosity coefficients. The current density J, magnetic field B and electric field E are related by Maxwell's equations

$$\nabla_1 \times E = \frac{\partial B}{\partial t}, \ \nabla_1 \cdot B = 0, \ \nabla_1 \times B = \mu' J, \ \ \nabla_1 \cdot J = 0$$

and $J = \sigma_e (E + Q \times B)$

where ∇_1 is the dimensional gradient, σ_e is electrical conductivity and μ' is the magnetic permeability. By nature of the flow, the velocity and micro-rotation components are axially symmetric and depend only on radial distance. Hence we assume that the velocity, micro-rotation vectors and the magnetic field are of the form

$$Q = V(r)\, e_\theta,\ l = C(r)\, e_z,\ B = B_0\, e_z \qquad (4)$$

Hence J×B simplifies to $J \times B = -\sigma_e B_0^2 Q$.

We introduce the following non-dimensional scheme

$$q = \frac{Q}{b\Omega_2},\ r = \frac{R}{b},\ \upsilon = \frac{l}{\Omega_2},\ p = \frac{P}{\rho b^2 \Omega_2^2},\ v = \frac{V}{b\Omega_2},$$

$$C = \frac{C}{\Omega_2}\quad r_0 = \frac{a}{b},\ \lambda = \frac{\Omega_1}{\Omega_2},$$

$$v_B = \frac{V_B}{b\Omega_2},\ e = \frac{h}{b},\ \sigma = \frac{b}{\sqrt{K}} \qquad (5)$$

Using (5) in (2) and (3) we get the equations for the flow in the following form

$$Re\, q.\nabla q = -Re \nabla p + c\,\nabla \times \upsilon - \nabla \times \nabla \times q - M^2 q \qquad (6)$$

$$\varepsilon\, q.\nabla \upsilon = -2s\,\upsilon + s\,\nabla \times q - \nabla \times \nabla \times \upsilon + \frac{1}{\delta}\nabla(\nabla \cdot \upsilon) \qquad (7)$$

where the non-dimensional parameters viz. Reynolds number Re, Hartmann number M, cross viscosity parameter or coupling number c, couple stress parameters s and δ and gyration parameter ε are defined by

$$Re = \frac{\rho b^2 \Omega_2}{\mu+\kappa},\ M = \sqrt{\frac{\sigma_e B_0^2 b^2}{\mu+\kappa}},\ c = \frac{\kappa}{\mu+\kappa},\ \varepsilon = \frac{\rho j b^2 \Omega_2}{\gamma},$$

$$s = \frac{\kappa b^2}{\gamma},\quad \delta = \frac{\gamma}{\alpha+\beta+\gamma} \qquad (8)$$

The velocity and micro-rotation are choosen in the form

$$q = v(r)e_\theta \quad \text{and} \quad \upsilon = C(r)e_z \tag{9}$$

Substituting (9) in (6) and comparing the components along e_r, e_θ directions, we get

$$\frac{dp}{dr} = \frac{v^2}{r} \tag{10}$$

$$-c\frac{dC}{dr} + D^2 v - M^2 v = 0 \tag{11}$$

where $D^2 = \frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr} - \frac{1}{r^2}$

Similarly using (9) in the equation (7), the axial direction component yields the following equation for micro-rotation C.

$$-2sC + s\left(\frac{dv}{dr} + \frac{v}{r}\right) + \left(\frac{d^2C}{dr^2} + \frac{1}{r}\frac{dC}{dr}\right) = 0 \tag{12}$$

Eliminating $\frac{dC}{dr}$ value from (11) and (12) we get the following equation for v as

$$D^4 v - \left(M^2 + (2-c)s\right)D^2 v + 2sM^2 v = 0$$

This can be expressed as

$$\left(D^2 - \lambda_1^2\right)\left(D^2 - \lambda_2^2\right)v = 0 \tag{13}$$

where

$$\lambda_1^2 + \lambda_2^2 = M^2 + s(2-c) \quad \text{and} \quad \lambda_1^2\lambda_2^2 = 2sM^2$$

As q is finite between the interval $r_0 < r < r_1 = 1-e$, the solution of (13) can be written as

$$v(r) = a_1 I_1(\lambda_1 r) + a_2 K_1(\lambda_1 r) + a_3 I_1(\lambda_2 r) + a_4 K_1(\lambda_2 r) \tag{14}$$

The constants a_1, a_2, a_3 and a_4 can be found by using the no slip boundary condition on azimuthal velocity v and hyper-stick boundary condition on micro-rotation C. These conditions at the inner cylinder and at the porous lining of outer cylinder are explicitly given as below.

BOUNDARY CONDITIONS

The equations (14) is solved for the velocities v and C, and can be found by using the boundary conditions

$V = a\Omega_1$ at $R = a$

$V = V_B$ at $R = b-h$

$$l_\Gamma = \frac{1}{2}\, curl\, Q_\Gamma \quad \text{at } R=a \tag{15}$$

$l_\Gamma = 0$ at $R = b-h$

where Γ represent the boundary of inner cylinder and V_B is the slip velocity obtained by using Beavers and Joseph condition

$$\frac{dV}{dR} = \frac{\alpha}{\sqrt{K}}\left(V_B - Q_D\right) \quad at\ R = b-h \tag{16}$$

a is the slip parameter, K is the porosity of the lining material, λ is the ratio of the angular velocities of the cylinders, Q_D is the Darcy velocity in the porous lining. In equation (16), the Darcy's velocity Q_D is given by the relation

$$Q_D = R\Omega_2 + \Phi \tag{17}$$

where $\Phi = \dfrac{K}{\mu}\dfrac{\int_0^{2\pi}\int_{b-h}^{b} \rho R\,\Omega_2^2\,(Rd\theta dR)}{\int_0^{2\pi}\int_{b-h}^{b}(Rd\theta dR)}$

which on simplification is given by

$$\Phi = \frac{2K\ \Omega_2^2\,\rho}{3\mu}\left(\frac{3b^2 - 3bh + h^2}{2b-h}\right) \tag{18}$$

The expression for Φ, as given above, is the one considered by Channabasappa et al [10]. In relation (17), the two terms on RHS arise due to the rotation of the porous medium along with the outer cylinder. Using the four boundary conditions of (15) in non-dimensional form for velocity and micro-rotation components, we get the following equations

$$a_1 I_1(\lambda_1 r_0) + a_2 K_1(\lambda_1 r_0) + a_3 I_1(\lambda_2 r_0) + a_4 K_1(\lambda_2 r_0) = \lambda r_0$$

$$a_1 \Delta_1 + a_2 \Delta_2 + a_3 \Delta_3 + a_4 \Delta_4 = \Delta_5 \tag{19}$$

$$a_1 \Delta_6 + a_2 \Delta_7 + a_3 \Delta_8 + a_4 \Delta_9 = 2sc\lambda$$

$$a_1 \Delta_{10} + a_2 \Delta_{11} + a_3 \Delta_{12} + a_4 \Delta_{13} = 0$$

where: $\Delta_1 = \alpha\sigma\, I_1(m_1) - \dfrac{I_1(m_1)}{1-e} - \lambda_1 I_2(m_1)$

$$\Delta_2 = \alpha\sigma\, K_1(m_1) - \frac{K_1(m_1)}{1-e} + \lambda_1 K_2(m_1)$$

$$\Delta_3 = \alpha\sigma\, I_1(m_2) - \frac{I_1(m_2)}{1-e} - \lambda_2 I_2(m_2)$$

$$\Delta_4 = \alpha\sigma\, K_1(m_2) - \frac{K_1(m_2)}{1-e} + \lambda_2 K_2(m_2)$$

with $m_1 = \lambda_1(1-e)$ and $m_2 = \lambda_2(1-e)$

$$\Delta_5 = \frac{3\alpha\,\sigma^2(e-1)(e-2)(1-c) + 2\alpha\, Re\left(e^2 - 3e + 3\right)}{3\sigma(2-e)(1-c)}$$

$$\Delta_6 = \left(sc + \lambda_1^2 - M^2\right)\left(\frac{2I_1(\lambda_1 r_0)}{r_0} + \lambda_1 I_2(\lambda_1 r_0)\right)$$

$$\Delta_7 = \left(sc + \lambda_1^2 - M^2\right)\left(\frac{2K_1(\lambda_1 r_0)}{r_0} - \lambda_1 K_2(\lambda_1 r_0)\right)$$

$$\Delta_8 = \left(sc + \lambda_2^2 - M^2\right)\left(\frac{2I_1(\lambda_2 r_0)}{r_0} + \lambda_2 I_2(\lambda_2 r_0)\right)$$

$$\Delta_9 = \left(sc + \lambda_2^2 - M^2\right)\left(\frac{2K_1(\lambda_2 r_0)}{r_0} - \lambda_2 K_2(\lambda_2 r_0)\right)$$

$$\Delta_{10} = \left(sc + \lambda_1^2 - M^2\right)\left(\frac{2I_1(m_1)}{1-e} + \lambda_1 I_2(m_1)\right)$$

$$\Delta_{11} = \left(sc + \lambda_1^2 - M^2\right)\left(\frac{2K_1(m_1)}{1-e} - \lambda_1 K_2(m_1)\right)$$

$$\Delta_{12} = \left(sc + \lambda_2^2 - M^2\right)\left(\frac{2I_1(m_2)}{1-e} + \lambda_2 I_2(m_2)\right)$$

and $\Delta_{13} = \left(sc + \lambda_2^2 - M^2\right)\left(\dfrac{2K_1(m_2)}{1-e} - \lambda_2 K_2(m_2)\right)$

The linear systems of equations in (19) are solved numerically using Mathematica for the four constants a_1, a_2, a_3, and a_4 for various values of micropolar parameters.

SKIN FRICTION

The constitutive equation for stress tensor is given by

$$T_{ij} = -P\,\delta_{ij} + (2\mu + \kappa)\, e_{ij} + \kappa\,\varepsilon_{ijm}\left(\omega_m - l_m\right) \tag{20}$$

where **ω** is the vorticity vector, e_{ij} is shear rate tensor, δ_{ij} is the Kronecker delta and ε_{ijm} is the alternating symbol. From equation (20), we get

$$\overline{T}_{r\theta} = \frac{dv}{dr} - (1-c)\frac{v}{r} - c\,C \tag{21}$$

where $\overline{T}_{r\theta} = \dfrac{T_{r\theta}}{\Omega_2 (\mu + k)}$ is the non dimensional stress.

Hence the coefficient of skin friction on the inner and outer cylinders is given by

$$C_f = \frac{2T_{r\theta}}{\rho U^2} \text{ at R=a and R=b-h} \tag{22}$$

where U = Characteristic velocity = $b\Omega_2$

This can be written in the following non-dimensional form as

$$C_f = \frac{2\overline{T}_{r\theta}}{Re} \text{ at } r=r_0 \text{ and } r=1-e \tag{23}$$

TORQUE

The torque acting on the cylinders about the common axis of the cylinders is given by

$$\tau = (T_{r\theta} \times 2\pi R) \times R\,. \tag{24}$$

Hence the non dimensional torque on inner and outer cylinders are calculated as

$$\overline{\tau}_{in} = 2\pi r_0^2 \, \overline{T}_{r\theta}\Big|_{r = r_0}$$

and
$$\overline{\tau}_{out} = 2\pi (1-e)^2 \, \overline{T}_{r\theta}\Big|_{r=1-e} \tag{25}$$

RESULTS AND DISCUSSIONS

The velocity filed is considered along tangential (azimuthal) direction only. In fact we can start with nonzero radial velocity and come to conclude that it should vanish by considering continuity equation and the condition that there is no suction on the walls. (See Channabasappa, Umapathy and Nayak [10].)

We have investigated the effects of the Hartmann number M, the porous lining thickness parameter e, Reynolds number Re, coupling number c and couple stress parameter s on azimuthal velocity v, micro-rotation velocity C and the coefficient of skin friction at the inner and outer cylinders are numerically obtained and are depicted through Figures 2 to 19. The azimuthal velocity v and Micro-rotation velocity C are computed for different values of M and e.

Figures 2-7 shows the azimuthal velocity v and micro-rotation velocity C against distance r for different values of M at a fixed value of porous lining thickness parameter e = 0.1, 0.3, 0.4. We have observed that v decreases as e increases and C increases as e increases. Both v and C decrease as M increases. It is observed that the nature of velocity profiles v is increasing with distance where as the nature of rotation C is increasing and decreasing as M increases. But for small values of M, C is decreasing with r. When M takes large values, the values of C are near to zero. i.e rotation of the particles can be neglected.

The Figures 2, 4 and 6 of velocity v are in good agreement with the results obtained by Bathaih and Venugopal [12] and Subotic and Lai [17], when there is no applied magnetic field (the curve with M =0.0001 indicates almost no magnetic field). Figures 8 and 9 give the velocity profiles v and C for different values of c. From this it is clear that an increase in coupling parameter c increases the values of both the velocities v and C. i.e. if micro-polarity of the fluid increases, the velocity v and micro-rotation C will also increase. In Figures 10 and 11 the velocity profiles v and C plotted against Re. From this it is clear that an increase in Re increases both the velocities.

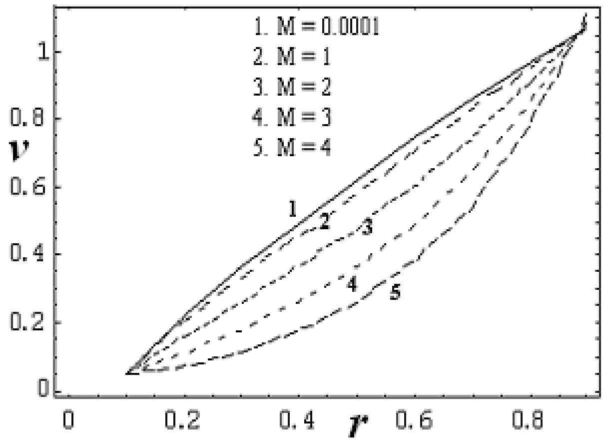

Figure 2. Variation of v with r at e = 0.1

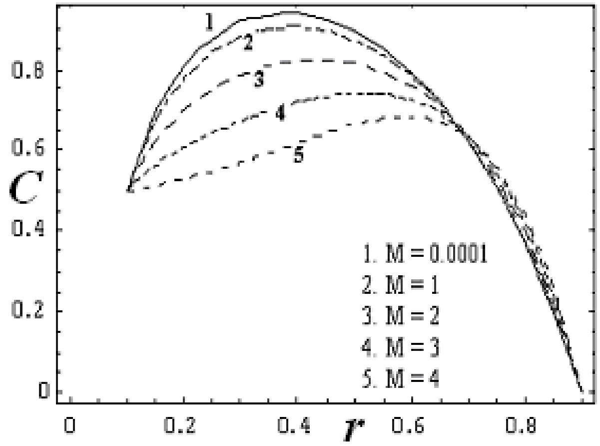

Figure 3. Variation of C with r at e = 0.1

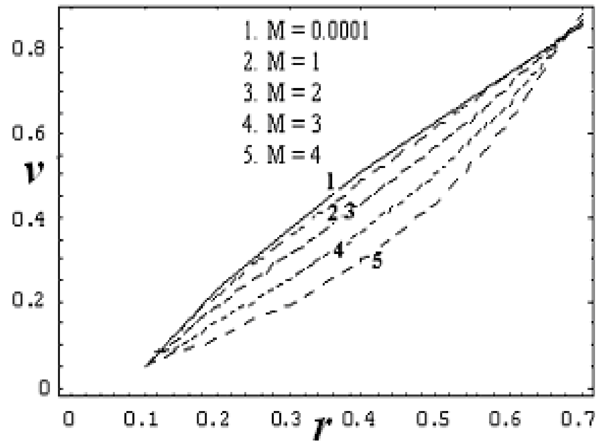

Figure 4. Variation of v with r at e = 0.3

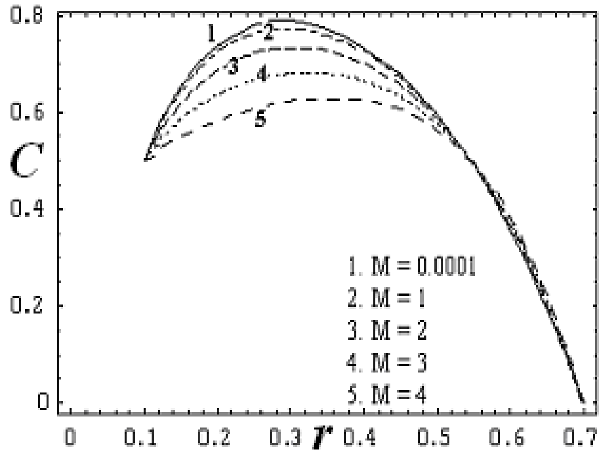

Figure 5. Variation of C with r at e = 0.3

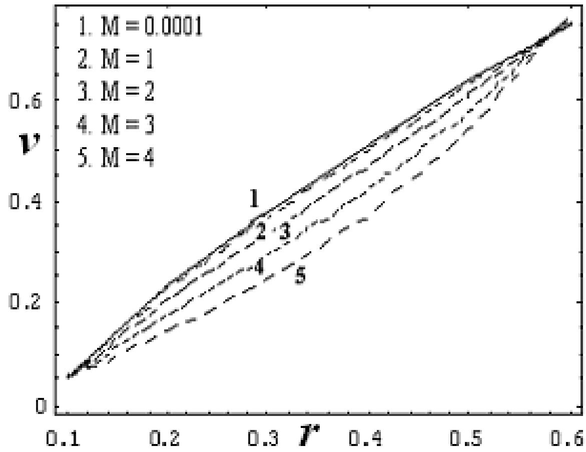

Figure 6. Variation of v with r at e = 0.4

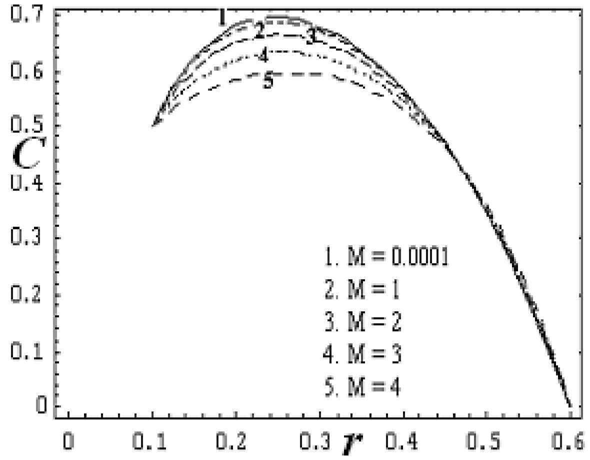

Figure 7. Variation of C with r at e = 0.4

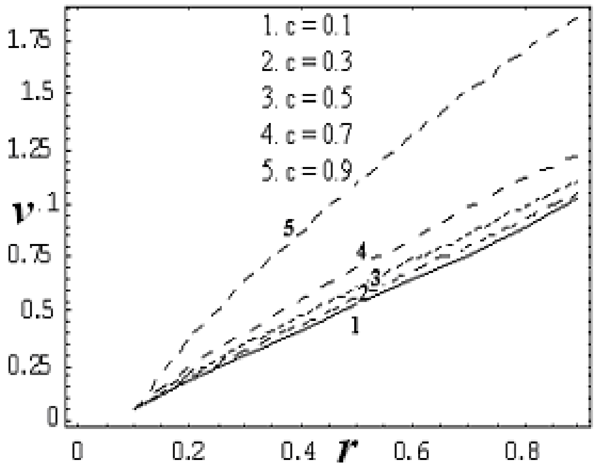

Figure 8. Variation of v with r

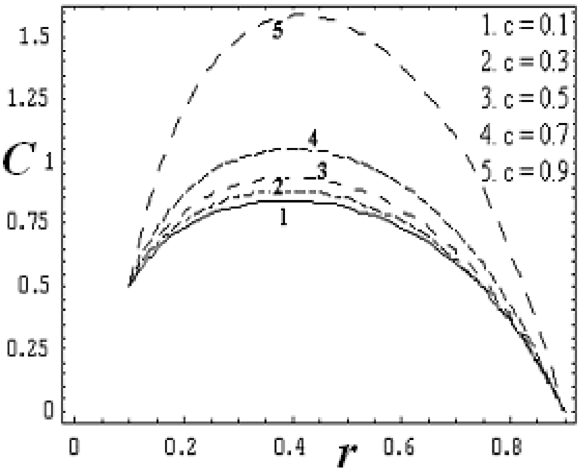

Figure 9. Variation of C with r

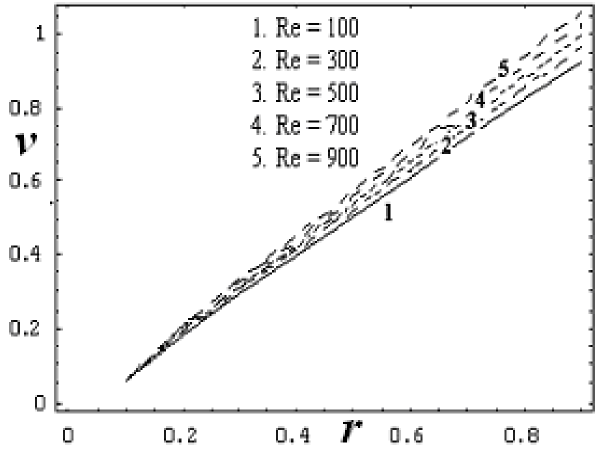

Figure 10. Variation of v with r

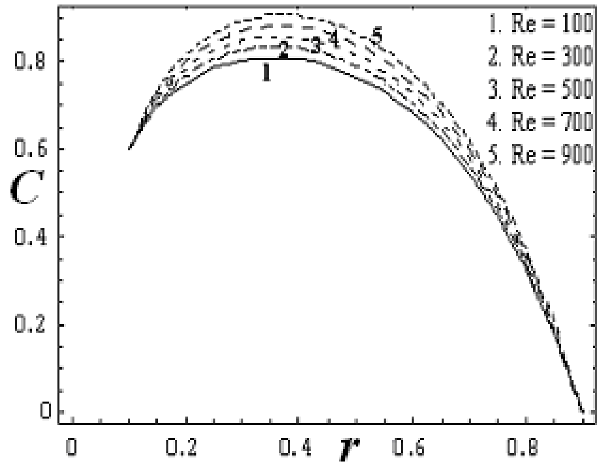

Figure 11. Variation of C with r

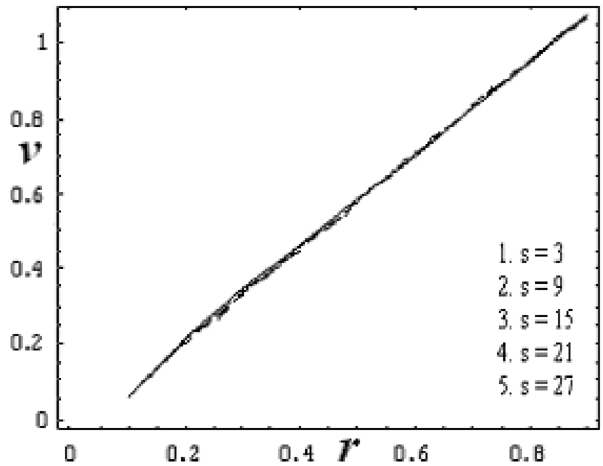

Figure 12. Variation of v with r

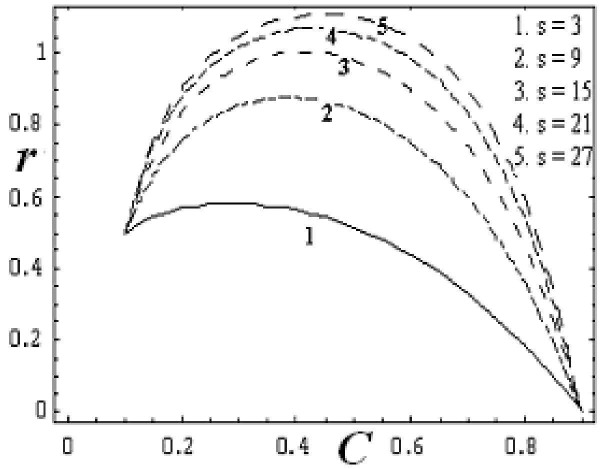

Figure 13. Variation of C with r

Figures 12-13 we have seen that as the couple stress parameter s increases both the velocities v and C are increasing. But the effect of s on the values of v is not very significant. i.e., the variation in the values of s does not result in much variation in the values v.

Figures 14–16 show the variation the coefficient of skin friction $C_f\big|_{in}$ *at the inner cylinder against c for different values of M, Re, s.*

We observe that $C_f\big|_{in}$ *decreases with increasing values of M, Re, s whereas in Figures 17–19, the skin-friction* $C_f\big|_{out}$ *at the outer cylinder increases with increasing values of M, Re, s.*

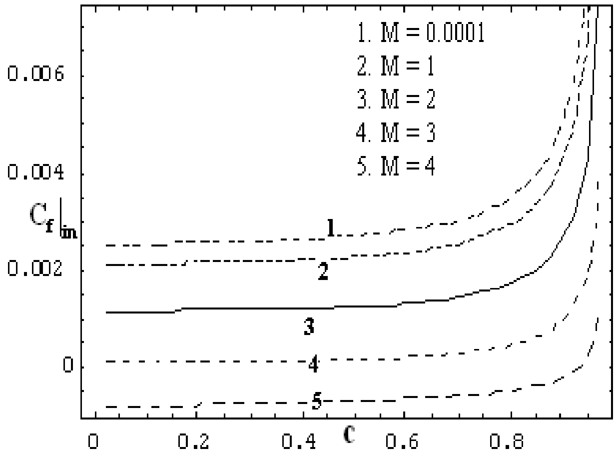

Figure 14. Variation of $C_f\big|_{in}$ *with c*

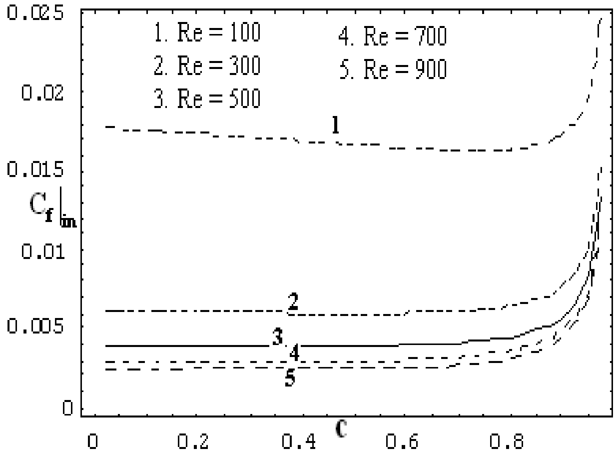

Figure 15. Variation of $C_f\big|_{in}$ *with c*

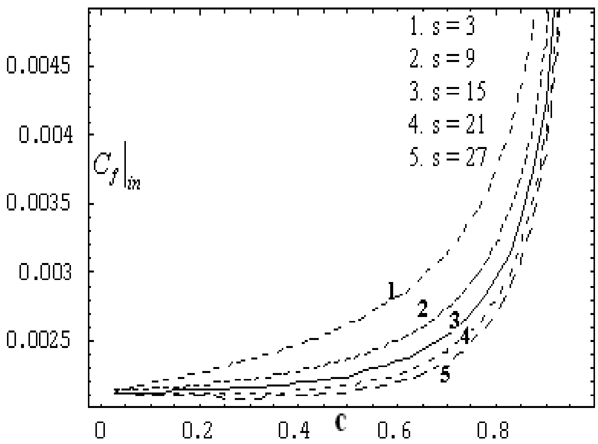

Figure 16. Variation of $C_f\big|_{in}$ *with c*

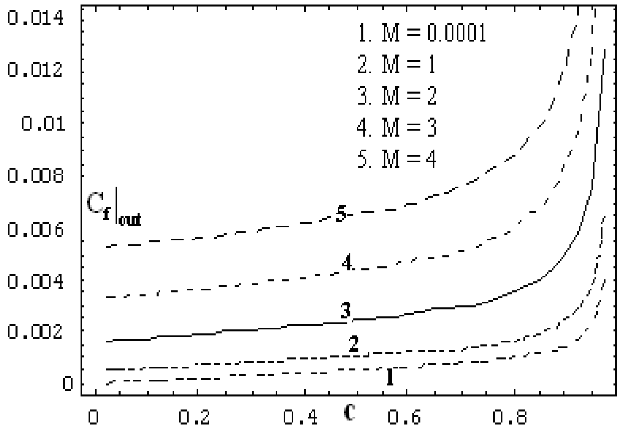

Figure 17. Variation of $C_f\big|_{out}$ *with c*

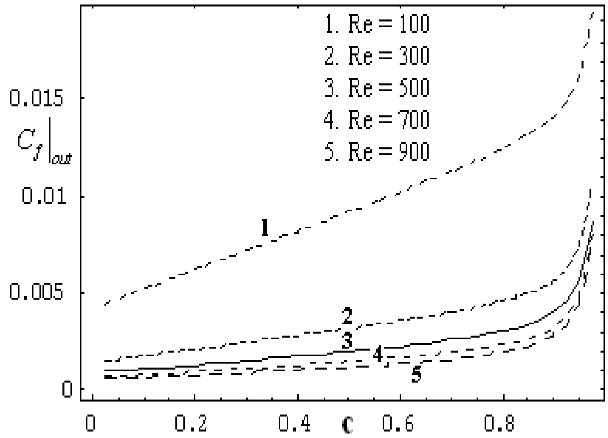

Figure 18. Variation of $C_f\big|_{out}$ *with c*

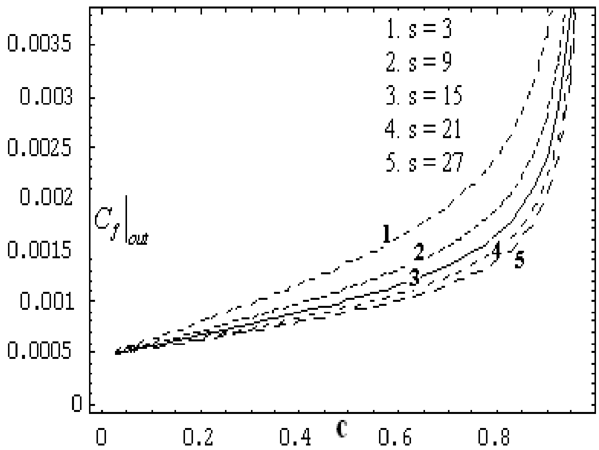

Figure 19. Variation of $C_f\big|_{out}$ *with c*

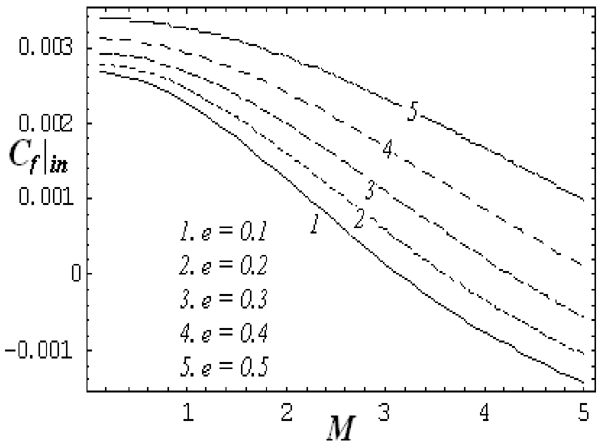

Figure 20. Variation of $C_f\big|_{in}$ *with e*

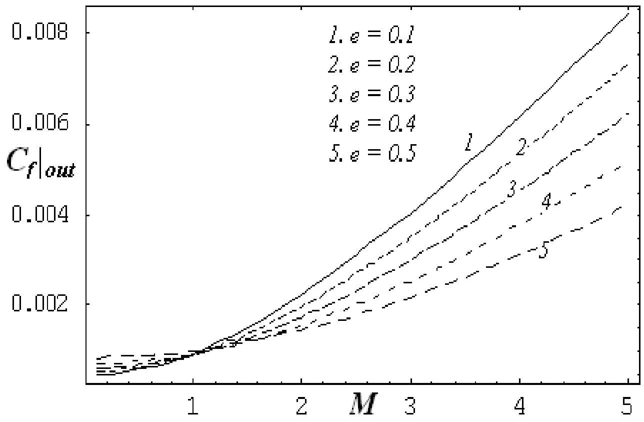

Figure 21. Variation of $C_f\big|_{out}$ with e

Figures 20-21 show the variation of the coefficient of skin friction at inner and outer cylinders against M for different values of e.

We observe that $C_f\big|_{in}$ increases, whereas $C_f\big|_{out}$ decreases with increasing values of e. These results are in correlation with the results of Bathiah and Venugopal [12].

CONCLUSIONS

In this paper, the effect of axial magnetic field on micropolar fluid flow due to steady rotation of concentric cylinders with inner porous lining is examined. It is observed that

1. Micro-polarity of the fluid affects the velocity but couple stress parameter can not affect the velocity profiles
2. As magnetic field strength increases velocity decreases and micro-rotation of the particles decreases and there by skin friction decreases at inner cylinder and increases at outer cylinder
3. As porous lining thickness increases, the skin friction at the inner cylinder increases and at the outer cylinder decreases.

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