Int. J. of Applied Mechanics and Engineering, 2018, vol.23, No.3, pp.623-633
DOI: 10.2478/ijame-2018-0034

UNSTEADY MHD FLOW DUE TO NON-COAXIAL ROTATIONS OF A POROUS DISK AND A FLUID AT INFINITY SUBJECTED TO A PERIODIC SUCTION

M. GURIA
Department of Mathematics, Ghatal Rabindra Satabarsiki Mahavidyalaya
Ghatal, Paschim Medinipur, West Bengal, INDIA
E-mail: mrinmoy9832@yahoo.com

The unsteady flow of a viscous incompressible electrically conducting fluid due to non-coaxial rotations of a porous disk subjected to a periodic suction and the fluid at infinity in the presence of applied transverse magnetic field has been studied. The fluid at infinity passes through a fixed point. The velocity field, shear stresses are obtained in a closed form.

Key words: Hall currents, eccentric, mhd, oscillating, rotating.

1. Introduction

The flow of a viscous incompressible fluid due to non-coaxial rotations of a disk and the fluid at infinity has been studied by a number of researchers. An exact solution of this type of problem was obtained by Berker [1]. Coirier [2] studied the flow due to a disk and the fluid at infinity which are rotating non-coaxially at a slightly different angular velocity. The non-Newtonian flow due to a disk and the fluid at infinity which are rotating non-coaxially at a slightly different angular velocity was studied by Erdogan [3]. An exact solution of the three dimensional Navier-Stokes equations for the flow due to non coaxial rotation of a porous disk and the fluid at infinity was studied by Erdogan [4, 5]. Murthy and Ram [6] studied the magnetohydrodynamic flow and heat transfer due to eccentric rotations of a porous disk and the fluid at infinity. The unsteady flow due to non-coaxial rotations of a disk, oscillating in its own plane and the fluid at infinity was studied by Kasiviswanathan and Rao [7]. Chakraborti *et al*. [8] studied the hydromagnetic flow due to non-coaxial rotations of a disk and the fluid at infinity with same angular velocity. The flow due to non-coaxial rotations of an oscillatory porous disk and the fluid at infinity about an axis passing through a fixed point parallel to the axis of rotation of the disk was investigated by Hayet *et al*. [9]. The flow due to non-coaxial rotations of an oscillating porous disk and the fluid at infinity which rotate about an axis passing through a fixed point parallel to the axis of rotation of the disk was studied by Guria *et al*. [10]. Hayet *et al.* [11] studied the unsteady MHD flow due to non-coaxial rotations of a porous disk and the fluid at infinity.

Hayet *et al*. [12] also investigated the peridic MHD flow due to non coaxial rotations of a porous disk and the fluid at infinity. Recently Ghosh *et al*. [13] studied the flow due to non coaxial rotations of a porous disk subjected to a periodic suction and the fluid at infinity. In the present paper, we have studied the MHD flow due to non coaxial rotations of a porous disk subjected to a periodic suction or blowing and the fluid at infinity in the presence of an applied tranverse magnetic field.

2. Formulation of the problem and its solution

Consider the unsteady flow of a viscous incompressible conducting fluid due to the rotation of a porous disk rotating about the z-axis with uniform angular velocity Ω. The fluid at infinity $(z \to \infty)$ rotates about an axis parallel to the z-axis passing through the point $\left(x_1^*, y_1^*\right)$ with the same angular velocity Ω. A uniform magnetic field B_0 is imposed parallel to the z-axis [See Fig.1]. Due to the periodic suction the flow becomes three-dimensional.

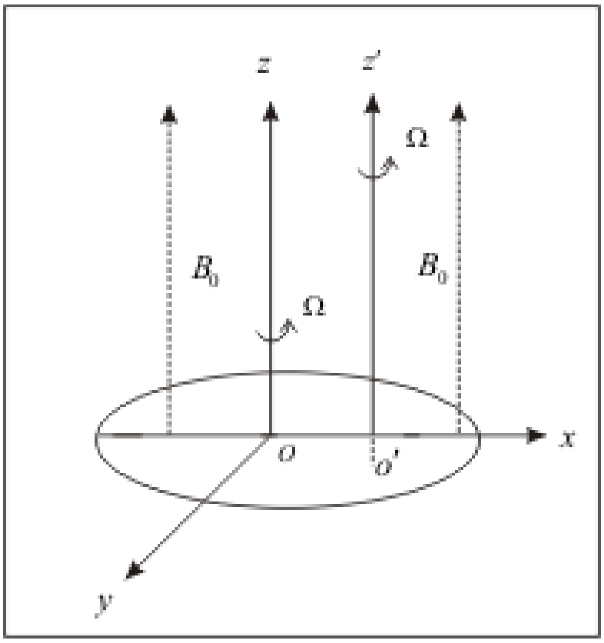

Fig.1. Geometry of the problem.

We assume the velocity components of the form

$$u = -\Omega y + f(z,t), \quad v = \Omega x + g(z,t), \quad w = -V(t). \tag{2.1}$$

The boundary conditions of the problem are

$$\begin{aligned} &u = -\Omega y, \quad v = \Omega x, \quad w = -V(t) \quad \text{at} \quad z = 0, \\ &u = -\Omega\left(y - y_1\right), \quad v = \Omega\left(x - x_1\right), \quad w = -V\left(t\right) \quad \text{as} \quad z \to \infty . \end{aligned} \tag{2.2}$$

The Navier-Stokes equations of motion are

$$\nabla . \boldsymbol{q} = 0 , \tag{2.3}$$

$$\frac{\partial \boldsymbol{q}}{\partial t} + \left(\boldsymbol{q}.\nabla\right)\boldsymbol{q} = -\frac{1}{\rho}\nabla p + \nu\nabla^2 \boldsymbol{q} + \frac{1}{\rho}\left(\boldsymbol{J} \times \boldsymbol{B}\right), \tag{2.4}$$

$$\frac{1}{\rho}(\boldsymbol{J}\times\boldsymbol{B}) = -\frac{\sigma}{\rho}B_0^2 V. \tag{2.5}$$

Introducing Eq.(2.1), the Navier Stokes eqations become respectively

$$-\frac{1}{\rho}\frac{\partial p}{\partial x} = \Omega^2 x + \Omega g + \frac{\partial f}{\partial z} + \frac{\partial f}{\partial t} + \nu\frac{\partial^2 f}{\partial z^2} - \frac{\sigma}{\rho}B_0^2\left[f(z,t) - \Omega y\right], \tag{2.6}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial y} = \Omega^2 y - \Omega f + V(t)\frac{\partial g}{\partial z} - \frac{\partial g}{\partial t} + \nu\frac{\partial^2 g}{\partial z^2} - \frac{\sigma}{\rho}B_0^2\left[g(z,t) + \Omega x\right] \tag{2.7}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial z} = \frac{\sigma}{\rho}B_0^2 V(t) + \frac{\partial V(t)}{\partial t} \tag{2.8}$$

where (u,v,w) are the velocity components along the coordinate axes, ρ is the fluid density, ν is the kinematic coefficient of viscosity. $\frac{\partial p}{\partial z}$ is a function of t only, if we differentiate with respect to x and y then it is zero.

The perodic suction velocity distibution of the form

$$V(t) = -W_0\left[1 + \varepsilon A e^{i\sigma t}\right] \tag{2.9}$$

where w_0 is a positive constant, $\varepsilon > 0$ is very small and A is a real positive constant such that $\varepsilon A \le 1$. Differentiating Eqs (2.6) and (2.7), we get

$$\Omega\frac{\partial g}{\partial z} + V(t)\frac{\partial^2 f}{\partial z^2} - \frac{\partial^2 f}{\partial z\partial t} + \nu\frac{\partial^3 f}{\partial z^3} - \frac{\sigma}{\rho}B_0^2\frac{\partial f}{\partial z} = 0, \tag{2.10}$$

$$-\Omega\frac{\partial f}{\partial z} + V(t)\frac{\partial^2 g}{\partial z^2} - \frac{\partial^2 g}{\partial z\partial t} + \nu\frac{\partial^3 g}{\partial z^3} - \frac{\sigma}{\rho}B_0^2\frac{\partial g}{\partial z} = 0, \tag{2.11}$$

Combining Eqs (2.10) and (2.11), we get

$$\nu\frac{\partial^3 F}{\partial z^3} + V(t)\frac{\partial^2 F}{\partial z^2} - \frac{\partial^2 F}{\partial z\partial t} - \left(i\Omega + \frac{\sigma}{\rho}B_0^2\right)\frac{\partial F}{\partial z} = 0 \tag{2.12}$$

where

$$F = f + ig, \qquad i = \sqrt{-1}. \tag{2.13}$$

The corresponding boundary conditions become

$$F(0,t) = 0, \qquad F(\infty,t) = -i\Omega(x_1 + iy_1). \tag{2.14}$$

We assume

$$F(z,t) = F_0(z,t) + \varepsilon F_1(z,t)e^{i\sigma t}\,. \tag{2.15}$$

Substituitng (2.15) in Eq.(2.12) and comparing the harmonics terms and neglecting the coefficients of ε^2.

$$\nu\frac{d^3F_0}{dz^3} + w_0\frac{d^2F_0}{\partial z^2} - \left(i\Omega + \frac{\sigma}{\rho}B_0^2\right)\frac{dF_0}{\partial z} = 0\,, \tag{2.16}$$

$$\nu\frac{d^3F_1}{dz^3} + w_0\frac{d^2F_1}{\partial z^2} - \left(i\Omega + i\sigma + \frac{\sigma}{\rho}B_0^2\right)\frac{dF_1}{\partial z} = -w_0 A\frac{d^2F_0}{dz^2}\,. \tag{2.17}$$

Introducing the non-dimensional variables

$$\eta = \sqrt{\frac{\Omega}{2\nu}}z, \qquad S = \frac{w_0}{2\sqrt{\Omega\nu}}, \qquad n = \sqrt{1+\frac{\sigma}{\Omega}}, \qquad M^2 = \frac{2\sigma B_0^2}{\rho\Omega}, \tag{2.18}$$

Eqs (2.16) and (2.17) become

$$\frac{d^3F_0}{d\eta^3} + 2\sqrt{2}S\frac{d^2F_0}{\partial\eta^2} - \left(2i + M^2\right)\frac{dF_0}{\partial\eta} = 0\,, \tag{2.19}$$

$$\frac{d^3F_1}{dz^3} + 2\sqrt{2}S\frac{d^2F_1}{\partial\eta^2} - \left(2i\eta^2 + M^2\right)\frac{dF_1}{\partial\eta} = -2\sqrt{2}SA\frac{d^2F_0}{d\eta^2}\,. \tag{2.20}$$

The boundary conditions (2.14) become

$$F_0(0) = 0, \quad F_0(\infty) = -i\Omega(x_1 + iy_1), \quad F_1(0) = 0, \quad F_1(\infty) = 0. \tag{2.21}$$

Solving Eqs (2.19) and (2.20) subject to the boundary conditions (2.21) and using Eq.(2.13), we get

$$\begin{aligned}\frac{f}{\Omega} &= y_1\left(1 - e^{-\alpha_0\eta}\cos\beta_0\eta\right) + x_1 e^{-\alpha_0\eta}\sin\beta_0\eta + \\ &+ \frac{\varepsilon\sqrt{2}SA}{\left(n^2-1\right)}\Big[\left(\alpha_0 x_1 - \beta_1 y_1\right)\left\{e^{-\alpha_1\eta}\cos\left(\beta_1\eta - \sigma t\right) - e^{-\alpha_0\eta}\cos\left(\beta_0\eta - \sigma t\right)\right\} + \\ &+ \left(\alpha_0 y_1 + \beta_0 x_1\right)\left\{e^{-\alpha_1\eta}\sin\left(\beta_1\eta - \sigma t\right) - e^{-\alpha_0\eta}\sin\left(\beta_0\eta - \sigma t\right)\right\}\Big],\end{aligned} \tag{2.22}$$

$$\begin{aligned}\frac{g}{\Omega} &= y_1 e^{-\alpha_0\eta}\sin\beta_0\eta - x_1(1 - e^{-\alpha_0\eta})\cos\beta_0\eta + \\ &+ \frac{\varepsilon\sqrt{2}SA}{\left(n^2-1\right)}\Big[\left(\alpha_0 y_1 + \beta_0 x_1\right)\left\{e^{-\alpha_1\eta}\cos\left(\beta_1\eta - \sigma t\right) - e^{-\alpha_0\eta}\cos\left(\beta_0\eta - \sigma t\right)\right\} + \\ &+ \left(\alpha_0 x_1 - \beta_0 y_1\right)\left\{e^{-\alpha_1\eta}\sin\left(\beta_1\eta - \sigma t\right) - e^{-\alpha_0\eta}\sin\left(\beta_0\eta - \sigma t\right)\right\}\Big]\end{aligned} \tag{2.23}$$

where

$$\alpha_0 = \sqrt{2}S + \gamma_0, \qquad \alpha_1 = \sqrt{2}S + \gamma_1$$

$$\gamma_0 = \left\{ \frac{2S^2 + M^2 + \sqrt{\left(2S^2 + M^2\right)^2 + 4}}{4} \right\}^{1/2},$$

$$\beta_0 = \left\{ \frac{-\left(2S^2 + M^2\right) + \sqrt{\left(2S^2 + M^2\right)^2 + 4}}{4} \right\}^{1/2},$$

$$\gamma_1 = \left\{ \frac{2S^2 + M^2 + \sqrt{\left(2S^2 + M^2\right)^2 + 4n^4}}{4} \right\}^{1/2},$$

$$\beta_1 = \left\{ \frac{-\left(2S^2 + M^2\right) + \sqrt{\left(2S^2 + M^2\right)^2 + 4n^4}}{4} \right\}^{1/2}. \tag{2.24}$$

The effect of variable suction introduces a transient part depending on ε, A and σ superposed on the steady solution corresponding to uniform suction at the disk. If $S = 0$, the problem recovers the solution for the steady Ekman layer on the disk.

Case.I: When $A=0$

$$\frac{f}{\Omega} = y_1\left(1 - e^{-\alpha_0\eta}\cos\beta_0\eta\right) + x_1 e^{-\alpha_0\eta}\sin\beta_0\eta$$

$$\frac{g}{\Omega} = y_1 e^{-\alpha_0\eta}\sin\beta_0\eta - x_1(1 - e^{-\alpha_0\eta})\cos\beta_0\eta$$

Case.II: When $x_1 = 0$, $y_1 = l$

$$\begin{aligned}\frac{f}{\Omega l} &= \left(1 - e^{-\alpha_0\eta}\cos\beta_0\eta\right) + \\ &+ \frac{\varepsilon\sqrt{2}SA}{\left(n^2 - 1\right)}\Big[-\beta_0\left\{e^{-\alpha_1\eta}\cos\left(\beta_1\eta - \sigma t\right) - e^{-\alpha_0\eta}\cos\left(\beta_0\eta - \sigma t\right)\right\} + \\ &+ \alpha_0\left\{e^{-\alpha_1\eta}\sin\left(\beta_1\eta - \sigma t\right) - e^{-\alpha_0\eta}\sin\left(\beta_0\eta - \sigma t\right)\right\}\Big],\end{aligned} \tag{2.25}$$

$$\frac{g}{\Omega l}=e^{-\alpha_0\eta}\sin\beta_0\eta+$$
$$+\frac{\varepsilon\sqrt{2}SA}{\left(n^2-1\right)}\Big[\left(\alpha_0 y_1+\beta_0 x_1\right)\left\{e^{-\alpha_1\eta}\cos\left(\beta_1\eta-\sigma t\right)-e^{-\alpha_0\eta}\cos\left(\beta_0\eta-\sigma t\right)\right\}+ \tag{2.26}$$
$$+\left(\alpha_0 x_1-\beta_0 y_1\right)\left\{e^{-\alpha_1\eta}\sin\left(\beta_1\eta-\sigma t\right)-e^{-\alpha_0\eta}\sin\left(\beta_0\eta-\sigma t\right)\right\}.$$

Case.III: When $A=0, M^2=0$, the results (2.22) and (2.23) are the same as reference [7].

Case.IV: When $x_1=0, y_1=l, A=0, M^2=0$ and $-f$ by g and g by f, the results are the same as reference [4].

Case.V: If $A=0$, the problem is reduced to Hayet *et al.* [12].

The flow very near the porous disk

$$\frac{f}{\Omega l}=\alpha_0\eta+\frac{\varepsilon\sqrt{2}SA}{\left(n^2-1\right)}\Big[\left(\alpha_1-\alpha_0\right)\beta_0\eta\cos\sigma t-\left(\beta_1-\beta_0\right)\beta_0\eta\sin\sigma t+$$
$$+\left(\beta_1-\beta_0\right)\alpha_0\eta\cos\sigma t-\left(\alpha_1-\alpha_0\right)\beta_0\eta\sin\sigma t\Big], \tag{2.27}$$

$$\frac{g}{\Omega l}=\beta_0\eta+\frac{\varepsilon\sqrt{2}SA}{\left(n^2-1\right)}\Big[-\left(\alpha_1-\alpha_0\right)\alpha_0\eta\cos\sigma t+\left(\beta_1-\beta_0\right)\beta_0\eta\sin\sigma t+$$
$$+\left(\alpha_1-\alpha_0\right)\beta_0\eta\sin\sigma t+\left(\beta_1-\beta_0\right)\beta_0\eta\sin\cos\sigma t\Big]. \tag{2.28}$$

The inclination of the fluid velocity vector with the y axis near $z=0$ becomes $\theta=\tan^{-1}\left(C/D\right)$, where

$$C=\beta_0\left(n^2-1\right)+\varepsilon\sqrt{2}SA\Big[\left(\alpha_1-\alpha_0\right)\beta_0\eta\cos\sigma t-\left(\beta_1-\beta_0\right)\beta_0\eta\sin\sigma t+$$
$$+\left(\beta_1-\beta_0\right)\alpha_0\eta\cos\sigma t-\left(\alpha_1-\alpha_0\right)\beta_0\eta\sin\sigma t\Big],$$

$$D=\alpha_0\left(\eta^2-1\right)+\varepsilon\sqrt{2}SA\left(n^2-1\right)\Big[\left(\alpha_1-\alpha_0\right)\beta_0\eta\cos\sigma t+$$
$$-\left(\beta_1-\beta_0\right)\beta_0\eta\sin\sigma t+\left(\beta_1-\beta_0\right)\alpha_0\eta\cos\sigma t-\left(\alpha_1-\alpha_0\right)\beta_0\eta\sin\sigma t\Big].$$

If $\sigma t=\pi/2, S\neq 0, A\neq 0,$ the inclination of the fluid velocity to the y axis near the z axis will be

$$\theta=\tan^{-1}\left\{\frac{\beta_0\left(n^2-1\right)+\varepsilon\sqrt{2}SA\left[\left(\beta_1-\beta_0\right)\alpha_0+\left(\alpha_1-\alpha_0\right)\beta_0\right]}{\alpha_0\left(n^2-1\right)+\varepsilon\sqrt{2}SA\left[\left(\alpha_1-\alpha_0\right)\alpha_0-\left(\beta_1-\beta_0\right)\beta_0\right]}\right\} \tag{2.29}$$

3. Results and discussion

I have presented the non-dimensional primary velocity $f/\Omega l$ and the secondary velocity $g/\Omega l$ against η for several values of σt, the magnitude of fluctuation of suction velocity A, the suction or blowing parameter S, the magnetic parameter M^2. Figure 2 shows the variations of the primary velocity for several values of σt. It is observed that the primary velocity decreases with an increase in σt near the disk and it is almost stationary away from the disk. The reverse effect is observed for secondary velocity. In Fig.3 it is observed that both the primary and secondary velocities increase with an increase in A. Figure 4 shows that the effect of suction or blowing parameter. It is seen that suction creates thinning of the boundary layer. The crossing of the graphs shown in the figure is due to the presence of suction because suction result in thinning of the boundary layer near the disk and thickening of the boundary layer away from the disk. Figure 5 represents the variations of $f/\Omega l$ and the secondary velocity $g/\Omega l$ for several values of the magnetic parameter M^2. It is found that $f/\Omega l$ increases but $g/\Omega l$ decreases with an increase in magnetic parameter.

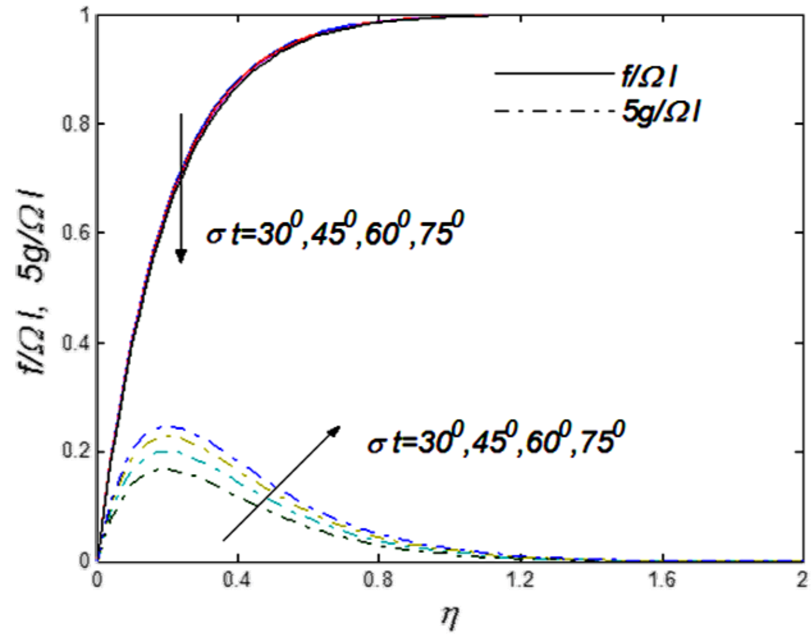

Fig.2. Variation of primary velocity for $S = 1$, $A = 2$, $M^2 = 10$, $t = 0.1$, $n^2 = 1.5$, $x_1 = 0$, $y_1 = 1$.

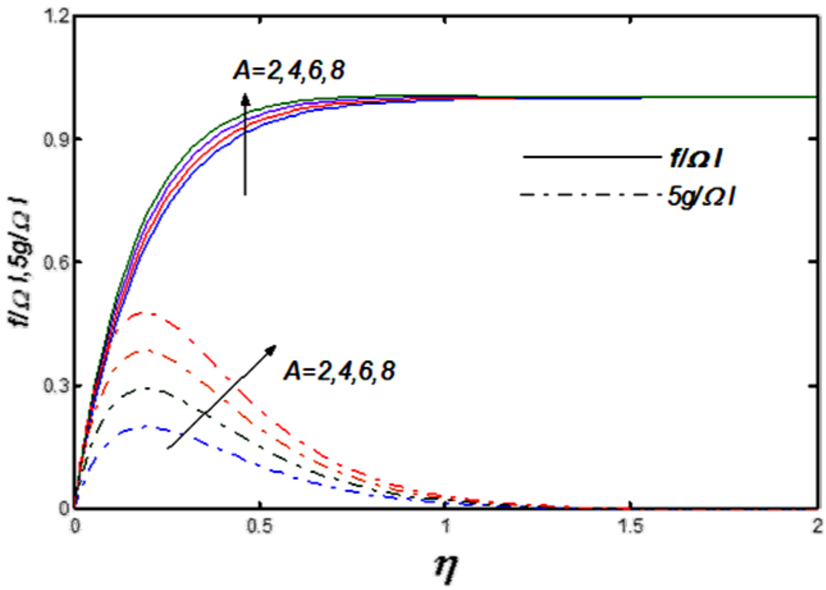

Fig.3:Variation of primary velocity for $S = 1$, $M^2 = 10$, $\sigma t = \pi / 4$, $t = 0.1$, $n^2 = 1.5$, $x_1 = 0$, $y_1 = 1$.

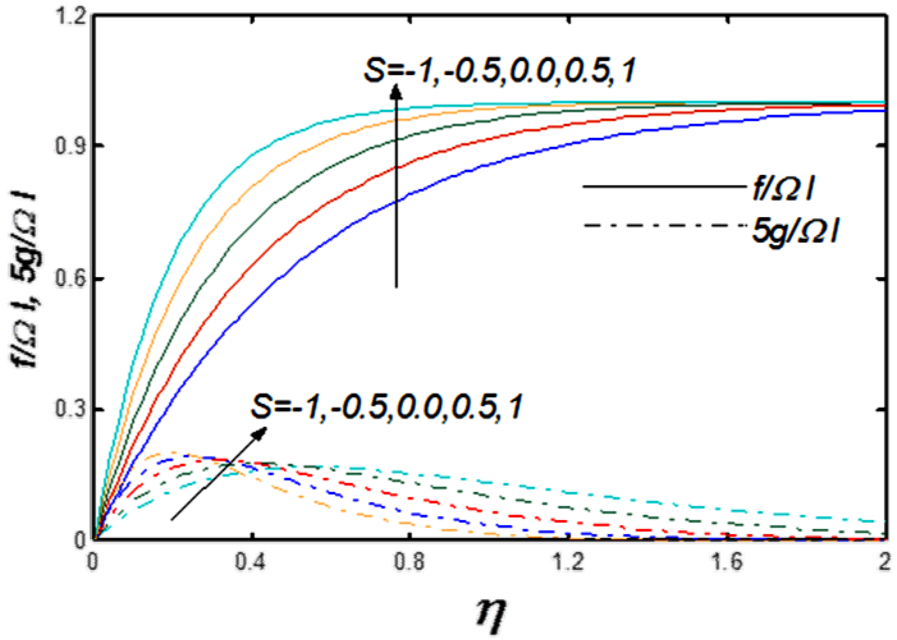

Fig.4. Variation of primary velocity for $M^2 = 10$, $\sigma t = \pi / 4$, $t = 0.1$, $n^2 = 1.5$, $x_1 = 0$, $y_1 = 1$.

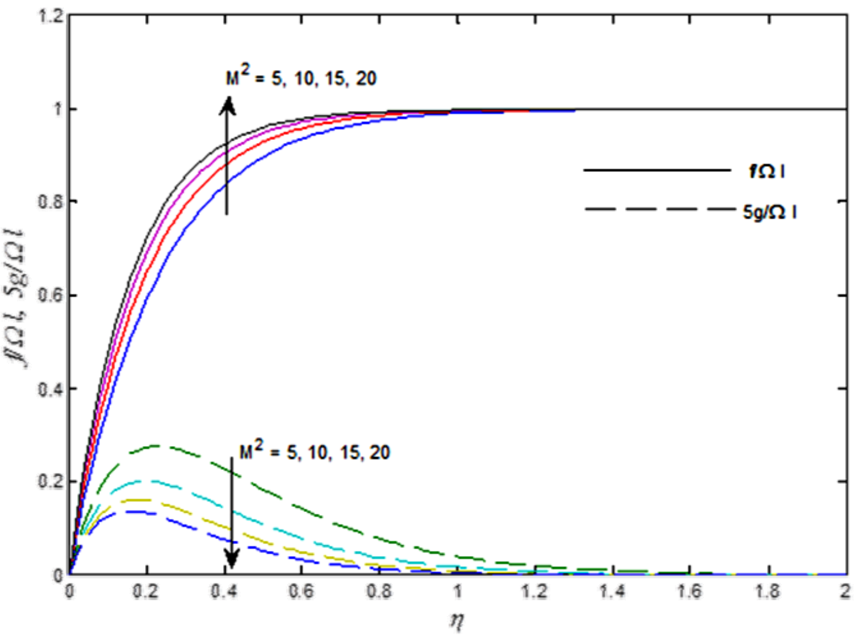

Fig.5. Variation of primary velocity for $S = 1$, $\sigma t = \pi / 4$, $t = 0.1$, $n^2 = 1.5$, $x_1 = 0$, $y_1 = 1$.

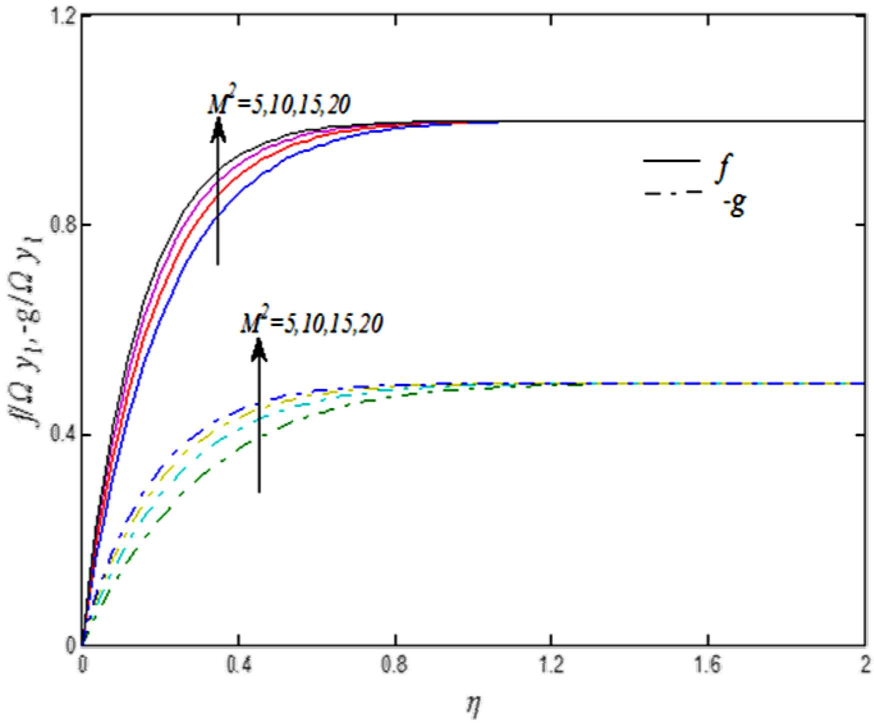

Fig.6. Variation of primary velocity for $S = 1$, $\sigma t = \pi / 4$, $t = 0.1$, $n^2 = 1.5$.

Using Eq.(2.22) and Eqs (2.35) and (2.36), we get the non-dimensional shear stress components τ_x and τ_y at the disk as

$$\frac{\partial}{\partial\eta}\left(\frac{f}{\Omega y_1}\right)=\left(\alpha_0+\beta_0\frac{x_1}{y_1}\right)+\frac{\varepsilon\sqrt{2}SA}{\left(n^2-1\right)}\left[\left(\alpha_0\frac{x_1}{y_1}-\beta_0\right)\left\{\left(\beta_1-\beta_0\right)\sin\sigma t-\left(\alpha_1-\alpha_0\right)\cos\sigma t\right\}+\right.$$
$$\left.+\left(\alpha_0+\beta_0\frac{x_1}{y_1}\right)\left\{\left(\alpha_1-\alpha_0\right)\sin\sigma t+\left(\beta_1-\beta_0\right)\cos\sigma t\right\}\right], \tag{3.1}$$

$$\frac{\partial}{\partial\eta}\left(\frac{g}{\Omega y_1}\right)=\left(\beta_0-\alpha_0\frac{x_1}{y_1}\right)+\frac{\varepsilon\sqrt{2}SA}{\left(n^2-1\right)}\left[\left(\alpha_0+\beta_0\frac{x_1}{y_1}\right)\left\{\left(\beta_1-\beta_0\right)\sin\sigma t-\left(\alpha_1-\alpha_0\right)\cos\sigma t\right\}+\right.$$
$$\left.-\left(\alpha_0\frac{x_1}{y_1}-\beta_0\right)\left\{\left(\alpha_1-\alpha_0\right)\sin\sigma t+\left(\beta_1-\beta_0\right)\cos\sigma t\right\}\right]. \tag{3.2}$$

The non-dimensional shear stresses τ_x and τ_y due to the primary and the secondary flows at the disk are entered in Tab.1 for different values of m and ω with $S = 1, \sigma = 5, \sigma\tau = \frac{\pi}{2}, x_1 = y_1 = 1, M^2 = 5$.

Table 1. Shear stresses due to the primary and secondary flows for $M^2 = 5$.

	τ_x			$-\tau_y$		
$S \setminus M^2$	5	10	15	5	10	15
-2.0	0.88	1.38	2.28	0.55	1.21	2.28
-1	1.44	2.11	3.21	0.90	1.78	3.07
0	2.71	3.49	4.70	1.83	2.86	4.25
1	5.06	5.73	6.84	3.76	4.62	5.90
2	8.13	8.64	9.53	6.24	6.88	7.96

It is observed that the shear stresses τ_x and magnitude of τ_y increase with an increase in both suction parameter and magnetic parameter.

Conclusion

The unsteady flow of a viscous incompressible fluid due to non-coaxial rotations of a porous disk and the fluid at infinity subjected to a periodic suction in the presence of a magnetic field has been studied. It is seen that suction creates thinning of the boundary layer. The crossing of the graphs shown in the figure is due to the presence of suction because suction creates thinning of the boundary layer near the disk and thickening of the boundary layer away from the disk. It is found that the primary velocity increases but secondary velocity decreases with an increase in the magnetic parameter.

Nomenclature

A – amplitude of the suction velocity
B – magnetic field vector
B_0 – applied magnetic field
C,D – constants
$f / \Omega l, g / \Omega l$ – dimensionless velocity components in the x, z -axes, respectively
J – current density
l – distance between the axes of rotation
M^2 – magnetic parameter
n – rotational parameter
p – pressure
S – constant suction velocity
u, v, w – velocity components in the x, y, z -axes respectively
V – suction velocity
w_0 – constant
x,y,z – Cartesian coordinate system
Ω – angular velocity
η – dimensionless z coordinate system
ν – kinematic viscosity
ρ – density of the fluid
ε – constant
τ_x, τ_z – shear stress due to primary and secondary flows
α_0, α_1 – constants
β_0, β_1 – constants
γ_0, γ_1 – constants
θ – angle

References

[1] Berker R. (1963): *Handbook of Fluid Dynamics*. – Vol VIII/3. Springer, Berlin.

[2] Coirier J. (1972): *Rotations non-coaxiales d'un disque et d'un fluid á infini.* – J. de Mechanique, vol.11, pp.317-340.

[3] Erdogan M.E. (1976): *Non-Newtonian flow due to non-coaxially rotations of a porous disk and a fluid at infinity.* – Z. Angew. Math. Mech., vol.56, pp.141-146.

[4] Erdogan M.E. (1976): *Flow due to eccentric rotating a porous disk and a fluid at infinity*. – ASME, J. Appl. Mech., vol.43, pp.203-204.

[5] Erdogan M.E. (1977): *Flow due to non-coaxially rotations of a porous disk and a fluid at infinity.* – Rev. Roum. Sci Tech Mec, Appl., vol.22, pp.171-178.

[6] Murthy S.N. and Ram R.K.P. (1978): *MHD flow and heat transfer due to eccentric rotations of a porous disk and a fluid at infinity.* – Int. J. Engng Sci., vol.16, No.12, pp.943-949.

[7] Kasiviswanathan S.R. and Rao A.R. (1987): *An unsteady flow due to eccentrically rotating porous disk and a fluid at infinity.* – Int. J. Engng Sci., vol.25, pp.1419-1425.

[8] Chakrabarti A., Gupta A.S., Das B.K. and Jana R.N. (2005): *Hydromagnetic flow past a rotating porous plate in a conducting fluid rotating about a non-coincident parallel axis.* – Acta Mechanica, vol.176, pp.107-119.

[9] Hayet T., Asghar S. and Siddiqui A.M. (1999): *Unsteady flow of an oscillating porous disk and a fluid at infinity.* – Mecanica, vol.34, pp.259-265.

[10] Guria M., Das B.K. and Jana R.N. (2007): *Oscillatory flow due to eccentrically porous disk and a fluid at infinity.* – Mecanica, vol.42, pp.487-493.

[11] Hayet T., Asghar S., Siddiqui A.M. and Haroon T. (2001): *Unsteady MHD flow due to non-coaxial rotations of a porous disk and a fluid at infinity.* – Acta Mechanica, vol.151, pp.127-134.

[12] Hayet T., Ellahi R. and Asghar S. (2004): *Unsteady periodic flows of a magnetohydrodynamic fluid due to noncoaxial rotations of a porous disk and a fluid at infinity*. – Journal Mathematical and Computer Modelling, vol.40, pp.173-179.

Received: August 17, 2016
Revised: January 19, 2018