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Oscillatory MHD flow past a porous plate in a rotating system with periodic suction

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ABSTRACT

An analytical solution to the problem of an MHD oscillatory boundary layer flow past a porous horizontal plate with periodic suction is presented. The fluid in the boundary layer rotates about an axis normal to the plate with a uniform angular velocity. A magnetic field of uniform strength is assumed to be applied normal to the plate. The equations governing the flow and heat transfer are solved by regular perturbation technique assuming the solution to be consist of a mean part and a perturbed part. The expressions for the temperature fields, skin friction at the plate due to primary and secondary velocity fields and the rate of heat transfer from the plate to the fluid in terms of Nusselt number are obtained in non dimensional form. The dimensionless expressions for the amplitude and phases of the fluctuating parts of the skin friction, Nusselt number at the plate are also derived. The skin friction τ_x due to primary velocity and skin friction τ_y due to secondary velocity at the plate, the amplitude and phase of the fluctuating part of τ_x, the rate of heat transfer from the plate to the fluid in terms of Nusselt number and amplitudes and phases of the fluctuating parts of it are demonstrated graphically and the effects of the parameters M (Hartmann number), Ω (rotation parameter)and A (suction parameter)on these fields are discussed.It is seen that M, Ω ,A have significant effect on the flow and heat transfer characteristics.2000 Mathematics subject classification: 76W05

Introduction

Many natural phenomena and technological problems are susceptible to MHD analysis. Geophysics encounters MHD characteristics in the interactions of conducting fluids and magnetic fields, engineers employ MHD principle, in the design of heat exchangers pumps and flow meters, in space vehicle propulsion, thermal protection, braking, control and re-entry, in creating novel power generating systems etc. The study of MHD is quite important in the field of aerodynamics, since the temperature that occurs in such flight speeds are sufficient to dissociate or ionize the air appreciably and the motion of this ionized air may be controlled by applying a magnetic field suitably. The study of MHD is also relevant in medical science. For instance there have been researches on Arteriosclerosis (the cause of a cardiac arrest) where the effect of externally applied transverse magnetic field on a pulsalite flow in constricted arteries (tubes) is considered. When an electrically conducting fluid flows past a flat plate, its motion can be retarded by applying a transverse magnetic field and the Lorentz force acts as a resistance force in the direction opposite to the direction of the fluid velocity. Due to this the skin friction at the plate is reduced and hence the boundary flow may be controlled by transverse magnetic field.

The geophysical importance of the flows in rotating frame of reference has attracted the attention of a number of scholars. There appeared a number of studies in this literature viz Vidyanidhy and Nigam [1], Jana and Datta [2]. The effects of uniform transverse magnetic field with or without suction on different flow characteristics was investigated by Gupta [3], Soundalgekar and Pop [4] and Mazumdar *et al.*[5]. The similarity solutions of the unsteady Navier-Stokes equations in a rotating frame of reference was obtained by Gupta [6]. Singh *et al.* [7] studied the unsteady MHD Couette flow of electrically conducting fluid in a rotating system. Singh *et al.* [8] studied a periodic solution of oscillatory Couette flow in rotating system through porous medium. Recently Ahmed and Kalita [9] have studied MHD oscillatory flow past a porous plate in a rotating system with constant suction. The object of the present work is to investigate the effects of the transverse magnetic field and rotation parameter on an oscillatory flow past a horizontal porous plate with periodic suction, because of the importance of such problems in industry as well as in aerodynamics. This work is an extension to work done by Ahmed and Kalita from constant suction to periodic suction.

Mathematical formulation:

We consider an unsteady flow of a viscous incompressible fluid past a horizontal porous plate with periodic suction - $w_0(1+\varepsilon A e^{i\bar{\omega}\bar{t}})$, where w_0 is the mean constant suction velocity , A is a positive constant such that $\varepsilon A<1$, ε is small reference parameter.

Our investigation is restricted to the following assumptions:

1. All the fluid properties except the density in the buoyancy force term are constants.
2. A magnetic field of uniform strength B_0 is applied normal to the plate.

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3. The magnetic Reynolds number is so small that the induced magnetic field can be neglected.
4. The fluid is rotating about a normal to the plate with angular velocity $\bar{\Omega}$.
5. The flow far away from the plate is not affected by the rotation.

We choose the origin on the plate, the X-axis along the direction of the free stream, Y-axis perpendicular to it horizontally and Z-axis normal to the plate which is the axis of rotation. Since the plate is infinite in extent in X,Y directions, therefore all the quantities except the pressure p are dependent of $\bar{z}$ and $\bar{t}$ only. Let $\vec{q} = \hat{i}\bar{u} + \hat{j}\bar{v} + \hat{k}\bar{w}$ be the fluid velocity at the point $(\bar{x}, \bar{y}, \bar{z})$.

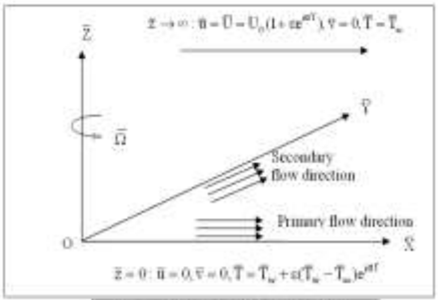

Figure 1: physical model of the problem

The equation of continuity gives $\dfrac{\partial \bar{w}}{\partial \bar{z}} = 0$

which holds for $\bar{w} = -w_0(1+\varepsilon A e^{i\bar{\omega}\bar{t}})$ (2.1)

With the forgoing assumptions and under the usual boundary layer approximations, the equations governing the flow and heat transfer are:

$$\frac{\partial \bar{u}}{\partial \bar{t}} = \upsilon \frac{\partial^2 \bar{u}}{\partial \bar{z}^2} + \frac{\partial \bar{U}}{\partial \bar{t}} + \bar{\Omega}\bar{v} + w_0(1+\varepsilon A e^{i\bar{\omega}\bar{t}})\frac{\partial \bar{u}}{\partial \bar{z}} + \frac{\sigma B_0^2}{\rho}(\bar{U}-\bar{u}) \quad (2.2)$$

$$\frac{\partial \bar{v}}{\partial \bar{t}} = \upsilon \frac{\partial^2 \bar{v}}{\partial \bar{z}^2} + \bar{\Omega}(\bar{U}-\bar{u}) + w_0(1+\varepsilon A e^{i\bar{\omega}\bar{t}})\frac{\partial \bar{v}}{\partial \bar{t}} - \frac{\sigma B_0^2 \bar{v}}{\rho} \quad (2.3)$$

$$\frac{\partial \bar{T}}{\partial \bar{t}} = \alpha \frac{\partial^2 \bar{T}}{\partial \bar{z}^2} + w_0(1+\varepsilon A e^{i\bar{\omega}\bar{t}})\frac{\partial \bar{T}}{\partial \bar{z}} + \frac{\upsilon}{c_p}\left\{\left(\frac{\partial \bar{u}}{\partial \bar{z}}\right)^2 + \left(\frac{\partial \bar{v}}{\partial \bar{z}}\right)^2\right\} + \frac{\sigma B_0^2}{\rho c_p}\left\{(\bar{U}-u)^2 + (\bar{v})^2\right\} \quad (2.4)$$

with relevant boundary conditions:

$$\left.\begin{aligned} &\bar{z}=0: \bar{u}=0, \bar{v}=0, \bar{T}=\bar{T}_w + \varepsilon(\bar{T}_w - \bar{T}_\infty)e^{i\bar{\omega}\bar{t}} \\ &\bar{z}\to\infty: \bar{u}=\bar{U}=U_0(1+\varepsilon e^{i\bar{\omega}\bar{t}}), \bar{v}=0, \bar{T}=\bar{T}_\infty \end{aligned}\right\} \quad (2.5)$$

We now introduce the following non-dimensional quantities:

$$u=\frac{\bar{u}}{U_0}, v=\frac{\bar{v}}{U_0}, U=\frac{\bar{U}}{U_0}, t=\frac{\bar{t}w_0^2}{\upsilon}, \omega=\frac{\upsilon\bar{\omega}}{w_0^2}, \Omega=\frac{\bar{\Omega}\upsilon}{w_0^2}, z=\frac{\bar{z}w_0}{\upsilon},$$

$$M=\frac{\sigma B_0^2 \upsilon}{\rho w_0^2}, \Pr=\frac{\upsilon}{\alpha}, T=\frac{\bar{T}-\bar{T}_\infty}{\bar{T}_w-\bar{T}_\infty}, E=\frac{U_0^2}{c_p(\bar{T}_w-\bar{T}_\infty)}$$

where, υ is the kinematic viscosity, ρ the density, c_p the specific heat at constant pressure, B_0 the applied magnetic field, U the mean velocity, ω the frequency of oscillation, M the Hartmann number, Pr the Prandtl number, E the Eckert number, T the temperature, α the thermal diffusivity, σ the electrical conductivity.

The non-dimensional form of the equations (2.2),(2.3) and (2.4) are:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial z^2} + \frac{\partial U}{\partial t} + \Omega v + (1+\varepsilon A e^{i\omega t})\frac{\partial u}{\partial z} + M(U-u) \quad (2.6)$$

$$\frac{\partial v}{\partial t} = \frac{\partial^2 v}{\partial z^2} + \Omega(U-u) + (1+\varepsilon A e^{i\omega t})\frac{\partial v}{\partial z} - Mv \quad (2.7)$$

$$\Pr\frac{\partial T}{\partial t} - P(1+\varepsilon A e^{i\omega t})\frac{\partial T}{\partial z} = \frac{\partial^2 T}{\partial z^2} + E\Pr\left\{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right\} + ME\Pr\left\{(U-u)^2 + v^2\right\} \quad (2.8)$$

with relevant boundary conditions:

$$\left.\begin{aligned} &z=0: \quad u=0,\ v=0, T=1+\varepsilon e^{i\omega t} \\ &z\to\infty: \quad u=1+\varepsilon e^{i\omega t}, v=0, T=0 \end{aligned}\right\} \quad (2.9)$$

Solution of the problem:

We introduce the complex variable q defined by q=u+iv (3.1)

where $i^2 = -1$

The non-dimensional form of the equations can be rewritten as follows:

$$\frac{\partial q}{\partial t} = \frac{\partial^2 q}{\partial z^2} + \frac{\partial U}{\partial t} + (1+\varepsilon A e^{i\omega t})\frac{\partial q}{\partial z} + \left\{(U-q)(M+i\Omega)\right\} \quad (3.2)$$

$$\Pr\frac{\partial T}{\partial t} = \Pr(1+\varepsilon A e^{i\omega t})\frac{\partial T}{\partial z} + \frac{\partial^2 T}{\partial z^2} + E\Pr\left|\frac{\partial q}{\partial z}\right|^2 + ME\Pr(U-q)(U-\bar{q}) \quad (3.3)$$

($\bar{q}$ being the conjugate complex of q)

Subject to boundary conditions:

$$\left.\begin{aligned} &z=0: \quad q=0, T=1+\varepsilon e^{i\omega t} \\ &z\to\infty: \ q=1+\varepsilon e^{i\omega t}=U, T=0 \end{aligned}\right\} \quad (3.4)$$

We represent the velocity q and temperature T assuming the small amplitude oscillation ε <<1 as follows:

$$q = q_0(z) + \varepsilon e^{i\omega t} q_1(z) + 0(\varepsilon^2) \quad (3.5)$$

$$T = T_0(z) + \varepsilon e^{i\omega t} T_1(z) + 0(\varepsilon^2) \quad (3.6)$$

Substituting (3.5) and (3.6) in (3.2) and (3.3) and by equating the coefficients of the harmonic terms and neglecting ε^2 the following differential equations are obtained.

$$q_0'' + q_0' - (M+i\Omega)q_0 = -(M+i\Omega) \quad (3.7)$$

$$q_1'' + q_1' - (M+i\Omega+i\omega)q_1 = -(M+i\Omega+i\omega) - Aq_0' \quad (3.8)$$

$$T_0'' + \Pr T_0' = -E\Pr\left|\frac{dq_0}{dz}\right|^2 - ME\Pr(1-q_0)(1-\bar{q}_0) \quad (3.9)$$

$$T_1'' + \Pr T_1' - \Pr i w T_1 + AP T_0' = -E\Pr\left\{\frac{dq_1}{dz}\bar{q}_0'(z) + \frac{d\bar{q}_1}{dz}q_0'(z)\right\} - ME\Pr\left\{\begin{aligned}&(1-\bar{q}_0)(1-q_1)+\\&(1-q_0)(1-\bar{q}_1)\end{aligned}\right\}$$

(3.10)

subject to the boundary conditions

$$\left.\begin{aligned} &z=0: \quad q_0=0, q_1=0, T_0=1, T_1=1 \\ &z\to\infty: \quad q_0=1, q_1=1, T_0=0, T_1=0 \end{aligned}\right\} \quad (3.11)$$

Here $\bar{q}_0$ and $\bar{q}_1$ are the conjugates of the complex numbers q_0 and q_1 respectively.

The solutions of the equations (3.7), (3.8), (3.9) and (3.10) subject to the boundary conditions (3.11) are

$$q_0(z) = 1 - e^{-\lambda_1 z} \quad (3.12)$$

$$q_1(z) = \left(AL_1 - 1\right)e^{-\lambda_2 z} + 1 - AL_1 e^{-\lambda_1 z} \quad (3.13)$$

$$T_0(z) = \left(1 + E\,Pr\,L_4\right)e^{-Pr z} - E\,Pr\,L_4 e^{-\left(\lambda_1 + \bar{\lambda}_1\right)z} \quad (3.14)$$

$$T_1(z) = \left(1 + L_{12} + L_{13} + L_{14} + L_{15}\right)e^{-\lambda_3 z} - L_{12}e^{-\left(\bar{\lambda}_1 + \lambda_2\right)z} - L_{13}e^{-\left(\lambda_1 + \bar{\lambda}_2\right)z} - L_{14}e^{-\left(\lambda_1 + \bar{\lambda}_1\right)z} - L_{15}e^{-Pr z} \quad (3.15)$$

where,

$$\lambda_1 = \frac{1 + \sqrt{1 + 4\left(M + i\Omega\right)}}{2}, \quad \lambda_2 = \frac{1 + \sqrt{1 + 4\left(M + i\Omega + i\omega\right)}}{2},$$

$$\lambda_3 = \frac{Pr + \sqrt{Pr^2 + 4\,Pr\,i\omega}}{2}, \quad L_1 = \frac{\lambda_1}{\lambda_1^2 - \lambda_1 - \left(M + i\Omega + i\omega\right)},$$

$$L_2 = \frac{\lambda_1\bar{\lambda}_1}{\left(\lambda_1 + \bar{\lambda}_1\right)^2 - Pr\left(\lambda_1 + \bar{\lambda}_1\right)}, \quad L_3 = \frac{1}{\left(\lambda_1 + \bar{\lambda}_1\right)^2 - Pr\left(\lambda_1 + \bar{\lambda}_1\right)},$$

$$L_4 = L_2 + ML_3, \quad L_5 = \frac{\bar{\lambda}_1\lambda_2}{\left(\bar{\lambda}_1 + \lambda_2\right)^2 - Pr\left(\bar{\lambda}_1 + \lambda_2\right) - Pi\omega},$$

$$L_6 = \frac{\lambda_1\bar{\lambda}_2}{\left(\lambda_1 + \bar{\lambda}_2\right)^2 - Pr\left(\lambda_1 + \bar{\lambda}_2\right) - Pr\,i\omega},$$

$$L_7 = \frac{2\lambda_1\bar{\lambda}_1}{\left(\lambda_1 + \bar{\lambda}_1\right)^2 - Pr\left(\lambda_1 + \bar{\lambda}_1\right) - Pr\,i\omega},$$

$$L_8 = \frac{1}{\left(\bar{\lambda}_1 + \lambda_2\right)^2 - Pr\left(\bar{\lambda}_1 + \lambda_2\right) - Pr\,i\omega},$$

$$L_9 = \frac{1}{\left(\lambda_1 + \bar{\lambda}_2\right)^2 - Pr\left(\lambda_1 + \bar{\lambda}_2\right) - Pr\,i\omega},$$

$$L_{10} = \frac{2}{\left(\lambda_1 + \bar{\lambda}_1\right)^2 - Pr\left(\lambda_1 + \bar{\lambda}_1\right) - Pr\,i\omega}$$

$$L_{11} = \frac{\lambda_1 + \bar{\lambda}_1}{\left(\lambda_1 + \bar{\lambda}_1\right)^2 - Pr\left(\lambda_1 + \bar{\lambda}_1\right) - Pr\,i\omega},$$

$$L_{12} = E\,Pr\left\{\left(1 - AL_1\right)L_5 + M\left(1 - AL_1\right)L_8\right\},$$

$$L_{13} = E\,Pr\left\{\left(1 - AL_1\right)L_6 + M\left(1 - AL_1\right)L_9\right\},$$

$$L_{14} = E\,Pr\left\{AL_1L_7 + MAL_1L_{10} + Pr\,AL_4L_{11}\right\},$$

$$L_{15} = \frac{A\,Pr\left(1 + E\,Pr\,L_4\right)}{i\omega}$$

where L_2, L_3 and L_4 are real and the others are complex constants, whose real and imaginary parts are shown in the Appendix.

Velocity and temperature fields:

The non-dimensional velocity field is given by

$$q = q_0(z) + \varepsilon e^{i\omega t}q_1(z) \quad (4.1)$$

By splitting it into real and imaginary parts, the primary and secondary velocity components are derived as follows:

$$u = u_0 + \varepsilon|A|\cos(\omega t + \alpha) \quad (4.2)$$

$$v = v_0 + \varepsilon|A|\sin(\omega t + \alpha) \quad (4.3)$$

where ,

$$u_0 + iv_0 = q_0 \quad (4.4)$$

$$|A| = |q_1(z)| \quad (4.5)$$

$$\alpha = \arg q_1(z) \quad (4.6)$$

The temperature in the non-dimensional form is given by

$$T = T_0(z) + \text{Real part of } \left\{\varepsilon e^{i\omega t}T_1(z)\right\}$$

$$= T_0(z) + \varepsilon|B|\cos(\omega t + \beta) \quad (4.7)$$

where,

$$|B| = |T_1(z)| \quad (4.8)$$

$$\beta = \arg T_1(z) \quad (4.9)$$

Skin friction:

The skin frictions τ_x and τ_y at the plate in the direction of primary and secondary velocities respectively are given by

$$\tau_x = \left.\frac{du}{dz}\right]_{z=0} = \tau_{x0} + \varepsilon|G|\cos(\omega t + \gamma) \quad (5.1)$$

$$\tau_y = \left.\frac{dv}{dz}\right]_{z=0} = \tau_{y0} + \varepsilon|G|\sin(\omega t + \gamma) \quad (5.2)$$

where,

$$|G| = |q_1'(0)| \quad (5.3)$$

$$\gamma = \arg\left\{q_1'(0)\right\} \quad (5.4)$$

$$\tau_{x0} = u_0'(0) \quad (5.5)$$

$$\tau_{y0} = v_0'(0) \quad (5.6)$$

Coefficient of heat transfer:

The rate of heat transfer in terms of Nusselt number from the plate to the fluid is given by

$$Nu = -\text{Real part of } \left(\frac{\partial T}{\partial z}\right)_{z=0}$$

$$= -\text{ Real part of } \left\{T_0'(0) + \varepsilon e^{i\omega t}T_1'(0)\right\}$$

$$= -T_0'(0) - \varepsilon\,\text{Real part of}\left\{e^{i\omega t}T_1'(0)\right\}$$

$$= -T_0'(0) - \varepsilon|H|\cos(\omega t + \delta)$$

where, $|H| = |T_1'(0)|$ (6.1)

$$\delta = \arg\left\{T_1'(0)\right\} \qquad (6.2)$$

7. Results and discussion:

In order to study the effects of magnetic field, rotation parameter and suction parameter on the flow and heat transfer characteristics, we have carried out numerical calculations for the amplitudes and the phase of the fluctuating parts of the skin frictions at the plate due to primary and secondary velocity fields, heat transfer amplitude and phase, Nusselt number at the plate for different values of the physical parameters involved. These values are plotted in figures 1-13.Our investigation is restricted to Pr=0.7(Prandtl number), which corresponds to air, E=.05(Eckert number) and $\omega t = \frac{\pi}{2}$, $\omega = 1$(frequency of oscillation). The values of the other parameters are chosen arbitrarily.

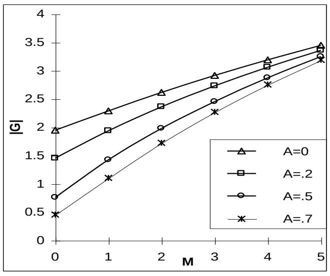

Figure 2: The skin friction amplitude |G| versus Hartmann number M for $\Omega = 5$

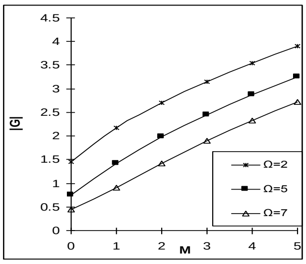

Figure 3: The skin friction amplitude |G| versus Hartmann number M for A=.5

Figure 2 and 3 demonstrate the variation of the amplitude of the perturbed part of the skin friction |G| against Hartmann number M under the influence of suction parameter A and rotation parameter Ω. These figures show that an increase in suction parameter A or rotation parameter Ω causes |G| (skin friction amplitude) to decrease whereas |G| increases significantly under the effect of applied magnetic field.

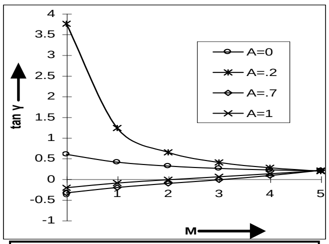

Figure 4: The skin friction phase $\tan\gamma$ versus Hartmann number M for $\Omega = 5$

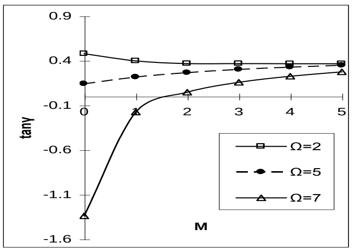

Figure 5: The skin friction phase $\tan\gamma$ versus Hartmann number M for A=.5

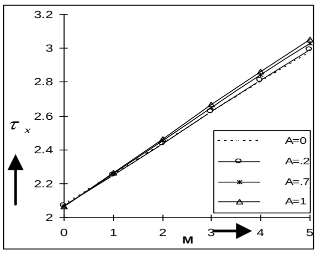

Figure 6: The skin friction τ_x due to primary velocity versus Hartmann number M for $\Omega = 5$

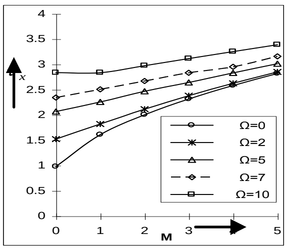

Figure 7: The skin friction τ_x due to primary velocity versus Hartmann number M for A=.5

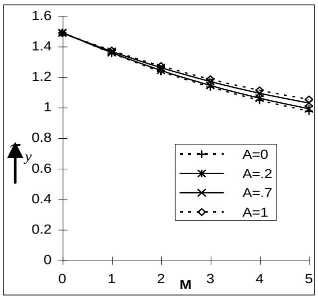

Figure 8: The skin friction τ_y due to secondary velocity versus Hartmann number M for $\Omega = 5$

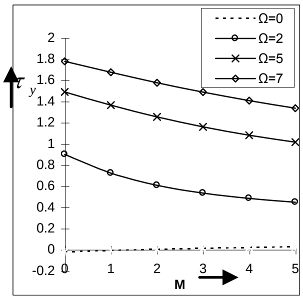

Figure 9: The skin friction τ_y due to secondary velocity versus Hartmann number for A=.5

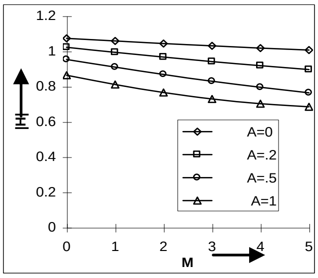

Figure 10: The heat transfer amplitude |H| versus Hartmann number M for $\Omega = 5$

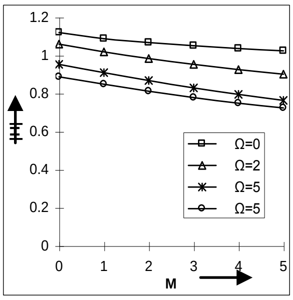

Figure 11: The heat transfer amplitude |H| versus Hartmann number M for A=.5

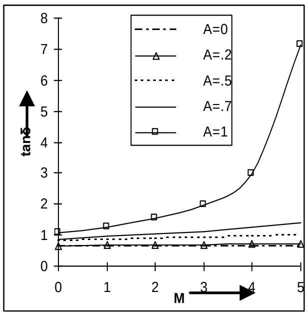

Figure 12: The heat transfer phase $\tan\delta$ versus Hartmann number M for $\Omega = 5$

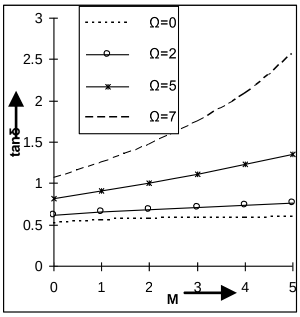

Figure 13: The heat transfer phase $\tan\delta$ versus Hartmann number M for A=.5

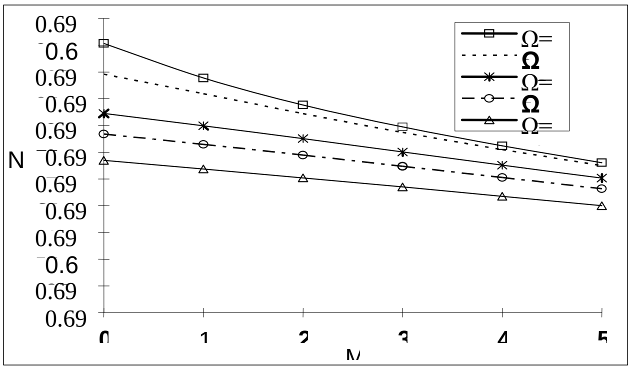

Figure 14: The Nusselt number Nu at the plate versus Hartmann number M for A=.5

The variation of the skin friction phase $\tan\gamma$ versus Hartmann number M is presented in figures 4 and 5. Figure 4 shows that for large suction parameter A, $\tan\gamma$ decreases as M increases and the rate of decrease of $\tan\gamma$ is very sharp for small M. For small and moderate values of A, the effect of M on $\tan\gamma$ is not so pronounced. The same figure further indicates that $\tan\gamma$ decrease as A increases and it is seen that for large M, $\tan\gamma$ is not significantly affected by A. In other words it may be stated that due to application of a strong magnetic field the effect of the suction parameter A on $\tan\gamma$ is uncountable. It is inferred from figure 5 that the rotation of the fluid ceases to act on $\tan\gamma$ when the strength of the applied transverse magnetic field is high.

Figure 6 and 7 demonstrate how the skin friction τ_x due to primary velocity is affected by the parameter M, A and Ω. It is clear from these two figures that there is a steady growth in τ_x under the effect of the magnetic field, suction parameter A and rotation parameter Ω. It signifies that the viscous drag on the plate in the direction of the free stream rises due to the application of the transverse magnetic field and under the effect of rotation and suction parameter.

The behavior of the skin friction τ_y due to secondary velocity under the influence of M, A and Ω is shown in figures 8 and 9. We observe from these two figures that viscous drag on the plate due to secondary velocity s reduced when the strength of the magnetic field as well as the suction parameter A is increased or the angular velocity of rotation of the fluid is decreased.

Figure 10 and 11 exhibit the behavior of the amplitude of the perturbed part of the heat transfer |H| at the plate under the effect of M, A and Ω. These figures clearly show that |H| falls under the effect of these parameters.

It is seen from figures 12 and 13 that there is a growth in the heat transfer phase $\tan\delta$ at the plate due to application of the transverse magnetic field or under the effect of rotation and suction parameters.

There is a clear indication from figures 14 that the Nusselt number Nu decreases when M or Ω are increased. In other words we can see that the rate of heat transfer from the plate to the fluid is reduced when a magnetic field is applied transversely to the flow or fluid is made to rotate about a normal to the plate.

Conclusions:

1. The applied magnetic field increases the amplitude of the perturbed part of the skin friction at the plate.
2. The viscous drag on the plate in the direction of the free stream rises due to application of the transverse magnetic field or under the effects of rotation and suction parameter.
3. The application of the magnetic field or suction or rotation causes the skin friction at the plate due to secondary velocity to decrease.

4 |H|, the amplitude of the perturbed part of the rate of heat transfer falls when the values of the parameters M, A and Ω are increased.

5. There is a reduction in the rate of heat transfer from the plate to the fluid due to application of the transverse magnetic field or rotation of the fluid about a normal to the plate.

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Appendix:

$$\lambda_1 = A_1 + iB_1, A_1 = \frac{1+X_1}{2}, B_1 = \frac{Y_1}{2},$$

$$X_1 = \sqrt{\frac{(1+4M) + \sqrt{16\Omega^2 + (1+4M)^2}}{2}},$$

$$Y_1 = \sqrt{\frac{\sqrt{16\Omega^2 + (1+4M)^2} - (1+4M)}{2}},$$

$$\lambda_2 = A_2 + iB_2, A_2 = \frac{1+X_2}{2}, B_2 = \frac{Y_2}{2},$$

$$X_2 = \sqrt{\frac{(1+4M)^2 + \sqrt{(1+4M)^2 + 16(\Omega+\omega)}}{2}},$$

$$Y_2 = \sqrt{\frac{\sqrt{(1+4M)^2 + 16(\Omega+\omega)} - (1+4M)}{2}},$$

$$L_1 = X_4 + iY_4, X_4 = \frac{A_1X_3 + B_1Y_3}{X_3^2 + Y_3^2}, \qquad Y_4 = \frac{B_1X_3 - A_1Y_3}{X_3^2 + Y_3^2},$$

$$X_3 = A_1^2 - B_1^2 - A_1 - M,$$

$$Y_3 = 2A_1B_1 - B_1 - \Omega - \omega,$$

$$\lambda_3 = A_3 + iB_3, A_3 = \frac{P+X_5}{2}, B_3 = \frac{Y_5}{2},$$

$$X_5 = \sqrt{\frac{P^2 + \sqrt{P^4 + 16P^2\omega^2}}{2}}, Y_5 = \sqrt{\frac{-P^2 + \sqrt{P^4 + 16P^2\omega^2}}{2}},$$

$$L_5 = X_{10} + iY_{10},$$

$$X_{10} = \frac{X_6X_9 + Y_6Y_9}{X_9^2 + Y_9^2}, Y_{10} = \frac{X_9Y_6 - X_6Y_9}{X_9^2 + Y_9^2}, X_9 = X_7^2 - Y_7^2 + X_8$$

$$, Y_9 = Y_8 - 2X_7Y_7, X_8 = -P(A_1 + A_2), Y_8 = P(B_1 - B_2 - \omega),$$

$$X_7 = (A_1 + A_2), \; Y_7 = (B_1 - B_2),$$

$$X_6 = A_1A_2 + B_1B_2, Y_6 = A_1B_2 - A_2B_1,$$

$$L_6 = X_{12} + iY_{12}, X_{12} = \frac{X_6X_{11} - Y_6Y_{11}}{X_{11}^2 + Y_{11}^2},$$

$Y_{12}=\dfrac{-\left(X_6Y_{11}+Y_6X_{11}\right)}{X_{11}^{\,2}+Y_{11}^{\,2}}$, $X_{11}=X_7^{\,2}-Y_7^{\,2}+X_8$, $Y_{11}=2X_7Y_7-Y_8$,

$L_7=X_{14}+iY_{14}$,

$X_{14}=\dfrac{A_1^{\,2}X_{13}+B_1^{\,2}X_{13}}{X_{13}^{\,2}+Y_{13}^{\,2}}$, $Y_{14}=\dfrac{A_1^{\,2}Y_{13}+B_1^{\,2}Y_{13}}{X_{13}^{\,2}+Y_{13}^{\,2}}$,

$X_{13}=2A_1^{\,2}-PA_1$, $Y_{13}=P\omega$,

$L_8=X_{16}+iY_{16}$, $X_{16}=\dfrac{X_{10}X_{15}+Y_{10}Y_{15}}{X_{15}^{\,2}+Y_{15}^{\,2}}$, $Y_{16}=\dfrac{Y_{10}X_{15}-X_{10}Y_{15}}{X_{15}^{\,2}+Y_{15}^{\,2}}$,

$X_{15}=A_1A_2+B_1B_2$,

$Y_{15}=A_1B_2-A_2B_1$, $L_9=X_{18}+iY_{18}$, $X_{18}=\dfrac{X_{12}X_{17}+Y_{12}Y_{17}}{X_{17}^{\,2}+Y_{17}^{\,2}}$,

$Y_{18}=\dfrac{X_{17}Y_{12}-X_{12}Y_{17}}{X_{17}^{\,2}+Y_{17}^{\,2}}$, $X_{17}=A_1A_2+B_1B_2$,

$Y_{17}=A_2B_1-A_1B_2$, $L_{10}=X_{19}+iY_{19}$, $X_{19}=\dfrac{X_{14}}{A_1^{\,2}+B_1^{\,2}}$,

$Y_{19}=\dfrac{Y_{14}}{A_1^{\,2}+B_1^{\,2}}$, $L_{11}=X_{20}+iY_{20}$,

$X_{20}=A_1X_{19}$, $Y_{20}=A_1Y_{19}$, $L_{12}=X_{26}+iY_{26}$,

$X_{26}=EPX_{25}$, $Y_{26}=EPY_{25}$, $X_{25}=X_{23}+MX_{24}$, $Y_{25}=Y_{23}+MY_{24}$,

$X_{24}=X_{16}-AX_{22}$, $Y_{24}=Y_{16}-AY_{22}$, $X_{23}=X_{10}-AX_{21}$, $Y_{23}=Y_{10}-AY_{21}$,

$X_{22}=X_4X_{16}-Y_4Y_{16}$, $Y_{22}=X_4Y_{16}+Y_4X_{16}$, $X_{21}=X_4X_{10}-Y_4Y_{10}$,

$Y_{21}=Y_4X_{10}+X_4Y_{10}$, $L_{13}=X_{32}+iY_{32}$, $X_{32}=EPX_{31}$, $Y_{32}=EPY_{31}$,

$X_{31}=X_{29}+MX_{30}$, $Y_{31}=Y_{29}+MY_{30}$, $X_{30}=X_{18}-AX_{28}$,

$Y_{30}=Y_{18}-AY_{28}$,

$X_{29}=X_{12}-AX_{27}$, $Y_{29}=Y_{12}-AY_{27}$, $X_{28}=X_4X_{18}-Y_4Y_{18}$,

$Y_{28}=X_4Y_{18}+X_{18}Y_4$,

$X_{27}=X_4X_{12}-Y_4Y_{12}$, $Y_{27}=X_4Y_{12}+X_{12}Y_4$, $L_{14}=X_{36}+iY_{36}$,

$X_{36}=EP\left(AX_{33}+MAX_{34}+X_{35}\right)$, $Y_{36}=EP\left(AY_{33}+MAY_{34}+Y_{35}\right)$,

$X_{35}=PAL_4X_{20}$, $Y_{35}=PAL_4Y_{20}$, $X_{34}=X_4X_{19}-Y_4Y_{19}$,

$Y_{34}=X_4Y_{19}+Y_4X_{19}$,

$X_{33}=X_4X_{14}-Y_4Y_{14}$, $Y_{33}=X_4Y_{14}+Y_4X_{14}$, $L_{15}=-iX_{37}$,

$X_{37}=\dfrac{AP\left(1+EPL_4\right)}{\omega}$.