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Unsteady Magnetohydrodynamic Flow and Heat Transfer From a rotating wall

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Abstract

The importance of the effects of rotation and electromagnetic force on the hydrodynamic flow and their application to cosmical fluid dynamics and solar physics have drawn attention of many research workers recently. In this paper we have investigated unsteady magnetohydrodynamic flow and heat transfer from a rotating wall. The wall is taken electrically non-conducting and whole system is rotating with a constant angular velocity about an axis normal to the wall. A constant induced magnetic field has been included. The temperature distribution with distance is shown Graphically.

Key words : Magnetohydrodynamic, Unsteady flow, Rotating wall, Temperature distribution, Heat Transfer.

1. Introduction

The importance of the effects of rotation and electromagnetic force on the hydromagnetic flow and their applications to cosmical fluid dynamics and solar physics have drawn attention of many research workers recently. In order to investigate the effects of rotation on the hydromagnetic flow phenomena and in order to examine the structures of the associated boundary layers, the initial value investigation of the Stokes and Ekman problems in the presence of a magnetic field are of considerable interest in geophysical and cosmical fluid dynamics.

Hide and Roberts⁹ have made a steady state analysis of the hydromagnetic flow induced in a viscous incompressible rotating conducting fluid in the presence of a magnetic field by the harmonic oscillation of an infinite rigid wall. Thornely¹³ studied unsteady non-magnetic case of the above problem with rotating fluid. Debnath²⁻⁶ has made a major contribution to the unsteady hydrodynamic and hydromagnetic boundary layer flows with or without Hall current effects in a rotating viscous fluid system. His initial value investigations into these problems have provided many new and interesting information on the steady-state and transient flows, the structure of the boundary layers and the propagation of a series of inertial oscillations and diffused hydromagnetic waves.

Despite of these studies, the effects of the free convection and of the viscous dissipation on the hydromagnetic boundary layer flows received much less attention. However, the effects seem to be important and play interesting roles on the flows. Agarwal, Ram and Singh¹ studied the combined influence of dissipation and Hall effects on free convective flow in a rotating fluid. Gupta⁸ has studied an exact solution for the steady-state three dimensional Navier-Stokes equations for the flow past a plate with uniform suction in a rotating coordinate system. Debnath and Mukherjee⁷ have studied the motion of an incompressible homogeneous viscous fluid bounded by porous plates with uniform suction (blowing). Both the fluid and the plates are in a state of solid body rotation with constant angular velocity Ω about z -axis normal to the plate and additionally a non-torsional oscillation of a given frequency ω is imposed on the plate for generation of unsteady flow in a rotating system. Kishore, Tejpal and Tiwary¹⁰ considered the hydrodynamic flow past an accelerated porous plate in rotating system. Kumar and Varshney¹¹ studied the unsteady viscous flow through porous medium past an oscillating plate in rotating system.

Murthy and Sapre¹² studied the effect of magnetic field on laminar boundary layer flow on a flat plate. They found that the effect of magnetic field has a decreasing effect on the component of the velocity which is parallel to the plate while the magnetic field has the effect of increasing displacement thickness.

Takhar, Singh, and Nath¹⁴ explored unsteady MHD flow and heat transfer on a rotating disk in an ambient fluid, providing valuable insights into the dynamic interactions between magnetic fields and fluid motion. Khan *et al.*,¹⁵ conducted a numerical study addressing unsteady MHD flow and entropy generation in a rotating permeable channel with slip and Hall effects, contributing to the understanding of complex transport phenomena in magnetized flows. Waini *et al.*¹⁶ extended the

exploration to hybrid ferrofluids, investigating unsteady MHD flow due to a rotating disk and shedding light on the unique characteristics of hybrid magnetic fluids. Additionally, Krishna¹⁷ delved into the impact of Hall effects on magnetohydrodynamic rotating flow through a porous medium in a parallel plate channel, considering various oscillations of pressure gradient, further enriching the literature on MHD-related phenomena in porous environments.

In this Paper, we have investigated rotating MHD viscous flow past a wall. The wall is taken electrically non-conducting. The whole system is rotating with a constant angular velocity about an axis normal to the wall. A constant magnetic field is applied normal to the wall. The problem has been solved using Laplace transform technique.

2. Basic equations and formulation of the problem :

The wall is considered in $x-z$ plane, z -axis being in the vertical direction. Let us consider the unsteady free convection flow of a viscous incompressible electrically conducting fluid past the rotating wall. The whole system is rotating with a constant angular velocity Ω about y -axis, taken normal to the wall. A uniform magnetic field B_0 is imposed in y -direction. The wall is taken electrically non-conducting. As the wall is infinite in extent and flow is unsteady, the physical variables are functions of y and t only. Let the temperature of the wall $T_w = T_\infty + T_0 f(t) H(t)$ where $H(t)$ is Heaviside step function, $f(t)$ is a function of time, T_0 is a constant temperature and T_∞ is the temperature of the fluid. The equation of continuity $\nabla \cdot \vec{q} = 0$, gives on integration $v = -v_0$ ($v_0 > 0$) where $\vec{q} = (u, v, w)$. The induced magnetic field has to be assumed negligible so that $\vec{B} = (0, B_0, 0)$.

The equations governing the motion under the usual Boussinesq's approximation are:
Momentum Equations

$$\rho \left[\frac{\partial u}{\partial t} - v_0 \frac{\partial u}{\partial y} + 2\Omega w \right] = \mu \frac{\partial^2 u}{\partial y^2} - \sigma B_0^2 u \quad (1)$$

$$\rho \left[\frac{\partial w}{\partial t} - v_0 \frac{\partial w}{\partial y} - 2\Omega u \right] = \mu \frac{\partial^2 w}{\partial y^2} + \rho g \beta (T - T_\infty) - \sigma B_0^2 w \quad (2)$$

Energy Equation (Neglecting the heat generated by dissipation and joule heating effect)

$$\rho C_p \left[\frac{\partial T}{\partial t} - v_0 \frac{\partial T}{\partial y} \right] = k \frac{\partial^2 T}{\partial y^2} \quad (3)$$

The initial and boundary conditions are:

$$\begin{aligned} t \leq 0 : u = 0 = w, T &= T_\infty \\ t > 0 : y = 0; u = 0 = w, T &= T_\infty + T_0 f(t) \\ t > 0 : y \rightarrow \infty; u \rightarrow 0, w \rightarrow 0, T &\rightarrow T_\infty \end{aligned} \quad (4)$$

3. Solution of the Problem :

Let us introduce the following non-dimensional variables:

$$\begin{aligned} t' &= \frac{tv_0^2}{\nu}, y' = \frac{yv_0}{\nu}, u' = \frac{u}{v_0}, w' = \frac{w}{v_0}, \theta = \frac{T - T_\infty}{T_0} \\ \Omega' &= \frac{\Omega\nu}{v_0^2} \\ G(\text{Grashoff number}) &= \frac{\nu g \beta T_0}{v_0^3} \\ M(\text{Hartmann number}) &= \sqrt{\frac{\sigma B_0^2 \nu^2}{\mu v_0^2}} \\ \text{Pr}(\text{Prandtl number}) &= \frac{\mu C_p}{k} \end{aligned} \quad (5)$$

On introducing the above non-dimensional variables, the equations (1) to (3) reduce to the following equations, respectively (on dropping primes)

$$\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} + 2\Omega w = \frac{\partial^2 u}{\partial y^2} - M^2 u \quad (6)$$

$$\frac{\partial w}{\partial t} - \frac{\partial w}{\partial y} - 2\Omega u = \frac{\partial^2 w}{\partial y^2} + G\theta - M^2 w \quad (7)$$

$$\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial y} = \frac{1}{\text{Pr}} \frac{\partial^2 \theta}{\partial y^2} \quad (8)$$

The initial and Boundary conditions reduce to (on dropping primes)

$$\begin{aligned} t \leq 0 : u &= 0 = w, \theta = 0 \\ t > 0 : y &= 0; u = 0 = w, \theta = F(t) \\ t > 0 : y &\rightarrow \infty; u \rightarrow 0, w \rightarrow 0, \theta \rightarrow 0 \end{aligned} \quad (9)$$

$$\text{Where } F(t) = f\left(\frac{\nu t}{v_0^2}\right)$$

We introduce $q = u + iw$, then from equations (6) and (7), we get

$$\frac{\partial q}{\partial t} - \frac{\partial q}{\partial y} - 2i\Omega q = \frac{\partial^2 q}{\partial y^2} + iG\theta - M^2 q \quad (10)$$

The corresponding initial and boundary conditions are

$$\begin{aligned} t \leq 0 : q &= 0, \theta = 0 \\ t > 0 : y &= 0; q = 0, \theta = F(t) \\ t > 0 : y &\rightarrow \infty; q \rightarrow 0, \theta \rightarrow 0 \end{aligned} \quad (11)$$

Under the application of Laplace transform, equation (8) and conditions (11) reduce to

$$\frac{d^2 \bar{\theta}}{dy^2} + \text{Pr} \frac{d\bar{\theta}}{dy} - s \text{Pr} \bar{\theta} = 0 \quad (12)$$

And

$$\begin{aligned} y = 0, \bar{\theta} &= \bar{F}(s) \\ y \rightarrow \infty, \bar{\theta} &\rightarrow 0, \end{aligned} \quad (13)$$

$$\text{Where } \bar{\theta} = \int_0^{\infty} e^{-st} \theta dt$$

The solution of (12) with the help of (13) is given by

$$\begin{aligned} \bar{\theta} &= \bar{F}(s) e^{-\left(\frac{\text{Pr} + \sqrt{\text{Pr}^2 + 4s \text{Pr}}}{2}\right)y} \\ &= e^{-\frac{\text{Pr} y}{2}} \bar{F}(s) e^{\left\{-\sqrt{\text{Pr}} y \left(s + \frac{1}{4} \text{Pr}\right)^{1/2}\right\}} \end{aligned} \quad (14)$$

$$\text{If } F(t) = 1, \text{ then } \bar{F}(s) = \frac{1}{s}$$

$$\bar{\theta} = e^{-\text{Pr} y / 2} \frac{1}{s} e^{\left\{-\sqrt{\text{Pr}} y \sqrt{s + \frac{1}{4} \text{Pr}}\right\}}$$

We know that

$$\begin{aligned} L^{-1} \left[\exp(-\sqrt{\text{Pr}} \sqrt{s + \frac{\text{Pr}}{4}} y) \right] &= e^{-\frac{1}{4} \text{Pr} t} L^{-1} \left[\exp(-\sqrt{\text{Pr}} y \sqrt{s}) \right] \\ &= \frac{1}{2} \sqrt{\frac{\text{Pr}}{\pi}} \frac{y}{t^{3/2}} \exp \left\{ -\frac{1}{4} \text{Pr} t - \frac{\text{Pr} y^2}{4t} \right\} \end{aligned}$$

With the application of convolution theorems

$$\theta = \frac{1}{2} \sqrt{\frac{\text{Pr}}{\pi}} y e^{-\text{Pr} y / 2} \int_0^t \frac{F(t-\eta) \exp \left[-\frac{1}{4} \text{Pr} t - \frac{\text{Pr} y^2}{4t} \right]}{\eta^{3/2}} d\eta$$

If $\bar{F}(s) = \frac{1}{s}$, then

$$\begin{aligned} L^{-1} \left[\frac{1}{s} \exp \left\{ -\sqrt{\text{Pr}} y \left(s + \frac{1}{4} \text{Pr} \right)^{1/2} \right\} \right] &= L^{-1} \left[\frac{\exp \left\{ -\sqrt{\text{Pr}} y \left(s + \frac{\text{Pr}}{4} \right)^{1/2} \right\}}{\left(s + \frac{\text{Pr}}{4} \right) - \frac{\text{Pr}}{4}} \right] \\ &= L^{-1} \left[\frac{\exp \left\{ -\sqrt{\text{Pr}} y \left(s + \frac{1}{4} \text{Pr} \right)^{1/2} \right\}}{s} \right] \\ &= e^{-\frac{\text{Pr}}{4} t} L^{-1} \left[\frac{\exp(-\sqrt{\text{Pr}} y \sqrt{s})}{s - \frac{1}{4} \text{Pr}} \right] \end{aligned}$$

Using these results, we obtain

$$\theta = \frac{1}{2} \left[e^{-\text{Pr} y} \text{Erfc} \left(\frac{1}{2} \frac{\sqrt{\text{Pr}} y}{\sqrt{t}} - \frac{1}{2} \sqrt{\text{Pr} t} \right) + \text{Erfc} \left(\frac{\sqrt{\text{Pr}}}{2\sqrt{t}} y + \frac{1}{2} \sqrt{\text{Pr} t} \right) \right] \quad (15)$$

Where $\text{Erfc}(x) = 1 - \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-u^2} du$.

Taking Laplace transform, equation (10) and the conditions (11) reduce to

$$\frac{d^2 \bar{q}}{dy^2} + \frac{d\bar{q}}{dy} + (2i\Omega - s - M^2) \bar{q} = -iG\bar{\theta} \quad (16)$$

Where $\bar{q} = \int_0^\infty q e^{-st} dt$

And

$$\begin{aligned} y = 0 : \bar{q} &= 0 \\ y \rightarrow \infty : \bar{q} &\rightarrow 0 \end{aligned} \quad (17)$$

Solving (16) and using conditions (17), we get

$$\begin{aligned}
\bar{q} &= \frac{iG\bar{F}(s) \left[e^{-\left(\frac{1+\sqrt{1+4s+4M^2-8i\Omega}}{2}\right)y} - e^{-\left(\frac{\text{Pr}+\sqrt{\text{Pr}^2+4s\text{Pr}}}{2}\right)y} \right]}{\left(\frac{\text{Pr}+\sqrt{\text{Pr}^2+4s\text{Pr}}}{2}\right)^2 - \left(\frac{\text{Pr}+\sqrt{\text{Pr}^2+4s\text{Pr}}}{2}\right) + 2i\Omega - s - M^2} \\
&= \frac{2iG\bar{F}(s) \left[e^{-y/2} e^{-y\sqrt{s+\frac{1}{4}+M^2-2i\Omega}} - e^{-\frac{\text{Pr}y}{2}} e^{-\sqrt{\text{Pr}y}\sqrt{s+\frac{\text{Pr}}{4}}} \right]}{\text{Pr}(\text{Pr}-1) + 2(\text{Pr}-1)s + (\text{Pr}-1)\sqrt{\text{Pr}^2+4s\text{Pr}} + 2(2i\Omega - M^2)} \quad (18)
\end{aligned}$$

If $\bar{F}(s) = \frac{1}{s}$ then

$$\bar{q} = \frac{2iG \left[e^{-y/2} e^{-y\sqrt{s+\frac{1}{4}+M^2-2i\Omega}} - e^{-\frac{\text{Pr}y}{2}} e^{-\sqrt{\text{Pr}y}\sqrt{s+\frac{\text{Pr}}{4}}} \right]}{s \left\{ \text{Pr}(\text{Pr}-1) + 2(\text{Pr}-1)s + (\text{Pr}-1)\sqrt{\text{Pr}^2+4s\text{Pr}} + 2(2i\Omega - M^2) \right\}} \quad (19)$$

For $\text{Pr} = 1$

$$\bar{q} = \frac{iG}{2i\Omega - M^2} \left[\frac{e^{-y/2} e^{-y\sqrt{s+\frac{1}{4}+M^2-2i\Omega}} - e^{-\frac{y}{2}} e^{-y\sqrt{s+\frac{1}{4}}}}{s} \right] \quad (20)$$

Applying the inverse Laplace transform to equation (20), we obtain

$$q(y, t) = \frac{iGe^{-y/2}}{2(2i\Omega - M^2)} \left[\frac{e^{-y\sqrt{a}} \text{erfc}\left(\frac{y}{2\sqrt{t}} - \sqrt{at}\right) + e^{y\sqrt{a}} \text{erfc}\left(\frac{y}{2\sqrt{t}} + \sqrt{at}\right)}{-e^{y/2} \text{erf}\left(\frac{y}{2\sqrt{t}} + \frac{\sqrt{t}}{2}\right) - e^{-y/2} \text{erfc}\left(\frac{y}{2\sqrt{t}} - \frac{\sqrt{t}}{2}\right)} \right] \quad (21)$$

Where $a = \frac{1}{4} + M^2 - 2i\Omega$

For arbitrary values of y , inversion of (19) can be obtained for small and large values of time t . For large values of t i.e. s we have

$$\bar{q} : \frac{iG}{\text{Pr}-1} \left[\frac{e^{-y/2} e^{-y\sqrt{s}} - e^{-\text{Pr}y/2} e^{-\sqrt{\text{Pr}y}\sqrt{s}}}{s^2} \right] \quad (22)$$

Applying the inverse Laplace to (22), we get

$$q : \frac{iG}{Pr-1} \left[\begin{array}{l} e^{-y/2} \left\{ \left(\frac{y^2}{2} + t \right) \operatorname{erfc} \left(\frac{y}{2\sqrt{t}} \right) - \frac{y\sqrt{t}}{\sqrt{\pi}} e^{-y^2/4t} \right\} \\ -e^{-Pr y/2} \left\{ \left(\frac{Pr y^2}{2} + t \right) \operatorname{erfc} \left(\frac{\sqrt{Pr} y}{2\sqrt{t}} \right) - \frac{\sqrt{Pr} y \sqrt{t}}{\sqrt{\pi}} e^{-Pr y^2/4t} \right\} \end{array} \right] \quad (23)$$

$$t > 0$$

For small values of s equation (19) reduces to

$$\bar{q} : \frac{iG}{2(Pr-1)} \left[\frac{e^{-y/2} e^{-y\sqrt{s+a}} - e^{-\frac{Pr y}{2}} e^{-\sqrt{Pr} y \sqrt{s+\frac{Pr}{4}}}}{s(s+b)} \right]$$

Where $b = \frac{Pr}{2} + \frac{2i\Omega - M^2}{2(Pr-1)}$

$$q(y,t) : \frac{iG}{4b(Pr-1)} \left[\begin{array}{l} e^{-y/2} \left\{ e^{y\sqrt{a}} \operatorname{erfc} \left(\frac{y}{2\sqrt{t}} + \sqrt{at} \right) + e^{-y\sqrt{a}} \operatorname{erfc} \left(\frac{y}{2\sqrt{t}} - \sqrt{at} \right) \right. \\ \left. - e^{-bt} e^{\sqrt{a-by}} \operatorname{erfc} \left(\frac{y}{2\sqrt{t}} + \sqrt{(a-b)t} \right) - e^{-bt} e^{-\sqrt{a-by}} \operatorname{erfc} \left(\frac{y}{2\sqrt{t}} - \sqrt{(a-b)t} \right) \right\} \\ + e^{-Pr y/2} \left\{ e^{\sqrt{\frac{Pr}{4}-b}\sqrt{Pr} y} \operatorname{erfc} \left(\frac{y\sqrt{Pr}}{2\sqrt{t}} + \sqrt{t}\sqrt{\frac{Pr}{4}-b} \right) \right. \\ \left. + e^{-bt} e^{-\sqrt{\frac{Pr}{4}-b}\sqrt{Pr} y} \operatorname{erfc} \left(\frac{y\sqrt{Pr}}{2\sqrt{t}} - \sqrt{t}\sqrt{\frac{Pr}{4}-b} \right) \right. \\ \left. - e^{\frac{yPr}{2}} \operatorname{erfc} \left(\frac{y\sqrt{Pr}}{2\sqrt{t}} + \frac{\sqrt{Pr} t}{2} \right) - e^{-\frac{Pr y}{2}} \operatorname{erfc} \left(\frac{y\sqrt{Pr}}{2\sqrt{t}} - \frac{\sqrt{Pr} t}{2} \right) \right\} \end{array} \right] \quad (24)$$

$$t > 0$$

4. Conclusion

The velocity distribution includes the parameters Hartmann number M , Constant angular velocity Ω , Prandtl number Pr , Grashoff number G and t . (Equation 21) While temperature distribution includes parameters Pr , t (Equation 15). These solutions were numerically interpreted for various values of the parameters involved. The results so obtained have been displayed by graph Figure 1. Figure 1 shows that the non-dimensional temperature θ is maximum at the wall and decreases with the increase in distance from the wall.

Scope of Future work : Explore advanced mathematical models to capture additional complexities in the interaction between rotation, electromagnetic forces, and magnetohydrodynamic flows, refining the understanding of cosmical fluid dynamics. Extend the study to analyze the system in multiple dimensions, considering three-dimensional effects to better represent real-world scenarios in cosmical fluid dynamics.

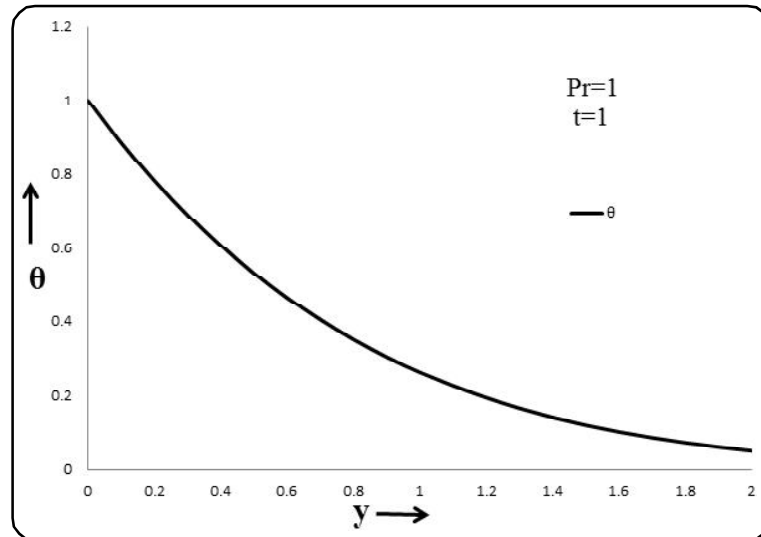


Fig. 1 θ vs y

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