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Hydromagnetic Free Convection Flow of Oscillating Viscus Liquid with Heat and Mass Transfer in Rotating System

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ABSTRACT: In this paper quest the unsteady free convection oscillating flow due to heat and mass transfer bounded by an infinite vertical porous plate in rotating system under the influence of a uniform transverse magnetic field of constant strength is studied. The fluid and the plate are in a state of solid body rotation with uniform angular velocity. The temperature and concentration at the plate are assumed oscillatory with time about a uniform non-zero mean. The problem is solved by using a regular expansion technique for small value of frequency parameter. Approximate solutions for the primary and secondary velocity, temperature and concentration fields are obtained. Expressions for skin-friction at the plate due to primary velocity and secondary velocity, rate of heat and mass transfer are also derived. Numerical calculations are carried out for different values of parameters shown through tables .

I. INTRODUCTION

Free convection oscillating flow is in fact the transport of energy resulting from a distributed force arising from variation of density of the fluid . Such a flow in porous medium, is one of the most interesting subject matter because of its wide applications in many industrial problems particularly in oil-refinery , chemical and nuclear industry. Such type of applications includes natural circulation in isothermal reservoir, aquifers, porous insulation, grain storage extraction of geothermal energy and thermal insulation design. The magnetic effects can also be vitally used in power generation.

Several buoyancy driven boundary layer flow have been studied by Cheng [1977, 1977], Debnath [1979], Raptis et. al. [1981, 82] etc. Oscillatory flow through porous medium has been analysed by Raptis [1983] for small amplitude of oscillations only. To over come this restriction Singh et. al. [1989] have analysed MHD flow through a porous medium by the presence of free stream velocity. Hossian et. al. [1998] have studied the effects of dust particles on the flow of incompressible fluid in a rotating system. Singh et. al. [2001] have studied effects of Hall current on unsteady hydromagnetic boundary layer flow in rotating dusty viscous liquid while Sharma et. al. [2001] have studied thermosolutal convection in Rivlin-Ericksen rotating flow in porous medium under transverse magnetic field. Recently, Takhar et. al. [2003] have studied unsteady mixed convection flow from a rotating vertical cone with a magnetic field, heat and mass transfer. More recently, Gupta et. al. [2005] have analysed free convection heat and mass transfer flow through a porous medium with heat source / sink under the influence of magnetic field.

The aim of the present investigation is to study the MHD unsteady free convection flow due to heat and mass transfer bounded by an infinite vertical porous plate under rotating system. Considering the fluid and the plate are in a state of solid body rotation with constant angular velocity, the problem of Kumar Ashish and Singh Atul . [2007] and is extended. Approximate solutions for the primary and secondary velocity, temperature and concentration fields are obtained. Expressions for skin-friction at the plate due to primary velocity and secondary velocity, rate of heat and mass transfer are also derived. The results obtained are discussed through tables and graphs.

II. FORMULATION OF THE PROBLEM

Consider oscillatory viscous flow of an incompressible, electrically conducting, viscous liquid past an infinite plate which is hot, vertical porous with constant heat source. In Cartesian coordinate (x, y, z) system in presence of uniform magnetic field. We assume x-axis and y-axis in the plane of the porous plate and z-axis

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normal to the plate with velocities (u,v,w) in these directions respectively. Both the liquid and the plate are considered in a state of rigid body rotation about z-axis with uniform angular velocity Ω. Further we assume that the uniform magnetic field $\overrightarrow{B_0} = \mu_e \overrightarrow{H}$ where $\overrightarrow{H} = (0,0,H_0)$ is applied in the z direction and the magnetic Reynolds number is assume small. The constant heat source Q is assumed at $z=0$ and the suction velocity at the plate is $w = -w_0\left(1+\varepsilon e^{\text{int}}\right)$ where w_0 and n are positive real numbers. In this analysis buoyancy force, Hall effect, effect due to perturbation of the field, induced magnetic field and polarization effect are ignored. Since the plate is infinite in extant, all physical variables depends on z and t only. Initially, when $t \le 0$ the plate and the fluid are assumed to be at the same temperature T_∞ and the foreign mass is assumed to be uniformly distributed in the flow region such that it is everywhere C_∞. At $t > 0$, the temperature of the plate is instantaneously raised to T_w and the concentration of species is raised to C_w and temperature maintained constant. Under the above stated assumptions and usual Bossiness's approximation the equations of motion are :

$$\frac{\partial u}{\partial t} - w\frac{\partial u}{\partial z} - 2\Omega v = \vartheta\frac{\partial^2 u}{\partial z^2} + g\beta\left(T-T_\infty\right) + g\beta^*\left(C-C_\infty\right) - \frac{\sigma\mu_e^2 H_0^2}{\rho}u \tag{1}$$

$$\frac{\partial v}{\partial t} - w\frac{\partial v}{\partial z} + 2\Omega u = \vartheta\frac{\partial^2 v}{\partial z^2} - \frac{\sigma\mu_e^2 H_0^2}{\rho}v \tag{2}$$

$$\frac{\partial T}{\partial t} - w\frac{\partial T}{\partial z} = \frac{\partial^2 T}{\partial z^2} + Q\left(T-T_\infty\right) \tag{3}$$

$$\frac{\partial C}{\partial t} - w\frac{\partial C}{\partial z} = D_M\frac{\partial^2 C}{\partial z^2} \tag{4}$$

For suction velocity, we have

$$w = -w_0\left(1+\varepsilon e^{\text{int}}\right) \tag{5}$$

where g is the acceleration due to gravity, β is the volumetric coefficient of the thermal expansion, $\beta*$ is the volumetric coefficient with concentration, σ is the electrical conductivity of the liquid, ρ is the density of the liquid, μ_e is the magnetic permeability, H_0 is the constant magnetic field, T is the temperature, C is the concentration, D_M is the molecular diffusivity and the other symbols have their usual meaning.

The boundary conditions relevant to the problem are :

$$u=0,\ v=0,\ T=T_w+\varepsilon\left(T_w-T_\infty\right)e^{int},$$
$$C=C_w+\varepsilon\left(C_w-C`_\infty\right)e^{int} \quad \text{at} \quad z=0$$
$$u\to 0,\ v\to 0,\ T\to T_\infty,\quad C\to C_\infty \quad \text{as} \quad z\to\infty \tag{6}$$

We introduce the following non-dimensional quantities :

$$u^* = \frac{u}{w_0 FG},\quad v^* = \frac{v}{w_0 FG},\quad T^* = \frac{T-T_\infty}{\left(T_w-T_\infty\right)F},\quad C^* = \frac{C-C_\infty}{\left(C_w-C_\infty\right)F},$$

$$z^* = \frac{w_0 z}{w},\qquad t^* = nt,\qquad n^* = \frac{nW}{w_0^2}$$

Introducing above non-dimensional variables, the equations (1)-(4), after ignoring the stars over them, reduce to :

$$\frac{\partial^2 u}{\partial z^2}+\frac{\partial u}{\partial z}-n\left(\frac{\partial u}{\partial t}+u\frac{F'}{F}\right)+T+CN-M^2u+2\Omega v=0 \tag{7}$$

$$\frac{\partial^2 v}{\partial z^2}+\frac{\partial v}{\partial z}-n\left(\frac{\partial v}{\partial t}+v\frac{F'}{F}\right)-M^2v-2\Omega u=0 \tag{8}$$

$$\frac{1}{S_c}\frac{\partial^2 C}{\partial z^2}+\frac{\partial C}{\partial z}-n\left(\frac{\partial C}{\partial t}+C\frac{F'}{F}\right)=0 \tag{9}$$

$$\frac{1}{P_r}\frac{\partial^2 T}{\partial z^2}+\frac{\partial T}{\partial z}-n\left(\frac{\partial T}{\partial t}+T\frac{F'}{F}\right)+ST=0 \tag{10}$$

Now using $q=u+iv$ in the equations (7)-(8), we get :

$$\frac{\partial^2 q}{\partial z^2}+\frac{\partial q}{\partial z}-n\left(\frac{\partial q}{\partial t}+q\frac{F'}{F}\right)-M^2q+2i\Omega q+T+CN=0 \tag{11}$$

The boundary conditions (6) are transformed to :

$$q=0,\quad T=1,\quad C=1 \quad \text{at} \quad z=0$$
$$q\to 0,\quad T\to 0,\quad C\to 0 \quad \text{as} \quad z\to\infty \tag{12}$$

where $F=1+\varepsilon e^{\text{int}}$, $N=\dfrac{G_m}{G_r}$, $G_r=\dfrac{vg\beta\left(T_w-T_\infty\right)}{w_0^3}$ (Grashof Number),

$G_m=\dfrac{vg\beta^*\left(C_w-C_\infty\right)}{w_0^3}$ (Modified Grashof number), $S_c=\dfrac{\vartheta}{D}$ (Schmidt number)

$M=\dfrac{\mu_e H_0}{w_0}\sqrt{\dfrac{\sigma\vartheta}{\rho}}$ (Hartmann number)

and $S=\dfrac{\vartheta Q}{w_0^2}$ (Heat source parameter)

III. SOLUTION OF THE PROBLEM

To solve the problem, we can express $q(z,t)$, $T(z,t)$ and $C(z,t)$ in the power series of n in the form :

$$q(z,t)=q_0(z)+\sum_{r=1}^{\infty} n^r q_r(z,t)$$
$$C(z,t)=C_0(z)+\sum_{r=1}^{\infty} n^r C_r(z,t)$$
$$T(z,t)=T_0(z)+\sum_{r=1}^{\infty} n^r T_r(z,t) \tag{13}$$

Using the expressions in (13) into (9)-(11), we get the following set of equations:

$$\frac{1}{P_r}\frac{\partial^2 T_0}{\partial z^2}+\frac{\partial T_0}{\partial z}+ST_0=0 \tag{14}$$

$$\frac{1}{P_r}\frac{\partial^2 T_1}{\partial z^2}+\frac{\partial T_1}{\partial z}+ST_1=\frac{F'}{F}T_0(z) \tag{15}$$

$$\frac{1}{P_r}\frac{\partial^2 T_2}{\partial z^2}+\frac{\partial T_2}{\partial z}+ST_2=\frac{\partial T_1(z,t)}{\partial t}+\frac{F'}{F}T_1(z,t) \tag{16}$$

$$\frac{1}{S_c}\frac{\partial^2 C_0}{\partial z^2}+\frac{\partial C_0}{\partial z}=0 \tag{17}$$

$$\frac{1}{S_c}\frac{\partial^2 C_1}{\partial z^2}+\frac{\partial C_1}{\partial z}=\frac{F'}{F}C_0(z) \tag{18}$$

$$\frac{1}{S_c}\frac{\partial^2 C_2}{\partial z^2}+\frac{\partial C_2}{\partial z}=\frac{\partial C_1(z,t)}{\partial t}+\frac{F'}{F}C_1(z,t) \tag{19}$$

$$\frac{\partial^2 q_0}{\partial z^2}+\frac{\partial q_0}{\partial z}-M^2q_0-2i\Omega q_0=-T_0(z)-NC_0(z) \tag{20}$$

$$\frac{\partial^2 q_1}{\partial z^2}+\frac{\partial q_1}{\partial z}-M^2q_1-2i\Omega q_1=\frac{F'}{F}q_0(z)-T_1(z,t)-NC_1(z,t) \tag{21}$$

$$\frac{\partial^2 q_2}{\partial z^2}+\frac{\partial q_2}{\partial z}-M^2q_2-2i\Omega q_2=\frac{\partial q_1(z,t)}{\partial t}+\frac{F'}{F}q_1(z,t)-T_2(z,t)-NC_2(z,t) \tag{22}$$

The transformed boundary conditions (12) are transformed to:

$$q_0=q_1=q_2=0,\quad T_0=1, T_1=T_2=0,\quad C_0=1, C_1=C_2=0 \quad \text{at} \quad z=0$$

$$q_0=q_1=q_2\to 0,\quad T_0=T_1=T_2\to 0,\quad C_0=C_1=C_2\to 0 \quad \text{as} \quad z\to\infty \tag{23}$$

The solutions of (14)-(22), under the transformed boundary conditions (23) are :

$$T_0(z)=e^{-R_1 z} \tag{24}$$

$$C_0(z)=e^{-S_c z} \tag{25}$$

$$q_0(z)=\left(\frac{1}{D_3}+\frac{N}{D_2}\right)e^{-D_1 z}-\frac{1}{D_3}e^{-R_1 z}-\frac{N}{D_2}e^{-S_c z} \tag{26}$$

$$T_1(z,t)=-\frac{P_rF'}{FR_2}ze^{-R_1 z} \tag{27}$$

$$C_1(z,t)=-\frac{F'}{F}ze^{-S_c z} \tag{28}$$

$$q_1(z,t)=\frac{F'}{F}\left[\left(D_4+D_5+D_6z\right)e^{-D_1z}-\left(D_5+\frac{P_rz}{R_2D_3}\right)e^{-R_1z}\right.$$
$$\left.-\left(D_4-\frac{Nz}{D_2}\right)e^{-S_cz}\right] \quad (29)$$

$$T_2(z,t)=\frac{P_r^2F''}{FR_2^2}\left(\frac{z}{2}+\frac{1}{R_2}\right)ze^{-R_1z} \quad (30)$$

$$C_2(z,t)=\frac{F''}{F}\left(\frac{z}{2}+\frac{1}{S_c}\right)ze^{-S_cz} \quad (31)$$

$$q_2(z,t)=\frac{F'}{F}\left[\left(D_9z-D_{10}-D_{11}+\frac{D_6z^2}{2(1-2D_1)}\right)e^{-D_1z}\right.$$
$$-\left(\frac{P_r^2z^2}{2R_2^2D_3}-D_7z-D_{10}\right)e^{-R_1z}$$
$$\left.-\left(\frac{Nz^2}{2D_2}-D_8z-D_{11}\right)e^{-S_cz}\right] \quad (32)$$

Hence primary velocity $u(z,t)$ and secondary velocity $v(z,t)$ are :

$$u(z,t)=u_0(z)+nu_1(z,t)+n^2u_2(z,t)$$
$$v(z,t)=v_0(z)+nv_1(z,t)+n^2v_2(z,t)$$

where $u_0=\left(R_{30}\cos B_1z-R_{31}\sin B_1z\right)e^{-A_1z}-R_7e^{-R_1z}+NR_9e^{-S_cz}$

$$v_0=-\left(R_{31}\cos B_1z+R_{30}\sin B_1z\right)e^{-A_1z}+R_8e^{-R_1z}-NR_{10}e^{-S_cz}$$

$$u_1(z,t)=\frac{-n\varepsilon\sin nt}{1+2\varepsilon\cos nt+\varepsilon^2}\left[e^{-A_1z}\left(R_{11}\cos B_1z+R_{12}\sin B_1z\right)\right.$$
$$\left.-\left(A_5-P_rR_7z\right)e^{-R_1z}-\left(A_4-NR_9z\right)e^{-S_cz}\right]$$
$$-\frac{n\varepsilon(\cos nt+\varepsilon)}{1+2\varepsilon\cos nt+\varepsilon^2}\left[e^{-A_1z}\left(R_{12}\cos B_1z-R_{11}\sin B_1z\right)\right.$$
$$\left.-\left(B_5+P_rR_8z\right)e^{-R_1z}-\left(B_4+NR_{10}z\right)e^{-S_cz}\right]$$

$$v_1(z,t)=\frac{n\varepsilon(\cos nt+\varepsilon)}{1+2\varepsilon\cos nt+\varepsilon^2}\left[e^{-A_1z}\left(R_{11}\cos B_1z+R_{12}\sin B_1z\right)\right.$$
$$\left.-\left(A_5-P_rR_7z\right)e^{-R_1z}-\left(A_4-NR_9z\right)e^{-S_cz}\right]$$
$$-\frac{n\varepsilon\sin nt}{1+2\varepsilon\cos nt+\varepsilon^2}\left[e^{-A_1z}\left(R_{12}\cos B_1z-R_{11}\sin B_1z\right)\right.$$

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$$-\left(B_5+P_rR_8z\right)e^{-R_1z}-\left(B_4+NR_{10}z\right)e^{-S_cz}\Big]$$

$$u_2(z,t)=\frac{-n^2\varepsilon(\cos nt+\varepsilon)}{1+2\varepsilon\cos nt+\varepsilon^2}\Big[e^{-A_1z}\Big\{\left(A_{12}z^2+A_9z-A_{10}-A_{11}\right)\cos B_1z$$
$$+\left(B_{12}z^2+B_9z-B_{10}-B_{11}\right)\sin B_1z\Big\}$$
$$-\left(\frac{P_r^2R_7}{2R_2^2}z^2-A_7z-A_{10}\right)e^{-R_1z}-\left(\frac{R_9}{2}z^2-A_8z-A_{11}\right)e^{-S_cz}\Big]$$
$$+\frac{n^2\varepsilon\sin nt}{1+2\varepsilon\cos nt+\varepsilon^2}\Big[e^{-A_1z}\Big\{\left(B_{12}z^2+B_9z-B_{10}-B_{11}\right)\cos B_1z$$
$$-\left(A_{12}z^2+A_9z-A_{10}-A_{11}\right)\sin B_1z\Big\}$$
$$+\left(\frac{P_r^2R_8}{2R_2^2}z^2+B_7z+B_{10}\right)e^{-R_1z}+\left(\frac{R_{10}}{2}z^2+B_8z+B_{11}\right)e^{-S_cz}\Big]$$

$$v_2(z,t)=\frac{-n^2\varepsilon\sin nt}{1+2\varepsilon\cos nt+\varepsilon^2}\Big[e^{-A_1z}\Big\{\left(A_{12}z^2+A_9z-A_{10}-A_{11}\right)\cos B_1z$$
$$+\left(B_{12}z^2+B_9z-B_{10}-B_{11}\right)\sin B_1z\Big\}$$
$$-\left(\frac{P_r^2R_7}{2R_2^2}z^2-A_7z-A_{10}\right)e^{-R_1z}-\left(\frac{R_9}{2}z^2-A_8z-A_{11}\right)e^{-S_cz}\Big]$$
$$-\frac{n^2\varepsilon(\cos nt+\varepsilon)}{1+2\varepsilon\cos nt+\varepsilon^2}\Big[e^{-A_1z}\Big\{\left(B_{12}z^2+B_9z-B_{10}-B_{11}\right)\cos B_1z$$
$$-\left(A_{12}z^2+A_9z-A_{10}-A_{11}\right)\sin B_1z\Big\}$$
$$+\left(\frac{P_r^2R_8}{2R_2^2}z^2+B_7z+B_{10}\right)e^{-R_1z}+\left(\frac{R_{10}}{2}z^2+B_8z+B_{11}\right)e^{-S_cz}\Big]$$

IV. SKIN-FRICTION AND RATE OF HEAT

The skin-friction (τ_p) due to primary velocity and skin-friction (τ_s) due to secondary velocity at the plate are obtained as follows :

$$\tau_p=\left(\frac{\partial u}{\partial z}\right)_{z=0}=R_{24}-\varepsilon\frac{n^2}{\left(1+2\varepsilon\cos nt+\varepsilon^2\right)}\left\{R_{26}\sin nt+R_{27}\left(\cos nt+\varepsilon\right)\right\}\quad(33)$$

$$\tau_s=\left(\frac{\partial v}{\partial z}\right)_{z=0}=R_{25}+\varepsilon\frac{n^2}{\left(1+2\varepsilon\cos nt+\varepsilon^2\right)}\left\{R_{26}\left(\cos nt+\varepsilon\right)-R_{27}\sin nt\right\}\quad(34)$$

The rate of heat transfer in terms of Nusselt number (N_u) at the plate is :

$$N_u = \left(\frac{\partial T}{\partial z}\right)_{z=0} = -R_1 + \varepsilon \frac{n^2}{\left(1+2\varepsilon\cos nt+\varepsilon^2\right)} \left\{ \frac{P_r^2 \sin nt}{R_2} - \frac{nP_r^2}{R_2^3}\left(\cos nt+\varepsilon\right) \right\} \quad (34)$$

The rate of mass transfer in terms of Sherwood number (S_h) at the plate is :

$$S_h = \left(\frac{\partial C}{\partial z}\right)_{z=0} = -S_c + \varepsilon \frac{n^2}{\left(1+2\varepsilon\cos nt+\varepsilon^2\right)} \left\{ \sin nt - \frac{n}{S_c}\left(\cos nt+\varepsilon\right) \right\} \quad (36)$$

TABLE-1

EFFECTS OF VARIOUS PARAMETERS ON SKIN-FRICTION (τ_p)

DUE TO PRIMARY VELOCITY

($S_c = 0.30$, $n = 0.2$, $t = 1.0$ and $\varepsilon = 0.1$)

P_r	M	G_r	G_m	S	τ_p
0.71	0.5	12.0	14.0	0.4	2.62412
7.00	0.5	12.0	14.0	0.4	0.68527
0.71	1.0	12.0	14.0	0.4	2.18758
0.71	0.5	15.0	14.0	0.4	4.32647
0.71	0.5	12.0	18.0	0.4	5.18268
0.71	0.5	12.0	14.0	0.6	2.48715

TABLE-2

EFFECTS OF VARIOUS PARAMETERS ON SKIN-FRICTION (τ_s)

DUE TO SECONDARY VELOCITY

($S_c = 0.30$, $n = 0.2$, $t = 1.0$ and $\varepsilon = 0.1$)

P_r	M	G_r	G_m	S	τ_s
0.71	0.5	12.0	14.0	0.4	-1.74785
7.00	0.5	12.0	14.0	0.4	-0.79412
0.71	1.0	12.0	14.0	0.4	-1.56712
0.71	0.5	15.0	14.0	0.4	-3.49021
0.71	0.5	12.0	18.0	0.4	-4.56514
0.71	0.5	12.0	14.0	0.6	-1.67587

TABLE-3

EFFECTS OF P_r AND S ON RATE OF HEAT TRANSFER

IN TERMS OF NUSSELT NUMBER (N_u)

(at $n = 0.2$, $t = 1.0$ and $\varepsilon = 0.1$)

P_r	S	N_u
0.71	0.5	-1.88627

7.00	0.5	-7.05724
11.4	0.5	-11.64986
0.71	1.0	-1.84717
0.71	0.0	-1.34108
0.71	-0.5	-4.13587

TABLE-4

EFFECTS OF S_c ON RATE OF MASS TRANSFER

IN TERMS OF SHERWOOD NUMBER (S_h)

(at $n=0.2$, $t=1.0$ and $\varepsilon=0.1$)

S_c	S_h
0.22	-0.22743
0.30	-0.30467
0.60	-0.60582
0.66	-0.66594
0.78	-0.78493

V. DISCUSSION AND CONCLUSIONS

The conclusions of the study are as follows :

1. The primary velocity increases near the plate and after attaining a maximum value it decreases as z increases.
2. An increase in G_r, G_m or S increases the primary velocity while an increase in P_r or M decreases the primary velocity.
3. The secondary velocity decreases near the plate and after attaining a minimum value it increases as z increases.
4. An increase in P_r, M or S increases the skin-friction (τ_s)due to secondary velocity while an increase in G_r or G_m decreases the skin-friction (τ_s) due to secondary velocity.
5. An increase in P_r decreases the rate of heat transfer in terms of Nusselt number (N_u) while an increase in S increases the rate of heat transfer in terms of Nusselt number (N_u).
6. An increase in Schmidt number (S_c) decreases the rate of mass transfer in terms of Sherwood number (S_h).
7. An increase in G_r, G_m or S decreases the secondary velocity while an increase in P_r or M increases the secondary velocity.
8. An increase in P_r or S decreases the temperature field.
9. It is interesting to note that for constant heat sink the temperature field increases while for constant heat source the temperature field decreases.
10. An increase in S_c decreases the concentration filed.
11. An increase in G_r or G_m increases the skin-friction (τ_p) due to primary velocity while an increase in P_r, M or S decreases the skin-friction (τ_p) due to primary velocity.

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