FLUCTUATING THERMAL AND MASS DIFFUSION ON UNSTEADY FREE CONVECTION FLOW PAST A VERTICAL PLATE IN SLIP-FLOW REGIME

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***Abstract* - The unsteady free convective viscous incompressible flow past an infinite vertical porous flat plate with periodic heat and mass transfer in slip-flow regime is discussed. Assuming variable suction at the porous plate, approximate solutions are obtained for velocity, skin-friction, temperature, heat transfer and species concentration. During the course of discussion, the effects of Gr (Grashof number based on temperature), Gc (modified Grashof number based on concentration difference), Sc (Schmidt number), A (suction parameter) and ω (frequency) for Pr=0.71 (air) have been presented.**

***Keyword* - Free convection, incompressible fluid, heat and mass transfer.**

I. INTRODUCTION

The phenomenon of free convection arises in the fluid when temperature changes cause density variation leading to buoyancy forces acting on the fluid elements. This can be seen in our everyday life in the atmospheric flow, which is driven by temperature differences. Now, free convective flow past vertical plate has been studied extensively by Ostrach (1952, 1953, 1954). Siegel (1958) investigated the transient free convection from a vertical flat plate. The free convective heat transfer on a vertical semi-infinite plate has been investigated by Berezovsky *et al.* (1977). Martynenko *et al.* (1984) investigated the laminar free convection from a vertical plate. In all these papers, the plate was assumed to be maintained at a constant temperature, which is also the temperature of the surrounding stationary fluid. But in many applications, quite often the plate temperature starts oscillating about a non-zero mean temperature. The free-convection flow is enhanced by superimposing oscillating temperature on the mean plate temperature. In many engineering applications, transient free convective flow occurs as such a flow acts as a cooling device. Also free convection is of interest in the early stages of melting adjacent to a heated surface. There are many transport processes occurring in nature due to tempe-rature and chemical differences. The process of heat and mass transfer is encountered in aeronautics, fluid fuel nuclear reactor, chemical process industries and many engineering applications in which the fluid is the working medium. The wide range of its technological and industrial applications has stimulated considerable amount of interest in the study of heat and mass transfer in convection flows. The natural convection flows adjacent to both vertical and horizontal surface, which result from the combined buoyancy effects of thermal and mass diffusion, was first investigated by Gebhart and Pera (1971) and Pera and Gebhart (1972). In case of unsteady free convective flows Soundalgekar (1972) studied the effects of viscous dissipation on the flow past an infinite vertical porous plate. It was assumed that the plate temperature oscillates in such a way that its amplitude is small. The combined effect of buoyancy forces from thermal and mass diffusion on forced convection was studied by Chen *et al.* (1980). The free convection on a horizontal plate in a saturated porous medium with prescribed heat transfer coefficient was studied by Ramanaiah and Malarvizhi (1991). Vighnesam and Soundalgekar (1998) investigated the combined free and forced convection flow of water from a vertical plate with variable temperature. Das *et al.* (1999) studied the transient free convection flow past an infinite vertical plate with periodic temperature variation. Recently Hossain *et al.* (2001) studied the influence of fluctuating surface temperature and concentration on natural convection flow from a vertical flat plate. The present analysis discussed here has many applications as suggested by Soundalgekar and Wavre (1977a, 1977b). In many practical applications, the particle adjacent to a solid surface no longer takes the velocity of the surface. The particle at the surface has a finite tangential velocity; it “slips” along the surface. The flow regime is called the slip-flow regime and this effect can not be neglected. Using these assumption Sharma and Chaudhary (2003) and Sharma and Sharma (2004) have also discussed the free convection flow past a vertical plate in slip-flow regime and also discussed its various applications for engineering purpose. Therefore the object of present paper is to study the effect of periodic heat and mass transfer on unsteady free convection flow past a vertical flat plate in slip flow regime when suction velocity oscillates in time about a non-zero constant mean because in actual practice temperature, species concentration and suction velocity may not always be uniform.

II. FORMULATION OF THE PROBLEM

An unsteady free convective flow of a viscous incompressible fluid past an infinite vertical porous flat plate in slip-flow regime, with periodic temperature and concentration when variable suction velocity distribution $[V^* = -V_0^* (1+\varepsilon A e^{i\omega^* t^*})]$ fluctuating with time is applied. We introduce a co-ordinate system with wall lying vertically in x*-y* plane. The x^*-axis is taken in vertically upward direction along the vertical porous plate and y^*- axis is taken normal to the plate. Since the plate is considered infinite in the x*-direction, hence all physical quantities will be independent of x*. Under these assumption, the physical variables are function of y* and t* only. Then neglecting viscous dissipation and assuming variation of density in the body force term (Boussinesq's approximation) the problem can be governed by the following set of equations:

$$\frac{\partial u^*}{\partial t^*} - V_0^* (1+\varepsilon A e^{i\omega^* t^*})\frac{\partial u^*}{\partial y^*} = g\beta(T^* - T_\infty^*) + g\beta^o (C^* - C_\infty^*) + \nu\frac{\partial^2 u^*}{\partial y^{*2}} \quad (1)$$

$$\rho C_p [\frac{\partial T^*}{\partial t^*} - V_0^* (1+\varepsilon A e^{i\omega^* t^*})\frac{\partial T^*}{\partial y^*}] = \kappa(\frac{\partial^2 T^*}{\partial y^{*2}}) \quad (2)$$

$$\frac{\partial C^*}{\partial t^*} - V_0^* (1+\varepsilon A e^{i\omega^* t^*})\frac{\partial C^*}{\partial y^*} = D(\frac{\partial^2 C^*}{\partial y^{*2}}) \quad (3)$$

The boundary conditions of the problem are:

$$\left.\begin{aligned} & u^* = L^*(\frac{\partial u^*}{\partial y^*}), T^* = T_w^* + \varepsilon(T_w^* - T_\infty^*)e^{i\omega^* t^*}, \\ & C^* = C_w^* + \varepsilon(C_w^* - C_\infty^*)e^{i\omega^* t^*} \text{ at } y^* = 0 \\ & u^* \to 0,\ T^* \to T_\infty^*,\ C^* \to C_\infty^* \text{ as } y^* \to \infty \end{aligned}\right\} \quad (4)$$

We now introduce the following non-dimensional quantities into Eqs. (1) to (4)

$$y = y^* V_0^* / \nu,\ t = t^* V_0^{*2} / 4\nu,\ u = u^* / V_0^*,$$
$$\omega = 4\nu\omega^* / V_0^{*2},\ \theta = (T^* - T_\infty^*)/(T_w^* - T_\infty^*),$$
$$C = (C^* - C_\infty^*)/(C_w^* - C_\infty^*).$$

Grashof number: The Grashof number usually occurring in free convection problem. This gives the relative importance of buoyancy force to the viscous forces. This number in our notation can be defined as

$$\text{Gr (Grashof number)} = \frac{g\beta\nu(T_w^* - T_\infty^*)}{V_0^{*3}}$$

Modified Grashof number: The modified Grashof number usually occurring in free convection problem, when the effect of mass transfer is also considered. This number in our notation can be defined as

$$\text{Gc (Modified Grashof number)} = \frac{g\beta^o \nu(C_w^* - C_\infty^*)}{V_0^{*3}}$$

Prandtl number: It is a measure of the relative importance of heat conduction and viscosity of the fluid. The Prandtl number, like the viscosity and thermal conductivity, is a material property and it thus varies from fluid to fluid. Usually Prandtl number is large when thermal conductivity is small and viscosity is large and small when viscosity is small and thermal conductivity is large. It is defined as

$$\text{Pr (Prandtl number)} = \mu C_p / \kappa = \nu/(\kappa/\rho C_p)$$

Schmidt number: This number is the ratio of kinematics viscosity to the diffusivity constant. It is defined as

$$\text{Sc (Schmidt number)} = \nu / D$$

Rarefaction parameter: The relative importance of effects due to the Rarefaction of a fluid may be indicated by a comparison of the magnitude of the mean free molecular path in the fluid with some significant body dimension hence if L* is some body dimension which is a characteristic dimension in the flow field, the effect of rarefaction phenomena on flow field become important. It is defined as

$$\text{h (rarefaction parameter)} = V_0^* L^* / \nu.$$

All physical variables are defined in nomenclature. The (*) stands for dimensional quantities. The subscript (∞) denotes the free stream condition. Then equations (1) to (3) reduce to the following non-dimensional form:

$$\frac{1}{4}\frac{\partial u}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial u}{\partial y} = Gr\,\theta + Gc\,C + (\frac{\partial^2 u}{\partial y^2}) \quad (5)$$

$$\frac{1}{4}\frac{\partial \theta}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial \theta}{\partial y} = \frac{1}{Pr}(\frac{\partial^2 \theta}{\partial y^2}) \quad (6)$$

$$\frac{1}{4}\frac{\partial C}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial C}{\partial y} = \frac{1}{Sc}(\frac{\partial^2 C}{\partial y^2}) \quad 7)$$

The boundary conditions to the problem in the dimensionless form are:

$$\left.\begin{aligned} & u = h(\frac{\partial u}{\partial y}),\ \theta = 1+\varepsilon e^{i\omega t}, C = 1+\varepsilon e^{i\omega t}, \text{at } y = 0 \\ & u \to 0,\ \theta \to 0,\ C \to 0, \text{ at } y \to \infty. \end{aligned}\right\} \quad (8)$$

III SOLUTION OF THE PROBLEM

Assuming the small amplitude oscillations (ε<<1), we can represent the velocity u, temperature θ and concentration C near the plate as follows:

$$\left.\begin{aligned} & u(y,t) = u_0(y) + \varepsilon u_1(y) e^{i\omega t}, \\ & \theta(y,t) = \theta_0(y) + \varepsilon \theta_1(y) e^{i\omega t}, \\ & C(y,t) = C_0(y) + \varepsilon C_1(y) e^{i\omega t} \end{aligned}\right\} \quad (9)$$

Substituting (9) in (5) to (7), equating the coefficients of harmonic and non harmonic terms, neglecting the coefficients of ε2, we get:

$$\left.\begin{aligned}
&\theta_0'' + \Pr\theta_0' = 0\ ,\\
&\theta_1'' + \Pr\theta_1' - i\,\omega\Pr\theta_1/4 = -A\Pr\theta_0'\ ,\\
&u_0'' + u_0' = -Gr\,\theta_0 - Gc\,C_0\ ,\\
&u_1'' + u_1' - i\,\omega\,u_1/4 = -Gr\,\theta_1 - Gc\,C_1 - Au_0',\\
&C_0'' + Sc\,C_0' = 0\ ,\\
&C_1'' + Sc\,C_1' - i\,\omega\,Sc\,C_1/4 = -A\,Sc\,C_0'
\end{aligned}\right\} \tag{10}$$

The corresponding boundary conditions reduce to:

$$\left.\begin{aligned}
&u_0 = h(\frac{\partial u_0}{\partial y}), u_1 = h(\frac{\partial u_1}{\partial y}),\\
&\theta_0 = 1, \theta_1 = 1,\ C_0 = 1,\ C_1 = 1,\ at\ y = 0,\\
&u_0 = 0, u_1 = 0, \theta_0 = 0,\\
&\theta_1 = 0,\ C_0 = 0,\ C_1 = 0, \quad as\ \ y \to \infty.
\end{aligned}\right\} \tag{11}$$

where primes denote differentiation with respect to 'y'. Solving the set of equation (10) under the boundary conditions (11) we get:

$$\theta_0(y) = e^{-\Pr y} \tag{12}$$

$$C_0(y) = e^{-Sc\, y} \tag{13}$$

$$u_0(y) = B_7\, e^{-y} - B_5\, e^{-\Pr y} - B_6\, e^{-Sc\, y} \tag{14}$$

$$\theta_1(y) = B_1\, e^{-m_1 y} + B_2\, e^{-\Pr y} \tag{15}$$

$$C_1(y) = B_3\, e^{-m_2 y} + B_4\, e^{-Sc\, y} \tag{16}$$

$$u_1(y) = B_{13} e^{-m_3 y} - B_8 e^{-m_1 y} - B_9 e^{-m_2 y} - B_{10} e^{-\Pr y} - B_{11} e^{-Sc\, y} - B_{12} e^{-y} \tag{17}$$

where

$$\begin{aligned}
&m_1 = [\Pr + \sqrt{\Pr^2 + i\omega\Pr}\ ]/2,\\
&m_2 = [Sc + \sqrt{Sc^2 + i\omega Sc}\ ]/2,\\
&m_3 = [\,1 + \sqrt{1 + i\,\omega}\ \,]/2,\\
&B_1 = 1 - 4A\,i\Pr/\omega\ ,\ B_2 = 1 - B_1\ ,\\
&B_3 = 1 - 4A\,i\,Sc/\omega\ ,\ B_4 = 1 - B_3\ ,\\
&B_5 = Gr[\Pr^2 - \Pr]^{-1}, B_6 = Gc[Sc^2 - Sc]^{-1},\\
&B_7 = [B_5(h\Pr + 1) + B_6(hSc + 1)].(h+1)^{-1},\\
&B_8 = Gr\,B_1/[(\Pr - 1).(m_1 + i\omega/4)],\\
&B_9 = Gc\,B_3/[(Sc - 1).(m_2 + i\omega/4)],\\
&B_{10} = (Gr\,B_2 + AB_5\Pr)/(\Pr^2 - \Pr - i\,\omega/4),\\
&B_{11} = (Gc\,B_4 + AB_6\,Sc)/(Sc^2 - Sc - i\,\omega/4),\\
&B_{12} = -4Ai\ B_7/\omega,\\
&B_{13} = (h\,m_3 + 1)^{-1}.[B_8(h\,m_1 + 1) + B_9(h\,m_2 + 1)\\
&\qquad + B_{10}(h\Pr + 1) + B_{11}(hSc + 1) + B_{12}(h + 1)].
\end{aligned}$$

The important characteristics of the problem are the skin-friction and heat transfer at the plate.

Skin-friction: The dimensionless shearing stress on the surface of a body, due to a fluid motion, is known as skin-friction and is defined by the Newton's law of viscosity

$$\tau^* = \mu(\frac{\partial u^*}{\partial y^*}) \tag{18}$$

Substituting Eqs. (14) and (17) into Eq. (9) we can calculate the shearing stress component in dimensionless form as

$$\tau = \frac{\tau^*}{\rho V_0^{*2}} = (\frac{\partial u}{\partial y})_{y=0} \tag{19}$$

In terms of the amplitude and phase, the skin-friction can be written as:

$$\tau = \tau_m + \varepsilon|M|\cos(\omega t + \phi)$$

where

$$\begin{aligned}
&\tau_m\,(Mean\,skin - friction) = -B_7 + B_5\Pr + B_6\,Sc\\
&M = M_r + i\,M_i = -B_{13}\,m_3 + B_8\,m_1 + B_9\,m_2\\
&\qquad + B_{10}\Pr + B_{11}\,Sc + B_{12}\,,
\end{aligned}$$

and

$$\tan\phi = M_i/M_r\ .$$

Heat Transfer: In the dynamics of viscous fluid one is not much interested to know all the details of the velocity and temperature fields but would certainly like to know quantity of heat exchange between the body and the fluid. Since at the boundary the heat exchanged between the fluid and the body is only due to conduction, according to Fourier's law, we have

$$q_w^* = -\kappa(\frac{\partial T^*}{\partial y^*})_{y^*=0} \tag{20}$$

where y* is the direction of the normal to the surface of the body. Substituting equations (12) and (15) into (9), we can calculate the dimensionless coefficient of heat transfer which is generally known as the Nusselt number (Nu) as follows

$$Nu = \frac{q_w^*.\nu}{\kappa V_0^*(T_w^* - T_\infty^*)} = -(\frac{\partial\theta}{\partial y})_{y=0} \tag{21}$$

In terms of the amplitude and phase the Nusselt number can be written as:

$$Nu = \Pr + |N|\cos(\omega t + \varphi)$$

where $N = N_r + i\,N_i = B_1\ m_1 + B_2\Pr$ and $\tan\varphi = N_i/N_r$.

IV. DISCUSSION

The convection flows driven by a combination of diffusion effects are very important in many applications. The foregoing formulations may be analyzed to indicate the nature of the interaction of the various contributions to buoyancy. Here we restricted our discussion to the aiding or favorable case only, for fluids with Prandtl number Pr=0.71 which represent air at 20 ^oC at 1 atmosphere. The values of Gr and Gc are chosen arbitrarily, we take Gr>0 corresponds to the cooling of the plate. The values of the Schmidt number, Sc are chosen to represent the presence of various species Carbon dioxide (Sc=0.94) and Water vapor (Sc=0.60). The velocity profiles in air are presented in Fig. 1(a-c) for water vapor and 1 (d-f) for carbon dioxide. It is observed from the figures that the velocity increases rapidly near the plate and then decreases far away from the plate. The increase in Gr or Gc leads to an increase in velocity. The values of velocity are greater for ωt=0 than in ωt=π/2. The velocity increases with increasing suction parameter and rarefaction parameter in both the situations (water vapor and carbon dioxide).

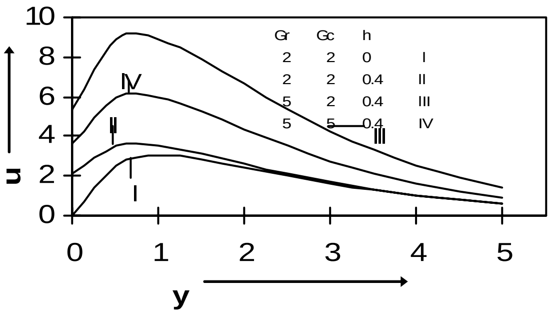

Fig.1(a). The velocity profiles of water vapor for Pr=0.71, ω = 10, ωt = 0, A = 5 and ε = 0.2

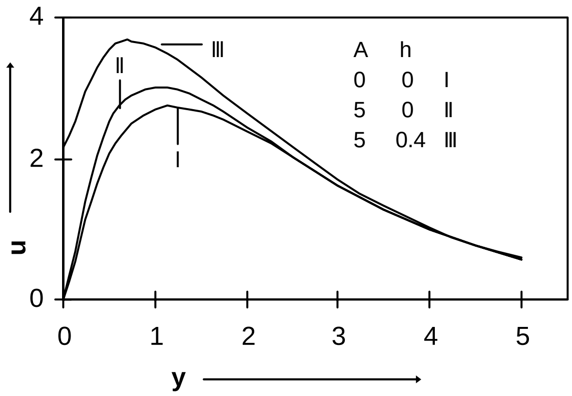

Fig.1(b). The velocity profiles of water vapor for Pr=0.71, ω=10, Gr=2, Gc=2, ωt=0 and ε=0.2

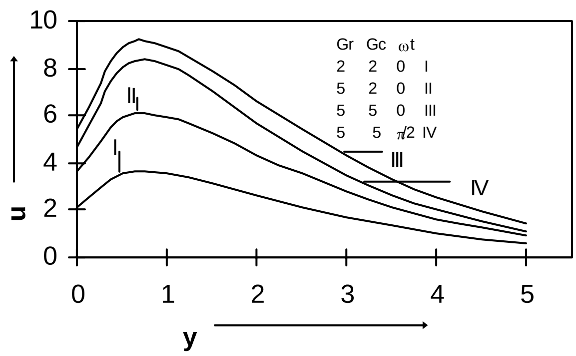

Fig.1(c). The velocity profiles of water vapor for Pr=0.71, ω=10, A=5, h=0.4 and ε=0.2

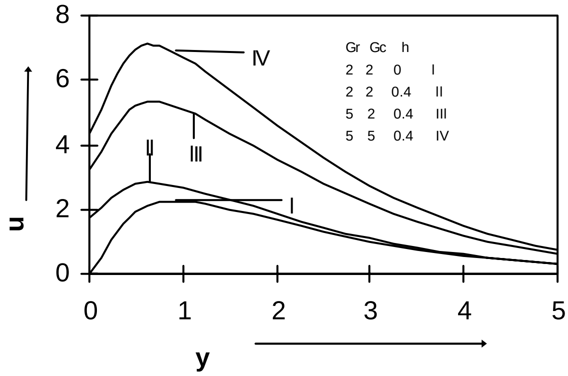

Fig.1 (d). The velocity profiles of carbon dioxide for Pr=0.71,ω=10, ωt=0, A=5 and ε=0.2

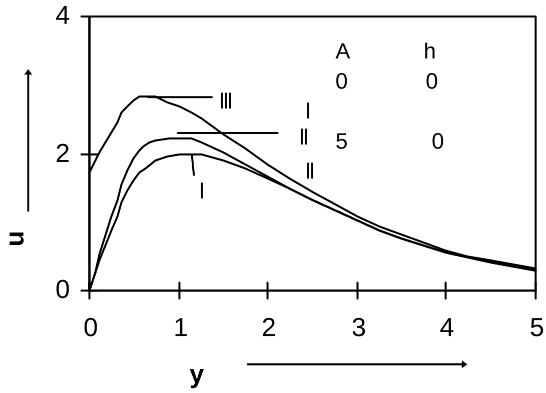

Fig.1 (e). The velocity profiles of carbon dioxide for Pr=0.71,Gr=2, Gc=2, ωt=0, ω=10 and ε=0.2

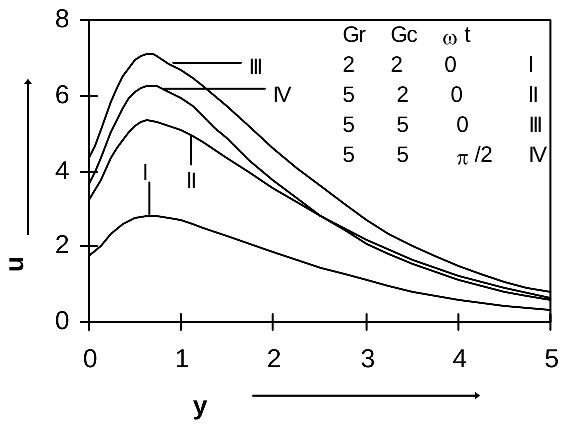

Fig.1 (f). The velocity profiles of carbon dioxide for Pr=0.71,A=5,h=0.4,ω=10 and ε=0.2

Figure 2 shows that mean skin-friction decreases with increasing with rarefaction parameter. The mean skin-friction increases due to the increase in Gr or Gc for both the cases of water vapor and carbon dioxide.

The amplitude $|M|$ of the skin-friction is shown in Fig. 3. It is observed from this figure that amplitude increases with increasing A (suction parameter), while the reverse effect should be observed for h (rarefaction parameter). An increase in Gr or Gc leads to an increase in amplitude.

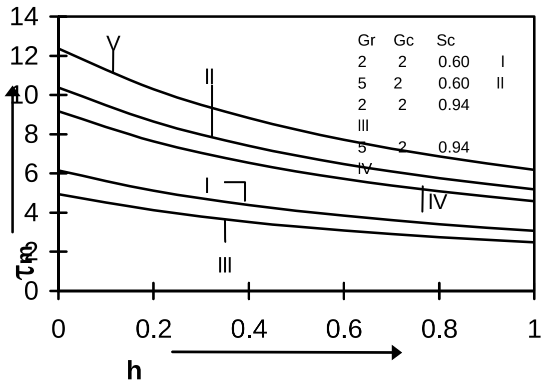

Fig.2. The mean skin-friction for Pr = 0.71

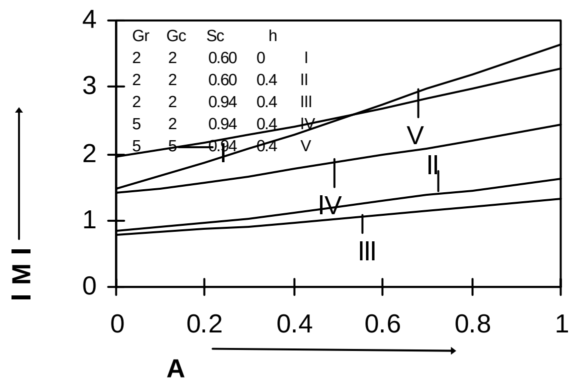

Fig.3. The amplitude of skin-friction for Pr = 0.71 for ω = 10

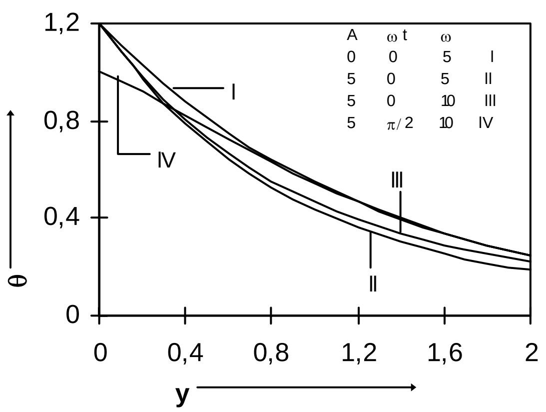

Fig.4. The temperature profiles for Pr=0.71 and ε=0.2

The numerical values of phase of skin-friction are presented in Table 1. It is observed that phase of skin-friction increases with increasing A, while reverse effect is observed for h. The phase of skin-friction decreases with increasing Gr or Gc both. It is also observed that there is always a phase lag.

The temperature profiles are presented in Fig. 4. From this figure it is observed that it decreases with increasing the suction parameter while increases with the increase of ω (frequency of fluctuation). This figures further shows that the values of temperature are greater in vicinity of the plate and decreases exponentially far away from the plate.

Table 1. The phase of skin-friction (tan ϕ) for ω = 10 and Pr=0.71

	Sc 0.94	Sc 0.94	Sc 0.60	Sc 0.60
A	Gr= 2 Gc=2 h=0	Gr= 2 Gc=2 h=0.4	Gr= 5 Gc=2 h=0.4	Gr= 2 Gc=5 h=0.4
0	-0.9525	-1.5939	-1.6869	-1.7017
0.2	-0.7058	-1.1822	-1.2314	-1.2387
0.4	-0.5634	-0.9383	-0.9854	-0.9926
0.6	-0.4708	-0.7770	-0.8313	-0.8397
0.8	-0.4056	-0.6623	-0.7259	-0.7356
1.0	-0.3573	-0.5767	-0.6491	-0.6601

Table 2. The amplitude and phase of rate of heat transfer.

A	ω=5 $\vert N\vert$	ω=10 $\vert N\vert$	ω=5 tanφ	ω=10 tanφ
0	1.2370	1.6120	0.5800	0.6831
0.2	1.2794	1.6358	0.5083	0.6321
0.4	1.3255	1.6616	0.4449	0.5847
0.6	1.3748	1.6893	0.3886	0.5406
0.8	1.4272	1.7188	0.3380	0.4995
1.0	1.4821	1.7501	0.2925	0.4611

The amplitude $|N|$ and phase tan φ of rate of heat transfer are presented in Table 2. This table shows that both increases with increasing frequency ω. The amplitude increases with increasing suction parameter A while, reverse effect is observed for phase of heat transfer. This Table further shows that there is always a phase lag.

The concentration profiles for water vapor and carbon dioxide are presented in Fig. 5 and 6. It is observed from the figures that the concentration decreases exponentially with increasing distance from the plate.

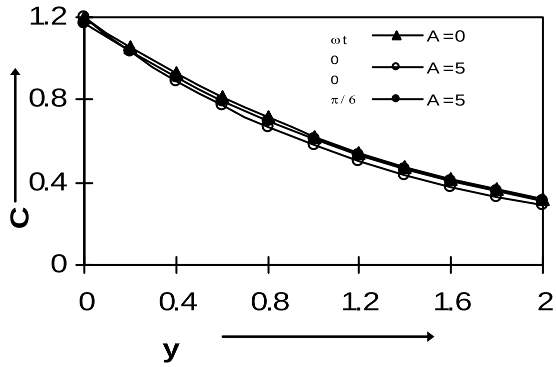

Fig.5.The concentration profiles of water vapor for ω=10 and ε=0.2

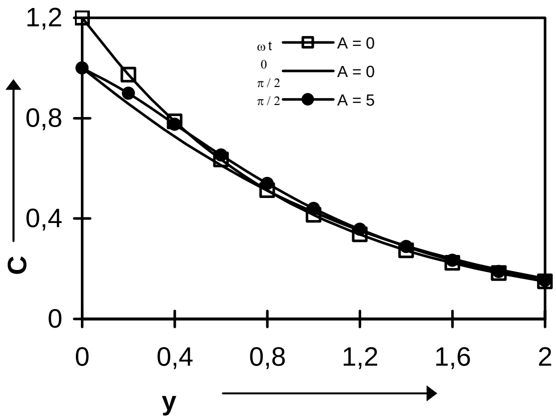

Fig.6.The concentration profiles of carbon dioxide for ω = 10 and ε = 0.2

The concentration decreases with increasing A for water vapor. It is also observed that the concentration increases in the vicinity of the plate and decreases far away from the plate in both the cases (water vapor and carbon dioxide).

V. CONCLUSIONS

1. The velocity increases with increasing Gr and Gc for both the cases water vapor and carbon dioxide in air.
2. The mean skin-friction increases with increasing either Gr or Gc but it decreases with increasing h.
3. The amplitude |M| of skin-friction increases with increasing Gr and Gc both.
4. Due to more cooling of the plate, the velocity, mean skin-friction and amplitude of skin-friction increases.
5. The temperature and concentration both are increases near the plate and decreases far away from the plate.
6. The amplitude |N| of rate of heat transfer increases due to the increase in A and ω both.
7. The phase of skin-friction increases with increasing A, while reverse effect is observed for phase of rate of heat transfer.

NOMENCLATURE

ε = amplitude (<<1),
β = coefficient of thermal expansion,
βo = coefficient of thermal expansion with concentration,
ω = dimensionless frequency,
θ = dimensionless temperature,
μ = viscosity,
ν = kinematics viscosity,
α = thermal diffusivity,
ω* = frequency,
κ = thermal conductivity,
ρ = density,
τ = dimensionless shearing stress,
τ*. = shearing stress,
A = suction parameter,
C = dimensionless species concentration,
C* =species concentration,
Cp = specific heat at constant pressure,
C^*_∞ = concentration in free stream,
C^*_w = concentration at the wall,
D = molecular diffusivity of the species,
g = gravity,
Gc = modified Grashof number,
Gr = Grashof number,
h = Rarefaction parameter,
L* = constant,
|M| = amplitude of skin-friction,
|N| = amplitude of rate of heat transfer,
Nu = Nusselt number,
Pr = Prandtl number,
qw* = heat flux at the wall,
Sc = Schmidt number,
t = dimensionless time,
T* = temperature,
T^*_∞ = temperature of fluid in free stream,
T^*_w = temperature of wall,
t* = time,
u = dimensionless velocity component,
u* = velocity component,
V = suction velocity,
V0* =constant mean suction velocity.

ACKNOWLEDGEMENT

The author is highly thankful to Prof. R.C.Chaudhary, Department of Mathematics, University of Rajasthan, Jaipur and Prof. S. C. Rajvanshi , Institute of Engineering and Technology, BHADDAL, Ropar, Punjab. for their very useful suggestions which led to a definite improvement of the paper. Also the author is extremely thankful to the referees of the paper for their valuable comments and suggestions.

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Received: April 7, 2003
Accepted for publication: May 17, 2005
Recommended by Subject Editor R. Piacentini