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UNSTEADY FREE CONVECTION FLOW PAST AN INFINITE VERTICAL PLATE WITH CONSTANT SUCTION AND MASS TRANSFER

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Abstract—An analysis of a two-dimensional unsteady free convective flow, in the presence of a foreign mass, past an infinite, vertical porous plate is carried out when the plate temperature oscillates in time about a constant mean. Assuming constant suction at the plate, approximate solutions to coupled non-linear equations are derived for the mean flow, the transient flow, the amplitude and the phase of the skin-friction and the rate of heat transfer. During the course of discussion, the effects of *Gr* (Grashof number based on temperature), *Gc* (modified Grashof number based on concentration difference), *Pr* (Prandtl number), *Ec* (Eckert number), *Sc* (Schmidt number) and ω (frequency) have been presented.

NOMENCLATURE

$|B|$, amplitude of the skin-friction;
C_p, specific heat at constant pressure;
Ec, Eckert number;
g_x, acceleration due to gravity;
Gr, Grashof number;
k, thermal conductivity;
M_r, M_i, fluctuating parts of the velocity profile;
Pr, Prandtl number;
p, pressure;
q, dimensionless rate of heat transfer;
$|Q|$, amplitude of the rate of heat transfer;
t, dimensionless time;
T', temperature of fluid;
T'_w, temperature of the plate;
T'_∞, temperature of the fluid in the free stream;
T_r, T_i, fluctuating part of the temperature profile;
u', v', velocity components in x', y' direction;
u, dimensionless velocity;
v_0, suction velocity;
U', free stream velocity;
U_0, mean of $U'(t')$;
U, dimensionless free stream velocity;
u_0, mean velocity;
u_1, unsteady part of the velocity;
x', y', co-ordinate system;
y, dimensionless co-ordinate normal to the wall;
ω', frequency of oscillations;
ω, dimensionless frequency;
τ', skin friction;
τ, dimensionless skin friction;
C, non-dimensional species concentration;
D, chemical molecular diffusivity;
Sc, Schmidt number;
ν, kinematic viscosity;
β^*, volumetric coefficients of expansion with concentration;
β', volumetric coefficients of thermal expansion;
ρ', fluid density in the boundary layer;
ρ'_∞, density of fluid in the free stream;
μ, viscosity;
θ, dimensionless temperature;
Gc, modified Grashof number;
α, phase angle of skin-friction;
β, phase angle of rate of heat transfer.

1. INTRODUCTION

THERE are many transport processes occurring in nature due to temperature differences. This difference causes the density difference. The density difference is also caused by chemical composition differences and gradients or by material or phase constitutions. This can be seen in our everyday life in the atmospheric flow which is driven appreciably by both temperature and H_2O concentration differences. In water also the density is considerably affected by the temperature differences and by the concentration of dissolved materials or by suspended particulate matter. The flow caused by density difference which in turn is caused by concentration difference is known as the mass transfer flow.

Now, free convective flow past vertical plate has been studied extensively by Ostrach [1–5] and many others. The usual assumption in such studies is to neglect the viscous dissipative effects in the flow. However it was shown by Gebhart [6], Gebhart and Mollendorf [7] that viscous dissipative effects play an important role in natural convection flow field of extreme size, or extremely low temperature or in high gravity. These studies are confined to steady flows only. In case of unsteady free convective flows Soundalgekar [8] studied the effects of viscous dissipation on 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 effects of mass transfer on free convective flow was studied by Somers [9], Mathers *et al.* [10], Wilcox [11], Gill *et al.* [12], Lowell and Adams [13], Adams and Lowell [14], Cardner and Hellums [15], Lightfoot [16], Adams and Mcfadden [17], Dan Bouter *et al.* [18], Manganaro and Hanna [19], Saville and Churchill [20] and Gebhart and Pera [21]. In these studies it is assumed that the level of species concentration is very low. Because of this assumption the Soret–Dufour (thermal diffusion and diffusion-thermo) effects can be neglected. The free convective flow with Soret–Dufour effects has been studied by Sparrow *et al.* [22] and Sparrow [23]. However the effects of mass transfer with or without Soret–Dufour effects on unsteady free convective flow has not been studied in literature at all. Hence it is now proposed to study the effects of mass transfer on the unsteady free convective flow past an infinite porous plate with constant suction. In Section 2, the mathematical analysis has been presented and in Section 3, the conclusions are set out.

2. MATHEMATICAL ANALYSIS

An unsteady free convective flow of a viscous incompressible fluid past an infinite vertical porous plate, with constant suction is considered. The x' axis is chosen along the plate in the upward direction and y' axis is taken normal to the plate. The concentration level being very small, the Soret–Dufour effects are neglected in the energy equation. Under these assumptions, the physical variables are functions of y' and t' only. Then under usual Boussinesq approximation the governing equations are as follows:

$$\rho'\left(\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'}\right) = g(\rho_\infty - \rho) + \mu\frac{\partial^2 u'}{\partial y'^2} \quad (1)$$

$$\frac{\partial v'}{\partial t'} = -\frac{1}{\rho'}\frac{\partial p'}{\partial y'}. \quad (2)$$

Energy equation

$$\rho' C_p\left(\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'}\right) = k\frac{\partial^2 T'}{\partial y'^2} + \mu\left(\frac{\partial u'}{\partial y'}\right)^2. \quad (3)$$

Continuity equation

$$\frac{\partial v'}{\partial y'} = 0. \quad (4)$$

Species

$$\frac{\partial C'}{\partial t'} + V'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2}. \quad (5)$$

All the physical variables are defined in notation. Also in equation (5) the chemical reaction is assumed to be absent. The boundary conditions are

$$\left.\begin{aligned} &u' = 0,\ T' = T'_w(1+\varepsilon e^{i\omega' t'}),\ C' = C'_w \ \text{at}\ y' = 0 \\ &u' \to 0,\ T' \to T'_\infty,\ C' \to C'_\infty \ \text{as}\ y' \to \infty. \end{aligned}\right\} \quad (6)$$

In order to express $\rho'_\infty - \rho'$ in terms of T' and C', we expand $\rho'_\infty - \rho'$ in powers of $T' - T'_\infty$ and $C' - C'_\infty$ and retain the linear terms in $T' - T'_\infty$ and $C' - C'_\infty$ for we assume that $\beta'\Delta T \ll 1$ and $\beta^*\Delta C \ll 1$ where $\beta' = [-(1/\rho')(\partial\rho'/\partial T')]_{p',\rho'}$ and $\beta^* = [-(1/\rho')(\partial\rho'/\partial C)]_{T',p'}$ are respectively the volumetric coefficient of thermal expansion and the volumetric coefficient of expansion with concentration. This later condition on concentration difference is met in most atmospheric and oceanic flows. Hence

$$g_x(\rho'_\infty - \rho') = g_x\beta'\rho'(T' - T'_\infty) + g_x\beta^*\rho'(C' - C'_\infty). \quad (7)$$

(For ideal gas behaviour $\beta^* = [(MWa/MWc) - 1]1/\rho'$, where MWc is the molecular weight of diffusing species and MWa refer to the other component). Hence from (1) and (7) we have on eliminating $g_x(\rho'_\infty - \rho')$,

$$\frac{\partial u'}{\partial t'} + V'\frac{\partial u'}{\partial y'} = \beta g_x(T' - T'_\infty) + g_x\beta^*(C' - C'_\infty) + \nu\frac{\partial^2 u'}{\partial y'^2} \quad (8)$$

where $\nu = \mu/\rho$ is the kinematic viscosity.

If the constant suction velocity is assumed, then in case of a binary mixture, it can be shown that

$$V' = -V_0\left[\frac{1-\mu'/\mu}{1+\mu_1\rho/\mu\rho_1}\right] = -V'_0 \quad (9)$$

where ρ_1 and μ_1 are respectively the density and viscosity of the foreign mass assumed constant. Also the negative sign in (9) indicates that the suction is towards the plate.

On introducing the following non-dimensional quantities

$$\begin{gathered} y = y'V_0/\nu, \quad t = t'V_0^2/4\nu, \quad \omega = 4\nu\omega'/V_0'^2 \\ u = u'/V'_0, \quad \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty} \\ Gr = \frac{\nu g_x\beta(T'_w - T'_\infty)}{V_0'^3}, \quad Pr = \frac{\mu C_p}{K}, \quad Ec = \frac{V_0'^2}{C_p(T'_w - T'_\infty)} \\ Gc = \frac{\nu g_x\beta^*(C'_w - C'_\infty)}{V_0'^3}, \quad Sc = \nu/D \end{gathered} \quad (10)$$

and taking into account equation (9), equations (3), (5) and (8) reduce to the following non-dimensional form:

$$\frac{1}{4}\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = Gr\theta + GcC + \frac{\partial^2 u}{\partial y^2} \tag{11}$$

$$\frac{Pr}{4}\frac{\partial \theta}{\partial t} - Pr\frac{\partial \theta}{\partial y} = \frac{\partial^2 \theta}{\partial y^2} + PrEc\left(\frac{\partial u}{\partial y}\right)^2 \tag{12}$$

$$\frac{Sc}{4}\frac{\partial C}{\partial t} - Sc\frac{\partial C}{\partial y} = \frac{\partial^2 C}{\partial y^2}. \tag{13}$$

The corresponding boundary conditions are

$$\left.\begin{aligned} &u = 0,\ \theta = \theta_w = (1+\varepsilon e^{i\omega t}),\ C = 1 \ \text{at}\ y = 0 \\ &u = 0,\ \theta = 0,\ C = 0 \ \text{as}\ y \to \infty . \end{aligned}\right\} \tag{14}$$

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

$$u(y,t) = u_0(y) + \varepsilon e^{i\omega t} u_1(y) \tag{15}$$

$$\theta(y,t) = \theta_0(y) + \varepsilon e^{i\omega t} \theta_1(y) \tag{16}$$

$$C(y,t) = C_0(y) + \varepsilon e^{i\omega t} C_1(y). \tag{17}$$

Substituting (15)–(17) in (11)–(14), equating the coefficients of harmonic and nonharmonic terms, neglecting the coefficients of ε^2, we get

$$u_0'' + u_0' = -Gr\theta_0 - GcC_0 \tag{18}$$

$$u_1'' + u_1' - \frac{i\omega}{4}u_1 = -Gr\theta_1 - GcC_1 \tag{19}$$

$$\theta_0'' + Pr\theta_0' = -PrEcu_0'^2 \tag{20}$$

$$\theta_1'' + Pr\theta_1' - \frac{i\omega Pr}{4}\theta_1 = -2PrEcu_0'u_1' \tag{21}$$

$$C_0'' + ScC_0' = 0 \tag{22}$$

$$C_1'' + ScC_1' - \frac{i\omega Sc}{4}C_1 = 0 \tag{23}$$

$$\begin{aligned} &u_0 = 0,\quad u_1 = 0,\quad \theta_0 = 1,\quad \theta_1 = 1; \\ &\qquad C_0 = 1,\quad C_1 = 0 \quad \text{at} \quad y = 0 \\ &u_0 = 0,\quad u_1 = 0;\quad \theta_0 = 0,\quad \theta_1 = 0; \\ &\qquad C_0 = 0,\quad C_1 = 0 \quad \text{as} \quad y \to \infty . \end{aligned} \tag{24}$$

In equations (18)–(24) primes denote differentiation with respect to y. These equations are still coupled and nonlinear and hence very difficult to solve analytically. To solve them, we again expand $u_0, u_1, \theta_0, \theta_1, C_0, C_1$ in powers of Ec, the Eckert number, as the Eckert number for all incompressible fluids is always $\ll 1$. Hence we now assume

$$u_0(y) = u_{01}(y) + Ecu_{02}(y) + O(Ec^2) \tag{25}$$

$$\theta_0(y) = \theta_{01}(y) + Ec\theta_{02}(y) + O(Ec^2) \tag{26}$$

$$C_0(y) = C_{01}(y) + EcC_{02}(y) + O(Ec^2) \tag{27}$$

$$u_1(y) = u_{11}(y) + Ecu_{12}(y) + O(Ec^2) \tag{28}$$

$$\theta_1(y) = \theta_{11}(y) + Ec\theta_{12}(y) + O(Ec^2) \tag{29}$$

$$C_1(y) = C_{11}(y) + EcC_{12}(y) + O(Ec^2). \tag{30}$$

Substituting (25)–(30) in (18)–(24), equating the coefficients of different powers of Ec, we have the set of following equations:

$$u_{01}'' + u_{01}' = -Gr\theta_{01} - GcC_{01} \tag{31}$$

$$u_{02}'' + u_{02}' = -Gr\theta_{02} - GcC_{02} \tag{32}$$

$$u_{11}'' + u_{11}' - \frac{i\omega}{4}u_{11} = -Gr\theta_{11} - GcC_{11} \tag{33}$$

$$u_{12}'' + u_{12}' - \frac{i\omega}{4}u_{12} = -Gr\theta_{12} - GcC_{12} \tag{34}$$

$$\theta_{01}'' + Pr\theta_{01}' = 0 \tag{35}$$

$$\theta_{02}'' + Pr\theta_{02}' = -Pru_{01}'^2 \tag{36}$$

$$\theta_{11}'' + Pr\theta_{11}' - \frac{i\omega Pr}{4}\theta_{11} = 0 \tag{37}$$

$$\theta_{12}'' + Pr\theta_{12}' - \frac{i\omega Pr}{4}\theta_{12} = -2Pru_{01}'u_{11}' \tag{38}$$

$$C_{01}'' + ScC_{01}' = 0 \tag{39}$$

$$C_{02}'' + ScC_{02}' = 0 \tag{40}$$

$$C_{11}'' + ScC_{11}' - \frac{i\omega}{4}ScC_{11} = 0 \tag{41}$$

$$C_{12}'' + ScC_{12}' - \frac{i\omega}{4}ScC_{12} = 0 \tag{42}$$

$$\left.\begin{aligned} &u_{01} = 0,\quad \theta_{01} = 1,\quad C_{01} = 1 \\ &u_{02} = 0,\quad \theta_{02} = 0,\quad C_{02} = 0 \\ &u_{11} = 0,\quad \theta_{11} = 1,\quad C_{11} = 0 \\ &u_{12} = 0,\quad \theta_{12} = 0,\quad C_{12} = 0 \end{aligned}\right\} \quad \text{at} \quad y = 0 \tag{43}$$

$$\left.\begin{aligned} &u_{01} = 0,\quad \theta_{01} = 0,\quad C_{01} = 0 \\ &u_{02} = 0,\quad \theta_{02} = 0,\quad C_{02} = 0 \\ &u_{11} = 0,\quad \theta_{11} = 0,\quad C_{11} = 0 \\ &u_{12} = 0,\quad \theta_{12} = 0,\quad C_{12} = 0 \end{aligned}\right\} \quad \text{as} \quad y \to \infty \tag{44}$$

Equations (31)–(42) are coupled linear equations and can be solved in closed form. The solutions are derived and substituted in (25)–(30). They are as follows:

$$C_0(y) = e^{-Scy} \tag{45}$$

$$\begin{aligned} \theta_0(y) = e^{-Pry} + Ec\{&X_1 e^{-Pry} - X_2 e^{-2y} \\ &- X_3 e^{-2Pry} - X_4 e^{-2Scy} + X_5 e^{-(Pr+1)y} \\ &+ X_6 e^{-(Sc+1)y} - X_7 e^{-(Pr+Sc)y}\} \end{aligned} \tag{46}$$

$$\begin{aligned} u_0(y) = \{&1 + B_5 e^{-y} - B_3 e^{-Pry} - B_4 e^{-Scy}\} \\ &+ Ec\{X_{15} e^{-y} - X_8 e^{-Pry} + X_9 e^{-2y} \\ &+ X_{10} e^{-2Pry} + X_{11} e^{-2Sc.y} - X_{12} e^{-(Pr+1)y} \\ &- X_{13} e^{-(Sc+1)y} + X_{14} e^{-(Pr+Sc)y}\} \end{aligned} \tag{47}$$

$$\begin{aligned} \theta_1(y) = e^{-\eta y} + Ec\{&Z_3(e^{-(Pr+\eta)y} - e^{-\eta y}) \\ &+ Z_4(e^{-(Pr+h)y} - e^{-\eta y}) + Z_5(e^{-(Sc+\eta)y} - e^{-\eta y}) \\ &+ Z_6(e^{-(Sc+h)y} - e^{-\eta y}) - Z_7(e^{-(\eta+1)y} - e^{-\eta y}) \\ &- Z_8(e^{-(h+1)y} - e^{-\eta y})\} \end{aligned} \tag{48}$$

$$U_1(y) = B_6(e^{-hy}-e^{-\eta y})+Ec\{Z_{10}(e^{-hy}-e^{-\eta y}) +Z_{11}(e^{-hy}-e^{-(Pr+\eta)y})+Z_{12}(e^{-hy} -e^{-(Pr+h)y}) -Z_{13}(e^{-hy}-e^{-(Sc+\eta)y}+Z_{14}(e^{-hy} -e^{-(Sc+h)y}) -Z_{15}(e^{-hy}-e^{-(\eta+1)y})-Z_{16}(e^{-hy} -e^{-(h+1)y})\} \quad (49)$$

where

$$B_3 = \frac{Gr}{Pr^2-Pr}, \quad B_4 = \frac{Gc}{Sc^2-Sc},$$

$$B_5 = \frac{Gr}{Pr^2-Pr}+\frac{Gc}{Sc^2-Sc}-1,$$

$$B_6 = -\frac{Gr}{\eta^2-\eta+M_1}$$

$$X_2 = \frac{PrB_5^2}{4-2Pr}, \quad X_3 = \frac{PrB_3^2}{2}, \quad X_4 = \frac{PrScB_4^2}{2(2Sc-Pr)},$$

$$X_5 = \frac{2Pr^2B_3B_5}{Pr+1}, \quad X_6 = \frac{2PrB_5ScB_4}{(Sc+1)(Sc-Pr+1)},$$

$$X_7 = \frac{2Pr^2B_3B_4}{(Pr+Sc)(Sc-Pr+1)},$$

$$X_1 = X_2+X_3+X_4-X_5-X_6+X_7$$

$$X_8 = \frac{GrX_1}{Pr^2-Pr}, \quad X_9 = \frac{GrX_2}{2}, \quad X_{10} = \frac{GrX_3}{4Pr^2-2Pr},$$

$$X_{11} = \frac{GrX_4}{4Sc^2-2Sc}, \quad X_{12} = \frac{GrX_5}{Pr(Pr+1)},$$

$$X_{13} = \frac{GrX_6}{Sc(Sc+1)}, \quad X_{14} = \frac{GrX_7}{(Pr+Sc)(Pr+Sc-1)},$$

$$X_{15} = X_8-X_9-X_{10}-X_{11}+X_{12}+X_{13}-X_{14},$$

$$\eta = \frac{Pr+\sqrt{Pr^2+i\omega Pr}}{2}, \quad h = \frac{1+\sqrt{1+i\omega}}{2},$$

$$M_1 = -\frac{i\omega}{4}, \quad M_2 = -\frac{i\omega Pr}{4},$$

$$Z_1 = \frac{-Gr}{\eta^2-\eta-M_1}, \quad Z_2 = \frac{Gr}{\eta^2-\eta-M_1},$$

$$Z_3 = \frac{2Pr^2Sc\eta Z_1}{(Pr+\eta)^2-Pr(Pr+\eta)+M_2},$$

$$Z_4 = \frac{2Pr^2B_3hZ_2}{(Pr+h)^2-Pr(Pr+h)+M_2},$$

$$Z_5 = \frac{2PrSc\eta Z_1B_4}{(Sc+\eta)^2-Pr(Sc+\eta)+M_2},$$

$$Z_6 = \frac{2PrhZ_2ScB_4}{(h+Sc)^2-Pr(h+Sc)+M_2},$$

$$Z_7 = \frac{2Pr\eta B_5Z_1}{(\eta+1)^2-Pr(\eta+1)+M_2},$$

$$Z_8 = \frac{2PhZ_2B_5}{(h+1)^2-Pr(h+1)+M_2},$$

$$Z_9 = -Z_3-Z_4-Z_5-Z_6+Z_7+Z_8,$$

$$Z_{10} = \frac{GrZ_9}{\eta^2-\eta+M_1},$$

$$Z_{11} = \frac{GrZ_3}{(Pr+\eta)^2-(Pr+\eta)+M_1},$$

$$Z_{12} = \frac{GrZ_4}{(Pr+h)^2-(Pr+h)+M_1},$$

$$Z_{13} = \frac{GrZ_5}{(Sc+\eta)^2-(Sc+\eta)+M_1},$$

$$Z_{14} = \frac{GrZ_6}{(Pr+\eta)^2-(Pr+\eta)+M_1},$$

$$Z_{15} = \frac{GrZ_7}{(\eta+1)^2-(\eta+1)+M_1},$$

$$Z_{16} = \frac{GrZ_8}{(h+1)^2-(h+1)+M_1}.$$

Substituting (45)–(49) in (15)–(17), we get the expressions for the velocity, the temperature and the concentration profiles. These can now be expressed in terms of fluctuating parts of the unsteady part as follows:

$$u(y,t) = u_0(y)+\varepsilon(M_r\cos\omega t - M_i\sin\omega t) \quad (50)$$

$$\theta(y,t) = \theta_0(y)+\varepsilon(T_r\cos\omega t - T_i\sin\omega t) \quad (51)$$

where

$$\left.\begin{aligned} M_r+iM_i &= u_1 \\ T_r+iT_i &= \theta_1 \end{aligned}\right\} \quad (52)$$

where u_1 and θ_1 are given by (49) and (48) respectively.

Hence we can now obtain the expressions for the transient velocity and temperature profiles from (50)–(51) respectively, for $\omega t = \pi/2$ as

$$u(y,\pi/2\omega) = u_0(y)-\varepsilon M_i \quad (53)$$

and

$$\theta(y,\pi/2\omega) = \theta_0(y)-\varepsilon T_i. \quad (54)$$

Here u_0 and θ_0 are respectively the mean velocity and mean temperature and it can be seen from (47) and (46) that they are considerably affected by the Grashof number Gr, the modified Grashof number Gc and the Schmidt number Sc. Hence it is necessary to know these effects from the point of view of an experimentalist. As such experiments have not been carried out in literature, our predictions may be found useful for carrying out the experiment.

Now during the course of numerical calculations in this paper, the values of Gr and Gc are chosen arbitrarily whereas in order to be realistic, the value of Prandtl number is chosen in such a way that it represents air ($Pr = 0.71$) and water ($Pr = 7$). The value of Schmidt number is chosen in such a way that they represent the diffusing chemical species of most common interest in air and water.

Table 1. Thermodynamic and transport properties at 25°C and 1 atm

Species	*Sc*	Species	*Sc*
H_2	0.24 air	CO_2	1.002 air
He	0.30 air	Arbitrary	100 water
H_2O	0.60 air	Cl_2	617 water
NH_3	0.78 air		

MEAN FLOW

In Fig. 1 the mean velocity profiles are shown for different values of *Gr*, *Gc* and *Sc*. It is interesting to see that, due to the presence of H_2, the mean velocity increases. But in the presence of He, H_2O, NH_3, CO_2, though there is a rise in the mean velocity it is not so high as in case of H_2. If we define all other gases as heavier one as compared to H_2 which can then be called a lighter one, then we observe that when *Gr* and *Gc* are constant, the rise in the velocity is very high in the presence of a lighter gas. In order that our results may be found useful to an experimentalist, we give below the percentage changes. Thus for $Gr = 5$, $Gc = 2$, there is 162.5% rise in the maximum value of mean velocity when H_2 is present, 47.5% rise when H_2O is present and 20% rise when CO_2 is present. Again an increase in *Gr* or *Gc* leads to an increase in the mean velocity. However in order to get more insight into the physical nature of this problem due to a rise in *Gr* and *Gc* in case of light or heavy gases, we observe that for $Gr = 5$, when He ($Sc = 0.30$) is present and *Gc* is increased from 2 to 4 there is 13.3% fall in the value of maximum mean velocity whereas when H_2O ($Sc = 0.60$) is present, under similar circumstances the maximum mean velocity increases by 37.3%. Hence this study leads us to conclude that the effect of increasing *Gc* in case of a light gas is to reduce the mean velocity and in case of heavy gas the mean velocity increases. To find out a similar effect of increasing *Gr* in case of light and heavy gas, we see from Fig. 1 that for $Gc = 2$ there is an increase of 77.7% in the value of the maximum mean velocity in the presence of He and *Gr* is increased from 5 to 10 whereas in the presence of H_2O, under similar circumstances there has been observed to be 3.4% reduction in the value of maximum mean velocity. Hence the effects of *Gr* and *Gc* are opposite to each other in the presence of a light or heavy gas.

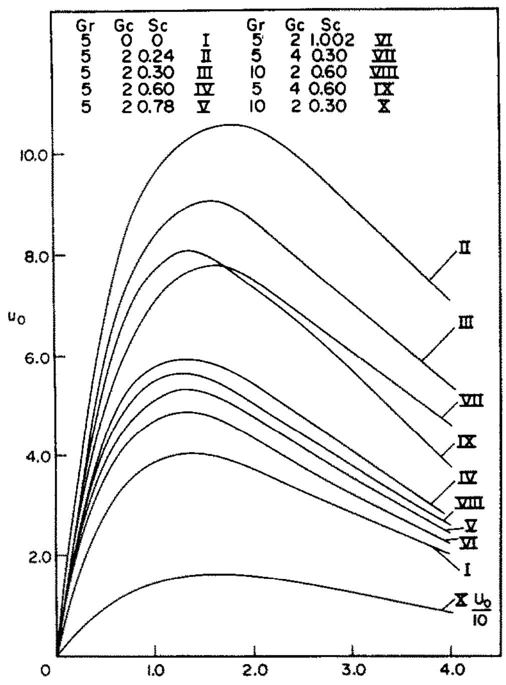

FIG. 1. Mean velocity profiles, $Pr = 0.71$, $Ec = 0.01$.

On Fig. 2, the mean velocity and mean temperature for water are shown. The value of *Sc* in case of water is always very high for all types of concentration. Thus $Sc = 617$ represents Cl_2 whereas $Sc = 100$ is an arbitrary chosen value. We observed from this figure that an increase in *Sc* leads to an increase in the mean velocity and a fall in mean temperature.

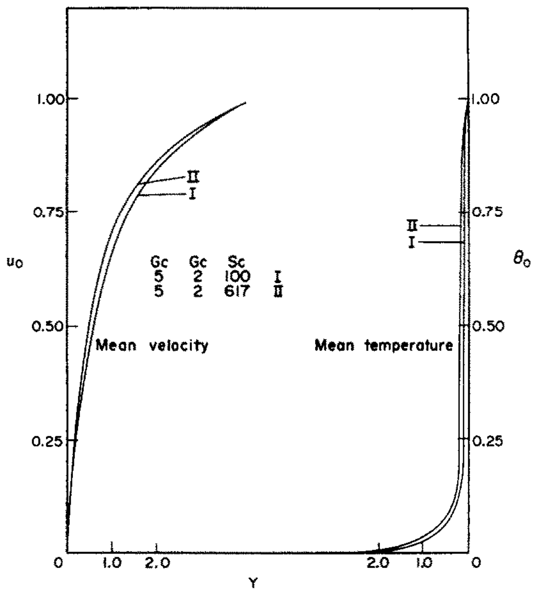

FIG. 2. Mean profiles. $Pr = 7$, $Ec = 0.01$.

On Fig. 3, mean temperature profiles are shown. It is observed that there is always a rise in mean temperature due to the presence of a foreign mass. However the mean temperature decreases due to an increase in *Sc* and for air at high values of *Sc* the mean temperature may become less than the one observed in absence of foreign mass. In order to study the effects of *Gr* and *Gc* for light or heavy gases we observe that when $Sc = 0.30$, $Gr = 5$ and *Gc* is increased from 2 to 4, there is 9.6% increase in the mean temperature at $y = 0.2$ and when $Sc = 0.30$, $Gc = 2$ there is 8.6% rise in the mean temperature due to a change in *Gr* from 5 to 10. Under similar circumstances when $Sc = 0.60$ there is 3.3% rise in mean temperature when *Gc* is increased from 2 to 4 and 6.6% rise in the mean temperature when *Gr* is increased from 5 to 10. This leads us to conclude that the rise in mean temperature is more due to an increase in *Gr* or *Gc* when a light foreign gas is present.

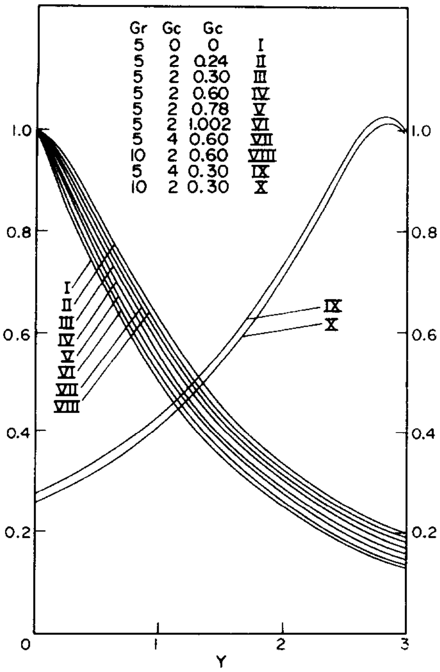

FIG. 3. Mean temperature profiles. $Pr = 0.71$, $Ec = 0.01$.

Knowing the mean velocity field, from the practical point of view it is important to know the effects of mass transfer on mean skin friction. It is given by

$$\zeta' = \mu(\mathrm{d}u'/\mathrm{d}y) \quad \text{at} \quad y' = 0 \tag{55}$$

and in view of (10) and (15), (55) reduces to the following

$$\zeta = (u_0' + \varepsilon e^{i\omega t} u_1')_{y=0}. \tag{56}$$

Denoting the mean skin friction by ζ_m we get

$$\zeta_m = \left.\frac{\mathrm{d}u_0}{\mathrm{d}y}\right|_{y=0} \tag{57}$$

substituting (47) in (57) we have

$$\zeta_m = -B_5 + B_3 Pr + Sc B_4 + Gr Ec \left\{ \frac{X_1}{Pr} - \frac{X_2}{2} - \frac{X_3}{2Pr} - \frac{X_4}{2Sc} + \frac{X_5}{Pr+1} + \frac{X_6}{Sc+1} - \frac{X_7}{Pr+Sc} \right\} \tag{58}$$

The numerical values of ζ_m are entered in Table 2.

We observe from this table that the mean skin friction increases due to presence of either H_2, He, H_2O, or NH_3 whereas in the presence of high Schmidt number gases the mean skin friction decreases. An increase in *Gr* or *Gc* leads to an increase in the value of mean skin friction. But in the presence of lighter gas the increase is more as compared to one in the presence of heavier gas. The effect of *Gr* is the same.

We now study the effects of the foreign mass on the mean rate of heat transfer. The rate of heat transfer is given by

$$q' = -k \left.\frac{\partial T'}{\partial y'}\right|_{y'=0} \tag{59}$$

Table 2. Values of mean skin-friction

Pr	*Gr*	*Sc/Gc*	*Ec* = 0.01 0	2	4
0.71	5	0	8.496		
		0.24		23.14	33.4
		0.30	1	19.09	26.01
		0.60		11.92	12.39
		0.78		9.43	5.18
		1.002		−1.6002	−6.4016
	10	0	18.57		
		0.30		45.018	64.19
		0.60		25.592	26.70

Values of mean rate of heat transfer

Pr	*Gr*	*Sc/Gc*	*Ec* = 0.01 0	2	4
0.71	5	0	0.57425		
		0.24		0.06072	−0.85042
		0.30		0.20328	−0.41042
		0.60		0.43427	0.24499
		0.78		0.47748	0.35449
		1.002		0.50673	0.11524
	10	0	0.23614		
		0.30		−0.34802	−1.1749
		0.60		−0.00437	−2.9419

which in view of (10) reduces to

$$q = \frac{q'v}{kv_0(T_w' - T_\infty')} = -\left.\frac{\mathrm{d}\theta}{\mathrm{d}y}\right|_{y=0} = -\left.\frac{\mathrm{d}\theta_0}{\mathrm{d}y}\right|_{y=0} - \varepsilon e^{i\omega t} \left.\frac{\mathrm{d}\theta_1}{\mathrm{d}y}\right|_{y=0}. \tag{60}$$

Then the mean rate of heat transfer is given by

$$q_m = -\left.\frac{\mathrm{d}\theta_0}{\mathrm{d}y}\right|_{y=0}. \tag{61}$$

Substituting for θ_0 from (46) in (61) we have

$$q_m = -Pr + Ec\{X_4(2Sc - Pr) + X_2(2 - Pr) + X_3 Pr + X_7 Sc - X_5 - X_6(Sc + 1 - Pr)\}.$$

The numerical values of q_m are entered in Table 3. We observe from this table that due to the presence of a foreign mass the mean rate of heat transfer always decreases and it decreases more when *Gr* or *Gc* increases.

UNSTEADY FLOW

The velocity and temperature fields as given by (15)–(17) respectively can be expressed in terms of the fluctuating parts as follows:

$$u = u_0(y) + \varepsilon e^{i\omega t}(M_r + iM_i) \tag{62}$$

$$\theta = \theta_0(y) + \varepsilon e^{i\omega t}(T_r + iT_i) \tag{63}$$

where $M_r + iM_i = u_1(y)$ and $T_r + iT_i = \theta_1(y)$. We can now write expressions for transient velocity and transient temperature from (62) and (63) for $\omega t = \pi/2$ as follows:

$$u(y, \pi/2\omega) = u_0(y) - \varepsilon M_i \tag{64}$$

$$\theta(y, \pi/2\omega) = \theta_0(y) - \varepsilon T_i. \tag{65}$$

Table 3. Values of $|B|$ the amplitude of the skin-friction

Pr	*Gr*	*Gc*	$Sc/\omega\rightarrow$	$Ec = 0.01$ 5	10	15
0.71	5	0	0	7.0524	4.4281	3.0588
		2	0.24	9.2953	6.2120	4.1446
			0.30	9.0015	6.0547	4.0327
			0.60	8.7120	6.1374	4.1775
			0.78	9.3275	6.2285	4.3571
			1.002	195.64	120.57	88.22
		4	0.24	11.510	7.7015	5.1337
			0.30	10.918	7.3286	4.8768
			0.60	10.383	7.4583	5.0722
			0.78	11.653	7.8126	5.4714
			1.002	397.9799	245.36	179.39
	10	2	0.24	53.303	36.645	24.457
			0.30	52.079	36.058	24.027
			0.60	50.652	35.542	24.235
			0.78	53.100	35.174	24.768
			1.002	766.04	472.36	345.36
7	5	2	100	0.62745	0.56304	0.50678
			617	0.62746	0.56305	0.50679
		4	100	0.62746	0.56304	0.50678
			617	0.62746	0.56305	0.50679
	10	2	100	1.2386	1.1269	1.0169
			617	1.2386	1.1270	1.0169

The transient velocity and transient temperature as calculated from (64) and (65) are shown on Figs. 4–6. We observe from Fig. 4 that the effects of *Gr*, *Gc* and *Sc* are the same as that in case of mean flow.

We only consider here the effect of frequency ω on the transient velocity in the presence of a foreign mass especially in the presence of H_2 ($Sc = 0.24$) and H_2O ($Sc = 0.60$).

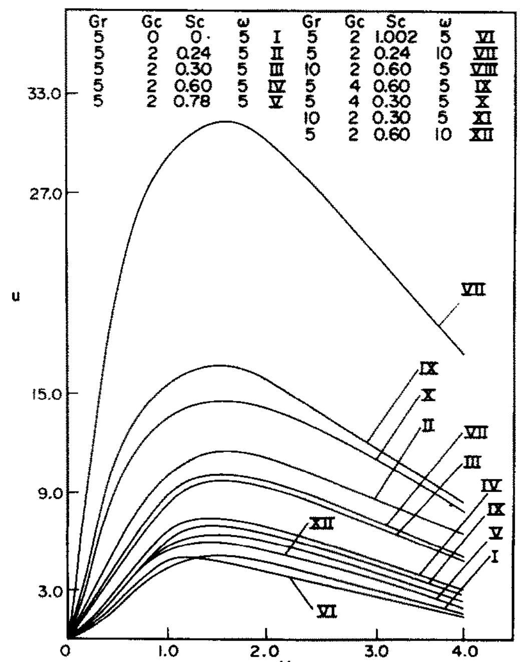

FIG. 4. Transient velocity profiles. $Pr = 0.71$, $Ec = 0.01$, $\omega t = \pi/2$, $\varepsilon = 0.2$.

Thus when $Gr = 5$, $Gc = 2$, $Sc = 0.24$, an increase in ω from 5 to 10 leads to an increase of 181.8% in the value of maximum transient velocity of air, but under similar conditions when $Sc = 0.60$ there is 73.3% rise in the maximum transient velocity. Hence the effect of frequency on the transient velocity is more significant when a light foreign mass is present. From Fig. 5 we observe that in water, an increase in ω also leads to an increase in transient velocity. From Fig. 6 the trend of the effect of *Gr*, *Gc* and *Sc* is same as in the case of mean

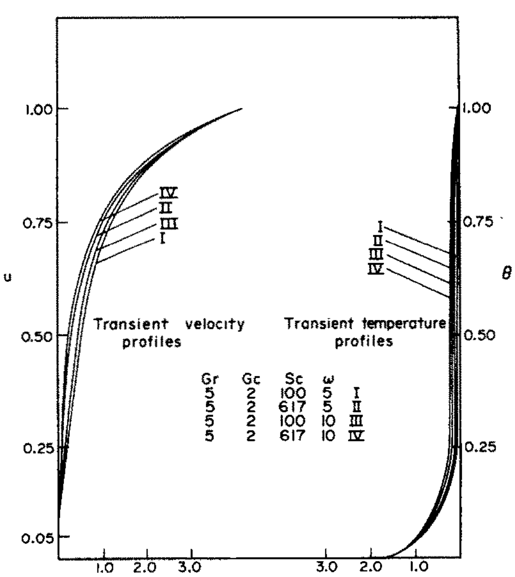

FIG. 5. Transient profiles. $Pr = 7$, $Ec = 0.01$, $\omega t = \pi/2$, $\varepsilon = 0.2$.

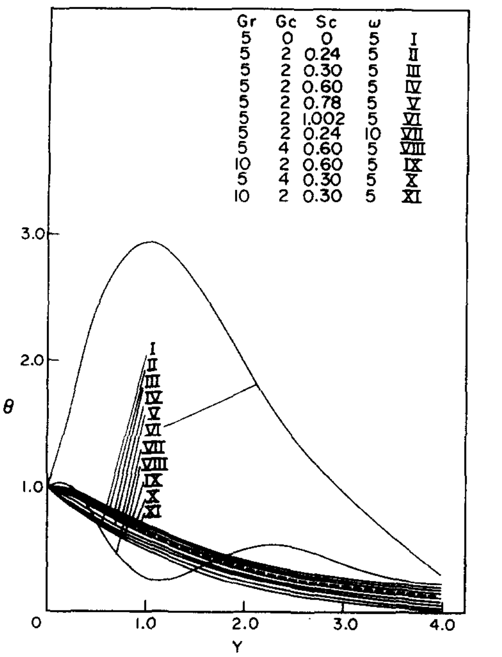

FIG. 6. Transient temperature profiles. $Pr = 0.71$, $Ec = 0.01$, $\omega t = \pi/2$, $\varepsilon = 0.2$.

temperature profiles except when $Gr = 5$, $Gc = 2$, $Sc = 1.002$ (CO_2), $\omega = 5$ and $Gr = 5$, $Gc = 2$, $Sc = 0.24$ and $\omega = 10$.

Thus we observe that in the presence of CO_2 the effect of the frequency ω is very significant on the transient temperature profiles. There is significant rise in transient temperature due to the oscillatory flow in the presence of CO_2. The curve (VII) is also significant in character. In the presence of H_2 an increase in ω completely changes the nature of the transient temperature profile. From the nature of this profile, we conclude that the flow may become thermally unstable when the plate temperature is oscillating in the presence of H_2.

It is now proposed to study the behaviour of the amplitude and the phase of the skin friction. From (56) and (49), we have

$$\zeta = \zeta_m + \varepsilon e^{i\omega t}\{Z_2(\eta - h) + Er[(\eta - h)Z_{10} + (Pr + \eta - h)Z_{11} + PrZ_{12} - Z_{13}(Sc + \eta - h) + Z_{14}Sc - Z_{15}(Sc + \eta - h) - Z_{16}]\}. \quad (66)$$

We can express (66) in terms of the amplitude and phase of the skin friction as

$$\zeta = \zeta_m + \varepsilon|B|\cos(\omega t + \alpha) \quad (67)$$

where $B = B_r + iB_i$ = coefficient of $\varepsilon e^{i\omega t}$ in (66) and

$$\tan\alpha = B_i/B_r. \quad (68)$$

The numerical values of $|B|$ are entered in Table 3. It is observed from this table that due to the presence of a foreign mass in air, the amplitude of the skin friction increases but an increase in ω leads to a decrease in the amplitude $|B|$. When $Sc \sim 1$ the increase in the value of $|B|$ is very sharp. An increase in Gr or Gc also leads to an increase in amplitude of skin friction. To get more insight into the effects of increasing Gr or Gc in the presence of light or heavy gas, we now present these results quantitatively. Thus for $Gr = 5$, $\omega = 5$, and $Sc = 0.30$ the value of the amplitude of skin friction increases by 21.1% when Gc is increased from 2 to 4 and for $Sc = 0.60$ under similar circumstances it increases by 18.4%. This leads us to conclude that the effect of Gc is more prominent in the presence of a light gas. In order to find the effects of Gr we see that for $Gc = 2$, $\omega = 5$ and $Sc = 0.30$ there is an increase of 477.7% in the value of $|B|$ when Gr is increased from 5 to 10, and under similar circumstances for $Sc = 0.60$ there is 481.6% increase in the value of $|B|$. Hence we conclude that an increase in Gr is more effective in the presence of a heavy gas. In case of water the amplitude of skin friction is affected by Gr, Gc or Sc in significant manner. However, the effect of ω remains the same.

In Table 4 the values of $\tan\alpha$, the phase of skin friction, are entered. We observe from this table that when the value of ω or Sc is large, the values of $\tan\alpha$ are positive and hence there is a phase lead. Again when Gr is large the values of $\tan\alpha$ are again positive and hence there is a phase lead. Otherwise there is always a phase lag. But in case of water there is always a phase lag.

We now study the amplitude and phase of rate of heat transfer. From (60) and (48) we have

$$q = q_m + \varepsilon e^{i\omega t}\{\eta + Ec(PrZ_3 - Z_4(\eta - Pr - h) + Sc.Z_5 - Z_6(\eta - Sc - h) - Z_i + Z_8(\eta - h - 1)\}. \quad (69)$$

This can be expressed in terms of the amplitude and phase of the rate of heat transfer as follows.

$$q = q_m + \varepsilon|Q|\cos(\omega t + \beta) \quad (70)$$

where

$$Q = Q_r + iQ_i = \text{coefficient of } \varepsilon e^{i\omega t} \text{ in (69)} \quad (71)$$

and

$$\tan\beta = Q_i/Q_R. \quad (72)$$

The numerical values of $|Q|$ and $\tan\beta$ are entered in Table 5 and 6 respectively. We observe from Table 5 that due to the presence of a foreign mass, the amplitude of the rate of heat transfer increases. When $Sc \sim 1$, it increases sharply. An increase in Gr and Gc leads to an increase in the value of $|Q|$. To get more insight into the effects of Gr or Gc in the presence of light or heavy gas, we present some results quantitatively. Thus for $Gr = 5$, $\omega = 5$ and $Sc = 0.30$ when Gc is increased from 2 to 4 there is a 20% rise in the value of $|Q|$ and under similar conditions for $Sc = 0.60$ there is a 17.5% rise in the value of $|Q|$. Hence the effect of Gc is more when the light gas is present. Again for $Gc = 2$, $\omega = 5$ and $Sc = 0.30$ there is 176% rise in the value of $|Q|$ when Gr is increased from 5 to 10 and under similar conditions for $Sc = 0.60$ there is 178.4% rise in the value of $|Q|$. This leads us to conclude that the increase in $|Q|$ due to increasing Gr is more in the presence of a heavy gas. It is interesting to note that in the case of air and in the presence of a foreign mass, an

Table 4. Values of tan α, the phase of skin-friction

Pr	*Gr*	*Gc*	*Sc*/ω→	*Ec* = 0.01 5	10	15
0.71	5	0	0	−0.01379	0.011371	0.061993
		2	0.24	−0.076476	0.068020	0.16725
			0.30	−0.085887	0.044373	0.14926
			0.60	−0.098809	−0.089914	0.03583
			0.78	−0.079035	−0.090947	0.044509
			1.002	0.14884	0.14408	0.33142
		4	0.24	−0.034556	0.12664	0.24658
			0.30	−0.046264	0.10062	0.22590
			0.60	−0.062816	−0.69511	0.066551
			0.78	−0.036587	−0.054387	0.095147
			1.002	0.14363	0.13866	0.32409
	10	2	0.24	0.062737	0.23853	0.40772
			0.30	0.058289	0.21598	0.39332
			0.60	0.051076	0.080795	0.27483
			0.78	0.059274	0.066533	0.26041
			1.002	0.143678	0.13701	0.32188
7	5	2	100	−0.30363	−0.43074	−0.50672
			617	−0.30363	−0.43074	−0.50672
		4	100	−0.30362	−0.43073	−0.50671
			617	−0.30364	−0.043075	−0.50672
	10	2	100	−0.34419	−0.46382	−0.53337
			617	−0.34420	−0.46383	−0.53337

Table 5. The values of $|Q|$, the rate of heat transfer

Pr	*Gr*	*Gc*	*Sc*/ω→	*Ec* = 0.01 5	10	15
0.71	5	0	0	3.0180	2.9775	3.0216
		2	0.24	3.8694	3.6888	3.6297
			0.30	3.7564	3.5899	3.5446
			0.60	3.6627	3.4997	3.4671
			0.78	3.9220	3.7099	3.6476
			1.002	77.403	66.698	60.012
		4	0.24	4.7324	4.4253	4.2687
			0.30	4.5045	4.2244	4.0938
			0.60	4.3158	4.0454	3.9380
			0.78	4.8393	4.4775	4.3135
			1.002	157.68	136.02	122.50
	10	2	0.24	10.622	9.413	8.6929
			0.30	10.39	9.2020	8.5046
			0.60	10.198	9.0047	8.3292
			0.78	10.729	9.4492	8.7269
			1.002	151.74	130.95	117.92
7	5	2	100	7.1976	7.8160	8.4795
			617	7.1970	7.8155	8.4792
		4	100	7.1976	7.8159	8.4795
			617	7.1970	7.8155	8.4792
	10	2	100	7.1082	7.7472	8.4258
			617	7.1057	7.7455	8.4246

Table 6. The value of tan β, the phase of rate of heat transfer

Pr	Gr	Gc	$Sc/\omega \rightarrow$	$Ec = 0.01$ 5	10	15
0.71	5	0	0	0.02193	0.09630	0.16324
		2	0.24	−0.05597	0.00084	0.05869
			0.30	−0.04876	0.01092	0.07046
			0.60	−0.04249	0.01968	0.08081
			0.78	−0.05931	−0.00401	0.05351
			1.002	−0.31257	−0.41326	−0.04777
		4	0.24	−0.09965	−0.06097	−0.01464
			0.30	−0.89773	−0.04678	0.00249
			0.60	−0.08087	−0.03440	0.17652
			0.78	−0.10416	−0.06875	−0.02311
			1.002	−0.30607	−0.4014	−0.46056
	10	2	0.24	−0.20915	−0.23125	−0.22762
			0.30	−0.20719	−0.22832	−0.22363
			0.60	−0.20553	−0.22629	−0.22060
			0.78	−0.21014	−0.23413	−0.23075
			1.002	−0.30632	−0.40153	−0.46118
7	5	2	100	0.16846	0.28660	0.36593
			617	0.16845	0.28659	0.36592
		4	100	0.16846	0.28660	0.36593
			617	0.16845	0.28659	0.36592
	10	2	100	0.17192	0.29141	0.37103
			617	0.29140	0.37099	0.42753

increase in ω leads to a decrease in the value of $|Q|$ whereas in the case of water under similar circumstances, $|Q|$ increases with increasing ω.

Table 6 shows that in air for all ω and in absence of foreign mass there is always a phase-lead but when ω is small and Sc is also small there is a phase-lag. However for large Sc and large ω there is again observed to be a phase lag. At large values of Gr and Gc there is always observed to be a phase-lag for all ω. But in the case of water there is always a phase-lead.

3. CONCLUSIONS

Air

1. There is a rise in the mean velocity in the presence of a light gas.

2. In the presence of light gas and increasing Gc leads to a decrease in the mean velocity whereas it leads to an increase in the mean velocity in the presence of a heavy gas.

3. An increase in Gr leads to an increase in the mean velocity when a light gas is present and the mean velocity is reduced due to an increase in Gr when a heavy gas is present.

Water

4. An increase in Sc leads to an increase in mean velocity and a fall in mean temperature.

5. Due to the presence of a foreign mass, there is always a rise in the mean temperature of air.

6. At high values of Sc, in air, the mean temperature may become less than the one observed in the absence of a foreign mass.

7. The effects of increasing Gr or Gc on the mean temperature is more when a light gas is present.

8. Due to the presence of the foreign mass of low Schmidt number, the mean skin friction, for air, increases. But at high values of Sc, for air, the mean skin friction decreases.

9. The mean skin friction also increases with an increase in Gr or Gc.

10. The mean rate of heat transfer for air, decreases due to the presence of a foreign mass. It decreases more due to increasing Gr or Gc.

11. Both in air and water in the presence of a foreign mass, the transient velocity increases with increasing ω.

12. $|B|$ increases due to the presence of a foreign mass in air and decreases with increasing ω. $|B|$ also increases with increasing Gr or Gc.

13. At large values of ω, Sc or Gr, for air, there is a phase lead, otherwise there is always a phase lag.

14. In water there is always a phase-lag.

15. $|Q|$ increases due to the presence of a foreign mass and the increase is sharp when $Sc \sim 1$. $|Q|$ increases with increasing Gr or Gc for air.

16. At small values of ω and Sc, there is a phase-lag in case of the rate of heat transfer.

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CONVECTION NATURELLE INSTATIONNAIRE AUTOUR D'UNE PLAQUE VERTICALE AVEC TRANSFERT MASSIQUE CONSTANT PAR ASPIRATION

Résumé—On analyse la convection naturelle, bidimensionnelle et instationnaire autour d'une plaque poreuse, verticale, infinie, et avec une température qui oscille dans le temps autour d'une moyenne constante. En admettant une aspiration constante, on obtient des solutions approchées des équations couplées et non linéaires, pour l'écoulement moyen, l'écoulement variable, l'amplitude et la phase du frottement pariétal et le flux thermique. On présente, dans la discussion, les effets de *Gr* (nombre de Grashof basé sur la température), *Gc* (nombre modifié de Grashof basé sur la différence de concentration), *Pr* (nombre de Prandtl), *E* (nombre d'Eckert), *Sc* (nombre de Schmidt) et ω (fréquence).

INSTATIONÄRE FREIE KONVEKTION AN EINER UNENDLICH AUSGEDEHNTEN, VERTIKALEN PLATTE MIT KONSTANTER ABSAUGUNG UND STOFFÜBERGANG

Zusammenfassung—Es wird die zweidimensionale, instationäre freie Konvektionsströmung in Anwesenheit von Fremdstoffen an einer unendlich ausgedehnten, porösen, vertikalen Platte mit periodisch veränderlicher Plattentemperatur untersucht. Unter Annahme einer konstanten Absaugung an der Platte werden Näherungslösungen der gekoppelten, nichtlinearen Gleichungen für die Strömung, den Verlauf der Wandreibung und den Wärmeübergang abgeleitet. Der Einfluß von *Gr* (Temperatur:Grashof–Zahl), *Gc* (modifizierte Konzentrations-Grashof–Zahl), *Pr* (Prandtl–Zahl), *Ec* (Eckert–Zahl), *Sc* (Schmidt–Zahl) und ω (Frequenz) wird diskutiert.

НЕСТАЦИОНАРНОЕ ОБТЕКАНИЕ БЕСКОНЕЧНОЙ ВЕРТИКАЛЬНОЙ ПЛАСТИНЫ В УСЛОВИЯХ СВОБОДНОЙ КОНВЕКЦИИ С ПОСТОЯННЫМ ОТСОСОМ И МАССОПЕРЕНОСОМ

Аннотация — Изучается нестационарное обтекание бесконечной пористой пластины в условиях свободной конвекции при наличии инородной массы в случае осцилляции температуры около постоянного значения. В предположении постоянного отсоса на поверхности получены приближенные решения системы нелинейных уравнений для осредненного потока, неустановившегося потока амплитуды и фазы поверхностного трения, а также для теплового потока.

Обсуждается влияние чисел Грасгофа (*Gr*), модифицированного Грасгофа (*Gc*), Прандтля (*Pr*), Эккерта (*Ec*), Шмидта (*Sc*) и частоты колебаний ω.