ENERGY RESEARCH, VOL. 10, 409–416 (1986)

EFFECTS OF MASS TRANSFER AND FREE CONVECTION ON THE UNSTEADY MHD FLOW PAST A VERTICAL POROUS PLATE WITH CONSTANT SUCTION

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SUMMARY

Effects of free convection currents and mass transfer on the unsteady flow of an electrically conducting and viscous incompressible fluid past an infinite vertical porous plate subjected to uniform suction, in the presence of transverse magnetic field, have been studied taking into account that the external flow velocity varies periodically with time in magnitude but not in direction. The effect of the induced magnetic field has been neglected. Approximate solutions to the transient flow, the amplitude and the phase of the skin-friction and the rate of heat transfer have been derived. During the course of the discussion, the effects of the Grashoff number Gr, the modified Grashoff number Gc (depending on the concentration difference), the Schmidt number Sc, the Eckert number Ec, the magnetic field parameter M, and the frequency ω have been discussed.

KEY WORDS MHD Free convection Mass transfer

INTRODUCTION

The flows arising from differences in concentration or material constitution and in conjunction with temperature difference have great significance not only for their own interest but also for their applications to geophysics, aeronautics and engineering. Because of many interesting aspects of such flows, in recent years, analytical solutions to the problems of free convection flow with mass transfer effects have been investigated by many authors, such as Somers (1956), Wilcox (1961), Gill *et al.* (1965), Adams and Lowell (1968) and Gebhart and Pera (1971). In these studies, the level of the concentration of species is assumed to be very low. Because of this assumption the Soret–Dufour effects (thermal diffusion and diffusion thermo) can be neglected. The free convective flow with Soret–Dufour effects has been studied by Sparrow *et al.* (1964) and Sparrow (1964). Soundalgekar and Wavre (1977a, b) have recently studied the effects of mass transfer and suction on the unsteady free convective flow, neglecting the Soret–Dufour effects on the energy equation. Very recently, Hossain and Begum (1984) and Hossain *et al.* (1984a) have studied the effect of a free convection current in the presence of foreign masses on the oscillatory flow of a viscous incompressible fluid past a vertical porous plate with constant and variable suction velocity. The problem studied by Hossain and Begum (1984) has again been extended by Hossain *et al.* (1984b) by bringing in the effects of oscillatory free convection currents on the flow field.

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0363-907X/85/040409-08$05.00

Received 5 December 1984

It is also of interest, from the technological point of view, to make an investigation on the effects of a transverse magnetic field and mass transfer on the free convection flow of an electrically conducting viscous fluid past a vertical plate, with or without effects of thermal diffusion and diffusion thermo. Hence, in the present paper, it is proposed to investigate the effects of free convection currents and mass transfer on the unsteady flow of an electrically conducting viscous incompressible fluid around an infinite vertical porous plate subjected to uniform suction, in the presence of a transverse magnetic field, when the free-stream velocity oscillates in magnitude but not in direction. The induced magnetic field is, however, neglected. In this study the plate temperature is assumed to be constant and the temperature difference $T'_w - T'_\infty$ between the plate and the free stream is considered very large and positive so that free convection currents can take place in the boundary layer region. Owing to the presence of free convection currents and the foreign species, the problem is governed by coupled non-linear equations. The mathematical formalisms are presented under suitable assumptions in the next section and in the following section an overall discussion on the results is set out.

MATHEMATICAL FORMALISMS

An unsteady free convective flow of an electrically conducting viscous incompressible fluid past an infinite vertical porous plate with constant suction is considered. A magnetic field of uniform strength is assumed to be applied along the normal direction to the plate. The x'-axis is chosen along the plate in the upward direction and the y'-axis is taken normal to the plate. The concentration 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 the usual Boussinesq approximation the flow is governed by the following non-dimensional equations:

Momentum equation:

$$\frac{1}{4}\frac{\partial u}{\partial t} - \lambda\frac{\partial u}{\partial y} = \frac{\mathrm{d}U}{\mathrm{d}t} + \frac{\partial^2 u}{\partial y^2} - M(u-U) + GrT + GcC \tag{1}$$

Energy equation:

$$\frac{1}{4}\frac{\partial T}{\partial t} - \lambda\frac{\partial T}{\partial y} = \frac{1}{Pr}\frac{\partial^2 T}{\partial y^2} + Ec\left(\frac{\partial u}{\partial y}\right)^2 \tag{2}$$

Species:

$$\frac{1}{4}\frac{\partial C}{\partial t} - \lambda\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \tag{3}$$

The boundary conditions are as follows:

$$\left.\begin{aligned} u = 0, T = 1, C = 1 \quad &\text{at} \quad y = 0 \\ u = U(t), T = 0, C = 0 \quad &\text{as} \quad y \to \infty \end{aligned}\right\} \tag{4}$$

where the non-dimensional variables in the above equations are defined in the Nomenclature.

We now assume that the free-stream velocity is given by

$$U(t) = 1 + \varepsilon \mathrm{e}^{\mathrm{i}\omega t}, \ \varepsilon \ll 1 \tag{5}$$

For small amplitude oscillatory boundary layer flow, we assume the solutions of equations (1–3) in the following form:

$$(u, T, C) = (u_0, T_0, C_0) + \varepsilon \mathrm{e}^{\mathrm{i}\omega t}(u_1, T_1, C_1) \tag{6}$$

Substituting (5) and (6) into equations (1–4) and equating the coefficients of the harmonic and non-harmonic terms, neglecting the coefficients of ε^2, we get

$$u_0'' + \lambda u_0' - Mu_0 = -M - GrT_0 - GcC_0 \tag{7}$$

$$T_0'' + \lambda PrT_0' = -PrEcu_0'^2 \tag{8}$$

$$C_0'' + \lambda Sc C_0' = 0 \tag{9}$$

$$\left.\begin{aligned} u_0(0) = 0, T_0(0) = C_0(0) = 1 \\ u_0(\infty) = 1, T_0(\infty) = C_0(\infty) = 0 \end{aligned}\right\} \tag{10}$$

$$u_1'' + \lambda u_1' - (M + \tfrac{1}{4}\mathrm{i}\omega)u_1 = -(M + \tfrac{1}{4}\mathrm{i}\omega) - GrT_1 - GcC_1 \tag{11}$$

$$T_1'' + \lambda PrT_1' - \tfrac{1}{4}\mathrm{i}\omega PrT_1 = -2PrEcu_0'u_1' \tag{12}$$

$$C_1'' + \lambda ScC_1' - \tfrac{1}{4}\mathrm{i}\omega ScC_1 = 0 \tag{13}$$

$$\left.\begin{aligned} u_1(0) = T_1(0) = C_1(0) = 0 \\ u_1(\infty) = 1, T_1(\infty) = T_1(\infty) = 0 \end{aligned}\right\} \tag{14}$$

Here the primes denote differentiation of the functions with respect to y. In this problem, the equations (7) and (11) are quite different from the similar set obtained by Hossain and Begum (1984) and this is due to the effect of the magnetic field. This implies that the unsteady flow is considerably affected by the magnetic field.

Eqiations (7)–(14) are coupled non-linearly and hence difficult to solve analytically. To linearize these equations, we expand the functions u_i and T_i only in powers of the Eckert number Ec (as this number is far less than unity for an incompressible fluid). Substituting these series expansions of the functions u_i, T_i into equations (7), (8), (11) and (12) and then taking the terms of the order $O(Ec)$ (omitting the higher order terms, which are negligible), we obtain a set of coupled linear equations for the functions u_{ij} and T_{ij} $(i, j = 0, 1)$, which can easily be solved. Solutions of these equations finally take the following form:

$$\begin{aligned} u_0(y) = 1 &- A_1\mathrm{e}^{-\lambda Scy} - A_2\mathrm{e}^{-\lambda Pry} - A_3\mathrm{e}^{-my} + Ec(A_{18}\mathrm{e}^{-my} - A_{11}\mathrm{e}^{-\lambda Pry} \\ &+ A_{12}\mathrm{e}^{-2\lambda Pry} + A_{13}\mathrm{e}^{-2\lambda Scy} + A_{14}\mathrm{e}^{-(m+\lambda Pr)y} + A_{15}\mathrm{e}^{-(m+\lambda Sc)y} \\ &+ A_{16}\mathrm{e}^{-\lambda(Pr+Sc)y} + A_{17}\mathrm{e}^{-2my}) \end{aligned} \tag{15}$$

$$\begin{aligned} T_0(y) = \mathrm{e}^{-\lambda Pry} &+ Ec(A_{10}\mathrm{e}^{-\lambda Pry} - A_4\mathrm{e}^{-2\lambda Pry} - A_5\mathrm{e}^{-2\lambda Scy} - A_6\mathrm{e}^{-(m+\lambda Pr)y} \\ &- A_7\mathrm{e}^{-(m+\lambda Sc)y} - A_8\mathrm{e}^{-\lambda(Pr+Sc)y} - A_9\mathrm{e}^{-2my}) \end{aligned} \tag{16}$$

$$C_0(y) = \mathrm{e}^{-\lambda Scy} \tag{17}$$

where

$$\begin{aligned}
A_1 &= Gc/f(\lambda Sc),\ A_2 = Gr/f(\lambda Pr),\ A_3 = 1 - A_1 - A_2 \\
A_4 &= PrA_2^2/2,\ A_5 = PrScA_1^2/2(2Sc - Pr),\ A_6 = 2Pr^2A_2A_3/(m + \lambda Pr) \\
A_7 &= 2\lambda mPrScA_1A_3/(m + \lambda Sc)(m + \lambda(Pr + Sc)),\ A_8 = 2Pr^2A_1A_2/(Pr + Sc) \\
A_9 &= 2mPrA_3^2/(2m - \lambda Pr),\ A_{10} = A_4 + A_5 + A_6 + A_7 + A_8 + A_9 \\
A_{11} &= GrPrA_{10}/f(\lambda Pr),\ A_{12} = PrGrA_4/f(2\lambda Pr),\ A_{13} = GrPrA_5/f(2\lambda Sc) \\
A_{14} &= GrPrA_6/f(m + \lambda Pr),\ A_{15} = GrPrA_7/f(m + \lambda Sc),\ A_{16} = GrPrA_8/f(\lambda Pr + \lambda Sc) \\
A_{17} &= GrPrA_9/f(2m),\ A_{18} = A_{11} - A_{12} - A_{13} - A_{14} - A_{15} - A_{16} - A_{17}
\end{aligned}$$

and

$$u_1(y) = 1 - \mathrm{e}^{-ny} + Ec(B_9\mathrm{e}^{-ny} - B_5\mathrm{e}^{-ly} + B_6\mathrm{e}^{-(m+n)y} + B_7\mathrm{e}^{-(n+\lambda Pr)y} + B_8\mathrm{e}^{-(n+\lambda Sc)y}) \tag{18a}$$

$$T_1(y) = Ec(B_4\mathrm{e}^{-ly} - B_1\mathrm{e}^{-k(m+n)y} - B_2\mathrm{e}^{-(n+\lambda Pr)y} - B_3\mathrm{e}^{-(n+\lambda Sc)y}) \tag{18b}$$

where

$$\begin{aligned}
B_1 &= 2mnPrA_3/h(m + n),\ B_2 = 2nPr^2A_2/h(n + \lambda Pr),\ B_3 = 2\lambda PrScnA_1/h(n + \lambda Sc) \\
B_4 &= B_1 + B_2 + B_3,\ B_5 = GrB_4/g(1),\ B_6 = GrB_1/g(m + n),\ B_7 = GrB_2/g(n + \lambda Pr) \\
B_8 &= GrB_3/g(n + \lambda Sc),\ B_9 = B_5 - B_6 - B_7 - B_8
\end{aligned}$$

with

$$f(x) = x^2 - \lambda x - M,\ g(x) = x^2 - \lambda x - (M + \tfrac{1}{4}\mathrm{i}\omega),\ h(x) = x^2 - \lambda Prx - \tfrac{1}{4}\mathrm{i}\omega Pr$$

and

$$m = \tfrac{1}{2}[\lambda + \sqrt{(\lambda^2 + 4M)}],\ n = \tfrac{1}{2}[\lambda + \sqrt{(\lambda^2 + (4M + i\omega))}],\ l = \tfrac{1}{2}[\lambda Pr + \sqrt{(\lambda^2 Pr^2 + i\omega Pr)}]$$

Substituting the values of u_0, u_1, T_0, T_1 from the above into equation (6), we get the expressions for the velocity and the temperature distributions in the flow field. These can be written in terms of the fluctuating parts of the velocity and the temperature as

$$u(y, t) = u_0(y) + \varepsilon(M_r \cos \omega t - M_i \sin \omega t) \tag{19}$$

and

$$T(y, t) = T_0(y) + \varepsilon(N_r \cos \omega t - N_i \sin \omega t) \tag{20}$$

where $(M_r, N_r) = \mathrm{Re}(u_1, T_1)$ and $(M_i, N_i) = \mathrm{Im}(u_1, T_1)$. Hence the expressions for the transient velocity and the transient temperature for $\omega t = \pi/2$ are written as

$$u(y, \pi/2\omega) = u_0(y) - \varepsilon M_i,\ T(y, \pi/2\omega) = T_0(y) - \varepsilon N_i \tag{21}$$

The transient velocity and the transient temperature profiles are shown in Figures 1 and 2, respectively, for different values of the parameters.

In our numerical calculations of the transient velocity and the transient temperature profiles, the value of the Prandtl number Pr is taken in such a way that it represents air ($Pr = 0{\cdot}71$). The values of the Schmidt number Sc are chosen to represent the diffusing chemical species which is of the most common interest. The value of Sc

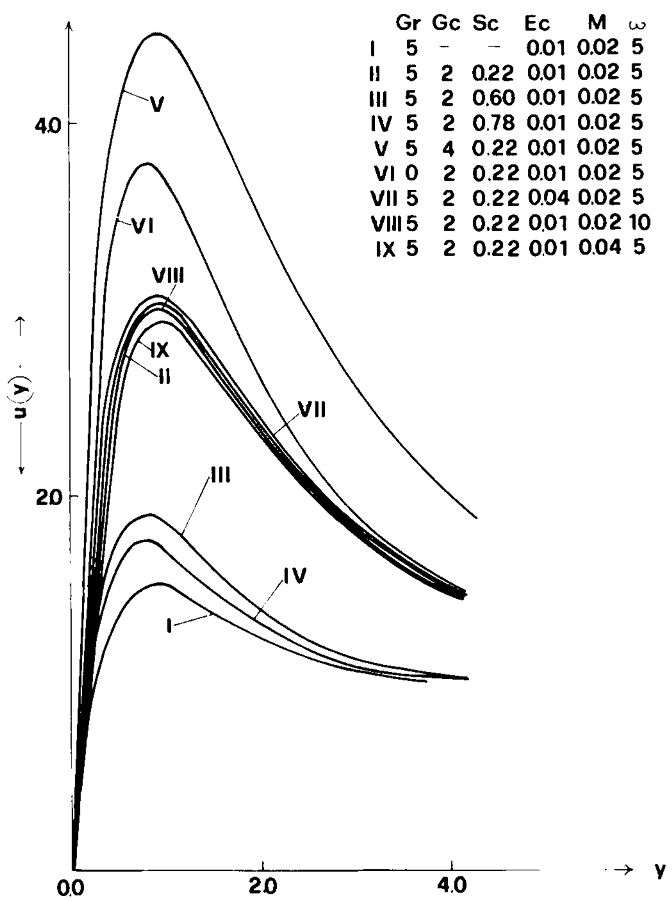

Figure 1. The transient velocity profiles: $Pr = 0{\cdot}71$, $\varepsilon = 0{\cdot}2$, $\lambda = 2{\cdot}0$, $\omega t = \pi/2$

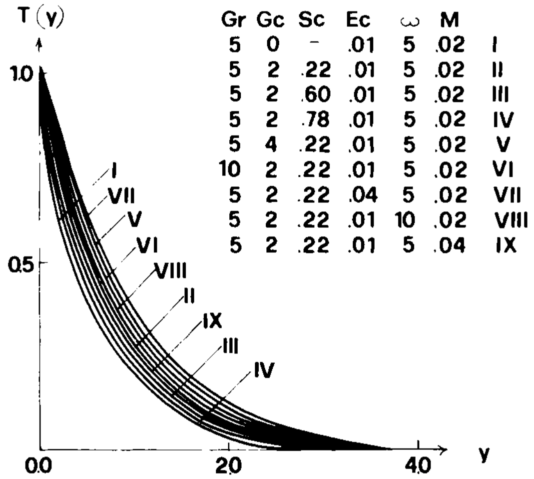

Figure 2. The transient temperature profiles: $Pr = 0{\cdot}71$, $\varepsilon = 0{\cdot}2$, $\lambda = 2{\cdot}0$, $\omega t = \pi/2$

at 25 °C and 1 atm in air for H_2 is 0·22, for He it is 0·30, for H_2O it is 0·60 and for NH_3 it is 0·78 (Gebhart, 1965). The values of *Gr* and *Gc* are chosen arbitrarily large; whereas, in order to be realistic, the values of the Eckert number *Ec* and the magnetic field parameter *M* are chosen very small. Throughout the calculations, the values of λ and ε are considered to be 2 and 0·2. The problem reduces to that of Hossain and Begum (1984) for the substitution of $M = 0$.

RESULTS AND DISCUSSION

Figures 1 and 2 represent the transient velocity and the transient temperature profiles, respectively, for different values of the parameters. Comparing the curves of Figure 1 with the corresponding curves of the paper by Hossain and Begum (1984, Figure 1) we observe that owing to the application of the magnetic field there is a considerable fall in the transient velocity profiles. With the application of a constant magnetic field, the transient velocity near the plate rises in the presence of foreign species (I: II, III, IV), and this rise is higher when a lighter gas is present in the fluid. From this Figure we also observe that an increase in *Gr*, *Gc*, *Ec* or ω leads to a rise in the transient velocity of the fluid near the plate (II: V, VI, VII, VIII); whereas, owing to an increase in the magnetic field parameter *M*, there is a decrease in the transient velocity (II: IX). In order that these results be useful for the experimentalists, we indicate the percentage increase in the maximum value of the transient velocity. It should be noted here that during the course of numerical calculations of the functions, the value of the parameter *Gr* is changed from 5 to 10, *Gc* from 2 to 4, *Ec* from 0·01 to 0·04, ω from 5 to 10 and *M* from 0·02 to 0·04. Now, for $Gr = 5$, $Ge = 2$, $Ec = 0{\cdot}01$, $M = 0{\cdot}02$ and $\omega = 5$, the maximum value of the transient velocity increases by 659·6, 62·9 or 31·8 per cent due to the presence of H_2, H_2O or NH_3 in the fluid, respectively; whereas, for $Sc = 0{\cdot}22$ (when H_2 is present in the fluid), the respective increase in the maximum value of the transient velocity due to an increase in *Gc*, *Gr*, *Ec* or ω in the presence of H_2 is 75·2, 15·8, 342·6 or 0·16 per cent but an increase in *M* leads to a decrease in the maximum value of the transient velocity by 178·1 per cent.

Now comparing the curves representing the transient temperature distributions, in Figure 2, with the corresponding curves of Hossain and Begum (1984, Figure 2) we observe that, owing to the presence of the magnetic field there is a fall in the transient temperature near the plate. With the application of the magnetic field, the transient temperature of the fluid near the plate rises in the presence of foreign species (I: II, III, IV) for constant values of *Gr*, *Gc*, *Ec* and ω. From the same Figure we also observe that owing to an increase in *Gr*, *Gc*, *Ec* or ω, there is an increase in the transient temperature in the presence of H_2 (II: V, VI, VII, VIII). Under similar circumstances, the transient temperature decreases owing to an increase in *M*. We now discuss the results numerically. For different cases the numerical values of the transient temperature are obtained at $y = 0{\cdot}2$. From the numerical calculations, we see that for $Gr = 5$, $Gc = 2$, $Ec = 0{\cdot}01$, $\omega = 5$ and $M = 0{\cdot}02$, the transient temperature increases by 4·281, 0·34 or 0·16 per cent when there is a presence of H_2, H_2O or NH_3, respectively, and for $Sc = 0{\cdot}22$ (when H_2 is present in the fluid), the increase in the transient temperature is 0·77, 0·15 or 123·6 per cent with the rise of Gc, Gr or Ec, respectively; whereas, owing to in the value of M there is a fall in the transient temperature by 1·7 per cent. It is interesting to note that the increase in the transient temperature due to increase in the value of the frequency is too small and hence negligible.

From the practical point of view once the velocity and the temperature are known, it is important to know the effects of the parameters Gr, Gc, Sc, Ec, and M on the skin-friction and the rate of heat transfer. The skin-friction and the rate of heat transfer can be obtained from the following (non-dimensional) relations:

$$\tau = \tau_m + \varepsilon e^{i\omega t} u_1'(0) \tag{22}$$

and

$$q = q_m + \varepsilon e^{i\omega t} T_1'(0) \tag{23}$$

where τ_m and q_m are the mean skin-friction and the mean rate of heat transfer. The values of $u_1'(0)$ and $T_1'(0)$ can easily be obtained from the relations (18a) and (18b), respectively. In terms of amplitude and phase the above equations can be written as

$$\tau = \tau_m + \varepsilon |B| \cos(\omega t + \alpha) \tag{24}$$

and

$$q = q_m + \varepsilon |Q| \cos(\omega t + \beta), \tag{25}$$

where $B = B_r + iB_i$ = coefficient of $e^{i\omega t}$ in (22), $\tan\alpha = B_i/B_r$, and $Q = Q_r + iQ_i$ = coefficient of $e^{i\omega t}$ of (23), $\tan\beta = Q_i/Q_r$. The values of the amplitude $|B|$ and the phase $\tan\alpha$ of the skin-friction are shown in Table I and those of $|Q|$ and $\tan\beta$ of the rate of heat transfer are shown in Table II.

Table I. Values of the amplitude and the phase of skin friction. $Pr = 0{\cdot}71$, $\varepsilon = 0{\cdot}2$ and $\lambda = 2{\cdot}0$

					$\|B\|$		$\tan\alpha$	
M	Gc	Ec	Sc	ω	$Gr = 5$	$Gr = 10$	$Gr = 5$	$Gr = 10$
0·02	0	0·01	—	5	2·7737		0·0102	
0·02	2	0·01	0·22	5	2·7909	2·8922	0·0111	0·0457
0·02	2	0·01	0·60	5	2·7842		0·0128	
0·02	2	0·01	0·78	5	2·7873		0·0146	
0·02	4	0·01	0·22	5	2·8081		0·0121	
0·02	2	0·04	0·22	5	2·9165		0·0428	
0·02	2	0·01	0·22	10	3·3904		0·0049	
0·04	2	0·01	0·22	5	2·7927		0·0109	

Table II. Values of the amplitude and phase of the rate of heat transfer. $Pr = 0{\cdot}71$, $\varepsilon = 0{\cdot}2$ and $\lambda = 2{\cdot}0$

					$\|Q\|$		$\tan\beta$	
M	Gc	Ec	Sc	ω	$Gr = 5$	$Gr = 10$	$Gr = 5$	$Gr = 10$
0·02	0	0·01	—	5	0·0179		−0·3187	
0·02	2	0·01	0·22	5	0·0097	0·0349	−0·5114	−0·3488
0·02	2	0·01	0·60	5	0·0239		−0·3258	
0·02	2	0·01	0·78	5	0·0323		−0·2966	
0·02	4	0·01	0·22	5	0·0034		−17·9189	
0·02	2	0·04	0·22	5	0·0388		−0·5115	
0·02	2	0·01	0·22	10	0·0077		−0·6088	
0·04	2	0·01	0·22	5	0·0091		−0·5265	

From Table I we observe that in the presence of foreign species in the fluid, the amplitude $|B|$ of the skin-friction increases owing to the application of the magnetic force. Under similar circumstances, an increase in the values of Gc, Gr, Ec, ω or M leads to rise in the value of $|B|$ in presence of H_2. For $Gr = 5$, $Gc = 2$, $Ec = 0{\cdot}01$, $\omega = 5$ and $M = 0{\cdot}02$, the increase in $|B|$ is 7·8, 1·75 or 1·34 per cent, respectively, when H_2, H_2O or NH_3 is present in the fluid, and for $Sc = 0{\cdot}22$ when Gc, Gr, Ec, ω or M increases, the percentage increases in the value of $|B|$ are 0·86, 418·6, 11·9 or 9·2, respectively. From the same table we also observe that, owing to the application of the magnetic field, $\tan\alpha$, the value of the phase of the skin-friction, is always positive and hence there is always a phase lead in the skin-friction.

Finally, from Table II, we see that in the presence of an applied magnetic force the amplitude $|Q|$ of the rate of heat transfer decreases due to the presence of H_2, whereas its value increases due to the presence of H_2O or NH_3 in the fluid. On the other hand, an increase in the value of Gr or Ec leads to an increase in $|Q|$, but an increase in Gc or M produces a fall in the value of $|Q|$. From the numerical values of $|Q|$ we see that for $Gr = 5$, $Gc = 2$, $Ec = 0{\cdot}01$ and $M = 0{\cdot}02$, due to the presence of H_2 in the fluid the value of $|Q|$ decreases by 3·7 per cent, whereas the presence of H_2O or NH_3 leads to an increase in its value by 1·1 or 1·84 per cent, respectively. Again, in presence of H_2 the value of $|Q|$ decreases by 0·31, 0·04 or 3·1 per cent, owing to an increase in the value of Gc, ω or M, respectively, but an increase in Gr or Ec leads to a rise in the value of $|Q|$ by 0·5 or 97·0 per cent, respectively. In the same table we observe from the values of $\tan\beta$ that there is always a phase lag in the case of the rate of heat transfer.

ACKNOWLEDGEMENTS

One of the authors (M.A.H.) would like to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste. He would also like to thank Professor Vidossich for taking an interest and discussions.

NOMENCLATURE

B_0,	magnetic field
C_p,	specific heat at constant pressure
C',	species concentration
C,	non-dimensional species concentration $((C'C'_\infty)/(C'_w - C'_\infty))$
C'_w,	species concentration near plate
C'_∞,	species concentration in the free stream
C_0,	mean species concentration
C_1,	unsteady part of the species concentration
D,	chemical molecular diffusivity
Ec,	Eckert number $(U_0^2/C_p(T'_w - T'_\infty))$
Gr,	Grashoff number $(\nu g\beta(T'_w - T'_\infty)/U_0^3)$
Gc,	modified Grashoff number $(\nu g\beta^*(C'_w - C'_\infty)/U_0^3)$
g,	acceleration due to gravity
k,	thermal conductivity
M,	magnetic field parameter $(\mu_e^2 B_0^2\sigma/\rho U_0^3)$
p',	pressure
Pr,	Prandtl number $(\mu C_p/k)$
q,	dimensionless rate of heat transfer
q_m,	mean rate of heat transfer
Sc,	Schmidt number (ν/D)
t,	dimensionless time $(t'U_0^2/4\nu)$
T',	temperature of the fluid
T'_w,	temperature of the plate

T'_∞, temperature of the free stream
T, dimensionless temperature $(T'-T'_\infty)/(T'_w-T'_\infty)$
T_0, mean temperature
T_1, unsteady part of the temperature
u', v', velocity components along x' and y' directions
U', free stream velocity
U, non-dimensional free stream velocity (U'/U_0)
U_0, mean of U'
u, non-dimensional velocity (u'/U_0)
u_0, mean velocity
u_1, unsteady part of the velocity
v_0, suction velocity
y, dimensionless coordinate normal to the plate $(y'U_0/v)$
β, volumetric coefficient of thermal expansion
β^*, volumetric coefficient of expansion with concentration
λ, suction parameter (v_0/U_0)
μ, viscosity
μ_e, magnetic permeability
v, kinematic coefficient of viscosity
ρ, density of the fluid in the boundary layer
ρ'_∞, density of the fluid in the free stream
σ, the electrical conductivity of the fluid
τ', skin-friction
τ, non-dimensional skin-friction $((\mu du'/dy')$ at $y'=0)$
τ_m, mean skin-friction
ω', frequency of oscillation
ω, dimensionless frequency $(4v\omega'/U_0^2)$

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