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Hydromagnetic Unsteady Mixed Convection Flow Past an Infinite Vertical Porous Plate

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Abstract An approximate analysis of unsteady mixed convection flow of an electrically conducting fluid past an infinite vertical porous plate embedded in porous medium under constant transversely applied magnetic field is presented here. The periodic transverse suction velocity is applied to the surface due to which the flow becomes unsteady. The surface is kept at oscillating wall temperature. Analytical expressions for the transient velocity, temperature, amplitude and phase of the skin-friction and the rate of heat transfer are obtained and discussed in detail with the help of graphs, under different parameter values.

Keywords Hydromagnetic Flow, Mixed Convection, Heat Transfer, Porous Plate

1. Introduction

The problem laminar flow through a porous medium has become very important in recent years particularly in the fields of agricultural engineering to study the underground water resources, seepage of water in river beds, in chemical engineering for filtration and purification process; in petroleum technology to study the movement of natural gas, oil and water through the oil reservoirs. Oscillatory flows play an important role in technological field. The effects of free-stream oscillations on the flow past a semi-infinite plate were first studied by Lin[1] for finite amplitude and by Lighthill[2] for small amplitude oscillations. Lighthill studied this problem by employing momentum integral method. These results were confirmed experimentally by Hill and Stenning[3]. In many industrial, aeronautical engineering, atomic propulsion and space science, the oscillatory flow past an infinite vertical porous plate plays an important role. Free convection effects on the oscillatory flow past an infinite vertical porous plate with constant suction was initiated by Soundalgekar[4-5]. In both the papers, suction was assumed to be constant. However, in many engineering applications variable suction exists and the effect of variable suction on the flow past an infinite vertical porous plate was studied by Soundalgekar[6]. In all these studies, the plate temperature was assumed to be constant and hence isothermal.

But in many industrial applications, the flow is steady and in the upward direction and the plate temperature is oscillating. Such a study of the flow past an infinite vertical porous plate, under oscillating plate temperature and with constant or variable suction was presented by Soundalgekar et.al.[7]. The unsteady free convection flow past an infinite plate with constant suction and heat sources has been studied by Pop et.al.[8]. Raptis[9] studied the free convective flow through a porous medium bounded by an infinite vertical plate with oscillating plate temperature and constant suction. Raptis et.al.[10] further analysed the free convective flow through a highly porous medium bounded by an infinite vertical porous plate with constant suction when the free stream velocity oscillates about a mean constant value. Hooper et.al.[11] have presented the problem of mixed convection along an isothermal vertical plate in porous medium with injection and suction. Panda et. al.[12] considered the unsteady free convection flow and mass transfer past a vertical porous plate. Soundalgekar et. al.[13] considered the free convection effects on magnetohydrodynamics flow past an infinite vertical oscillating plate with constant heat flux. Chandran et. al.[14] studied the transient hydromagnetic natural convection on a vertical flat plate subject to heat flux. Sahoo et. al.[15] studied the magnetohydrodynamic unsteady free convection flow past an infinite vertical plate with constant suction and heat sink. Heat and mass transfer in magnetohydrodynamics flow of a viscous fluid past a vertical plate under oscillatory suction velocity has been studied by Singh et. al.[16]. Helmy[17] studied the magnetohydrodynamics unsteady free convection flow past a vertical porous plate. Acharya et. al.[18] made a systematic analysis of magnetic field effects on the free-convective and mass transfer flow through porous medium with constant suction and constant heat flux.

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Ahmed et. al.[19] extended Acharya's[18] works to unsteady case by considering a uniform motion of the plate. Jaiswal et. al.[20] further extended his problem. Unsteady free and forced convection magnetohydrodynamics flow past an infinite vertical porous plate with variable suction and oscillating plate temperature. Sharma et. al.[21-22] considered the hydromagnetic unsteady mixed convection and mass transfer flow past a vertical porous plate immersed in a porous medium. Recently, Effects of fluctuating surface temperature and concentration on unsteady convection flow past an infinite vertical plate with constant suction discussed by Sharma et. al[23].

In the above stated studies the flows with the oscillatory suction velocity and with the influence of uniform magnetic field are not considered while such flows are encountered in geophysical problems, astrophysical problems, soil sciences and so on. Therefore, the present investigation is to study the effects of permeability and magnetic field as the flow past a vertical plate embedded on a porous medium and subjected to oscillating suction and temperature field. It is found that the permeability and magnetic field have significant effects on the flow and heat transfer.

2. Mathematical Formulation

We consider the flow of an electrically conducting viscous incompressible fluid through a porous medium bounded by an infinite vertically porous flat plate. The x*-axis is taken along the plate, being the vertically upward direction of the flow and y*-axis is taken perpendicular to the plate directed into the fluid. The fluid flows with uniform free stream velocity U. A uniform magnetic field $\vec{B}$ is imposed along the y*-axis. The induced magnetic field is negligible which is possible on a laboratory scale. Since the plate is considered infinite in the x*-direction, hence all the fluid properties are independent of x*. Let u*, v* be the fluid velocities along x*, y*-axes respectively and the plate temperature T* is oscillating about a non-zero plate temperature T_w^*. The variation of the suction velocity distribution of the form

$$v^*(t^*) = -V(1+\in e^{i\omega^* t^*}) \tag{1}$$

Where V > 0 is the constant mean velocity and < 1, the negative sign in equation (1) indicates that the suction is towards the plate. Then under usual Boussineq's approximation, the magnetohydrodynamic flow in the porous medium is governed by the following differential equations

$$\frac{\partial v^*}{\partial y^*} = 0 \tag{2}$$

$$\frac{\partial u^*}{\partial t^*} + v^*\frac{\partial u^*}{\partial y^*} = \nu\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta(T^* - T_\infty^*) + \frac{\sigma B_0^2}{\rho}(U-u^*) + \frac{\nu}{K^*}(U-u^*) \tag{3}$$

$$\rho C_p\left(\frac{\partial T^*}{\partial t^*} + v^*\frac{\partial T^*}{\partial y^*}\right) = \kappa\frac{\partial^2 T^*}{\partial y^{*2}} + \mu\left(\frac{\partial u^*}{\partial y^*}\right)^2 \tag{4}$$

In these equations ρ is the density; t* is the time; ν the kinematic viscosity; g the acceleration due to gravity; β the coefficient of volume expansion; K* is the permeability of the porous medium; T* the characteristic temperature of the fluid, T_∞^* the temperature of the fluid far away from the plate; σ the scalar electrical conductivity ; U the uniform velocity of the fluid in the upward direction; C_p the specific heat at constant pressure; κ the thermal conductivity and μ is the coefficient of viscosity. The plate being infinite in length, the flow variables are functions of y* and t* only.

The boundary conditions of the problem are

$$\left.\begin{array}{l} y^* = 0\ ;\ u^* = 0,\ T^* = T_w^* + \in(T_w^* - T_\infty^*)\, e^{i\omega^* t^*} \\ y^* \to \infty;\ u^* = U,\ T^* = T_\infty^* \end{array}\right\} \tag{5}$$

Here ω^* is the frequency of the plate temperature oscillations and T_w^* is the temperature of the plate. The subscripts w and ∞ denotes physical quantities at the plate and in the free stream respectively.

Introducing the following non-dimensional quantities in equations (2) to (4)

$$y = y^* V/\nu,\ t = t^* V^2/\nu,\ u = U^*/U,$$

$$\omega = \nu\omega^*/V^2,\ \theta = (T^* - T_\infty^*)/(T_w^* - T_\infty^*),$$

$$K = \frac{K^* V^2}{\nu^2},$$

the Permeability parameter

$$M = \frac{\sigma B_0^2 \nu}{\rho V^2}$$

the Hartmann number

$$\Pr = \frac{\mu C_p}{\kappa}$$

the Prandtl number

$$Gr = \frac{\nu g\beta(T_w^* - T_\infty^*)}{U V^2}$$

the Grashof number

$$Ec = \frac{U^2}{C_p(T_w^* - T_\infty^*)}$$

the Eckert number, we get

$$\frac{\partial u}{\partial t} - (1+\in e^{i\omega t})\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\,\theta + M(1-u) + \frac{1}{K}(1-u) \tag{6}$$

$$\frac{\partial \theta}{\partial t} - (1+\in e^{i\omega t})\frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} + Ec\left(\frac{\partial u}{\partial y}\right)^2 \tag{7}$$

The corresponding boundary conditions reduce to

$$\left.\begin{array}{l} y = 0\ ;\ u = 0\ ,\ \theta = 1 + \in e^{i\omega t} \\ y \to \infty;\ u = 1,\ \theta = 0 \end{array}\right\} \tag{8}$$

3. Solution

When the amplitude $\in << 1$ is very small, in order to solve these coupled non-linear differential equations, we assume the solution in the neighbourhood of the plate that the unsteady flow is superimposed on the mean steady flow is represented mathematically of the form

$$\left.\begin{aligned} u(y,t) &= u_0(y) + \in e^{iwt} u_1(y) \\ \theta(y,t) &= \theta_0(y) + \in e^{iwt} \theta_1(y) \end{aligned}\right\} \quad (9)$$

Substituting equation (9) into equations (6) and (7), equating the coefficients of harmonic and non-harmonic terms, neglecting the coefficients of like powers $\in^2$ and $\in^3$, we get

$$u_0'' + u_0' - \left(M + \frac{1}{K}\right)u_0 = -\,Gr\,\theta_0 - \left(M + \frac{1}{K}\right) \quad (10)$$

$$u_1'' + u_1' - \left(M + \frac{1}{K} + i\omega\right)u_1 = -\,u_0' - Gr\,\theta_1 \quad (11)$$

$$\theta_0'' + Pr\,\theta_0' = -\,Pr\,Ec\,u_0^2 \quad (12)$$

$$\theta_1'' + Pr\,\theta_1' - i\,\omega\,Pr\,\theta_1 = -\,Pr\,\theta_0' - 2\,Pr\,Ec\,u_0'\,u_1' \quad (13)$$

where primes denote differentiation with respect to y.

The corresponding boundary conditions become

$$\left.\begin{aligned} y = 0\ &;\ u_0 = 0,\ u_1 = 0,\ \theta_0 = 1,\ \theta_1 = 1 \\ y \to \infty\ &;\ u_0 = 1,\ u_1 = 0,\ \theta_0 = 0,\ \theta_1 = 0 \end{aligned}\right\} \quad (14)$$

These are non-linear differential equations and their exact solutions are not possible. So we again expand u_0, u_1, θ_0 and θ_1 in terms of the Eckert number Ec (Ec < 1 for incompressible fluids), in the following manner

$$\left.\begin{aligned} u_0(y) &= u_{01}(y) + Ec\,u_{02}(y) \\ u_1(y) &= u_{11}(y) + Ec\,u_{12}(y) \\ \theta_0(y) &= \theta_{01}(y) + Ec\,\theta_{02}(y) \\ \theta_1(y) &= \theta_{11}(y) + Ec\,\theta_{12}(y) \end{aligned}\right\} \quad (15)$$

Substituting equation (15) into equations (10) to (13) and equating the coefficients of different powers of Ec, neglecting those of Ec^2, we get the following differential equations

$$u_{01}'' + u_{01}' - \left(M + \frac{1}{K}\right)u_{01} = -\,Gr\,\theta_{01} - \left(M + \frac{1}{K}\right) \quad (16)$$

$$u_{02}'' + u_{02}' - \left(M + \frac{1}{K}\right)u_{02} = -Gr\,\theta_{02} \quad (17)$$

$$\theta_{01}'' + Pr\,\theta_{01}' = 0 \quad (18)$$

$$\theta_{02}'' + Pe\,\theta_{02}' = -Pr\,u_{01}^2 \quad (19)$$

$$u_{11}'' + u_{11}' - \left(M + \frac{1}{K} + i\omega\right)u_{11} = -\,u_{01}' - Gr\,\theta_{11} \quad (20)$$

$$u_{12}'' + u_{12}' - \left(M + \frac{1}{K} + i\omega\right)u_{12} = -\,u_{02}' - Gr\,\theta_{12} \quad (21)$$

$$\theta_{11}'' + Pr\,\theta_{11}' - i\omega\,Pr\,\theta_{11} = -\,Pr\,\theta_{01}' \quad (22)$$

$$\theta_{12}'' + Pr\,\theta_{12}' - i\omega\,Pr\,\theta_{12} = -Pr\,\theta_{02}' - 2\,Pr\,u_{01}'\,u_{11}' \quad (23)$$

with corresponding boundary conditions

$$\left.\begin{aligned} y = 0\ &;\ u_{01} = 0, u_{02} = 0,\ u_{11} = 0,\ u_{12} = 0, \\ &\ \theta_{01} = 1,\ \theta_{02} = 0,\ \theta_{11} = 1,\ \theta_{12} = 0 \\ y \to \infty\ &;\ u_{01} = 1,\ u_{02} = 0,\ u_{11} = 0,\ u_{12} = 0, \\ &\ \theta_{01} = 0,\ \theta_{02} = 0,\ \theta_{11} = 0,\ \theta_{12} = 0 \end{aligned}\right\} \quad (24)$$

These are ordinary differential equations whose exact solutions of u_0, u_1, θ_0 and θ_1 under the boundary conditions are obtained as

$$\begin{aligned} u_0(y) = {} & A_1(e^{-Ly} - e^{-Pr\,y}) + 1 - e^{-Ly} + \\ & Ec\Big[A_5(e^{-Ly} - e^{-Pr\,y}) - A_6(e^{-Ly} - e^{-2Pry}) \\ & - A_7(e^{-Ly} - e^{-2Ly}) - A_8(e^{-Ly} - e^{-(Pr+L)y})\Big] \end{aligned} \quad (25)$$

$$\theta_0(y) = e^{-Pr\,y} + Ec\left[\begin{matrix} A_2(e^{-Pr\,y} - e^{-2Pr\,y}) \\ A_3(e^{-Pr\,y} - e^{-2Ly}) \end{matrix} + A_4\{e^{-Pr\,y} - e^{-(Pr+L)y}\}\right] \quad (26)$$

$$\begin{aligned} u_1(y) = {} & A_{10}(e^{-ny} - e^{-Pr\,y}) + A_{11}(e^{-ny} - e^{-Ly}) \\ & + A_{12}(e^{-ny} - e^{-my}) \\ & + Ec\Big[A_{21}(e^{Ly} - e^{-ny}) + A_{22}(e^{-ny} - e^{-Pr\,y}) \\ & \quad A_{23}(e^{-ny} - e^{-2Pr\,y}) \\ & - A_{24}(e^{-ny} - e^{-2Ly}) \\ & - A_{25}\{e^{-ny} - e^{-(Pr+L)y}\} \\ & + A_{26}(e^{-ny} - e^{-my}) \\ & + A_{27}\{e^{-ny} - e^{-(Pr+n)y}\} \\ & - A_{28}\{e^{-ny} - e^{-(Pr+m)y}\} \\ & + A_{29}\{e^{-ny} - e^{-(L+n)y}\} \\ & - A_{30}\{e^{-ny} - e^{-(L+m)y}\}\Big] \end{aligned} \quad (27)$$

$$\begin{aligned} \theta_1(y) = {} & e^{-my} - A_9(e^{-my} - e^{-Pr\,y}) + \\ & Ec\Big[A_{13}(e^{-Pr\,y} - e^{-my}) \\ & + A_{14}(e^{-my} - e^{-2Pr\,y}) + A_{15}(e^{-my} - e^{-2Ly}) + \\ & A_{16}\{e^{-my} - e^{-(Pr+L)y}\} \\ & - A_{17}\{e^{-my} - e^{-(Pr+n)y}\} + A_{18}\{e^{-my} - e^{-(Pr+m)y}\} \\ & - A_{19}\{e^{-my} - e^{-(L+n)y}\} \\ & + A_{20}\{e^{-my} - e^{-(L+m)y}\}\Big] \end{aligned} \quad (28)$$

where

$$L = \frac{1 + \sqrt{1 + 4(M + \frac{1}{K})}}{2}, \quad A_1 = \frac{Gr}{Pr^2 - Pr - (M + \frac{1}{K})},$$

$$A_2 = \frac{A_1^2\,Pr}{2},$$

$$A_3 = \frac{Pr\,L\,(1 - A_1)^2}{2(2L - Pr)},$$

$$A_4 = \frac{2A_1 Pr^2 (1 - A_1)}{(Pr + L)},$$

$$B_1 = A_2 + A_3 + A_4$$

$$B_2 = A_5 - A_6 - A_7 - A_8,$$

$$A_5 = \frac{Gr\,B_1}{Pr^2 - Pr - (M + \frac{1}{K})}, \quad A_6 = \frac{Gr\,A_2}{4Pr^2 - 2Pr - (M + \frac{1}{K})}$$

$$A_7 = \frac{Gr\,A_3}{4L^2 - 2L - (M + \frac{1}{K})},$$

$$A_8 = \frac{Gr\,A_4}{(Pr + L)^2 - (Pr + L) - (M + \frac{1}{K})}$$

$$m = \frac{Pr + \sqrt{Pr^2 + 4i\,Pr\,\omega}}{2},$$

$$n = \frac{1 + \sqrt{1 + 4(M + \frac{1}{K} + i\omega)}}{2},$$

$$A_9 = \frac{\Pr i}{\omega}, \quad A_{10} = \frac{A_1 \Pr + Gr\, A_9}{\Pr^2 - \Pr - (M + \frac{1}{K} + i\omega)},$$

$$A_{11} = \frac{L(1-A_1)}{L^2 - L - i\omega - (M + \frac{1}{K})},$$

$$A_{12} = \frac{Gr(1-A_9)}{m^2 - m - (M + \frac{1}{K} + i\omega)},$$

$$B_3 = A_{10} + A_{11} + A_{12}, \quad A_{13} = \frac{i \Pr B_1}{\omega},$$

$$A_{14} = \frac{2\Pr A_2 + 2A_1 \Pr^2 A_{10}}{2\Pr - i\omega},$$

$$A_{15} = \frac{2\Pr L\{A_3 + L(1-A_1)A_{11}\}}{4L^2 - 2\Pr L - i\omega\Pr},$$

$$A_{16} = \frac{\Pr(\Pr+L)A_4 + 2A_1 \Pr^2 L A_{11} + 2\Pr^2 L(1-A_1)A_{10}}{(\Pr + L)^2 - \Pr(\Pr+L) - i\omega\Pr},$$

$$A_{17} = \frac{2A_1 n B_3 \Pr^2}{n^2 - n\Pr - i\omega\Pr},$$

$$A_{18} = \frac{2A_1 m A_{12} \Pr^2}{m^2 - m\Pr - i\omega\Pr},$$

$$A_{19} = \frac{2n B_3 \Pr L(1-A_1)}{(L+n)^2 - \Pr(L+n) - i\omega\Pr},$$

$$A_{20} = \frac{2\Pr L m A_{12}(1-A_1)}{(L+m)^2 - \Pr(L+m) - i\omega\Pr},$$

$$B_{14} = -A_{13} + A_{14} + A_{15} + A_{16} - A_{17} + A_{18} - A_{19} + A_{20}$$

$$A_{21} = \frac{L B_2}{L^2 - L - (M + \frac{1}{K} + i\omega)},$$

$$A_{22} = \frac{\Pr A_5 + Gr\, A_{13}}{\Pr^2 - \Pr - (M + \frac{1}{K} + i\omega)},$$

$$A_{23} = \frac{2\Pr A_6 + Gr\, A_{14}}{4\Pr^2 - 2\Pr - (M + \frac{1}{K} + i\omega)},$$

$$A_{24} = \frac{2L A_7 + Gr\, A_{15}}{4L^2 - 2L - (M + \frac{1}{K} + i\omega)},$$

$$A_{25} = \frac{(\Pr + L)A_8 + Gr\, A_{16}}{(\Pr+L)^2 - (\Pr+L) - (M + \frac{1}{K} + i\omega)},$$

$$A_{26} = \frac{Gr\, B_4}{m^2 - m - (M + \frac{1}{k} + i\omega)},$$

$$A_{27} = \frac{Gr\, A_{17}}{(\Pr+n)^2 - (\Pr+n) - (M + \frac{1}{K} + i\omega)},$$

$$A_{28} = \frac{Gr\, A_{18}}{(\Pr+m)^2 - (\Pr+m) - (M + \frac{1}{K} + i\omega)},$$

$$A_{29} = \frac{Gr\, A_{19}}{(L+n)^2 - (L+n) - (M + \frac{1}{K} + i\omega)},$$

$$A_{30} = \frac{Gr\, A_{20}}{(L+m)^2 - (L+m) - (M + \frac{1}{K} + i\omega)}$$

$$B_5 = -A_{21} + A_{22} - A_{23} - A_{24} - A_{25} + A_{26} + A_{27} - A_{28} + A_{29} - A_{30}$$

Substituting u_0, θ_0, u_1 and θ_1 in equation (9) for u and θ, we get the expressions for the main flow velocity and temperature, which can be expressed in terms of the fluctuating parts as

$$u(y,t) = u_0 + \in e^{iwt}(M_r + i M_i) \tag{29}$$

$$\theta(y,t) = \theta_0 + \in e^{iwt}(T_r + i T_i) \tag{30}$$

where

$$M_r + i M_i = u_1, \quad T_r + i T_i = \theta_1$$

For $\omega t = \pi/2$, we can obtain the expressions for the transient velocity and temperature profiles as

$$\left.\begin{aligned} u(y, \pi/2\omega &= u_0 - \in M_i \\ \theta(y, \pi/2\omega) &= \theta_0 - \in T_i \end{aligned}\right\} \tag{31}$$

Now we can express the skin-friction in terms of the amplitude and the phase as

$$\tau = -\left(\frac{du_0}{dy}\right)_{y=0} - \in |B| \cos(\omega t + \alpha) \tag{32}$$

where

$$B = B_r + i B_i = \left(\frac{du_1}{dy}\right)_{y=0}$$

$$|B| = \sqrt{B_r^2 + B_i^2}, \quad \tan\alpha = \frac{B_i}{B_r} \tag{33}$$

$$\begin{aligned} B = {} & A_{10}(\Pr - n) + A_{11}(L-n) + A_{12}(m-n) \\ & + Ec \left[A_{21}(n-L) + A_{22}(\Pr - n) - A_{23}(2\Pr - n) - A_{24}(2L-n) - A_{25}(\Pr + L - n) \right. \\ & \left. + A_{26}(m-n) + A_{27}\Pr - A_{28}(\Pr + m - n) + A_{29}L - A_{30}(L+m-n) \right] \end{aligned} \tag{34}$$

Further we can express the rate of heat transfer in terms of its amplitude and phase as

$$q = q_m + \in e^{iwt}\left(\frac{\partial\theta_1}{\partial y}\right)_{y=0} = q_m + \in |Q| \cos(\omega t + \beta) \tag{35}$$

where

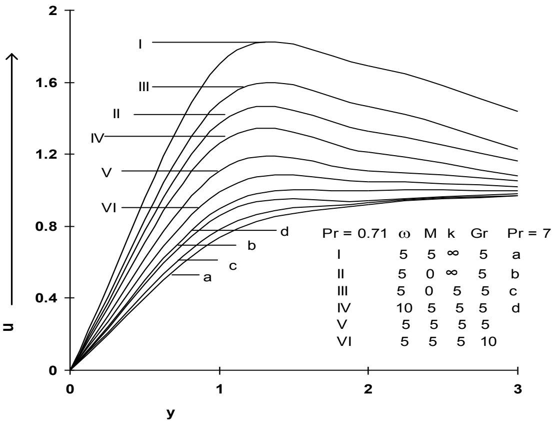
$$Q = Q_r + i Q_i = \left(\frac{d\theta_1}{dy}\right)_{y=0}$$

$$|Q| = \sqrt{Q_r^2 + Q_i^2}, \quad \tan\beta = \frac{Q_i}{Q_r} \tag{36}$$

$$Q = m(1-A_4) + \Pr A_4 + Ec\left[A_{13}(m - \Pr) + A_{14}(2\Pr - m) + A_{15}(2L - m) \right.$$

$$\left. \begin{array}{l} + A_{16}(\Pr + L - m) \ - A_{17}(\Pr + n - m) \ + \\ \Pr A_{18} \ - A_{19}(L + n - m) \ + L\, A_{20} \end{array} \right] \quad (37)$$

4. Discussion of Results



Figture 1. Transient velocity for $\in = 0.2$, $E_c = 0.1$ and $\omega t = \pi/2$.

The transient velocity has been shown in Figure 1, for $\in = 0.2$, $\omega t = \pi/2$, Ec = 0.1 and other values of parameters. It is observed that the transient velocity increases with the increase in ω or M but an increase in Gr, K or Pr leads to a decrease in the transient velocity. The transient velocity increases with increase in distance from plate until it attains its maximum value (nearly y = 1), after which it decreases. The value of the transient velocity is larger in the air (Pr = 0.71) than in water (Pr = 7). The effects of Hartmann number M, frequency ω, permeability K, Grashof number Gr and Prandtl number Pr on the transient temperature have been exhibited in Figure 2. It is observed that the transient temperature increases with the increase in ω or M but an increase in Gr, K or Pr leads to a decrease in the transient temperature. The transient temperature field falls more rapidly for water (Pr = 7) in comparison to air (Pr = 0.71). The transient temperature decreases with increase in distance from the plate and tends to zero. The value of the transient temperature is large in the air (Pr = 0.71) than in water (Pr = 7). Figure 3 is drawn for amplitude of skin-friction | B | against ω. We observe from it that the amplitude of the skin-friction | B | increases with increasing K or Gr but decreases when M is increased. It is observed that for M = 0, | B | is more in air (Pr = 0.71) than that of water (Pr = 7). However, the effect of magnetic field increases its magnitude in the case of water than air. As ω increases the amplitude | B | goes on decreasing steadily. There is always a phase lead. It is observed from Figure 4 that the phase of skin-friction tan α increases in case of air (Pr = 0.71) and decreases for water (Pr = 7). For the large values of ω, magnetic field M, permeability K and buoyancy Gr increases the phase for air, while reverse effect is observed in water. There is always phase lead for both air and water. Figure 5 is drawn for amplitude of rate of heat transfer | Q | against ω. It is observed for air (Pr = 0.71) that the amplitude of rate of heat transfer | Q | increases with increasing K or Gr but decreases when M is increased. It is noted here that in the case of water (Pr = 7), it behaves oppositely than that of air (Pr = 0.71). In the absence of magnetic field the magnitude of | Q | is more in air than that of water (Pr = 7). When frequency ω increases the amplitude of rate of heat transfer increases steadily. It is observed from Figure 6 that the phase of rate of heat transfer tan β decreases in case of air (Pr = 0.71) and increases in water (Pr = 7) for the small or large values of ω. The magnitude of tan β remains more in water than that of air whatever be the effect of M or K or Gr. There is always a phase lead.

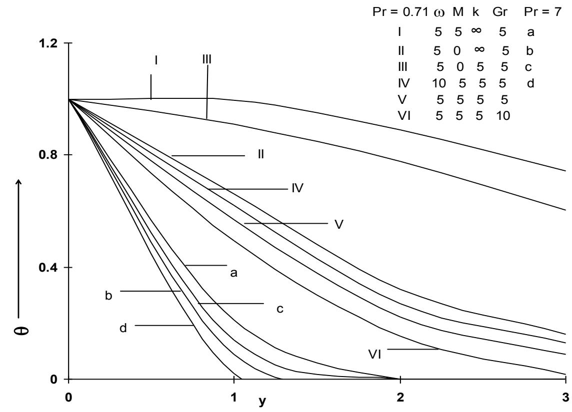


Figure 2. Transient temperature for $\in = 0.2$, Ec = 0.1 and $\omega t = \pi/2$.

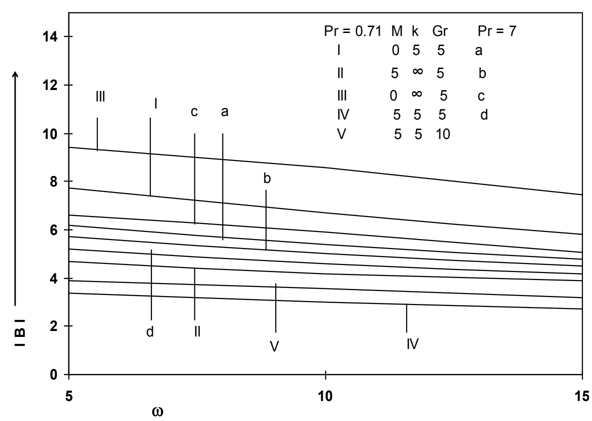


Figure 3. The amplitude of skin-friction for $\in = 0.2$, Ec = 0.1 and $\omega t = \pi/2$.

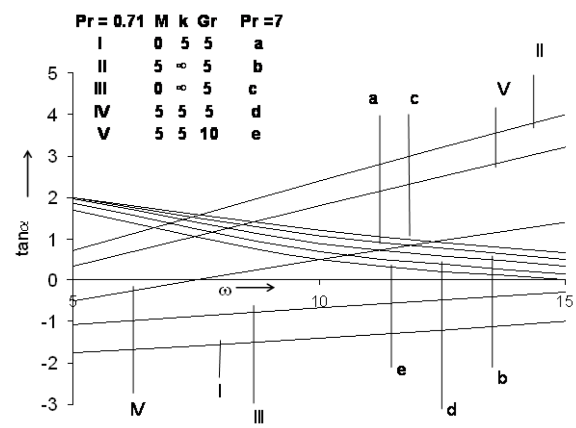
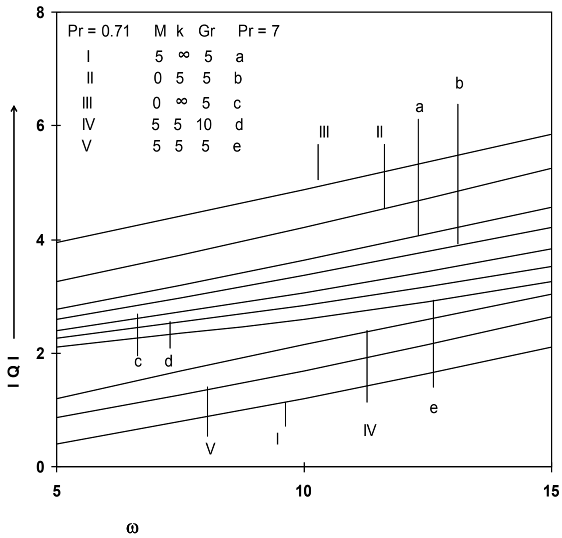
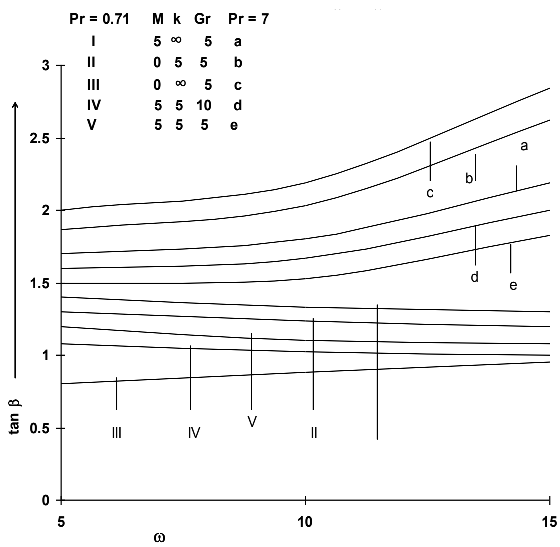


Figure 4. Phase of skin-friction for $\in = 0.2$, Ec = 0.1 and $\omega t = \pi/2$.



Figture 5. The amplitude of the rate of heat transfer for ∈ = 0.2, Ec = 0.1 and ωt = π/2.



Figture 6. Phase of rate of heat transfer for ∈ = 0.2, Ec = 0.1 and ωt = π/2.

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