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OSCILLATORY FREE CONVECTION MASS TRANSFER FLOW PAST A POROUS VERTICAL WALL UNDER CONSTANT MAGNETIC FIELD EFFECT

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ABSTRACT

The present study focuses on the oscillatory free convection mass transfer flow past a porous vertical wall under constant magnetic field effect. Due to free convection current, the problem involved the mixed non-linear equations. The permeability term in the momentum equation and viscous dissipative terms in thermal equation are taken into account. Velocity, temperature and mass concentration fields are obtained and discussed with the help of Tables and Graphs. Effects of different variables and magnetic field parameter on the skin friction and the rate of heat transfer are illustrated by Graphs and Tables. Study reveals that velocity increases with increase in porosity, velocity slip and suction velocity parameters. Temperature field decreases near the plate for non-magnetic case.

I. INTRODUCTION

In order to ensure that a flow with suction or blowing over a porous wall satisfies the simplifying conditions which form the basis of boundary layer theory, it is necessary to limit the perpendicular velocity v_0 at the wall to a magnitude of the order of $U_\infty R^{-1/2}$ where $R = \frac{U_\infty l}{v}$ and l denotes the characteristic dimension of the solid body placed in the flow, when the suction velocity is of such a order of magnitude, it is possible to neglect the loss of mass or sink effect on the external potential flow. In other words, the potential flow many be assumed to remain unaffected by such blowing or suction applied at the surface of the solid wall. The systematic study of flow past a porous medium constitute, a comparatively recent development in fluid mechanics with application in science, engineering and technology. There are numerous studies available in vertical and horizontal enclosures containing various layer of porous media having different permeabilities Beckermann et al. [2]

It is very necessary to study the free convection flow through a porous medium with variable permeability to make heat transfer at the surface more effective and to estimate its effect in mass and heat transfer. Bejan and Khair [1], Elbasbeshy [6], Gholami and Singh [7], Jothimani and Anjalidevi [11], Trevisan and Bejan [24] and Volchkov [25] have studied heat and mass transfer along a vertical plate in the presence of magnetic field. Unsteady free convection and mass transfer flow through a porous medium bounded by an infinite vertical surface with constant suction have been studied by Raptis and Kafousias [17], Raptis [18], Raptis and Tzivanidis [19] and Raptis et al. [20]. In above problems, the permeability of porous medium was assumed to be constant. In fact, a porous material containing the fluid is a non-homogeneous medium and the inhomogeneties which can be present in porous medium are numerous, thus taking permeability variation into consideration. The laminar flows of an incompressible viscous fluid through parallel and uniformly porous walls of different permeability have been discussed by Kalsi and Chaudhary [12], and Terril and Shrestha. [23]. The effect of variable permeability on combined free and forced convection in porous media was studied by Chandrasekhara et a!. [5]. The magnetohydrodynamic flow through porous medium of variable permeability have been analyzed by Bestman [3], Bodosa and Borkakati [4], Govindrajulu and Thangaraj [8], Hayat et al. [9]. Jain et al. [10], Khandelwal et al. [13], Khandelwal and Jain [14] and Singh et al. [22] have discussed magnetic field effects on free convection and mass transfer flow through porous medium with constant suction and constant heat and mass flux in slip flow regime. Singh et al. [21] have discussed effect of heat source on free convection and mass transfer through porous medium with constant suction and constant heat and mass flux in slip flow regime. Lai [15] and Ramana Kumari and Reddy [16] have been concerned the application of variable suction to free convection laminar flow.

Owing to the presence of free convection currents, the problem is governed by the coupled non-linear equations.

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To solve these equations we have assumed that the heat due to viscous dissipation is superimposed on the motion. Mathematically, this can be achieved by expanding the velocity and temperature terms in powers of Ec; the Eckert number. For incompressible fluid Ec is always very small. Expression for velocity, temperature and concentration fields have been obtained. Since free convection currents are in existence due to the temperature difference $T_w^{'} - T_\infty^{'}$, the positive or negative sign of the Grashof number Gr corresponds to the cooling or heating of the plate, respectively, by free convection currents. Different physical variable of the velocity, temperature and concentration fields are discussed with the help of Tables and Graphs. Effects of different variables and magnetic field parameter on the skin friction and rate of heat transfer are illustrated graphically followed by a discussion.

II. Mathematical Analysis

We consider a semi-infinite region of space boundary by a vertical porous plate occupied by a porous medium. The x' axis is taken along the plate in the upward direction and y' axis is normal to it. All the physical quantities will be independent of x' because the plate is assumed to be infinite in the x' direction.

Further we assume variable permeability $K(t) = K_0(1+\in Ae^{-nt})$ of the porous medium and variable suction velocity of the form $v(t) = v_0(1+\in Be^{-nt})$. Hence, two dimensional, unsteady free convective flow of an electrically, viscous incompressible fluid with mass transfer along a semi-infinite vertical porous plate with jump in temperature field and slip in velocity field in the presence of a transverse magnetic field of uniform strength B0 applied along y' axis so as the effects of induced magnetic field and Joules heating are neglected is governed by. the following equations :

$$\frac{\partial v'}{\partial y'} = 0 \qquad (1)$$

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = g\beta(T'-T_\infty) + \upsilon\frac{\partial^2 v'}{\partial y'} + \frac{\sigma B_0^2}{\rho}u' \; g\beta'(C'-c_\infty) - \frac{\upsilon}{K'}u' \qquad (2)$$

$$\frac{\partial P'}{\partial y'} = 0 \qquad (3)$$

$$\rho C_P\left[\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'}\right] = k\frac{\partial^2 T'}{\partial y'^2} + S'\left(T'-T_\infty\right) + \mu\left(\frac{\partial u'}{\partial y'}\right)^2 \qquad (4)$$

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} \qquad (5)$$

with corresponding boundary conditions

$$u' = L_1\frac{\partial u'}{\partial y'}, \quad T' = T_w + L_2\frac{\partial T'}{\partial y'}; \quad C' = C_w \quad \text{at} \quad y' = 0$$

$$u' \to 0, \; T' \to T_\infty, \quad C' \to C_\infty \quad \text{as} \quad y' \to \infty \qquad (2.6)$$

we assume variable permeability of porous medium

$$K' = K_0(1+\in Ae^{-mt}) \qquad (7)$$

and variable suction, hence on integrating (2.1) we write v' as a function of time t' such as

$$v' = v_0(1+\in Ae^{-nt}) \qquad (8)$$

such that $\in$ A and $\in$ B <<1 have ε is small positive number, A and B are the variable part on which permeability and suction velocity depends respectively, where negative sign indicates that suction is acting towards the plate.

Since pressure to towards y' axis is constant so on integrating (3) we get

P = (constant) (9)

where the notation have their usual meanings. Introducing the non-dimensional parameters where, $h_1 = \frac{L_1 v_0}{\upsilon}$ (Velocity Slip Parameter)

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$h_1 = \frac{L_2 v_0}{\upsilon}$ (Temperature Jump Parameter) $\alpha = \frac{K_0 v_0^2}{\upsilon}$ (Porosity Parameter) (10)

In view of equations (7), (8) and the non-dimensional transformations (10) and (6) the equations (2), (4) and (5) reduce to

$$\frac{\partial^2 u}{\partial y^2} + \left(1 + \in Be^{-nt}\right) + \frac{\partial u}{\partial y} - \left[M + \frac{1}{\alpha\left(1 + \in Ae^{-nt}\right)}\right] u - \frac{\partial u}{\partial t} = \text{-Gr? - Gm?} \quad (11)$$

$$\frac{\partial^2 \theta}{\partial y^2} + P_r\left(1 + \in Be^{-nt}\right)\frac{\partial \theta}{\partial y} - P_t \frac{\partial \theta}{\partial t} + S\theta = \Pr Ec\left(\frac{\partial u}{\partial t}\right)^2 \quad (12)$$

$$\frac{\partial^2 \phi}{\partial y^2} - S_c \frac{\partial \phi}{\partial t} + \left(1 + \in Be^{-nt}\right) S_c \frac{\partial \phi}{\partial y} = 0 \quad (13)$$

Corresponding boundary conditions are

$$u = h_1 \frac{\partial u}{\partial y}, \quad \theta = 1 + h_2 \frac{\partial \theta}{\partial y}; \quad \phi = 1 \quad \text{at } y=0$$

$$u \to 0, \; \theta \to 0, \; \Phi \to 0 \; \text{ as } \; y \to \infty \quad (14)$$

III. SOLUTION BY PERTURBATION METHOD

To solve the equations (11), (12) and (13) we assume $f(y,t) = f_0(y) + \in e^{-nt} f_,(y)$ (2.1)

where f stands for u, θ and ϕ.

Substituting (2.1) into (11), (12) and (13), equating the coefficients of harmonic and non-harmonic terms, neglecting the coefficient of $\in^2$, we get

Zeroth-order equations

$$u_0'' + u_0' - \left(M + \frac{1}{\alpha}\right) u_0 = -G_r\theta_0 - G_m\phi_0 \quad (2.2)$$

$$\theta_0'' + \Pr\theta_0' + S\theta_0 = -\Pr Ecu_0'^2 \quad (2.3)$$

$$\phi_0'' + Sc\phi_0' = 0 \quad (2.4)$$

In view of equation (2.1) boundary conditions reduce to

$$u_0 = h_1 u'_0; \quad \theta_0 = 1 + h_2\theta'_0; \; \phi_0 = 1 \text{ at } y=0$$

$$u_0 = 0, \theta_0 = 0, \Phi_0 = 0 \text{ as } y \to \infty \quad (2.5)$$

First-order equations

$$u_1'' + u_1' - \left(M + \frac{1}{\alpha} - n\right) u_1 = -\frac{Au_0}{\alpha} - u_0'B - G_r\theta_1 - G_m\phi_1 \quad (2.6)$$

$$\theta_1'' + \Pr\theta_1' + (n\Pr + S)\theta_1 = -\Pr B\theta_0' - 2\Pr Ecu_0'u_1' \quad (2.7)$$

$$\phi_1'' + Sc\phi_1' + nSc\phi_1 = -BSc\phi_0' \quad (2.8)$$

Corresponding boundary conditions are

$$u = h_1 u'_0; \quad \theta = 1 + h_2\theta'_0; \; \phi_1 = 1 \quad \text{at } y=0$$

$$u_1 = 0, \; \theta_1 = 0, \; \Phi_1 = 0 \text{ as } y \to \infty \quad (2.9)$$

In equations (2.2) - (2.9), the primes denotes the differentiation with respect to y. The equations (2.4) and (2.8) are ordinary second order differential equations solved under the boundary conditions given in equations (2.5) and (2.9) respectively.

Hence the expressions of $\phi_0(y)$ and $\phi_1(y)$ are given by

$$\Phi_0(y) = e^{-Scy} \quad (2.10)$$

$$\phi_1 = -\frac{BSc}{n}\left(e^{-s_1 y} - e^{-scy}\right) \quad (2.11)$$

Since equations (2.2), (2.3), (2.6) and (2.7) are still coupled and non-linear and so are difficult to solve. To solve them we again expand u_0, u_1, θ_0 and θ_1 in powers of Ec.

Hence we assume
$F_0 = F_{00} + Ec\, F_{01} + O(Ec^2)$
$F_1 = F_{10} + Ec\, F_{11} + O(Ec^2)$ (2.12)
where F stands for u and θ.
Using (2.12) in (2.2), (2.3), (2.6) and (2.7) along with boundary conditions (2.5) and (2.9). Equating the coefficients of different powers of Ec, neglecting the coefficients of Ec^2 and so on, we have

IV. Zeroth Order Equations -

$$u_{00}'' + u_{00}' - \left(M + \frac{1}{\alpha}\right)u_{00} - G_1\theta_{00} - G_m e^{-Scy} \quad (2.13)$$

$$u_{10}'' + u_{10}'' - \left(M + \frac{1}{\alpha} - n\right)u_{10} = \frac{A}{\alpha}u_{00} - u_{00}'B - Gr\theta_{10} + Gm\frac{BSc}{n}\left(e^{S_1 y} - e^{-Scy}\right) \quad (2.14)$$

$$\theta_{00}'' + \Pr\theta_{00}' + S\theta_{00} = 0 \quad (2.15)$$

$$\theta_{10}'' + \Pr\theta_{10}' + (n\Pr + S)\theta_{10} = -\Pr B\theta_{00}' \quad (2.16)$$

corresponding boundary conditions are

$$u_{00} = h_1 u'_{00};\ u_{10} = h_1 u'_{00} \quad \theta_{00} = 1 + h_2\theta'_{00};\ \phi_{10} = h_2\theta_{10}' \quad \text{at} \quad y=0$$

$$u_{00} = 0,\ u_{10} = 0\ \theta_{00} = 0,\ \Phi_{10} = 0 \ \text{as} \quad y \to \infty \quad (2.17)$$

First-order equations

$$u_{01}'' + u_{01}' - \left(M + \frac{1}{\alpha}\right)u_{00} - G_r\theta_{01} \quad (2.18)$$

$$u_{11}'' + u_{11}'' - \left(M + \frac{1}{\alpha} - n\right)u_{11} = \frac{A}{\alpha}u_{01} - u_{01}'BG_r\theta_{11} \quad (2.19)$$

$$\theta_{01}'' + \Pr\theta_{01}' + S\theta_{01} = -\Pr u_{02}'^2 \quad (2.20)$$

$$\theta_{11}'' + \Pr\theta_{11}' + (n\Pr + S)\theta_{11} = -\Pr B\theta_{01}' - 2\Pr u_{01}'u_{10}' \quad (2.21)$$

Corresponding boundary conditions are

$$u_{01} = h_1 u'_{01};\ u_{11} = h_1 u'_{11} \quad \theta_{01} = 1 + h_2\theta'_{01}; \quad \phi_{11} = h_2\theta_{11}' \quad \text{at} \quad y=0$$

$$u_{01} = 0;\ u_{11} = 0;\ \theta_{01} = 0;\ \Phi_{11} = 0 \ \text{as} \quad y \to \infty \quad (2.22)$$

We express the solution of velocity and temperature fields in the view of equations (2.1) and (2.12) as

$$u(y,t) = (u_{00} + Ecu_{01}) + \in (u_{10} + Ecu_{11})e^{-nt}$$

$\theta(y,t) = (\theta_{00} + Ec\theta_{01}) + \in (\theta_{10} + Ec\theta_{11})e^{-nt}$ and expression for concentration field as

$\phi(y,t) = \phi_0(y) + \in \phi_1(y)e^{-nt}$ where the values of u_{00}, u_0, u_{10}, u_{11}, θ_{00}, θ_{01}, θ_{10}, θ_{11}, ϕ_0 and ϕ_1 are shown below.

The equations (2.13)-(2.16) and (2.18) -(2.21) are ordinary second order differential equations solved under the boundary conditions (2.17) and (2.22) respectively. The solutions are given by

$$u_{00}(y) = E_1 e^{-M_1 y} - E_2 e^{-P_1 y} - E_3 e^{-Scy} \quad (2.23)$$

$$u_{01}(y) = Qe^{-M_1 y} - G_1 e^{-P_1 y} + G_2 e^{-2M_1 y} + G_3 e^{-2P_1 y} + G_4 e^{-2Scy} - G_5 e^{-(M_1+p_1)} - G_6 e^{-(M_1+Sc)y} + G_7 e^{-(P_1+Sc)y} \quad (2.24)$$

$$u_{10}(y) = -H_w e^{-P_4 y} - H_1 e^{-M_1 y} + H_2 e^{-P_1 y} + H_3 e^{-Scy} + H_4 e^{-P_3 y} + H_5 e^{-S_3 y} \quad (2.25)$$

$$u_{11}(y) = T_f e^{-P_4 y} - F_1 e^{M_1 y} + F_2 e^{-P_1 y} - F_3 e^{-2M_1 y} - F_4 e^{-2P_1 y} - F_5 e^{-2Scy} + F_6 e^{-(M_1 P_1)y} + F_7 e^{-(M_1+Sc)} - F_8 e^{-(P_1+Sc)} - F_9 e^{-(P_3)y} - F_{10} e^{-(M_1 P_4)y} + F_{11} e^{-(M_1+P_3)} + F_{12} e^{-(M_1 S_1)y} - F_{13} e^{-(P_1+P_4)y} + F_{14} e^{-(P_1+P_3)y} + F_{15} e^{-(P_1+S_1)y} - F_{16} e^{-(Sc+P_4)} + F_{17} e^{-(Sc+P_3)y} + F_{18} e^{-(Sc+S_1)y} \quad (2.26)$$

$$\theta_{00}(y) = \frac{1}{(1+h_2 P_1)}e^{-P_1 y} \quad (2.27)$$

$$\theta_{01}(y) = \Pr[L_1 e^{-p_1 y} - L_1 e^{-2M_1 y} - L_2 e^{-2P_1 y} - L_3 e^{-2Scy} + L_4 e^{-(M_1+P_1)y} + L_5 e^{-(M_1+Sc)y} - L_6 e^{-(P_1+Sc)y}] \quad (2.28)$$

$$\theta_{10}(y) = J_1 e^{-P_1 y} - J_1 T_{22} e^{-P_3 y} \quad (2.29)$$

$$\theta_{11}(y) = J_t e^{-P_4 y} + J_2 e^{-(M_1+P_4)y} - J_3 e^{-2M_1 yy} - J_4 e^{-(M_1+P_1)y}$$

$$J_5 e^{-(M_1+P_3)} + J_6 e^{-(M_1+S_1)} - J_7 e^{-(P_1+P_4)y} - J_8 e^{-2P_3 y} - J_9 e^{-(P_1+Sc)y} - J_{10} e^{-(P_1+P_3)y}$$
$$- J_{11} e^{-(P_3+S_1)y} - J_{12} e^{-(Sc+P_4)y} - J_{13} e^{-(M_1+Sc)y} - J_{14} e^{-2Scy} - J_{15} e^{-(P_3+Sc)y} - J_{16} e^{-(Sc+S_1)y} - J_{17} e^{-P_1 y} \quad (2.30)$$

where, E_1, E_2, ... constant are given on next pages.

V. Skin-friction

Knowing the velocity field, the expression for the skin-friction coefficient at the plate is given by

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0}$$

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0} = -E_1 M_1 + E_2 P_1 + E_3 Sc + Ec\{-QM_1 + G_1 P_1 - 2G_2 M_1$$
$$2G_3 P_1 - 2G_4 Sc + G_5(M_1 + P_1) + G_6(M_1 + Sc) - G_7(Sc + P_1) + \in [H_w P_4 - H_1 M_1 - H_2 P_1 - H_3 Sc$$
$$-H_4 P_3 - H_5 S_1 + Ec\{-T_f P_4 + F_1 M_1 - F_2 P_1 + 2F_3 M_1$$
$$+2F_4 P_1 + 2F_5 Sc - F_6(M_1 + P_1) - F_7(M_1 + Sc) + F_8(Sc + P_1) + F_9 P_3 + F_{10}(M_1 + P_4)$$
$$- F_{11}(M_1 + P_3) - F_{12}(M_1 + S_1) - F_{13}(P_4 + P_1) - F_{14}(P_3 + P_1) - F_{15}(S_1 + P_1) - F_{16}(Sc + P_4) - F_{17}(Sc + P_3) - F_{18}(Sc + S_1)\}]$$

VI. NUSSELT NUMBER

From the temperature field, the rate of heat transfer coefficients in terms of the Nusselt number Nu at the plate is given by

$$Nu = \left(\frac{\partial \theta}{\partial y}\right)_{y=0}$$

$$Nu = \left(\frac{\partial \theta}{\partial y}\right)_{y=0} = -\frac{P_1}{(1+h_2 p_1)} + Ec\Pr\{-L_t P_1 + 2L_1 M_1 + 2L_2 P_1 + 2L_3 Sc$$
$$- L_4(M_1 + P_1) - L_5(M_1 + Sc) + L_6(Sc + P_1) + \in [-J_1 P_1 + J_1 T_{22} P_3 + Ec\{-JtP_3 - J_2(M_1 + P_4)$$
$$2J_3 M_1 + J_4(M_1 + P_1) + J_5(M_1 + P_3)$$
$$+ J_6(M_1 + S_1) + J_7(P_4 + P_1) + 2J_8 P_1 + J_9(Sc + P_1) + J_{10}(P_3 + P_1) + J_{11}(S_1 + P_1) + J_{12}(Sc + P_4) + J_{13}(M_1 + Sc)$$
$$+ 2J_{14} Sc + J_{15}(P_3 + Sc) + J_{16}(S_1 + Sc) + J_{17} P_1\}]$$

Where,

$$S_1 = \frac{Sc + \sqrt{Sc^2 - 4nSc}}{2}; \qquad P_1 = \frac{\Pr + \sqrt{\Pr^2 - 4s}}{2};$$

$$P_3 = \frac{1 + \sqrt{1 + 4\left(M + \frac{1}{\alpha} - n\right)}}{2}; \qquad M_1 = \frac{1 + \sqrt{1 + 4\left(M + \frac{1}{\alpha}\right)}}{2};$$

$$E_1 = \frac{(1 + h_1 p_1)E_2 + (1 + h_1 Sc)E_3}{(1 + h_1 M_1)}; \qquad E_2 = \frac{Gr}{(1 + h_2 p_1)\left\{P_1^2 - P_1 - \left(M + \frac{1}{\alpha}\right)\right\}}$$

$$E_3 = \frac{Gm}{Sc^2 - Sc - \left(M + \frac{1}{\alpha}\right)};$$

$$L_1 = \frac{E_1^2 M_1^2}{(4M_1^2 - 2\Pr M_1 + S)}; \qquad L_2 = \frac{E_2^2 P_1^2}{(4P_1^2 - 2\Pr P_1 + S)}$$

$$L_3 = \frac{E_3^2 Sc^2}{(4Sc^2 - 2\Pr Sc + S)}; \qquad L_4 = \frac{2E_1 E_2 P_1 M_1}{\{(M_1 + P_1)^2 - 2\Pr(M_1 + P_1) + S\}};$$

$$L_5 = \frac{2E_1 E_3 M_1 Sc}{\{(M_1 + Sc)^2 - 2\Pr(M_1 + Sc) + S\}}; \qquad L_6 = \frac{2E_2 E_3 P_1 Sc}{\{(P_1 + Sc)^2 - 2\Pr(P_1 + Sc) + S\}};$$

$$T_1 = \frac{(1 + 2M_1 h_2)}{(1 + h_2 P_1)}; \qquad T_2 = \frac{(1 + 2P_1 h_2)}{(1 + h_2 P_1)}$$

$$T_3 = \frac{(1 + 2Sch_2)}{(1 + h_2 P_1)}; \qquad T_4 = \frac{\{1 + (M_1 + P_1)h_2\}}{(1 + h_2 P_1)}$$

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$$T_5=\frac{\{1+(M_1+Sc)h_2\}}{(1+h_2P_1)};\quad T_6=\frac{\{1+(P_1+Sc)h_2\}}{(1+h_2P_1)}$$

$$T_7=\frac{\{1+(M_1+P_4)h_2\}}{(1+h_2P_3)};\quad T_8=\frac{\{1+2M_1h_2\}}{(1+h_2P_3)}$$

$$T_9=\frac{\{1+(M_1+P_1)h_2\}}{(1+h_2P_3)};\quad T_{10}=\frac{\{1+(M_1+P_3)h_2\}}{(1+h_2P_3)}$$

$$T_{11}=\frac{\{1+(M_1+S_1)h_2\}}{(1+h_2P_3)};\quad T_{12}=\frac{\{1+(P_1+P_3)h_2\}}{(1+h_2P_3)}$$

$$T_{13}=\frac{\{1+2P_1h_2\}}{(1+h_2P_3)};\quad \mathrm{T}_{14}=\frac{\{1+(\mathrm{P}_1+\mathrm{Sc})\mathrm{h}_2\}}{(1+\mathrm{h}_2\mathrm{P}_3)}$$

$$T_{15}=\frac{\{1+(P_1+P_3)h_2\}}{(1+h_2P_3)};\quad T_{16}=\frac{\{1+(P_1+S_3)h_2\}}{(1+h_2P_3)}$$

$$T_{17}=\frac{\{1+(Sc+P_4)h_2\}}{(1+h_2P_3)};\quad T_{18}=\frac{\{1+(M_1+Sc)h_2\}}{(1+h_2P_3)}$$

$$T_{19}=\frac{\{1+2Sch_2\}}{(1+h_2P_3)};\quad T_{20}=\frac{\{1+(P_3+Sc)h_2\}}{(1+h_2P_3)}$$

$$T_{21}=\frac{\{1+(Sc+S_1)h_2\}}{(1+h_2P_3)};\quad T_{22}=\frac{\{1+P_1h\}}{(1+h_2P_3)}$$

$$U_1=\frac{T_1}{\left\{P_1^2-P_1-\left(M+\frac{1}{\alpha}\right)\right\}};\quad U_2=\frac{T_2}{\left\{P_1^2-P_1-\left(M+\frac{1}{\alpha}\right)\right\}};$$

$$U_3=\frac{T_3}{\left\{P_1^2-P_1-\left(M+\frac{1}{\alpha}\right)\right\}};\quad U_4=\frac{T_4}{\left\{P_1^2-P_1-\left(M+\frac{1}{\alpha}\right)\right\}};$$

$$U_5=\frac{T_5}{\left\{P_1^2-P_1-\left(M+\frac{1}{\alpha}\right)\right\}};\quad U_6=\frac{T_6}{\left\{P_1^2-P_1-\left(M+\frac{1}{\alpha}\right)\right\}};$$

$$V_1=\frac{1}{\left\{4M_1^2-2M_1-\left(M+\frac{1}{\alpha}\right)\right\}};\quad V_2=\frac{1}{\left\{4P_1^2-2P_1-\left(M+\frac{1}{\alpha}\right)\right\}};$$

$$V_3=\frac{1}{\left\{4Sc_1^2-2Sc_1-\left(M+\frac{1}{\alpha}\right)\right\}};\quad V_4=\frac{1}{\left\{(M_1+P_1)^2(M_1+P_1)-\left(M+\frac{1}{\alpha}\right)\right\}};$$

$$V_5=\frac{1}{\left\{(M_1+Sc)^2(M_1+Sc)-\left(M+\frac{1}{\alpha}\right)\right\}};\quad V_6=\frac{1}{\left\{(P_1+Sc)^2(P_1+Sc)-\left(M+\frac{1}{\alpha}\right)\right\}};$$

$$W_1=\frac{1+P_1h_1}{(1+h_1M_1)};\quad W_2=\frac{1+2M_1h_1}{(1+h_1M_1)}\quad W_3=\frac{1+2P_1h_1}{(1+h_1M_1)};$$

$$W_4=\frac{1+2Sch_1}{(1+h_1M_1)}\quad W_5=\frac{\{1+(M_1+P_1)h_1\}}{(1+h_1M_1)};\quad W_6=\frac{\{1+(M_1+Sc)h_1\}}{(1+h_1M_1)}$$

$$W_7=\frac{\{1+(P_1+Sc)h_1\}}{(1+h_1M_1)};\quad W_9=\frac{1+h_1M_1}{(1+h_2P_4)}\quad W_{10}=\frac{1+h_1P_1}{(1+h_2P_4)};$$

$$W_{11}=\frac{1+h_1Sc}{(1+h_2P_4)}\quad W_{12}=\frac{1+h_1P_3}{(1+h_2P_4)};\quad W_{13}=\frac{1+h_1S_1}{(1+h_2P_4)}$$

$$D_1=\frac{B\Pr P_1}{(1+h_2P_1)};$$

$$H_1=\frac{E_1\left(BM_1-\frac{A}{\alpha}\right)}{M_1^2-M_1-\left(M+\frac{1}{\alpha}-n\right)};\quad H_2=\frac{E_2\frac{A}{\alpha}-E_2BP_1-GrJ_1}{P_1^2-P_1-\left(M+\frac{1}{\alpha}-n\right)};\quad H_3=\frac{E_3\frac{A}{\alpha}-E_3BSc-\frac{GmScB}{n}}{Sc^2-Sc-\left(M+\frac{1}{\alpha}-n\right)};$$

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$H_4 = \dfrac{GrJ_1J_{22}}{P_3^2 - P_3 - \left(M + \frac{1}{\alpha} - n\right)}$; $H_5 = \dfrac{\mathrm{Gm\,B\,Sc}}{n\left\{S_1^2 - S_1 - \left(M + \frac{1}{\alpha} - n\right)\right\}}$;

$O_1 = 2\Pr^2 BL_1M_1$; $O_2 = 2\Pr^2 BL_2P_1$; $O_3 = 2\Pr^2 BL_3Sc$;

$O_4 = \Pr^2 BL_4(M_1 + P_1)$ $O_5 = \Pr^2 BL_5(Sc + M_1)$; $O_6 = \Pr^2 BL_6(Sc + P_1)$

$O_7 = \Pr^2 BL_1P_1$;

$Z_1 = 2\Pr E_1M_1P_4H_w$; $Z_2 = 2\Pr E_1M_1^2H_1$ $Z_3 = 2\Pr E_1M_1H_2P_1$;

$Z_4 = 2\Pr E_1M_1H_3Sc$ $Z_5 = 2\Pr E_1M_1H_4P_3$; $Z_6 = 2\Pr E_1M_1H_5S_1$

$Z_7 = 2\Pr E_2P_1P_4H_w$; $Z_8 = 2\Pr E_2P_1H_1M_1$ $Z_9 = 2\Pr E_2P_1^2H_2$;

$Z_{10} = 2\Pr E_2P_1H_3Sc$ $Z_{11} = 2\Pr E_2P_1H_4P_3$; $Z_{12} = 2\Pr E_2P_1H_5S_1$

$Z_{13} = 2\Pr ScE_3P_4H_w$; $Z_{14} = 2\Pr ScE_3H_1M_1$ $Z_{15} = 2\Pr ScE_3P_1H_2$;

$Z_{16} = 2\Pr ScE_3H_4Sc$ $Z_{17} = 2\Pr ScE_3P_3H_4$; $Z_{18} = 2\Pr ScE_3H_5S_1$

$J_1 = \dfrac{D_1}{\{P_1^2 - \Pr P_1 + (n\Pr + S)\}}$; $J_2 = \dfrac{Z_1}{\{(M_1 + P_4)^2 - \Pr(M_1 + P_4) + (n\Pr + S)\}}$;

$J_3 = \dfrac{(Z_2 + O_1)}{\{4M_1^2 - 2\Pr M_1 + (n\Pr + S)\}}$; $J_4 = \dfrac{(Z_3 + Z_8 - O_4)}{\{(M_1 + P_1)^2 - \Pr(M_1 + P_1) + (n\Pr + S)\}}$;

$J_5 = \dfrac{Z_5}{\{(M_1 + P_1)^2 - \Pr(M_1 + P_3) + (n\Pr + S)\}}$; $J_6 = \dfrac{Z_6}{\{(M_1 + S_1)^2 - \Pr(M_1 + S_1) + (n\Pr + S)\}}$;

$J_7 = \dfrac{Z_7}{\{(P_1 + P_4)^2 - \Pr(P_1 + P_4) + (n\Pr + S)\}}$; $J_8 = \dfrac{(Z_9 + O_2)}{\{4P_1^2 - 2\Pr P_1 + (n\Pr + S)\}}$;

$J_9 = \dfrac{(Z_{10} + Z_{15} - O_6)}{\{(P_1 + Sc)^2 - \Pr(P_1 + Sc) + (n\Pr + S)\}}$; $J_{10} = \dfrac{Z_{11}}{\{(P_1 + P_3)^2 - \Pr(P_1 + P_3) + (n\Pr + S)\}}$;

$J_{11} = \dfrac{Z_{12}}{\{(P_1 + S_1)^2 - \Pr(P_1 + S_1) + (n\Pr + S)\}}$; $J_{12} = \dfrac{Z_{13}}{\{(PSc + P_4)^2 - \Pr(Sc + S_4) + (n\Pr + S)\}}$;

$J_{13} = \dfrac{(Z_{14} + Z_4 - O_5)}{\{(M_1 + Sc_1)^2 - \Pr(M_1 + Sc) + (n\Pr + S)\}}$; $J_{14} = \dfrac{(Z_{16} + O_3)}{\{4Sc_1^2 - 2\Pr Sc + (n\Pr + S)\}}$;

$J_{15} = \dfrac{Z_{17}}{\{(Sc + P_3)^2 - \Pr(Sc + P_3) + (n\Pr + S)\}}$; $J_{16} = \dfrac{Z_{18}}{\{(Sc + S_1)^2 - \Pr(Sc + S_1) + (n\Pr + S)\}}$;

$J_{17} = \dfrac{O_7}{\{P_1^2 - \Pr P_1 + (n\Pr + S)\}}$;

$H_W = H_1W_9 + H_2W_{10} + H_3W_{11} + H_4W_{12} + H_5W_{13}$;

$L_1 = L_1T_1 + L_2T_2 + L_3T_3 - L_4T_4 - L_5T_5 + L_6T_6$;

$L_4 = L_1U_1 + L_2U_2 + L_3U_3 + L_6U_6 - L_4U_4 - L_5U_5$;

$Q_1 = Gr\Pr W_1Lu$; $Q_2 = Gr\Pr W_2L_1V_1$; $Q_3 = Gr\Pr W_2L_2V_2$;

$Q_4 = Gr\Pr W_4L_3V_3$; $Q_5 = Gr\Pr W_5L_4V_4$; $Q_6 = Gr\Pr W_6L_5V_5$;

$Q_7 = Gr\Pr W_2L_{64}V_6$;

$Q = Q_1 - Q_2 - Q_3 - Q_4 + Q_5 + Q_6 - Q_7$;

$G_1 = Gr\Pr Lu$; $G_2 = Gr\Pr L_1V_1$; $G_3 = Gr\Pr L_2V_2$;

$G_4 = Gr\Pr L_3V_3$; $G_5 = Gr\Pr L_4V_4$; $G_6 = Gr\Pr L_5V_5$;

$G_7 = Gr\Pr L_6V_6$;

$A_1 = \dfrac{A}{\alpha} + BM_1$; $A_2 = \dfrac{A}{\alpha}G_1 + BG_1P_1 + GrJ_{17}$;

$A_3 = \dfrac{A}{\alpha}G_2 - 2BG_2M_1 - GrJ_3$; $A_4 = \dfrac{A}{\alpha}G_3 - 2BG_3P_1 + GrJ_8$;

$A_5 = \dfrac{A}{\alpha}G_4 - 2BG_4Sc - GrJ_{14}$; $A_6 = \dfrac{A}{\alpha}G_5 + BG_5(M_1 + P_1) + GrJ_4$;

$A_7 = \frac{A}{\alpha}G_6 + BG_6(M_1 + Sc) + GrJ_{13}$; $A_8 = \frac{A}{\alpha}G_7 + BG_7(P_1 + Sc) + GrJ_9$;

$A_9 = GrJ_1$; $A_{10} = GrJ_2$;

$A_{11} = GrJ_5$; $A_{12} = GrJ_6$;

$A_{13} = GrJ_7$; $A_{14} = GrJ_{10}$;

$A_{15} = GrJ_{11}$; $A_{16} = GrJ_{12}$;

$A_{17} = GrJ_{15}$; $A_{18} = GrJ_{16}$;

$$F_1 = \frac{A_1}{M_1^2 - M - \left(M + \frac{1}{\alpha} - n\right)}; \quad F_2 = \frac{A_2}{P_1^2 - P_1 - \left(M + \frac{1}{\alpha} - n\right)};$$

$$F_3 = \frac{A_3}{4M_1^2 - 2M_1 - \left(M + \frac{1}{\alpha} - n\right)}; \quad F_4 = \frac{A_4}{4P_1^2 - 2P_1 - \left(M + \frac{1}{\alpha} - n\right)};$$

$$F_5 = \frac{A_5}{4Sc^2 - 2Sc - \left(M + \frac{1}{\alpha} - n\right)}; \quad F_6 = \frac{A_6}{(M_1 + P_1)^2 - (M_1 + P_1) - \left(M + \frac{1}{\alpha} - n\right)};$$

$$F_7 = \frac{A_7}{(M_1 + Sc)^2 - (M_1 + Sc) - \left(M + \frac{1}{\alpha} - n\right)}; \quad F_8 = \frac{A_8}{(P_1 + Sc)^2 - (P_1 + Sc) - \left(M + \frac{1}{\alpha} - n\right)};$$

$$F_9 = \frac{A_9}{P_3^2 - P_3 - \left(M + \frac{1}{\alpha} - n\right)}; \quad F_{10} = \frac{A_{10}}{(M_1 + P_4)^2 - (M_1 + P_4) - \left(M + \frac{1}{\alpha} - n\right)};$$

$$F_{11} = \frac{A_{11}}{(M_1 + P_3)^2 - (M_1 + P_3) - \left(M + \frac{1}{\alpha} - n\right)}; \quad F_{12} = \frac{A_{12}}{(M_1 + S_1)^2 - (M_1 + S_1) - \left(M + \frac{1}{\alpha} - n\right)};$$

$$F_{13} = \frac{A_{13}}{(P_1 + P_4)^2 - (P_1 + P_4) - \left(M + \frac{1}{\alpha} - n\right)}; \quad F_{14} = \frac{A_{14}}{(P_1 + P_3)^2 - (P_1 + P_3) - \left(M + \frac{1}{\alpha} - n\right)};$$

$$F_{15} = \frac{A_{15}}{(P_1 + S_1)^2 - (P_1 + S_1) - \left(M + \frac{1}{\alpha} - n\right)}; \quad F_{16} = \frac{A_{16}}{(Sc + P_4)^2 - (Sc + P_4) - \left(M + \frac{1}{\alpha} - n\right)};$$

$$F_{17} = \frac{A_{17}}{(Sc + P_3)^2 - (Sc + P_3) - \left(M + \frac{1}{\alpha} - n\right)}; \quad F_{18} = \frac{A_{18}}{(Sc + S_1)^2 - (Sc + S_1) - \left(M + \frac{1}{\alpha} - n\right)};$$

$$T_{23} = \frac{1 + h_1 M_1}{1 + h_1 P_4}; \quad T_{24} = \frac{1 + h_1 P_1}{1 + h_1 P_4}; \quad T_{25} = \frac{1 + 2h_1 M_1}{1 + h_1 P_4};$$

$$T_{26} = \frac{1 + 2h_1 P_1}{1 + h_1 P_4}; \quad T_{27} = \frac{1 + 2h_1 Sc}{1 + h_1 P_4}; \quad T_{29} = \frac{\{1 + h_1(M_1 + Sc)\}}{1 + h_1 P_4};$$

$$T_{30} = \frac{\{1 + h_1(P_1 + Sc)\}}{1 + h_1 P_4}; \quad T_{31} = \frac{1 + h_1 P_3}{1 + h_1 P_4}; \quad T_{32} = \frac{\{1 + h_1(M_1 + P_4)\}}{1 + h_1 P_4};$$

$$T_{33} = \frac{\{1 + h_1(M_1 + P_4)\}}{1 + h_1 P_4}; \quad T_{34} = \frac{\{1 + h_1(M_1 + S_1)\}}{1 + h_1 P_4}; \quad T_{35} = \frac{\{1 + h_1(P_1 + P_4)\}}{1 + h_1 P_4};$$

$$T_{36} = \frac{\{1 + h_1(P_1 + P_3)\}}{1 + h_1 P_4}; \quad T_{37} = \frac{\{1 + h_1(P_1 + S_1)\}}{1 + h_1 P_4}; \quad T_{38} = \frac{\{1 + h_1(Sc + P_4)\}}{1 + h_1 P_4};$$

$$T_{39} = \frac{\{1 + h_1(Sc + P_3)\}}{1 + h_1 P_4}; \quad T_{40} = \frac{\{1 + h_1(Sc + S_1)\}}{1 + h_1 P_4};$$

$$J_1 = -J_2 J_7 + J_3 J_8 + J_4 J_9 + J_5 J_{10} + J_6 J_{11} + J_7 J_{12} + J_8 J_{13} + J_9 J_{14}$$

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$$+J_{10}J_{15}+J_{11}J_{16}+J_{12}J_{17}+J_{13}J_{18}+J_{14}J_{19}+J_{15}J_{20}+J_{16}J_{21}+J_{17}J_{22}\ T_f=T_{23}F_1-T_{24}F_2+T_{25}F_3+T_{26}F_4+T_{27}F_5-T_{28}F_6-T_{29}F_7$$
$$+T_{30}F_8+T_{31}F_9+T_{32}F_{10}-T_{33}F_{11}-T_{34}F_{12}-T_{35}F_{13}-T_{36}F_{14}$$
$$-T_{36}F_{14}-T_{37}F_{15}-T_{38}F_{16}-T_{39}F_{17}-T_{40}F_{18}$$

VII. RESULTS AND DISCUSSION

Figures : 1 - 4 show the variations of real and imaginary parts for Gr > 0 and Gr < 0 respectively for fixed values of ε = 0.2, n = 0.1, S = 0.8, Sc = 0.7, A = 0.4, B = 0.2, Pr = 0.71 and Ec = 0.01 with respect to y.

From Figure : 1 we observed that the real part of velocity increases with the increase in α, h_1, Gr (>0) and Gm but decreases with increase in M, h_2 and t. Figure : 2 depicts that imaginary part of velocity increases with M but decreases with increase in a and Gr(> 0). It is also being observed that the real part of velocity is maximum near the plate and decreases to zero asymptotically whereas imaginary part of velocity is minimum near the plate and increases to zero asymptotically.

For Gr < 0, the variations of u_0 with y are shown in Figures : 3 and 4 which indicate that the application of magnetic field reduces the velocity u in the boundary layer region. Further in the presence of magnetic field real part of velocity increases with α and h_2. For imaginary part of velocity from Figure : 4 increases with α and Gr. The real part of velocity decreases with increase in the magnitude of Gr near the plate but from y = 1.8 it increases with increase in the magnitude of Gr.

Figures : 5 - 8 are prepared in order to see the effects of porosity parameter, α, magnetic field parameter M, velocity slip parameter hb temperature jump parameter h2, Grashof number Gr, modified Grashof number Gm and time t for fixed values of e = 0.2, n = 0.1, S = 0.8, Sc = 0.7, A = 0.4, B = 0.2, Pr = 0.71 .and ec = 0.01. Figure : 5 depicts that for non-magnetic case temperature decreases near the plate but from y = 2 temperature increases. For higher values of y temperature slightly decreases with Gr. From Figure 6 we observed that for non-magnetic case temperature decreases continuously up to y = 1 and then it increases continuously with y. imaginary part of temperature decreases with increase in Gr.

Temperature distribution plotted against y for Gr < 0 in Figures : 7 and 8. For non-magnetic case, temperature field increases. As we increase M, temperature decreases. There is no significant impact of variations of other parameters on temperature field. Hear we observed that real part of temperature field, from Figure: 7, decreases continuously with respect to y but upto y = 3.3 it increases, whereas the imaginary part of temperature, from Figure : 8, decreases continuously upto y = 1.3 but for higher values of y it increases continuously with respect to y.

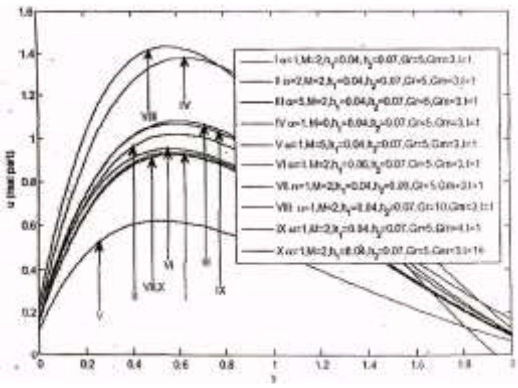

Figure :1 Velocity Distribution Against y for ε = 0.2, n = 0.1, S = 0.8, Sc = 0.7, A = 0.4, B = 0.2, Pr = 0.71 and Ec = 0.01.

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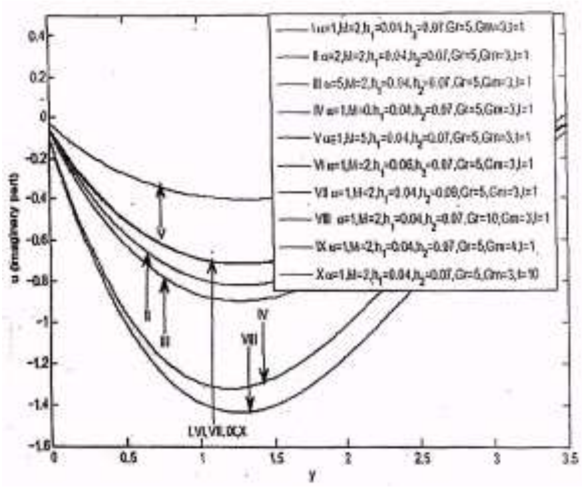

Figure 2: Velocity Distribution Against y for ε = 0.2, n = 0.1, S = 0.8, Sc = 0.7, A = 0.4, B = 0.2, Pr = 0.71 and Ec = 0.01.

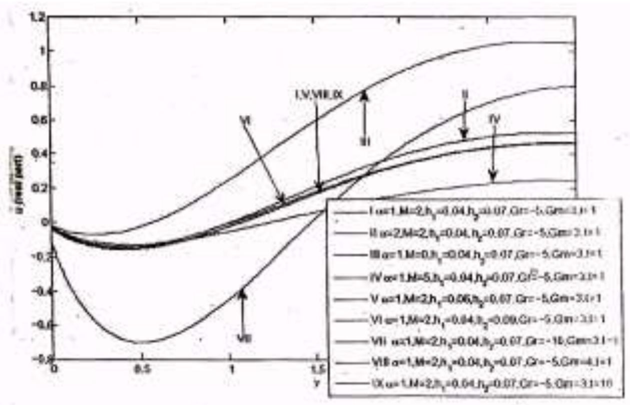

Figure 3: Velocity Distribution Against y for ε = 0.2, n = 0.1, S = 0.8, Sc = 0.7, A = 0.4, B - 0.2, = 0.71 and Ec = 0.01.

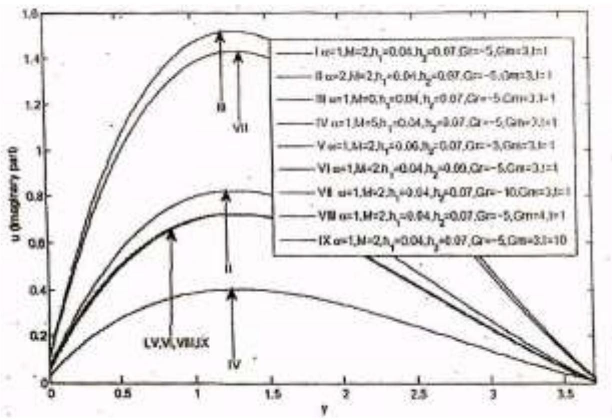

Figure 4: Velocity Distribution Against y for ε = 0.2, n = 0.1, S = 0.8, Sc = 0.7, A = 0.4, B = 0.2, Pr = 0.71 and Ec = 0.01.

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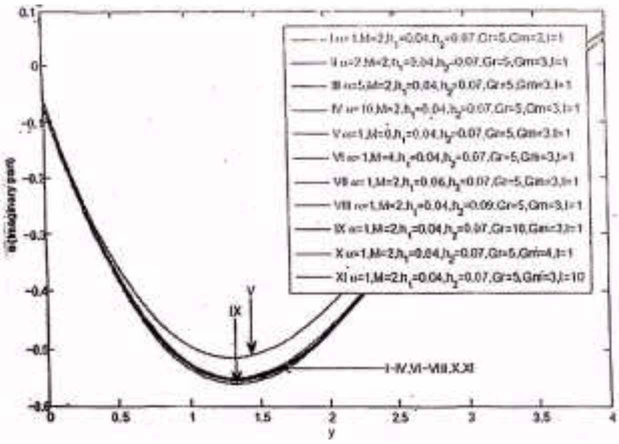

Figure 5: Temperature Distribution Against y for ε = 0.2, n - 0,1, S = 0.8, Sc = 0.7, A = 0.4, B = 0.2, Pr = 0.71 and Ec = 0.01.

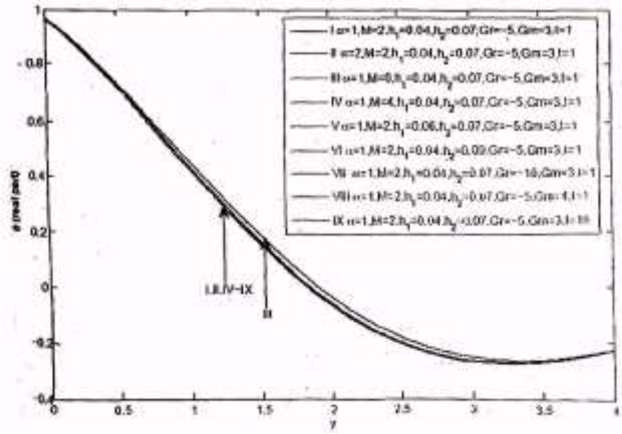

Figure 6: Temperature Distribution Against y for ε = 0.2, n = 0.1, S = 0.8, Sc = 0.7, A = 0.4, B = 0.2, Pr = 0.71 and Ec = 0.01.

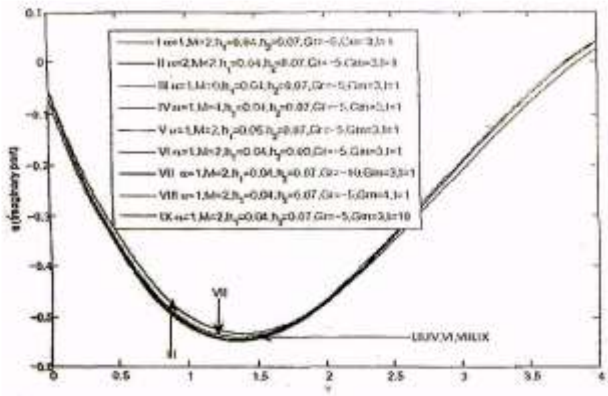

Figure 7: Temperature Distribution Against y for ε = 0.2, n = 0.1, S = 0.8, Sc = 0.7, A = 0.4, B = 0.2, Pr = 0.71 and Ec=0.01.

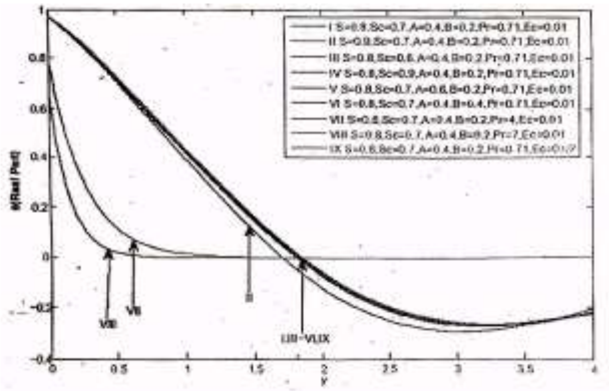

Figure 8; Temperature Distribution Against y for ε = 0.2, n = 0.1, S = 0.8, Sc - 0.7, A = 0.4, B = 0.2, Pr = 0.71 and Ec = 0.01.

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