

EFFECT OF CHEMICAL REACTION ON CONVECTIVE HEAT AND MASS TRANSFER FLOW OF A VISCOUS FLUID IN A NON-UNIFORMLY HEATED VERTICAL CHANNEL WITH HEAT GENERATING SOURCES

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1.INTRODUCTION:

The application of electromagnetic fields in controlling the heat transfer as in aerodynamic heating leads to the study of magneto hydrodynamics heat transfer. The MHD heat transfer has gained significance owing to advancement of space technology. Liquid in the geothermal region is an electrically conducting liquid because of high temperature. Hence the study of interaction of the geomagnetic field with the fluid in the geothermal region is of great interest, thus leading to interest in the study of magneto hydrodynamic convection flows through porous medium.

In the above mentioned investigations the boundary walls are maintained at constant temperature. However, there are a few physical situations which warrant the boundary temperature to be maintained non-uniform. It is evident that in forced or free convection flow in a channel (pipe) a secondary flow can be created either by corrugating the boundaries or by maintaining non-uniform wall temperature. Such a secondary flow can be of interest in a few technological processes (MCVD) (17, 36). Ravindra Reddy (33) has analyzed the effects of magnetic field on the combined heat and mass transfer in channels using finite element techniques. Ravindra (32) has investigated the mixed convection flow of an electrically conducting viscous fluid through a porous medium in a vertical channel. Nagaraja (24) has investigated the combined heat and mass transfer effects on the flow of a viscous fluid in a vertical channel.

Since many industrially and environmentally relevant fluids are not pure, it has been suggested that more attention should be paid to convective phenomena which can occur in mixture, but are not present in common fluids such as air or water. Applications involving liquid mixtures include the casting of alloys, ground water pollutant, migration and separation operations. In all these situations multi component liquids can undergo natural convection driven by temperature and species gradients. Keeping this in view several authors have investigated the Soret effect under varied conditions (3,6,11,12,13,19,26) Prasad (28a) has discussed the convective heat and mass transfer of a viscous electrically conducting fluid through a porous medium in a vertical channel taking into account the dissipative effects. Using a perturbation technique, the velocity, the temperature and the concentration, the rate of heat and mass transfer have been analyzed for different variations in the governing parameters. Srinivasa Reddy (38) has analyzed the Soret effect on the convective heat and mass transfer of a viscous fluid through a porous medium in a vertical channel, the walls being maintained at non-uniform temperature. The coupled equations governing the flow, heat and mass transfer have been solved by assuming that the Eckert Ec is much less than 1.

Many processes in engineering areas occur in high temperatures and consequently the radiation plays a significant role. Chandrasekhara and Nagaraju (4) examined the composite heat transfer in a variable porosity medium bounded by an infinite vertical flat plate in the

presence of radiation. Yih (41) studied the radiation effects on natural convection over a cylinder embedded in porous media. Mohammadien and El-Amin (23) considered the thermal radiation effects on power law fluids over a horizontal plate embedded in a porous medium. Raptis (31) studied the steady flow heat transfer in a porous medium with high porosity in the presence of radiation. Ramakrishna Reddy (29) has analyzed the Soret effect on mixed convective Heat and mass transfer flow of an electrically conducting fluid through a porous medium in a vertical channel. Vijaya Bhaskar Reddy (40a) has discussed the effect of non-uniform boundary temperature on convective heat and mass transfer flow of a viscous fluid in a vertical channel.

In this paper, we discuss the effect of chemical reaction on free convective and mass transfer flow in a non-uniformly heated vertical channel. The walls are maintained at non-uniform temperature. The coupled equations governing the flow, heat and mass transfer have been solved by using a perturbation technique with the slope of the boundary temperature as perturbation parameter. The expression for the velocity, the temperature, the concentration, the rate of heat and mass transfer are derived and are analysed for different variations of the governing parameters $G, M, D^{-1}, \alpha_1, Sc, So, N, k$ and x .

2. FORMULATION OF THE PROBLEM

We consider the motion of viscous, incompressible, electrically conducting fluid in a vertical channel bounded by flat walls. The thermal buoyancy in the flow field is created due to the non-uniform temperature on the walls. $y = \pm L$ while both the walls are maintained at uniform concentration. A uniform magnetic field of strength H_0 is applied normal to the walls. The Boussinesq approximation is used so that the density variation will be considered only in the buoyancy force. The viscous and Darcy dissipations are neglected in comparison to the heat conduction in the energy equation. Also the kinematic viscosity ν , the thermal conducting k are treated as constants. We choose a rectangular Cartesian system $O(x, y)$ with x -axis in the vertical direction and y -axis normal to the walls. The walls of the channel are at $y = \pm L$.

The equations governing the steady flow, heat and mass transfer in terms of Stokes Stream function are

$$[\psi_x(\nabla^2 \psi)_y - \psi_y(\nabla^2 \psi)_x] = \nu \nabla^4 \psi - \beta g(T - T_0)_y - \beta^* g(C - C_0)_y - \left(\frac{\sigma \mu_e^2 H_0^2}{\rho_e} \right) \frac{\partial^2 \psi}{\partial y^2} \quad (2.1)$$

$$\rho_e C_p \left(\frac{\partial \psi}{\partial y} \frac{\partial \theta}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial \theta}{\partial y} \right) = \lambda \nabla^2 \theta - Q(T - T_0) \quad (2.2)$$

$$\left(\frac{\partial \psi}{\partial y} \frac{\partial C}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial C}{\partial y} \right) = D_1 \nabla^2 C - k_1(C - C_0) + K_{11} \nabla^2 T \quad (2.3)$$

Introducing the non-dimensional variables in (2.1) - (2.3) as

$$x' = x/L, y' = y/L, \Psi' = \Psi/\nu, \theta = \frac{T - T_e}{\Delta T}, C' = \frac{C - C_2}{C_1 - C_2} \quad (2.4)$$

the governing equations in the non-dimensional form (after dropping the dashes) are

$$R \left(\frac{\partial(\psi, \nabla^2 \psi)}{\partial(x, y)} \right) = \nabla^4 \psi + \left(\frac{G}{R} \right) (\theta_y + NC_y) - M^2 \frac{\partial^2 \psi}{\partial y^2} \quad (2.5)$$

$$RP\left(\frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y}\right)=\nabla^2\theta-\alpha\theta \quad (2.6)$$

$$RSc\left(\frac{\partial\psi}{\partial y}\frac{\partial C}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial y}\right)=\nabla^2C-kC+\frac{ScS_0}{N}\nabla^2\theta \quad (2.7)$$

where

$$\begin{aligned} R &= \frac{qL}{\nu} \quad (\text{Reynolds number}) & G &= \frac{\beta g \Delta T_e L^3}{\nu^2} \quad (\text{Grashof number}) \\ P &= \frac{\mu C_p}{\lambda} \quad (\text{Prandtl number}), & M^2 &= \frac{\sigma \mu_e^2 H_o^2 L^2}{\nu^2} \quad (\text{Hartman Number}) \\ Sc &= \frac{\nu}{D_1} \quad (\text{Schmidt Number}) & \alpha &= \frac{QL^2}{\lambda} \quad (\text{Heat source parameter}) \\ K &= \frac{K_1 L^2}{D_1} \quad (\text{Chemical reaction parameter}) & S_o &= \frac{k_{11} \beta^*}{\nu \beta} \quad (\text{Soret parameter}) \\ N &= \frac{\beta^* (C_1 - C_2)}{\beta (T_1 - T_2)} \quad (\text{Buoyancy ratio}) \end{aligned}$$

The corresponding boundary conditions are

$$\begin{aligned} \psi(+1) - \psi(-1) &= 1 \\ \frac{\partial\psi}{\partial x} &= 0, \quad \frac{\partial\psi}{\partial y} = 0 \quad \text{at } y = \pm 1 \end{aligned} \quad (2.8)$$

$$\begin{aligned} \theta(x, y) &= \gamma(\delta x), \quad C = 1 \quad \text{on } y = -1 \\ \theta(x, y) &= \gamma(\delta x), \quad C = 0 \quad \text{on } y = +1 \\ \frac{\partial\theta}{\partial y} &= 0, \quad \frac{\partial C}{\partial y} = 0 \quad \text{at } y = 0 \end{aligned} \quad (2.9)$$

3. METHOD OF SOLUTION

The main aim of the analysis is to discuss the perturbations created over a combined free and forced convection flow due to non-uniform boundary temperature imposed on the boundaries.

Introduce the transformation such that

$$\bar{x} = \delta x, \quad \frac{\partial}{\partial x} = \delta \frac{\partial}{\partial \bar{x}}$$

the equations (2.5) – (2.7) reduce to

$$\delta R \left(\frac{\partial(\psi, \nabla_1^2 \psi)}{\partial(x, y)} \right) = \nabla_1^4 \psi + \left(\frac{G}{R} \right) (\theta_y + NC_y) - M^2 \frac{\partial^2 \psi}{\partial y^2} \quad (3.1)$$

$$\delta PR \left(\frac{\partial\psi}{\partial y} \frac{\partial\theta}{\partial x} - \frac{\partial\psi}{\partial x} \frac{\partial\theta}{\partial y} \right) = \nabla_1^2 \theta - \alpha \theta \quad (3.2)$$

$$\delta ScR \left(\frac{\partial\psi}{\partial y} \frac{\partial C}{\partial x} - \frac{\partial\psi}{\partial x} \frac{\partial C}{\partial y} \right) = \nabla_1^2 C - \gamma C + \frac{ScS_0}{N} \nabla_1^2 \theta \quad (3.3)$$

$$\nabla_1^2 = \delta^2 \frac{\partial^2}{\partial \bar{x}^2} + \frac{\partial^2}{\partial y^2}$$

We adopt the perturbation scheme and write

$$\psi(x, y) = \psi_0(x, y) + \delta \psi_1(x, y) + \delta^2 \psi_2(x, y) + \dots$$

$$\theta(x, y) = \theta_0(x, y) + \delta \theta_1(x, y) + \delta^2 \theta_2(x, y) + \dots$$

$$C(x, y) = C_0(x, y) + \delta C_1(x, y) + \delta^2 C_2(x, y) + \dots \quad (3.4)$$

On substituting (3.4) in (3.1) - (3.3) and separating the like powers of δ the equations and respective conditions to the zeroth order are

$$\psi_{0,yyyy} - M_1^2 \psi_{0,yy} = -\frac{G}{R}(\theta_{0,y} + N C_{0,y}) \quad (3.5)$$

$$\theta_{0,yy} - \alpha \theta_0 = 0 \quad (3.6)$$

$$C_{0,yy} - K C_0 = 0 + \frac{Sc S_0}{N} \theta_{0,yy} \quad (3.7)$$

with

$$\psi_{0(+1)} - \psi_{0(-1)} = 1, \quad \psi_{0,y} = 0, \quad \psi_{0,x} = 0 \quad \text{at } y = \pm 1 \quad (3.8)$$

$$\theta_0 = \gamma(\bar{x}), \quad C_0 = 1 \quad \text{on } y = -1 \quad (3.9)$$

The first order equations are

$$\psi_{1,yyyy} - M_1^2 \psi_{1,yy} = -\frac{G}{R}(\theta_{1,y} + N C_{1,y}) + R(\psi_{0,y} \psi_{0,xy} - \psi_{0,x} \psi_{0,yy}) \quad (3.10)$$

$$\theta_{1,yy} - \alpha \theta_1 = PR(\psi_{0,x} \theta_{0,y} - \psi_{0,y} \theta_{0x}) \quad (3.11)$$

$$C_{1,yy} - K C_1 = ScR(\psi_{0,x} C_{0,y} - \psi_{0,y} C_{0x}) + \frac{Sc S_0}{N} \theta_{1,yy} \quad (3.12)$$

with

$$\psi_{1(+1)} - \psi_{1(-1)} = 0, \quad \psi_{1,y} = 0, \quad \psi_{1,x} = 0 \quad \text{at } y = \pm 1 \quad (3.13)$$

The equations to the second order are

$$\psi_{2,yyyy} - M_1^2 \psi_{2,yy} = -\frac{G}{R}(\theta_{2,y} + N C_{2,y}) + R(\psi_{0,yy} \psi_{0,xy} + \psi_{0,x} \psi_{1,yy} + \psi_{1,x} \psi_{0,yy} - \psi_{0,y} \psi_{1,xy} - \psi_{1,y} \psi_{0,xy}) \quad (3.14)$$

$$\theta_{2,yy} - \alpha \theta_2 = PR(\psi_{0,x} \theta_{1,y} - \psi_{0,y} \theta_{1x} - \psi_{1,y} \theta_{0,x} + \psi_{1,x} \theta_{0,y}) \quad (3.15)$$

$$C_{2,yy} - K C_2 = ScR(\psi_{0,x} C_{1,y} - \psi_{0,y} C_{1x} - \psi_{1,y} C_{0,x} + \psi_{1,x} C_{0,y}) + \frac{Sc S_0}{N} \theta_{2,yy} \quad (3.16)$$

with

$$\psi_{2(+1)} - \psi_{2(-1)} = 0, \quad \psi_{2,y} = 0, \quad \psi_{2,x} = 0 \quad \text{at } y = \pm 1 \quad (3.17)$$

$$\theta_2(\pm 1) = 0, \quad C_2(\pm 1) = 0 \quad \text{at } y = \pm 1 \quad (3.18)$$

The equations (3.5)- (3.13) are analytically solved subject to the relevant boundary conditions

5. NUSSELT NUMBER and SHERWOOD NUMBER

The local rate of heat transfer coefficient Nusselt number (Nu) on the walls has been calculated using the formula

$$Nu = \frac{1}{\theta_m - \theta_w} \left(\frac{\partial \theta}{\partial y} \right)_{y=\pm 1}$$

$$\text{where } \theta_m = 0.5 \int_{-1}^1 \theta dy$$

and the corresponding expressions are

$$(Nu)_{y=+1} = \frac{(d_9 + \delta d_{11})}{(\theta_m - \gamma(x))}, \quad (Nu)_{y=-1} = \frac{(d_8 + \delta d_{10})}{(\theta_m - \gamma(x))},$$

$$\text{Where } \theta_m = d_{14} + \delta d_{15}$$

The local rate of mass transfer coefficient(Sherwood Number Sh) on the walls has been calculated using the formula

$$Sh = \frac{1}{C_m - C_w} \left(\frac{\partial C}{\partial y} \right)_{y=\pm 1}$$

$$\text{where } C_m = 0.5 \int_{-1}^1 C dy$$

and the corresponding expressions are

$$(Sh)_{y=+1} = \frac{(d_4 + \delta d_6)}{(C_m)}, \quad (Nu)_{y=-1} = \frac{(d_5 + \delta d_7)}{(C_m - 1)},$$

$$\text{where } C_m = d_{12} + \delta d_{13}$$

where d_1, d_2, \dots, d_{14} are constants.

6. DISCUSSION OF THE RESULTS:

In this analysis we discuss effect of chemical reaction and thermo-diffusion on the heat and mass transfer flow of viscous, electrically conducting fluid through a porous medium in a non-uniformly heated vertical channel in the presence of heat generating sources. We take the Prandtl number $P = 0.71$ and $\delta = 0.01$.

The axial velocity (u) is shown in figs. 1-5 for different values of $M, D^{-1}, \alpha, Sc, So$ and α_1, k, x . The actual axial flow is in the upward direction and hence $u < 0$ represents the reversal flow. Higher the Lorentz force/lesser the permeability of the porous medium smaller $|u|$ in the flow region (fig. 1). The axial velocity reduces with α in the entire flow region. An increase in the amplitude α_1 of the boundary temperature results in an enhancement in $|u|$ (fig. 2). With respect to Sc we find that lesser the molecular diffusivity smaller $|u|$ in the entire region. $|u|$ depreciates with $So > 0$ and enhances with $So < 0$ (fig.3). When the molecular buoyancy force dominates over the thermal buoyancy force $|u|$ enhances irrespective of the directions of the buoyancy forces (fig. 4). The variation of u with chemical reaction parameter k shows that higher the chemical reaction parameter larger $|u|$ in the entire flow region (fig.5).

The secondary velocity (v) which is due to the non-uniform boundary temperature is shown in figs.6-9 for different parametric values. The variation of v with M and D^{-1} shows the higher the Lorentz force /lesser the permeability of the porous medium higher $|v|$ (fig.6). An increase in $\alpha \leq 4$ enhances $|v|$ in the entire flow region while for higher $\alpha \geq 6$, it reduces in the flow region (fig.7). From fig. 8, we find that lesser the molecular diffusivity larger $|v|$ in the entire flow region. $|v|$ experiences an enhancement with increase in $|So|$ (fig.8). The secondary

velocity enhances with increase in $N > 0$ and reduces with $|N| (< 0)$. Also we find that an increase in the chemical reaction parameter k enhances $|v|$ in the entire flow region (fig. 9)

The non-dimensional temperature (θ) is shown in figs. 10-15 for different parametric values. The variation of θ with D^{-1} shows that lesser the permeability of the porous medium smaller the actual temperature. With respect to M we find that higher the Lorentz force smaller the actual temperature and for further higher Lorentz force larger the actual temperature (fig. 10). With respect to α we find that the actual temperature depreciates with increase in $\alpha \leq 4$ and enhances with higher $\alpha \geq 6$ (fig. 11). Lesser the molecular diffusivity larger the actual temperature. Also it enhances with increase in $So > 0$ and reduces with $|So| (< 0)$ (fig. 13). The variation of θ with the amplitude α_1 shows that the actual temperature enhances with increase in α_1 (fig. 12). When the molecular buoyancy force dominates over the thermal buoyancy force the actual temperature enhances in the entire flow region when buoyancy forces act in the same direction and for the forces acting in opposite directions, it reduces in the left half and enhances in the right half (fig. 14). With respect to the chemical reaction parameter k we find that an increase in k results in a depreciation of the actual temperature (fig. 15).

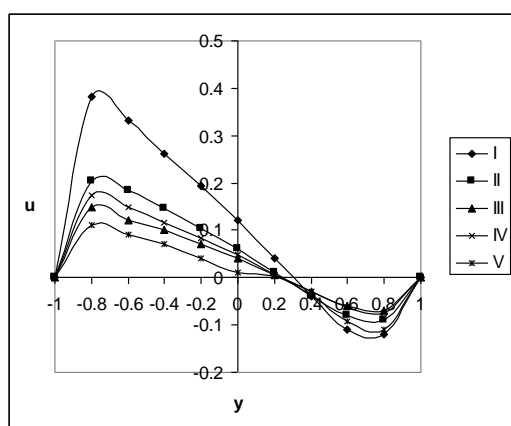


Fig. 1 : Variation of u with D^{-1} , M

	I	II	III	IV	V
D^{-1}	10^2	2×10^2	3×10^2	10^2	10^2
M	2	2	2	5	10

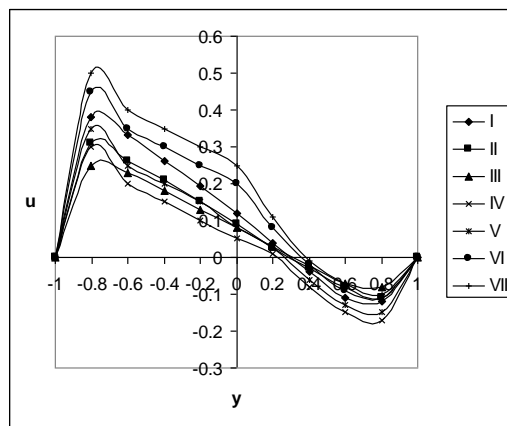


Fig. 2 : Variation of u with α , α_1

	I	II	III	IV	V	VI	VII
α	2	4	6	2	2	2	2
α_1	0.5	0.5	0.5	0.1	0.3	0.7	0.9

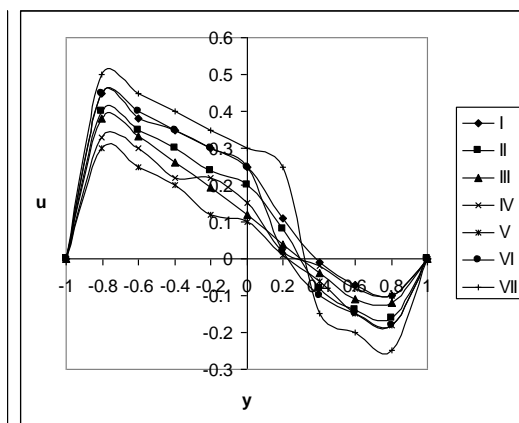


Fig.3 : Variation of u with Sc , S_0

	I	II	III	IV	V	VI	VII
Sc	0.24	0.6	1.3	2.01	1.3	1.3	1.3
S_0	0.5	0.5	0.5	0.5	1.0	-0.5	0.5

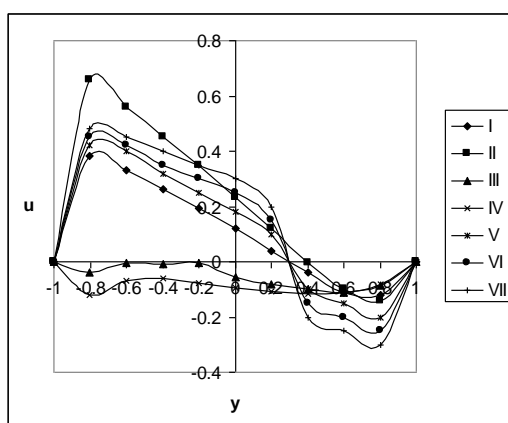


Fig.4 : Variation of u with N , k

	I	II	III	IV	V	VI	VII
N	1	2	-0.5	-0.8	1	1	1
k	0.5	0.5	0.5	0.5	1.5	2.5	3.5

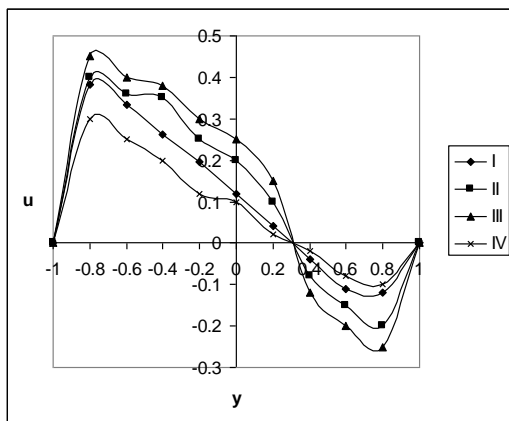


Fig. 5 : Variation of u with x

	I	II	III	IV
x	$\pi/4$	$\pi/2$	π	$3\pi/4$

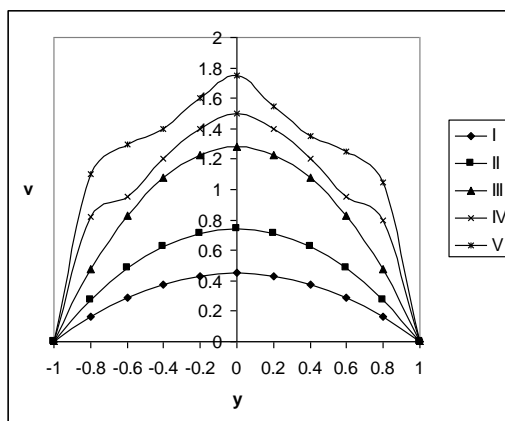


Fig.6 : Variation of v with D^{-1}, M

	I	II	III	IV	V
D^{-1}	10^2	2×10^2	3×10^2	10^2	10^2

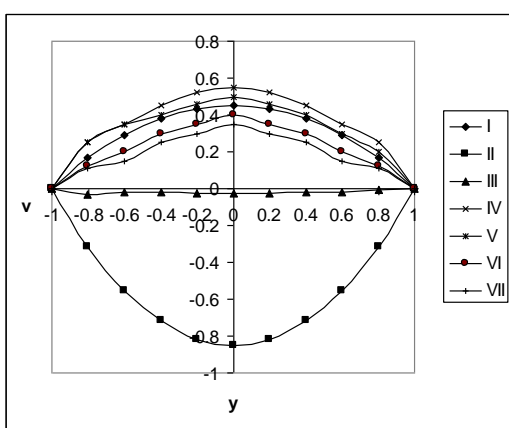


Fig. 7 : Variation of v with α, α_1

	I	II	III	IV	V	VI	VII
α	2	4	6	2	2	2	2
α_1	0.5	0.5	0.5	0.1	0.3	0.7	0.9

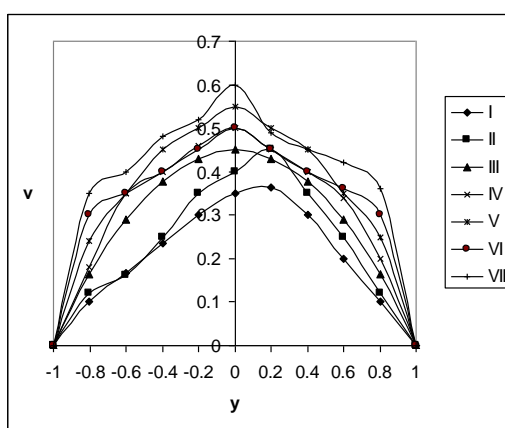


Fig. 8 : Variation of v with Sc, S_0

	I	II	III	IV	V	VI	VII
Sc	0.24	0.6	1.3	2.01	1.3	1.3	1.3
S_0	0.5	0.5	0.5	0.5	1.0	-0.5	0.5

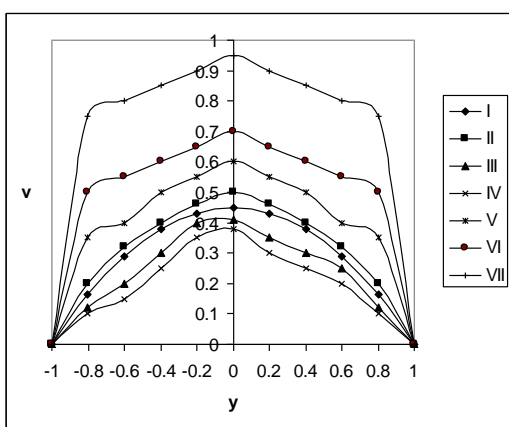


Fig. 9 : Variation of v with N, k

	I	II	III	IV	V	VI	VII
N	1	2	-0.5	-0.8	1	1	1
k	0.5	0.5	0.5	0.5	1.5	2.5	3.5

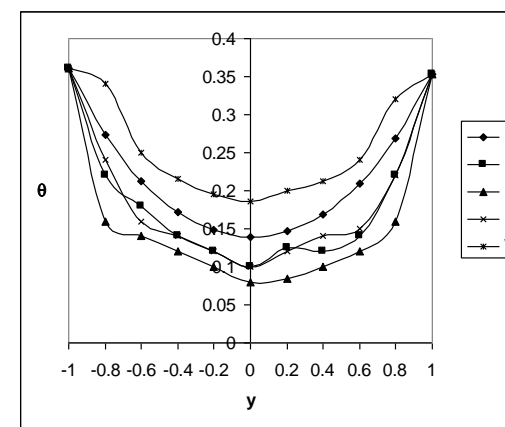


Fig. 10 : Variation of θ with D^{-1}, M

	I	II	III	IV	V
D^{-1}	10^2	2×10^2	3×10^2	10^2	10^2
M	2	2	2	5	10

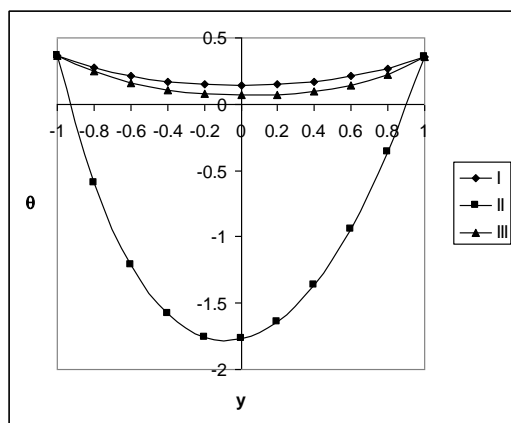


Fig. 11 : Variation of θ with α

	I	II	III
α	2	4	6

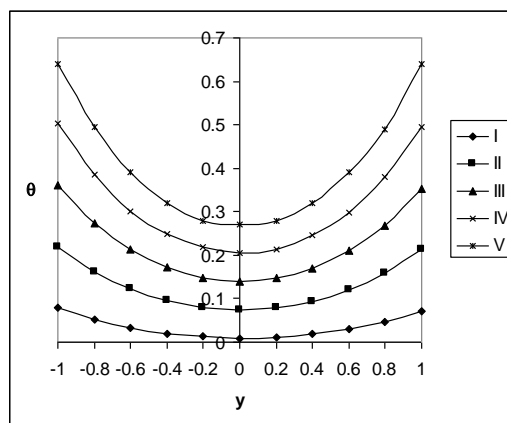


Fig. 12 : Variation of θ with α_1

	I	II	III	IV	V
α_1	0.1	0.2	0.5	0.7	0.9

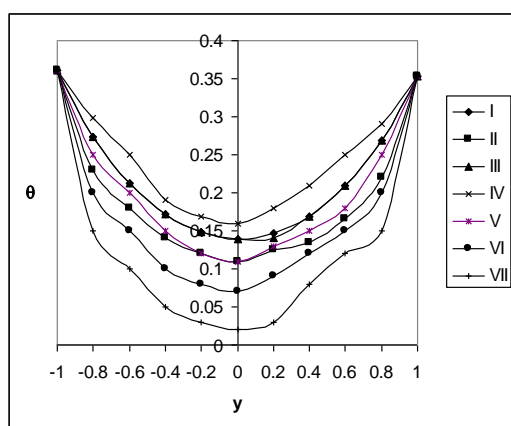


Fig. 13 : Variation of θ with Sc, S_0

	I	II	III	IV	V	VI	VII
Sc	0.24	0.6	1.3	2.01	1.3	1.3	1.3
S_0	0.5	0.5	0.5	0.5	1.0	-0.5	0.5

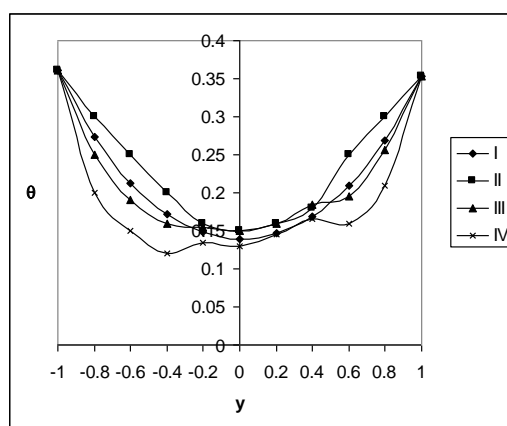


Fig. 14 : Variation of θ with N

	I	II	III	IV
N	1	2	-0.5	-0.8

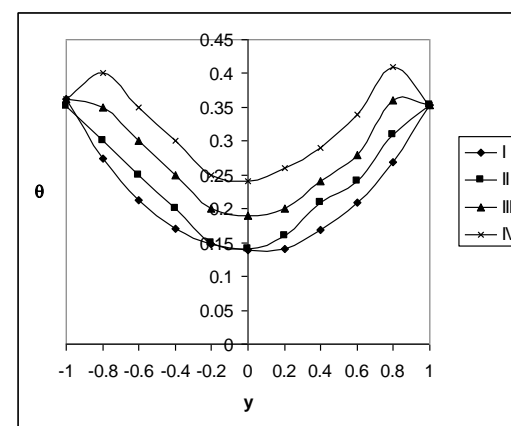


Fig. 15 : Variation of θ with k

	I	II	III	IV
k	0.5	1.5	2.5	3.5

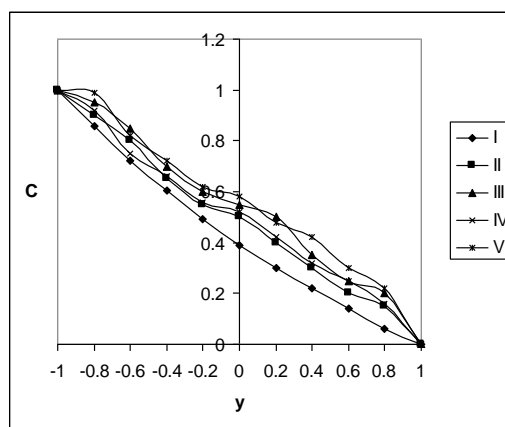


Fig. 16: Variation of C with D^{-1}, M

	I	II	III	IV	V
D^{-1}	10^2	2×10^2	5×10^2	10^2	10^2
M	2	2	2	5	10

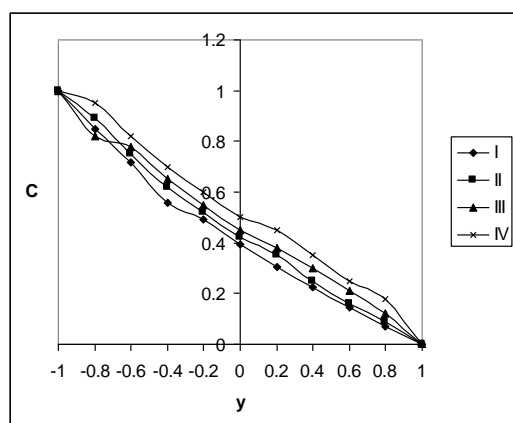


Fig. 17: Variation of C with Sc

I II III IV

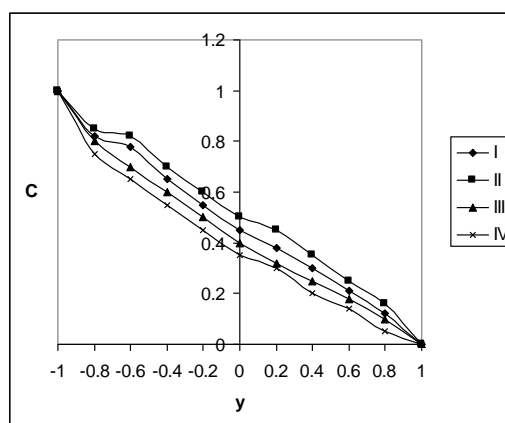


Fig. 18: Variation of C with S_0

I II III IV

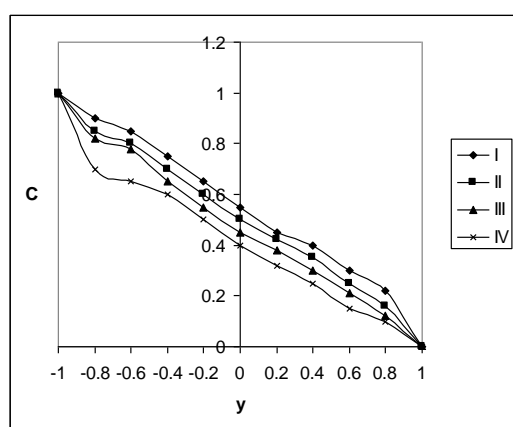


Fig. 19: Variation of C with α_1

α_1 I II III IV
0.1 0.3 0.5 0.7

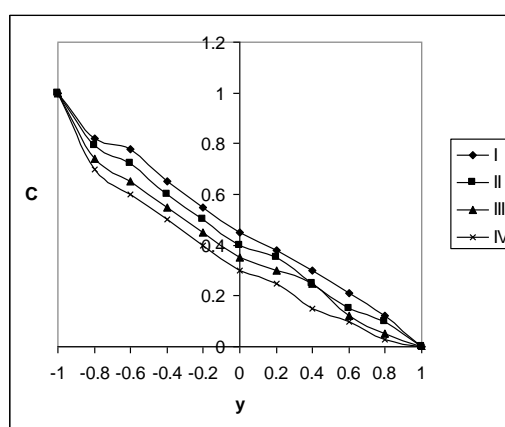


Fig. 20: Variation of C with k

k I II III IV
1 1.5 2.5 3.5

The non-dimensional concentration (C) is shown in figs. 16-20 for different parametric values. From fig.16 we find that higher the Lorentz force/ lesser the permeability of the porous medium larger the actual concentration. Lesser the molecular diffusivity larger the concentration in the entire flow region (fig.18). An increase in $S_0 > 0$ results in an enhancement in C and for $|S_0| < 0$ it depreciates (fig. 19). The variation of C with α_1 shows that the actual concentration reduces with increase in the amplitude α_1 of the boundary temperature in the entire flow region (fig.20). From fig. 21 we find a depreciation in the concentration with chemical reaction parameter k .

The rate of heat transfer for (Nusselt number) at $y = \pm 1$ is shown in tables 1-6 for different values of G , D^{-1} , M , α , Sc , S_0 , α_1 , k . It is found that the rate of heat transfer depreciates at $y = +1$ and enhances at $y = -1$ with $G > 0$ and for $G < 0$ it depreciates at $y = -1$ and enhances at $y = 1$. The variation of Nu with M and D^{-1} shows that higher the Lorentz force / lesser the permeability of the porous medium larger the rate of heat transfer at both the walls. An increase in the strength of the heat source leads to an enhancement in Nu at $y = \pm 1$ (tables.1&5). The variation of Nu with Sc shows that an increase in Sc enhances $|Nu|$ at $y = +1$ and depreciates at $y = -1$. An increase in γ leads to a depreciation in Nu at $y = 1$ and an enhancement in Nu at $y = -1$ (tables 2&6). The variation of Nu with amplitude α_1 shows that $|Nu|$ depreciates with α_1 at both the walls. The Nusselt Number reduces with $x < \pi$ and enhances with $x = 2\pi$ at $y = \pm 1$. When the molecular buoyancy force dominates over the thermal buoyancy force the rate of heat transfer enhances at both the walls when the 4 buoyancy forces act in the same direction and for the forces acting in opposite directions it enhances for $G > 0$.

and reduces for $G < 0$ at $y = 1$ and at $y = -1$ it reduces for $G > 0$ and enhances for $G < 0$ (tables 3&7). The variation of Nu with chemical reaction parameter k shows that $|Nu|$ depreciates with increase in $k \leq 1.5$ and enhances with higher $k \geq 2.5$ at both the walls

The rate of mass transfer Sherwood number (Sh) at $y = \pm 1$ is shown in tables 9-16 for different parametric values. It is found that $|Sh|$ enhances at $y = +1$ with increase in $|G|$ and at $y = -1$, it enhances for $G > 0$ and depreciates for $G < 0$. An increase in M reduces $|Sh|$ for $G > 0$ and enhances for $G < 0$ at $y = \pm 1$. The variation of Sh with D^{-1} shows that the rate of mass transfer at $y = 1$ reduces in the heating case and enhances in the cooling case. At $y = -1$, it enhances with increase in $D^{-1} \leq 2 \times 10^2$ and reduces with higher $D^{-1} \geq 3 \times 10^2$. An increase in the heat source parameter α results in a depreciation in $|Sh|$ at $y = +1$ while at $y = -1$, it enhances with $\alpha \leq 4$ and reduces with $\alpha \geq 6$ (tables 9&13). The variation of Sh with Sc shows that the rate of mass transfer at $y = 1$ enhances for $G > 0$ and reduces for $G < 0$ with increase in $Sc \leq 0.6$ and for higher $Sc > 1.3$ we notice a reversed effect in the behaviour of Sh . At $y = -1$, it reduces for $G > 0$ and enhances for $G < 0$ with increase in $Sc \leq 0.6$ and for higher $Sc > 1.3$ we notice an enhancement in Sh . An increase in the amplitude $\alpha_1 \leq 0.7$ and for higher $\alpha_1 \geq 0.9$ it depreciates for $G > 0$ and enhances for $G < 0$ at $y = 1$ and at $y = -1$ it enhances with α_1 in the heating case and in the cooling case it reduces (tables 10&14). The rate of mass transfer reduces for $G > 0$ and enhances for $G < 0$ at $y = 1$ and enhances at $y = -1$ for all G with $N > 0$ when the buoyancy forces act in the same direction and for the forces acting in opposite direction it enhances in the heating case and reduces in the cooling case at both the walls. With respect to k , we find a depreciation in $|Sh|$ with increase in k at $y = +1$ while at $y = -1$, it reduces with $k \leq 1.5$ and enhances with $k > 2.5$ (tables 11&15).

Table 1
Nusselt Number (Nu) at $y = 1$

G	I	II	III	IV	V	VI	VII
10^3	-1.7259	-1.7089	-1.6518	-1.6809	-1.7222	-2.9874	-5.1734
3×10^3	-1.7249	-1.7077	-1.6504	-1.6792	-1.7186	-2.9680	-5.1295
-10^3	-1.7392	-1.7134	-1.6537	-1.6832	-1.7264	-3.0095	-5.2264
-3×10^3	-1.7413	-1.7159	-1.6553	-1.6851	-1.7297	-3.0274	-5.2715
D^{-1}	10^2	3×10^2	5×10^2	10^2	10^2	10^2	10^2
M	2	2	2	4	6	2	2
α	2	2	2	2	2	4	6

Table 2
Nusselt Number (Nu) at $y = 1$

G	I	II	III	IV	V	VI
10^3	-1.7247	-1.7257	-1.7259	-1.7264	-1.7252	-1.7244
3×10^3	-1.7182	-1.7183	-1.7249	-1.7259	-1.7186	-1.7186
-10^3	-1.7342	-1.7346	-1.7392	-1.7396	-1.7354	-1.7354
-3×10^3	-1.7417	-1.7416	-1.7413	-1.7426	-1.7413	-1.7413
Sc	0.24	0.6	1.3	2.01	2	2
γ	2	2	2	2	4	6

Table 3
Nusselt Number (Nu) at $y = 1$

G	I	II	III	IV	V	VI	VII
10^3	-1.3571	-1.2255	-1.1578	-1.7259	-1.7205	-1.7288	-1.7338
3×10^3	-1.3546	-1.2242	-1.1571	-1.7249	-1.7074	-1.7356	-1.7391
-10^3	-1.3623	-1.2286	-1.1599	-1.7392	-1.7409	-1.7272	-1.7255
-3×10^3	-1.3647	-1.2299	-1.6073	-1.7413	-1.7527	-1.722	-1.7208
α_1	0.3	0.5	0.7	0.9	0.3	0.3	0.3
N	1	1	1	1	2	-0.5	-0.8

Table 4
Nusselt Number (Nu) at $y = 1$

G	I	II	III
10^3	-1.3571	-1.3656	-1.3717
3×10^3	-1.3546	-1.3624	-1.3707
-10^3	-1.3623	-1.3681	-1.3743
-3×10^3	-1.3647	-1.3699	-1.3754
K	0.5	1.5	2.5
P	0.71	0.71	0.71

Table 5
Nusselt Number (Nu) at $y = -1$

G	I	II	III	IV	V	VI	VII
10^3	0.9719	0.9815	1.0442	0.9746	1.0153	1.2702	1.6004
3×10^3	0.9724	0.9908	1.0471	0.9809	1.0185	1.2894	1.6293
-10^3	0.9537	0.9809	1.0411	0.9677	1.01143	1.2484	1.5626
-3×10^3	0.9466	0.9763	1.0381	0.9616	1.0080	1.2306	1.5328
R	35	35	35	35	35	35	35
D^{-1}	10^2	3×10^2	5×10^2	10^2	10^2	10^2	10^2
M	2	2	2	4	6	2	2
α	2	2	2	2	2	4	6

Table 6
Nusselt Number (Nu) at $y = -1$

G	I	II	III	IV	V
10^3	0.9732	0.9723	0.9719	0.97268	0.97351
3×10^3	0.9847	0.9846	0.9724	0.98428	0.98428
-10^3	0.9587	0.9584	0.9537	0.95751	0.95751
-3×10^3	0.9462	0.9464	0.9466	0.94664	0.94664
Sc	0.24	0.6	1.3	2	2
γ	2	2	2	4	6

Table 7
Nusselt Number (Nu) at $y = -1$

G	I	II	III	IV	V	VI	VII
10^3	0.9606	0.9559	0.9535	0.9719	0.9799	0.9654	0.9595
3×10^3	0.9658	0.9593	0.9558	0.9724	1.0029	0.9561	0.9504
-10^3	0.9525	0.9507	0.94916	0.9537	0.9695	0.9695	0.9719
-3×10^3	0.9472	0.9473	0.34739	0.9466	0.9576	0.9749	0.9805
α_1	0.3	0.5	0.7	0.9	0.3	0.3	0.3
x	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$
N	1	1	1	1	2	-0.5	-0.8

Table 8
Nusselt Number (Nu) at $y = -1$

G	I	II	III	IV
10^3	0.9606	1.2649	-0.2733	-0.5618
3×10^3	0.9658	0.1324	-0.2708	-0.5604
-10^3	0.9525	0.12138	-0.27743	-0.5648
-3×10^3	0.9472	0.11689	-0.27796	-0.5661
K	0.5	1.5	2.5	3.5

Table 9
Sherwood number (Sh) at $y = -1$

G	I	II	III	IV	V	VI	VII
10^3	-0.4125	-0.4103	-0.3914	-0.4132	-0.4013	-0.4145	-0.4153
3×10^3	-0.4972	-0.3822	-0.3256	-0.5911	-0.3553	-0.3949	-0.3972
-10^3	-0.4362	-0.4385	-0.4573	-0.4374	-0.4474	-0.4342	-0.4334
-3×10^3	-0.4601	-0.4666	-0.5232	-0.4677	-0.4936	-0.4539	-0.4516
D^{-1}	10^2	3×10^2	5×10^2	10^2	10^2	10^2	10^2
M	2	2	2	4	6	2	2
α	2	2	2	2	2	4	6

Table 10
Sherwood number (Sh) at $y = -1$

G	I	II	III	IV	V	VI	VII
10^3	-0.4125	-0.4222	-0.4189	-0.4105	-0.4072	-0.4019	-0.3961
3×10^3	-0.4972	-0.5178	-0.4079	-0.4058	-0.3731	-0.3573	-0.3416
-10^3	-0.4362	-0.4266	-0.4298	-0.4395	-0.4416	-0.4469	-0.45522
-3×10^3	-0.4601	-0.4309	-0.4408	-0.4712	-0.4761	-0.4922	-0.5083
Sc	0.24	0.6	1.3	2.01	1.3	1.3	1.3
α_1	0.3	0.3	0.3	0.3	0.5	0.7	0.9

Table 11
Sherwood number (Sh) at $y = +1$

G	I	II	III	IV	V	VI	VII
10^3	-0.4125	-0.4086	-0.4083	-0.4196	-0.2995	-0.2219	-0.1669
3×10^3	-0.4972	-0.3772	-0.4064	-0.4099	-0.2782	-0.2044	-0.1523
-10^3	-0.4362	-0.4402	-0.4304	-0.4292	-0.3209	-0.2396	-0.1814
-3×10^3	-0.4601	-0.4718	-0.4424	-0.4389	-0.3424	-0.2572	-0.1959
N	1	2	-0.5	-0.8	1	1	1
K	0.5	0.5	0.5	0.5	1.5	2.5	3.5

Table 13
Sherwood number (Sh) at $y = -1$

G	I	II	III	IV	V	VI	VII
10^3	5.8077	5.5575	5.495	5.7332	5.6249	6.0378	5.5470
3×10^3	5.9435	5.2143	5.6958	5.7424	5.4169	5.7899	5.7836
-10^3	5.6502	5.8992	5.6299	5.7240	5.8319	5.9142	5.8941
-3×10^3	5.4957	6.2396	5.7612	5.7149	6.0378	5.6676	5.6738
D^{-1}	10^2	3×10^2	5×10^2	10^2	10^2	10^2	10^2
M	2	2	2	4	6	2	2
α	2	2	2	2	2	4	6

Table 14
Sherwood number (Sh) at $y = -1$

G	I	II	III	IV	V	VI	VII
10^3	5.8077	5.743	5.7650	5.8492	5.8772	5.9471	6.0175
3×10^3	5.9435	5.7723	5.8303	6.0124	6.1819	6.3998	6.6222
-10^3	5.6502	5.7141	5.6923	5.7542	5.5824	5.5151	5.4482
-3×10^3	5.4957	5.6851	5.6203	5.5592	5.2971	5.1023	4.9111
Sc	0.24	0.6	1.3	2.01	1.3	1.3	1.3
α_1	0.3	0.3	0.3	0.3	0.5	0.7	0.9

Table 15
Sherwood number (Sh) at $y = -1$

G	I	II	III	IV	V	VI	VII
10^3	5.8077	5.7834	5.8442	5.8515	3.9764	3.7939	3.8261
3×10^3	5.9435	5.8948	6.0788	6.1009	3.9931	3.8060	3.8374
-10^3	5.6502	5.6743	5.6141	5.6069	3.9597	3.7819	3.8147
-3×10^3	5.4957	5.5672	5.3886	5.3672	3.9431	3.7698	3.8034
N	1	2	-0.5	-0.8	1	1	1
K	0.5	0.5	0.5	0.5	1.5	2.5	3.5

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