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Non-Darcy Convective Heat and Mass Transfer Flow in a Vertical Channel with Chemical Reaction and Soret Effect with Heat Sources

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ABSTRACT
In this paper, We made an attempt to study thermo-diffusion and dissipation effect on non-Darcy convective heat and Mass transfer flow of a viscous fluid through a porous medium in a vertical channel with Radiation and heat sources. The governing equations of flow, heat and mass transfer are solved by using regular perturbation method with δ, the porosity parameter as a perturbation parameter. The velocity, temperature, concentration, shear stress and rate of Heat and Mass transfer are evaluated numerically for different variations of parameter.
Keywords: Heat transfer, mass transfer, Soret effect, heat sources, Darcy effect

I. INTRODUCTION

Non – Darcy effects on natural convection in porous media have received a great deal of attention in recent years because of the experiments conducted with several combinations of solids and fluids covering wide ranges of governing parameters which indicate that the experimental data for systems other than glass water at low Rayleigh numbers, do not agree with theoretical predictions based on the Darcy flow model. This divergence in the heat transfer results has been reviewed in detail in cheng [19] and Prasad et al. [23] among others. The work of Vafai and Tien [21] was one of the early attempts to account for the boundary and inertia effects in the momentum equation for a porous medium. They found that the momentum boundary layer thickness is of order of $\sqrt{\frac{k}{\varepsilon}}$. Vafai and Thiyagaraja [22] presented analytical solutions for the velocity and temperature fields for the interface region using the Brinkman Forchheimer –extended Darcy equation.

A numerical study based on the Forchheimer-Brinkman-Extended Darcy equation of motion has also been reported recently by Beckerman et al [4]. They demonstrated that the inclusion of both the inertia and boundary effects is important for convection in a rectangular packed – sphere cavity. In view of the importance of this diffusion – thermo effect, recently Jha and singh [7] studied the free convection and mass transfer flow in an infinite vertical plate moving impulsively in its own plane taking into account the Soret effect. Kafousias [8] studied the MHD free convection and mass transfer flow taking into account Soret effect. The analytical studies of Jha and singh and Kafousias [7.8] were based on Laplace transform technique. Abdul Sattar and Alam [1] have considered an unsteady convectivion and mass transfer flow of viscous incompressible and electrically conducting fluid past a moving infinite vertical porous plate taking into the thermal diffusion effects. Similarity equations of the momentum energy and concentration equations are derived by introducing a time dependent length scale.

Recently Bharathi[3] has studied thermo-diffusion effect on unsteady convective Heat and Mass transfer flow of a viscous fluid through a porous medium in vertical channel. Radioactive flow plays a vital role in many industrial and environmental process e.g. heating and cooling chambers , fossil fuel combustion energy process, evaporation form larger open water reservoirs, ,astrophysical flows, solar power technology and space vehicle re-entry. Taneja et al [18] studied the effects of magnetic field on free convective flow through porous medium with radiation and variable permeability in the slip flow regime. Kumar et al [10] studied the effect of MHD free convection flow of viscous fluid past a porous vertical plate through non homogeneous porous medium with radiations and temperature gradient dependent heat source in slip flow regime. The effect of free convection flow with thermal radiation and mass transfer past a moving vertical porous plate was studied by Makinde [11]. Ayani et al [2] studied the effect of radiation on the laminar natural convection induced by a line source. Raphil [17] have discussed the effect of radiation and free convection flow through porous medium. MHD oscillating flow on free convection radiation through porous medium with constant suction velocity was investigated by El.Hakiem [6]

II. FORMULATION OF THE PROBLEM

We consider a fully developed laminar convective heat and mass transfer flow of a viscous fluid through a porous medium confined in a vertical channel bounded by flat walls. We choose a Cartesian co-ordinate system O(x, y, z) with x-axis in the vertical direction and y-axis normal to the walls. the walls are taken at y= ± L. The walls are maintained at constant temperature and concentration ..The temperature gradient in the flow field is sufficient to cause natural convection in the flow field .A constant axial pressure gradient is also imposed so that this resultant flow is a mixed convection flow. The porous medium is assumed to be isotropic and homogeneous with constant porosity and effective thermal diffusivity. The thermo physical properties of porous matrix are also assumed to be constant and Boussinque approximation is invoked by confining the density variation to the buoyancy term. In the absence of any extraneous force flow is unidirectional along the x-axis which is assumed to be infinite

The Brinkman-Forchheimer-extended Darcy equation which account for boundary inertia effects in the momentum equation, is used to obtain the velocity field. Based on the above assumptions the governing equations in the vector form are

$$\nabla.\overline{q} = 0 \qquad (Equation\ of\ \ continuity) \tag{2.1}$$

$$\frac{\rho}{\delta}\frac{\partial\overline{q}}{\partial t} + \frac{\rho}{\delta^2}(\overline{q}.\nabla)\overline{q} = -\nabla p + \rho g - (\frac{\mu}{k})\overline{q} - \frac{\rho F}{\sqrt{k}}\overline{q}.\overline{q}. + \mu\nabla^2\overline{q}$$
$$(Equation\ \ of\ \ \ linear\ momentum) \tag{2.2}$$

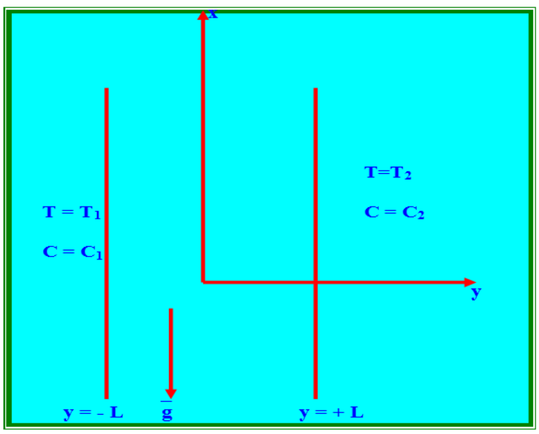
$$\rho C_p(\frac{\partial T}{\partial t} + (\overline{q}.\nabla)T) = \lambda\nabla^2 T + Q(T_o - T)$$
$$(Equation\ of\ \ energy) \tag{2.3}$$

$$\frac{\partial C}{\partial t} + (\overline{q}.\nabla)C = D_1\nabla^2 C - KC + k_{11}\nabla^2 T \tag{2.4}$$
$$(Equation\ of\ diffusion)$$

$$\rho - \rho_0 = -\beta\rho_0(T - T_0) - \beta^{\bullet}\rho_0(C - C_0) \tag{2.5}$$
$$(Equation\ of\ \ State)$$

where $\overline{q}$ =(u,0,0) is the velocity, T, C are the temperature and Concentration, p is the pressure ,ρ is the density of the fluid ,Cp is the specific heat at constant pressure, μ is the coefficient of viscosity, k is the permeability of the porous medium, δ is the porosity of the medium,β is the coefficient of thermal expansion ,λ is the coefficient of thermal conductivity ,F is a function that depends on the Reynolds number and the microstructure of porous medium, $\beta^{\bullet}$ is the volumetric coefficient of expansion with mass fraction concentration, k is the chemical reaction coefficient and D_1 is the chemical molecular diffusivity,k_{11} is the cross diffusivity and Q is the strength of the heat generating source. Here ,the thermophysical properties of the solid and fluid have been assumed to be constant except for the density variation in the body force term(Boussinesq approximation) and the solid particles and the fluid are considered to be in the thermal equilibrium) .

Configuration of the Problem



Since the flow is unidirectional, the continuity of equation (2.1) reduces to $\frac{\partial u}{\partial x}=0$ where u is the axial velocity implies u = u(y)

The momentum, energy and diffusion equations in the scalar form reduces to

$$-\frac{\partial p}{\partial x}+(\frac{\mu}{\delta})\frac{\partial^2 u}{\partial y^2}-(\frac{\mu}{k})u-\frac{\rho\delta F}{\sqrt{k}}u^2-\rho g=0 \tag{2.6}$$

$$\rho_0 C_p u\frac{\partial T}{\partial x}=\lambda\frac{\partial^2 T}{\partial y^2}+Q(T_o-T) \tag{2.7}$$

$$u\frac{\partial C}{\partial x}=D_1\frac{\partial^2 C}{\partial y^2}-k_1 C+k_{11}\frac{\partial^2 T}{\partial y^2} \tag{2.8}$$

The boundary conditions are

$$\begin{aligned} &u=0 \quad , \quad T=T_1 \quad C=C_1 \qquad on \quad y=-L \\ &u=0 \quad , \quad T=T_2 \quad C=C_2 \qquad on \quad y=+L \end{aligned} \tag{2.9}$$

The axial temperature and concentration gradients $\frac{\partial T}{\partial x}$ & $\frac{\partial C}{\partial x}$ are assumed to be constant, say A & B respectively.

We define the following non-dimensional variables as

$$\begin{aligned} &u'=\frac{u}{(\nu/L)},\ (x',y')=(x,y)/L\ ,\quad p'=\frac{p\delta}{(\rho\nu^2/L^2)} \\ &\theta=\frac{T-T_2}{T_1-T_2}\quad ,\quad C'=\frac{C-C_2}{C_1-C_2} \end{aligned} \tag{2.12}$$

Introducing these non-dimensional variables the governing equations in the dimensionless form reduce to (on dropping the dashes)

$$\frac{d^2 u}{dy^2}=\pi+\delta(D^{-1})u-\delta G(\theta+NC)-\delta^2\Delta u^2 \tag{2.13}$$

$$\frac{d^2\theta}{dy^2}-\alpha\theta=(PN_T)u \tag{2.14}$$

$$\frac{d^2 C}{dy^2}-\gamma C=(Sc\,N_C)u+\frac{ScSo}{N}\frac{d^2\theta}{dy^2} \tag{2.15}$$

where

$\Delta=FD^{-1/2}$ (Inertia or Forchheimer parameter)

$G=\frac{\beta g(T_1-T_2)L^3}{\nu^2}$ (Grashoff Number)

$D^{-1}=\frac{L^2}{k}$ (Darcy parameter)

$$Sc = \frac{\nu}{D_1}$$ (Schmidt number)

$$S_o = \frac{k_{11}\beta^{\bullet}}{\nu\beta}$$ (Soret parameter)

$$N = \frac{\beta^{\bullet}(C_1 - C_2)}{\beta(T_1 - T_2)}$$ (Buoyancy ratio)

$$P = \frac{\mu C_p}{\lambda}$$ (Prandtl Number)

$$\alpha = \frac{QL^2}{\lambda}$$ (Heat source parameter)

$$\gamma = \frac{k_1 L^2}{D_1}$$ (Chemical reaction parameter)

$$N_T = \frac{AL}{(T_1 - T_2)}$$ (non-dimensional temperature gradient)

$$N_c = \frac{BL}{(C_1 - C_2)}$$ (non-dimensional concentration gradient)

The corresponding boundary conditions are

$$u = 0 \;\;,\;\; \theta = 1 \;,\; C = 1 \quad on \;\; y = -1$$
$$u = 0 \;\;,\;\; \theta = 0 \;,\; C = 0 \quad on \;\; y = +1 \qquad (2.16)$$

III. SOLUTION OF THE PROBLEM

The governing equations of flow,heat and mass transfer are coupled non-linear differential equations. Assuming the porosity δ to be small we write

$$u = u_0 + \delta u_1 + \delta^2 u_2 + \ldots\ldots\ldots\ldots$$
.
$$\theta = \theta_0 + \delta \theta_1 + \delta^2 \theta_2 + \ldots\ldots\ldots$$
.
$$C = C_0 + \delta\, C_1 + \delta^2\, C_2 + \ldots\ldots\ldots \qquad (3.1)$$

Substituting the above expansions in the equations (2.13)-(2.15) and equating like powers of δ ,we obtain equations to the zero order as

$$\frac{d^2 u_0}{dy^2} = \pi \qquad (3.2)$$

$$\frac{d^2 \theta_0}{dy^2} - \alpha \theta_0 = (PN_T) u_0 \qquad (3.3)$$

$$\frac{d^2 C_0}{dy^2} - \gamma\, C_0 = (ScN_C) u_0 \qquad (3.4)$$

The equations to the first order are

$$\frac{d^2u_1}{dy^2} - (D^{-1})u_1 = -G(\theta_0 + NC_0) \tag{3.5}$$

$$\frac{d^2\theta_1}{dy^2} - \alpha\theta_1 = (PN_T)u_1 \tag{3.6}$$

$$\frac{d^2C_1}{dy^2} - \gamma C_1 = (ScN_C)u_1 \tag{3.7}$$

The equations to the second order are

$$\frac{d^2u_2}{dy^2} - (D^{-1})u_2 = -G(\theta_1 + NC_1) - \Delta u_0^2 \tag{3.8}$$

$$\frac{d^2\theta_2}{dy^2} - \alpha\theta_2 = (PN_T)u_2 \tag{3.9}$$

$$\frac{d^2C_2}{dy^2} - \gamma C_2 = (ScN_C)u_2 \tag{3.10}$$

The corresponding conditions are

$$u_0(1) = u_0(-1) = 0\ ,\ \theta_0(+1) = 0,\ \ \theta_0(-1) = 1, C_0(+1) = 0,\ \ C_0(-1) = 1 \tag{3.11}$$

$$u_1(1) = u_1(-1) = 0\ ,\ \theta_1(+1) = 0,\ \ \theta_1(-1) = 0, C_1(+1) = 0,\ \ C_1(-1) = 0 \tag{3.12}$$

$$u_2(1) = u_2(-1) = 0\ ,\ \theta_2(+1) = 0,\ \ \theta_2(-1) = 0, C_2(+1) = 0,\ \ C_2(-1) = 0 \tag{3.13}$$

Solving the equations (3.2)-(3.10) subject to the boundary conditions (3.11)-(3.13) we get

$$u_0(y) = \frac{\pi}{2}(y^2 - 1)$$

$$\theta_0 = a_2\left(1 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) - a_1(1 - y^2) + 0.5\left(\frac{Ch(\beta_1 y)}{Ch(\beta_1)} - \frac{Sh(\beta_1 y)}{Sh(\beta_1)}\right)$$

$$C_0 = a_7\left(1 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) + a_5(Ch(\beta_2 y) - Ch(\beta_2)) +$$
$$+ 0.5\left(\frac{Ch(\beta_1 y)}{Ch(\beta_1)} - \frac{Sh(\beta_1 y)}{Sh(\beta_1)} + a_6(Sh(\beta_2 y) - Sh(\beta_2)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}\right)$$

$$u_1 = a_{17}(\frac{Ch(M_1 y)}{Ch(M_1)}Ch(\beta_2) - Ch(\beta_2 y)) - a_{19}(\frac{Ch(M_1 y)}{Ch(M_1)}Ch(\beta_1) - Ch(\beta_1 y)) +$$
$$+ a_{21}(\frac{Ch(M_1 y)}{Ch(M_1)} - y^2). - a_{18}(Sh(\beta_2 y) - \frac{Sh(M_1 y)}{Sh(M_1)}Sh(\beta_2)) - a_{20}(Sh(\beta_1 y) -$$
$$- \frac{Sh(M_1 y)}{Sh(M_1)}Sh(\beta_1))$$

$$\theta_1 = a_{41}(Ch(M_1 y) - Ch(M_1)\frac{Ch(\beta_2 y)}{Ch(\beta_2)}) + a_{42}(Sh(M_1 y) - Sh(M_1)\frac{Sh(\beta_2 y)}{Sh(\beta_2)}) +$$
$$+ a_{43}(yCh(\beta_2 y) - Ch(\beta_2)\frac{Sh(\beta_2 y)}{Sh(\beta_2)}) + a_{44}(ySh(\beta_2 y) - Sh(\beta_2)\frac{Ch(\beta_2 y)}{Ch(\beta_2)}) +$$
$$+ a_{45}(Ch(\beta_1 y) - Ch(\beta_1)\frac{Ch(\beta_2 y)}{Ch(\beta_2)})) + a_{46}(Sh(\beta_1 y) - Sh(\beta_1)\frac{Sh(\beta_2 y)}{Sh(\beta_2)}) +$$
$$+ a_{47}(y^2 - \frac{Ch(\beta_2 y)}{Ch(\beta_2)}) + a_{48}(1 - \frac{Ch(\beta_2 y)}{Ch(\beta_2)})$$

$$C_1 = a_{25}(Ch(M_1 y) - Ch(M_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}) + a_{26}(Sh(M_1 y) - Sh(M_1)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}) -$$
$$- a_{27}(Ch(\beta_2 y) - Ch(\beta_2)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}) - a_{28}(Sh(\beta_2 y) - Sh(\beta_2)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}) +$$
$$+ (ySh(\beta_1 y) - Sh(\beta_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)})) - a_{30}((yCh(\beta_1 y) - Ch(\beta_1)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}) +$$
$$+ a_{31}(y^2 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)}) + a_{32}(1 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)})$$

$$u_2 = -a_{62}(\frac{Ch(M_1 y)}{Ch(M_1)}Ch(\beta_1) - Ch(\beta_1 y)) - a_{63}(\frac{Sh(M_1 y)}{Sh(M_1)}Sh(\beta_1) - Sh(\beta_1 y)) +$$
$$- a_{64}(\frac{Ch(M_1 y)}{Ch(M_1)}Sh(\beta_2) - Ch(\beta_2 y)) + a_{72}(\frac{Ch(M_1 y)}{Ch(M_1)} - y^4) - a_{73}(\frac{Ch(M_1 y)}{Ch(M_1)} - y^2)$$
$$- a_{70}(\frac{Ch(M_1 y)}{Ch(M_1)} - 1) - a_{65}(\frac{Sh(M_1 y)}{Sh(M_1)}Sh(\beta_2) - Sh(\beta_2 y)) + a_{66}(\frac{Ch(M_1 y)}{Ch(M_1)}Sh(M_1)$$
$$- ySh(M_1 y)) + a_{67}(\frac{Sh(M_1 y)}{Sh(M_1)}Ch(M_1) - yCh(M_1 y)) + a_{68}(\frac{Sh(M_1 y)}{Sh(M_1)}Ch(\beta_2) - yCh(\beta_2 y)) -$$
$$+ a_{69}(\frac{Ch(M_1 y)}{Ch(M_1)}Sh(\beta_2) - ySh(\beta_2 y))$$

$$C_2 = a_{77}(Ch(M_1y) - Ch(M_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}) + a_{78}(Sh(M_1y) - Sh(M_{12})\frac{Sh(\beta_1 y)}{Sh(\beta_1)}) +$$
$$+ a_{79}(yCh(\beta_1 y) - Ch(\beta_1)\frac{Sh(\beta_2 y)}{Sh(\beta_2)}) + a_{80}(y^2 - 1)Ch(\beta_1 y) +$$
$$+ a_{79}(y^4 - 1) + a_{81}(y^2 - 1) + a_{80}(ySh(\beta_1 y) -$$
$$- \frac{Ch(\beta_1 y)}{Ch(\beta_1)}Sh(\beta_1)) + a_{81}(Ch(\beta_2 y) - \frac{Ch(\beta_1 y)}{Ch(\beta_1)}Ch(\beta_2)) +$$
$$+ a_{82}(Sh(\beta_2 y) - \frac{Sh(\beta_1 y)}{Sh(\beta_1)}Sh(\beta_2)) - a_{83}(yCh(M_1y) - Ch(M_1)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}) -$$
$$- a_{84}(ySh(M_1y) - Sh(M_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}) - a_{85}(yCh(\beta_2 y) - Ch(\beta_2)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}) -$$
$$- a_{86}(ySh(\beta_2 y) - Sh(\beta_2)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}) - a_{87}(y^2 - 1)Ch(\beta_1 y) - a_{88}(y^2 - 1)Sh(\beta_1 y) -$$
$$- a_{89}(y^4 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)}) + a_{90}(y^2 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)}) + a_{91}(1 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)})$$

$$\theta_2 = b_{18}(Ch(\beta_1 y) - Ch(\beta_1)\frac{Ch(\beta_2 y)}{Ch(\beta_2)}) + b_{18}(Sh(\beta_1 y) - Sh(\beta_1)\frac{Sh(\beta_2 y)}{Sh(\beta_2)}) +$$
$$+ b_{20}(ySh(\beta_2 y) - Sh(\beta_2)\frac{Ch(\beta_2 y)}{Ch(\beta_2)}) + b_{21}(yCh(\beta_2 y) - Ch(\beta_2)\frac{Sh(\beta_2 y)}{Sh(\beta_2)})$$
$$+ b_{22}(Ch(M_1y) - Ch(M_1)\frac{Ch(\beta_2 y)}{Ch(\beta_2)}) + b_{23}(Sh(M_1y) - Sh(M_1)\frac{Sh(\beta_2 y)}{Sh(\beta_2)}) +$$
$$+ b_{24}(yCh(M_1y) - Ch(M_1)\frac{Sh(\beta_2 y)}{Sh(\beta_2)}) + b_{25}(ySh(M_1y) - Sh(M_1)\frac{Ch(\beta_2 y)}{Ch(\beta_2)}) +$$
$$+ b_{26}(yCh(\beta_1 y) - \frac{Sh(\beta_2 y)}{Sh(\beta_2)}Ch(\beta_1)) + b_{27}(ySh(\beta_1 y) - \frac{Ch(\beta_2 y)}{Ch(\beta_2)}Sh(\beta_1)) +$$
$$+ b_{28}(y^2 Ch(\beta_1 y) - \frac{Ch(\beta_2 y)}{Ch(\beta_2)}Ch(\beta_1)) + b_{29}(y^2 Sh(\beta_1 y) - \frac{Sh(\beta_2 y)}{Sh(\beta_2)}Ch(\beta_1) +$$
$$+ b_{30}(y^2 - 1)Sh(\beta_2 y) + b_{31}(y^2 - 1)Ch(\beta_2 y) + b_{32}(y^4 - \frac{Ch(\beta_2 y)}{Ch(\beta_2)}) +$$
$$+ b_{33}(y^2 - \frac{Ch(\beta_2 y)}{Ch(\beta_2)}) + b_{34}(1 - \frac{Ch(\beta_2 y)}{Ch(\beta_2)})$$

Where $a_1.a_2,a_3,\ldots\ldots\ldots\ldots\ldots a_{91}$ are constants .

IV. SHEAR STRESS,NUSSELT NUMBER AND SHERWOOD NUMBER

The shear stress on the boundaries $y = \pm 1$ is given by

$$\tau_{y=\pm L} = \mu(\frac{du}{dy})_{y=\pm L}$$

which in the non-dimensional form is

$$\tau_{\ y=\pm 1} = (\frac{du}{dy})_{y=\pm 1}$$

and the corresponding expressions are

$$\tau_{y=+1} = \pi + \delta\, b_{35} + \delta^2 b_{37}$$

$$\tau_{y=-1} = \pi + \delta\, b_{36} + \delta^2 b_{38}$$

The rate of heat transfer (Nusselt Number) is given by

$$Nu_{y=\pm i} = (\frac{d\theta}{dy})_{y=\pm 1}$$

and corresponding expressions are

$$Nu_{y=+1} = b_{38} + \delta\, b_{40} + \delta^2 b_{42}$$

$$Nu_{y=-1} = b_{39} + \delta\, b_{41} + \delta^2 b_{43}$$

The rate of mass transfer (Sherwood Number) is given by

$$Sh_{y=\pm 1} = (\frac{dC}{dy})_{y=\pm 1}$$

and corresponding expressions are

$$Sh_{y=+1} = b_{44} + \delta\, b_{46} + \delta^2 b_{48}$$

$$Sh_{y=-1} = b_{45} + \delta\, b_{47} + \delta^2 b_{49}$$

Where $b_1, b_2, \ldots\ldots\ldots, b_{49}$ are constants given in the Appendix.

V. DISCUSSION OF RESULTS

The velocity, the temperature and the concentration in the fluid region are analyzed for different sets of the governing parameter namely viz,. Grashoff number G, Darcy parameter D^{-1}, heat generating source parameter α, buoyancy ratio N, Schmidt number Sc , chemical reaction parameter γ, Soret parameter S_0 on Non-Darcy mixed convective heat and mass transfer flow of viscous fluid through a porous medium in a vertical channel whose walls are maintained at constant temperatures and concentrations. The equations governing the flow, heat and Mass transfer are solved by employing a perturbation technique with porous parameter δ as a perturbation parameter.

The axial velocity u is shown in figs. 1-9 for different values of D^{-1},α, Sc, S_0, k, N, P, N_T and N_C. The actual axial flow is in vertically upward direction so that u > 0 represents the actual flow and u < 0 represents the reversal flow. Fig.1 represents the variation of u with Grashof number G. It is found that the axial velocity experiences an enhancement with increase in |G| with maximum attain at y = 0.The variation of u with D^{-1} and α shows that lesser the permeability of the porous medium smaller u in the flow region. Also it enhances with increase in the strength of the heat generating source (fig-2). Fig-3 represents the variation of u with chemical reaction parameter k. It is observed that for smaller values of k ≤ 1.5; u is positive and higher k ≥ 2.5 it is negative in the flow region except in a narrow regions adjacent to the boundaries y = ±1.The variation of u with buoyancy ratio N shows that when the molecular buoyancy force dominates over the thermal buoyancy force the axial flow enhances in the entire flow region irrespective of the directions of buoyancy forces (fig-4). The variation of u with Schmidt Number Sc shows that lesser the molecular diffusivity smaller in the flow region(fig.5). The effect of thermo- diffusion on u is shown in fig-6. It is found that u depreciates with increase in $S_0 > 0$ and enhances with $|S_0|$. From fig-7 we notice that the axial velocity u experiences an enhancement with increase in thermal diffusivity. An increase in the temperature gradient N_T leads to an enhancement in u (fig-8).Also an increase in the concentration gradient N_C enhances u in the left half and reduces in the right half (fig-9).

Figs. 10-17 represent the variation of the Non-dimensional temperature θ with different parametric values.Fig.10 represents the variation of θ with G. It is found that the actual temperature enhances with increase in |G|.The variation of θ with D^{-1} and α shows that lesser the permeability of the porous medium/higher the strength of the heat sources smaller the actual temperature in the entire flow region (fig.11). The variation of θ with chemical reaction parameter k is shown in fig-12. It is found that an increase in k results in a depreciation in actual temperature. The variation of θ with buoyancy ratio N shows that the actual temperature enhances with |N| irrespective of the directions of the buoyancy forces (fig-13). From fig.14 we notice a marginal increment in the actual temperature with increase in Sc. The effect of thermo-diffusion on θ is shown in fig.15. It is found that the actual temperature reduces with increase in $S_0 > 0$ and enhances with $|S_0|$. Also an increase in the Prandtl number P results in an enhancement in actual temperature (fig.16). An increase in N_T enhances the actual temperature. The variation in θ is remarkably large for higher values of N_T (fig-17).

The Non-dimensional concentration C is shown in figs. 18-24 for different parametric values. We follow the convention that the non-dimensional concentration is positive or negative according as the actual concentration is greater or lesser than C_2. Fig.18 represents the variation of C with Grashof Number G. It is found that the actual concentration depreciates in the left half and enhances in the right half with increase in |G| with maximum attained at y = 0.6.The variation of C with D^{-1} and α shows that lesser the molecular diffusivity larger the actual temperature in the left half and smaller in the right half and for further lowering of the permeability it depreciates in the left half and enhances in the right half, while an increase in the heat source α reduces the actual concentration in the left half and enhances in the right half. The variation of C with chemical reaction parameter k shows that an increase in k ≤ 1.5 the actual concentration enhances in the left half and reduces in the right half and for higher k ≥ 2.5 it enhances in the entire flow region and for still higher k = 3.5 it depreciates in the flow region (fig-20).The variation of C with buoyancy ratio N shows that when the molecular buoyancy force dominates over the thermal buoyancy force, the actual concentration reduces in the left half and enhances in the right half irrespective of the directions of the buoyancy forces (fig.21). From fig.22 we notice that lesser the molecular diffusivity smaller the actual concentration in the left half and larger in the right half. An increase in $S_0 > 0$ reduces the actual concentration in the left half and enhances in the right half, while it enhances in the left half and reduces in the right half with increase in $|S_0|$ (fig.23). From fig.24 we find that the actual temperature reduces in left half and enhances in the right half with increase in radiation gradient N_T.

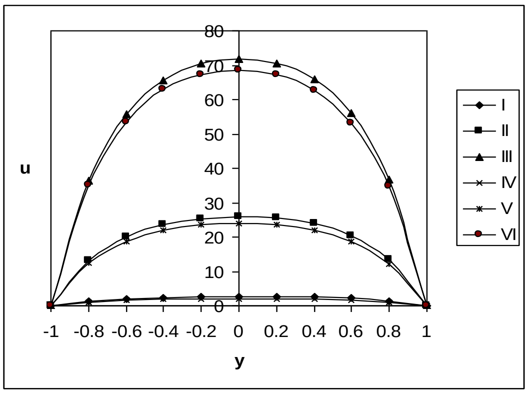


Fig. 1 : Variation of u with G

	I	II	III	IV	V	VI
G	10^2	$3x10^3$	$5x10^3$	$-1x10^3$	$-3x10^3$	$-5x10^3$

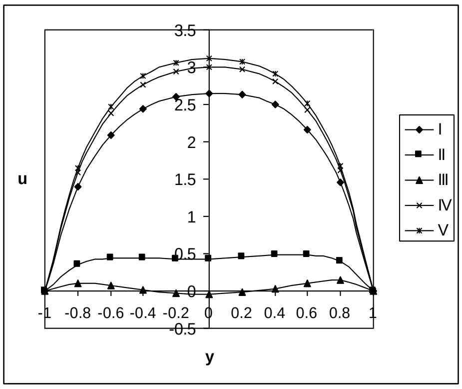


Fig. 2 : Variation of u with D^{-1}, α

	I	II	III	IV	V
D^{-1}	10^2	$3x10^2$	$5x10^2$	10^2	10^2
α	2	2	2	4	6

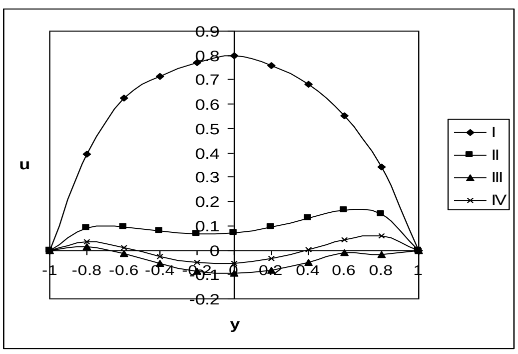


Fig. 3 : Variation of u with k

	I	II	III	IV
k	0.5	1.5	2.5	3.5

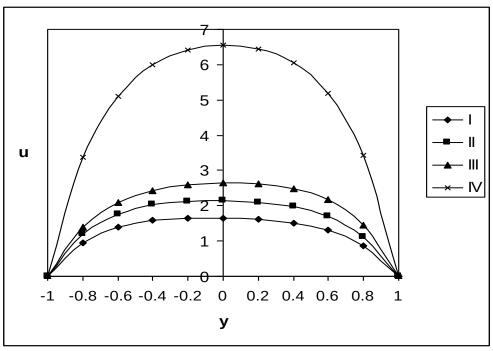


Fig. 4 : Variation of u with N

	I	II	III	IV
N	-0.5	-0.8	1	2

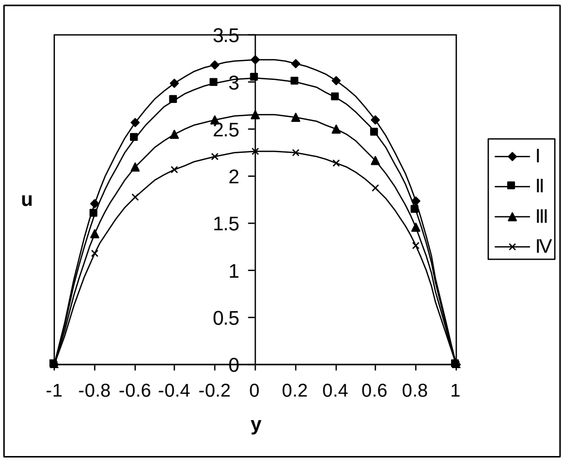


Fig. 5 : Variation of u with Sc

	I	II	III	IV
Sc	0.24	0.6	1.30	2.01

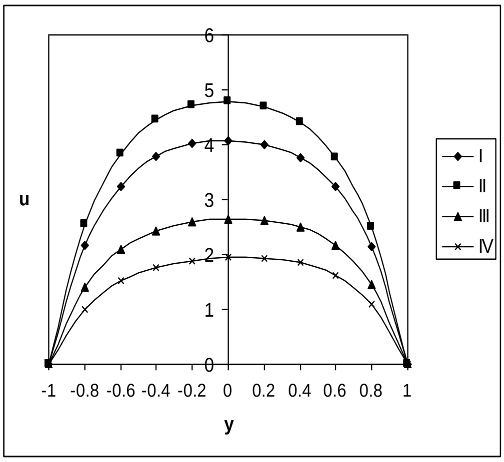


Fig. 6 : Variation of u with S_0

	I	II	III	IV
S_0	-0.5	-1	0.5	1

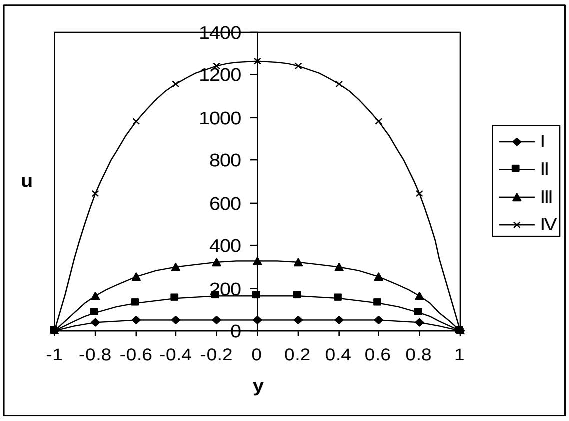


Fig. 7 : Variation of u with P

	I	II	III	IV
P	0.71	7	10	20

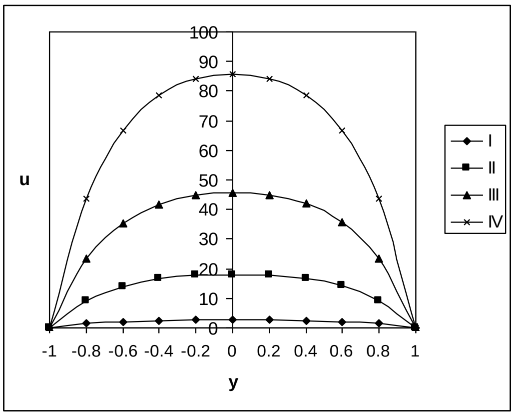


Fig. 8 : Variation of u with N_T

	I	II	III	IV
N_T	0.5	1.5	2.5	3.5

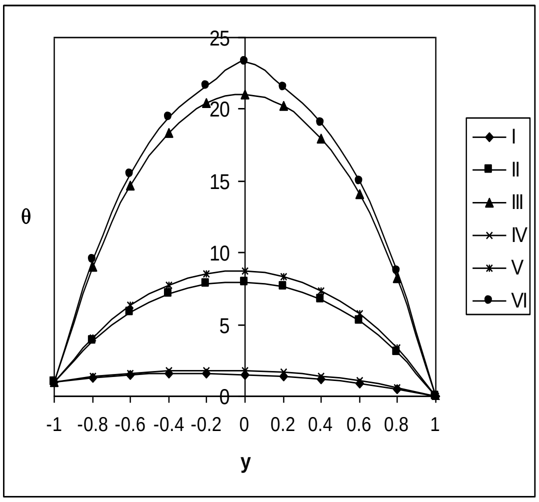


Fig 9 : Variation of u with N_C

	I	II	III
N_C	0.5	1.5	2.5

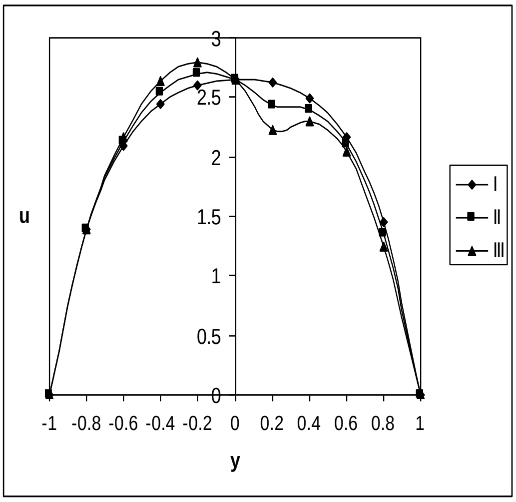


Fig. 10 : Variation of θ with G

	I	II	III	IV	V	VI
G	10^2	$3x10^3$	$5x10^3$	$-1x10^3$	$-3x10^3$	$-5x10^3$

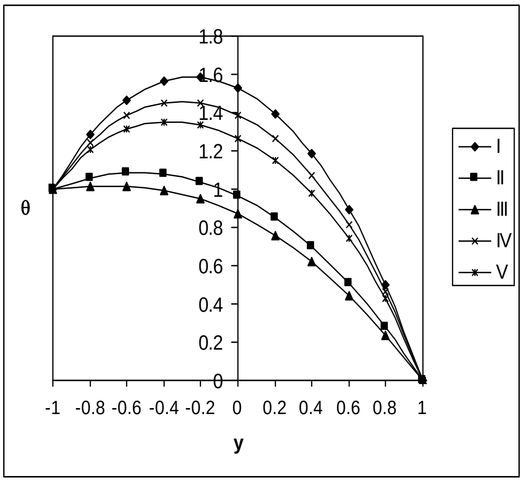


Fig 11 : Variation of θ with D^{-1}, α

	I	II	III	IV	V
D^{-1}	10^2	$3x10^2$	$5x10^2$	10^2	10^2
α	2	2	2	4	6

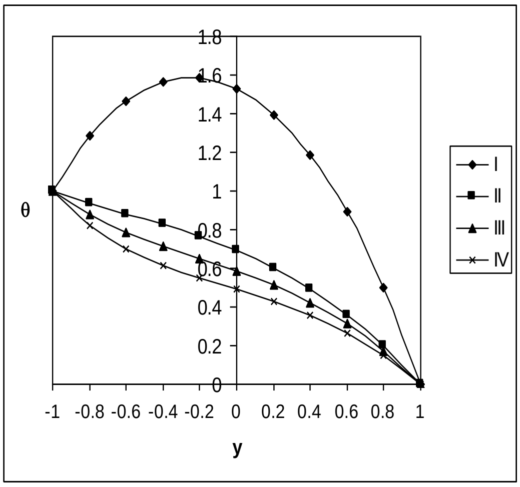


Fig. 12 : Variation of θ with k

	I	II	III	IV
k	0.5	1.5	2.5	3.5

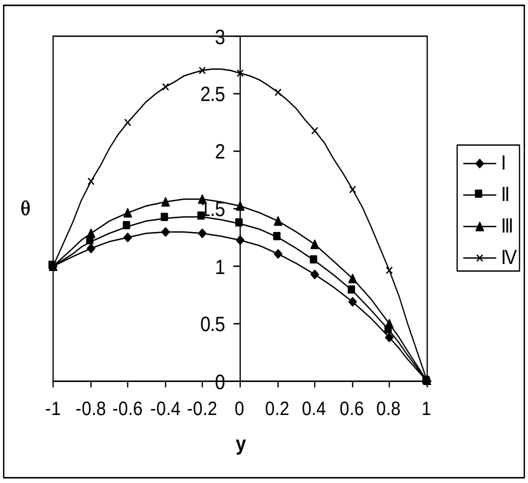


Fig 13 : Variation of θ with N

	I	II	III	IV
N	-0.5	-0.8	1	2

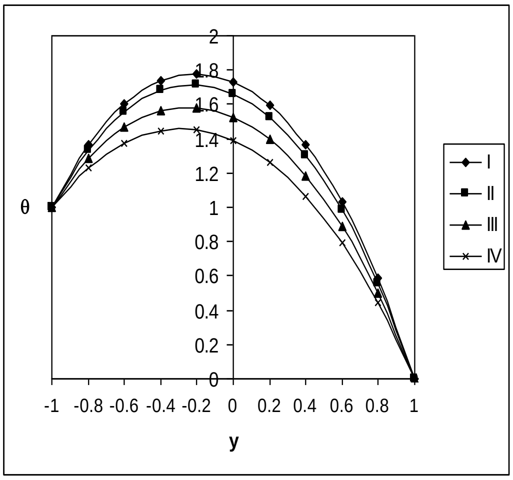


Fig. 14 : Variation of θ with Sc

	I	II	III	IV
Sc	0.24	0.6	1.30	2.01

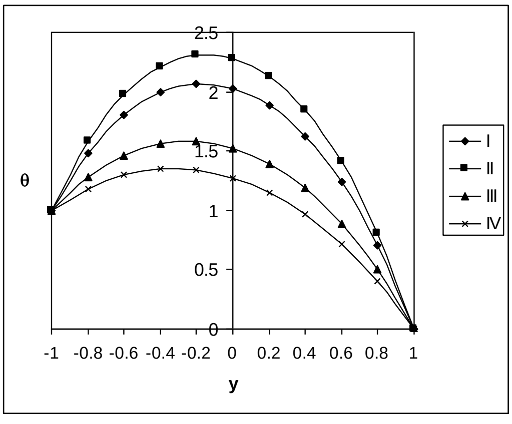


Fig. 15 : Variation of θ with S_0

	I	II	III	IV
S_0	-0.5	-1	0.5	1

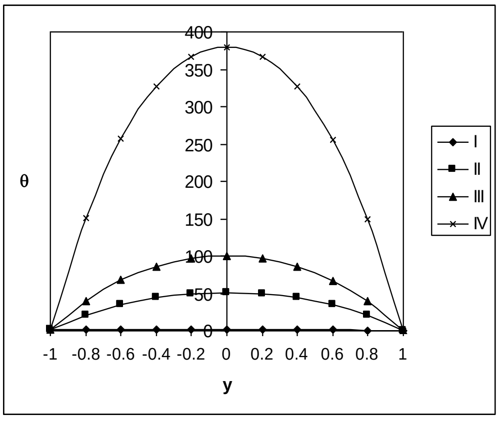


Fig. 16 : Variation of θ with P

	I	II	III	IV
P	0.71	7	10	20

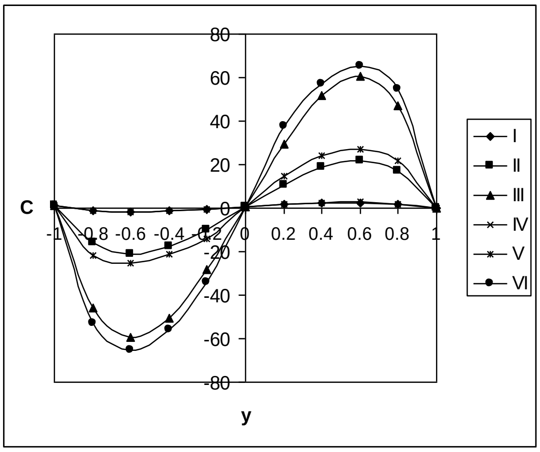


Fig. 17 : Variation of θ with N_T

	I	II	III	IV
N_T	0.5	1.5	2.5	3.5

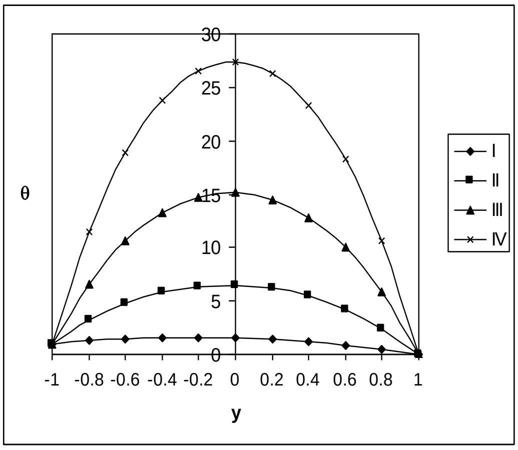


Fig. 18 : Variation of C with G

	I	II	III	IV	V	VI
G	10^2	$3x10^3$	$5x10^3$	$-1x10^3$	$-3x10^3$	$-5x10^3$

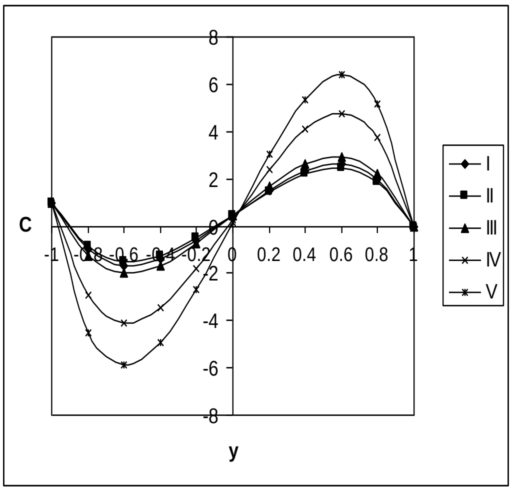


Fig 19 : Variation of C with D^{-1}, α

	I	II	III	IV	V
D^{-1}	10^2	$3x10^2$	$5x10^2$	10^2	10^2
α	2	2	2	4	6

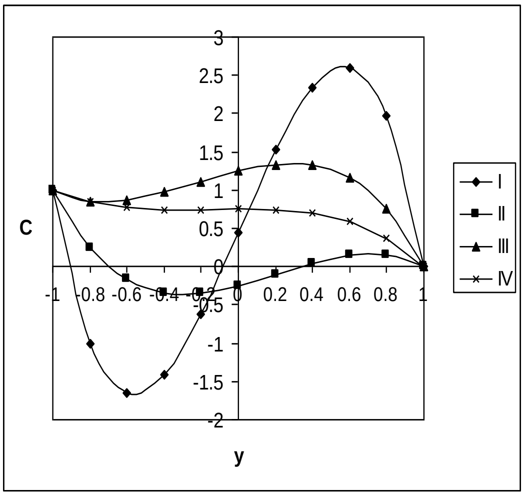


Fig. 20 : Variation of C with k

	I	II	III	IV
k	0.5	1.5	2.5	3.5

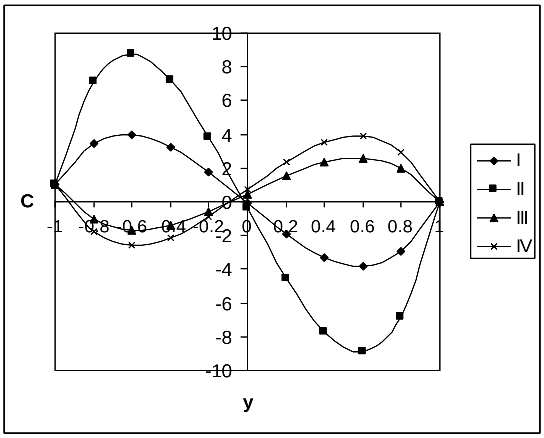


Fig. 23 : Variation of C with S_0

	I	II	III	IV
S_0	-0.5	-1	0.5	1

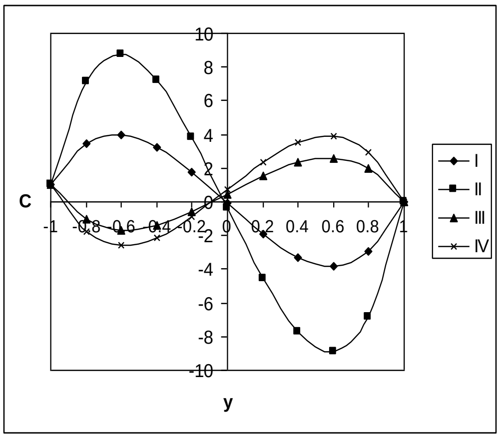


Fig. 24 : Variation of C with N_T

	I	II	III	IV
N_T	0.5	1.5	2.5	3.5

The Shear stress (τ) at the boundaries y = ±1 are shown in tables 1-6 for different values of G, D^{-1}, α, k, N, Sc and S_0. It is found that the shear stress enhances with increase in |G| and α and depreciates with D^{-1}.Thus lesser the permeability of the porous medium smaller the stress at both the walls(tables 1 and 4).The variation of τ with chemical reaction parameter k shows that an increase in k reduces $|\tau|$ at y = +1 while at y = -1, $|\tau|$ reduces with k ≤ 2.5 and enhances with k ≥ 3.5. Also $|\tau|$ experiences an enhancement with increase in the buoyancy ratio |N| irrespective of the directions of the buoyancy forces (tables.1-2).The variation of τ with Sc and S_0 shows that lesser the molecular diffusivity lesser $|\tau|$ at y = ±1. Also it depreciates with $S_0 \geq 0$ and enhances with $|S_0|$ at both the walls (tables 3 & 6).

The Nusselt number which measures the rate of heat transfer at y = ±1 is shown in tables 7-13 for different parametric values. It is found that the rate of heat transfer enhances with increase in |G| and reduces with D^{-1} and α at both the walls (tables 7-10).From tables 8 & 11 we notice that the rate of heat transfer depreciates with k at y = +1 and at y = -1 it depreciates with k ≤ 1.5 and enhances with higher k≥2.5.The rate of heat transfer experiences wioth N irrespective of the directions of the buoyancy forces at both the walls.Also lesser the molecular diffusivity |Nu| at y = ±1 .Also |Nu| depreciates with $S_0 > 0$ and enhances with $|S_0|$ and enhances with $|S_0|$ at y = ±1 (tables 9 & 12).

The Sherwood number (Sh) which measures the rate of mass transfer with different parametric values is shown in tables.11-13. It is found that the rate of mass transfer enhances with increase in |G| or α at y = ±1.The variation of Sh with D^{-1} shows that lesser the permeability of porous medium smaller |Sh| and for further lowering of permeability larger |Sh| at y = ±1 (tables 13 & 16). An increase in the chemical reaction parameter k enhances Sh for all G at y = +1 while at y = -1 it depreciates with k ≤ 2.5 and enhances with higher k ≥ 3.5. The rate of mass transfer enhances with increase in the buoyancy ratio N and depreciates |Sh| at y = ±1 (tables 14 & 17). From Tables 15 & 18 we find that the rate of mass transfer enhances at y = ±1 with increase in Sc .Also |Sh| experiences an enhancement with increase in $|S_0|$ at both the walls.

Table 1 Shear stress (τ) at y = +1

G	I	II	III	IV	V
$1x10^2$	-11.9675	-5.3676	-3.6409	-13.1087	-13.4908
$2x10^2$	-42.3888	-16.6361	-10.0391	-47.2207	-48.8349
$-1x10^2$	-9.4867	-3.5332	-2.1163	-10.8947	-11.3624
$-2x10^2$	-37.4266	-12.9673	-6.9897	-42.7929	-44.5780
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2
α	2	2	2	4	6

Table 2 Shear stress (τ) at y = +1

G	I	II	III	IV	V	VI	VII
$1x10^2$	-11.9675	-3.3260	-2.2311	-2.5822	-7.8976	-9.6658	-25.4098
$2x10^2$	-42.3888	-8.8368	-6.4438	-7.1703	-27.6014	-34.5946	-95.8637
$-1x10^2$	-9.4867	-1.8589	-2.7505	-2.4236	-6.9087	-8.5972	-22.6343
$-2x10^2$	-37.4266	-5.9026	-7.4827	-6.8531	-25.6237	-32.4574	-90.3126
k	0.5	1.5	2.5	3.5	0.5	0.5	0.5
N	1	1	1	1	-0.5	-0.8	2

Table 3 Shear stress (τ) at y = +1

G	I	II	III	IV	V	VI	VII
$1x10^2$	-13.8893	-13.2366	-11.9675	-10.6802	-16.6815	-19.038	-9.6104
$2x10^2$	-50.3902	-47.6727	-42.3888	-37.0293	-62.0150	-71.8281	-32.5756
$-1x10^2$	-11.7222	-10.9629	-9.4864	-7.9888	-14.9705	-17.7126	-6.7443
$-2x10^2$	-46.0560	-43.1253	-37.4266	-31.6465	-58.5931	-69.1764	-26.8434
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	-0.5	-1	1

Table 4 Shear stress (τ) at y = -1

G	I	II	III	IV	V
$1x10^2$	11.4873	4.9813	3.3074	12.8034	13.2408
$2x10^2$	41.4284	15.8635	9.3721	46.6102	48.3348
$-1x10^2$	9.9666	3.9196	2.4498	11.2000	11.6124
$-2x10^2$	38.3870	13.7400	7.6568	43.4034	45.0781
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2
α	2	2	2	4	6

Table 5 Shear stress (τ) at y = -1

G	I	II	III	IV	V	VI	VII
$1x10^2$	11.4873	2.8492	2.2293	2.4038	8.5543	10.1718	24.8720
$2x10^2$	41.4284	7.8832	6.4402	6.8134	28.9150	35.6066	94.7881
$-1x10^2$	9.9666	2.3357	2.7523	2.6021	6.2519	8.0912	23.1721
$-2x10^2$	38.3870	6.8563	7.4863	7.2100	24.3101	31.4454	91.3883
k	0.5	1.5	2.5	3.5	0.5	0.5	0.5
N	1	1	1	1	-0.5	-0.8	2

Table 6 Shear stress (τ) at y = -1

G	I	II	III	IV	V	VI	VII
$1x10^2$	13.6395	12.9085	11.4873	10.0457	16.7662	19.4057	8.8478
$2x10^2$	49.8905	47.0166	41.4284	35.7604	62.1845	72.5625	31.0503
$-1x10^2$	11.9721	11.2910	9.9666	8.6232	14.8858	17.3454	7.5070
$-2x10^2$	46.5558	43.7815	38.3870	32.9154	58.4236	68.4419	28.3687
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	-0.5	-1	1

Table 7 Nusselt number (Nu) at y = +1

G	I	II	III	IV	V
$1x10^2$	-2.82953	-1.50236	-1.27664	-2.68265	-2.50902
$2x10^2$	-8.38162	-2.81850	-1.82841	-7.57544	-6.77935
$-1x10^2$	-3.36044	-1.77884	-1.46590	-2.99489	-2.71971
$-2x10^2$	-9.44343	-3.37147	-2.20692	-8.19990	-7.20073
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2
α	2	2	2	4	6

Table 8 Nusselt number (Nu) at y = +1

G	I	II	III	IV	V	VI	VII
$1x10^2$	-2.82953	-1.08345	-0.97586	-0.84914	-2.13027	-2.45913	-5.52003
$2x10^2$	-8.38162	-8.8368	-1.90093	-1.76810	-5.65782	-7.00467	-19.06371
$-1x10^2$	-3.36044	-1.20986	-0.90899	-0.80898	-2.73443	-3.09471	-5.97103
$-2x10^2$	-9.44343	-2.22548	-1.76720	-1.68777	-6.86614	-8.27585	-19.96570
k	0.5	1.5	2.5	3.5	0.5	0.5	0.5
N	1	1	1	1	-0.5	-0.8	2

Table 9 Nusselt number (Nu) at y = +1

G	I	II	III	IV	V	VI	VII
$1x10^2$	-3.32008	-3.15348	-2.82953	-2.50096	-4.03275	-4.63436	-2.22792
$2x10^2$	-10.19160	-9.57689	-8.38162	-7.16928	-12.82119	-15.04098	-6.16183
$-1x10^2$	-3.69879	-3.58388	-3.36044	-3.13381	-4.19035	-4.60531	-2.94548
$-2x10^2$	-10.94902	-10.43769	-9.44343	-8.43497	-13.13639	-14.98287	-7.59695
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	-0.5	-1	1

Table 10 Nusselt number (Nu) at y = -1

G	I	II	III	IV	V
$1x10^2$	1.68912	0.35552	0.12650	1.53242	1.35543
$2x10^2$	7.26215	1.68619	0.68949	6.43633	5.63354
$-1x10^2$	2.17813	0.60295	0.29331	1.82240	1.55057
$-2x10^2$	8.24017	2.18105	1.02311	7.01628	6.02381
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2
α	2	2	2	4	6

Table 11 Nusselt number (Nu) at y = -1

G	I	II	III	IV	V	VI	VII
$1x10^2$	1.68912	-0.35204	-0.74386	-1.10321	0.94005	1.27573	4.38174
$2x10^2$	7.26215	0.55788	0.18241	-0.17489	4.43875	5.79924	17.94850
$-1x10^2$	2.17813	-0.26707	-0.81311	-1.16210	1.60192	1.95539	4.78659
$-2x10^2$	8.24017	0.72782	0.04390	-0.29267	5.76249	7.158556	18.75819
k	0.5	1.5	2.5	3.5	0.5	0.5	0.5
N	1	1	1	1	-0.5	-0.8	2

Table 12 Nusselt number (Nu) at y = -1

G	I	II	III	IV	V	VI	VII
$1x10^2$	2.16938	2.00627	1.68912	1.36743	2.86712	3.45612	1.10012
$2x10^2$	9.05157	8.44385	7.26215	6.06358	11.65129	13.84587	5.06750
$-1x10^2$	2.52676	2.40835	2.17813	1.94461	3.03326	3.46082	1.75056
$-2x10^2$	9.76632	9.24801	8.24017	7.21794	11.98356	13.85526	6.36848
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	-0.5	-1	1

Table 13 Nusselt number (Nu) at y = -1

G	I	II	III
$1x10^2$	12.94125	32.63869	60.78146
$2x10^2$	48.61034	123.73980	232.65050
$-1x10^2$	14.51225	35.29170	64.51646
$-2x10^2$	51.75235	129.04580	240.12060
P	0.71	0.71	0.71
N_T	1.5	2.5	3.5

Table 14 Sherwood number (Sh) at y = +1

G	I	II	III	IV	V
$1x10^2$	-13.66442	-12.75362	-15.45016	-27.62905	-39.48521
$2x10^2$	-54.21877	-50.44022	-61.23803	-65.1254	-79.0956
$-1x10^2$	-14.04267	-12.99654	-15.70471	-28.46951	-40.76753
$-2x10^2$	-54.97527	-50.92607	-61.74714	-66.1209	-80.1256
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2
α	2	2	2	4	6

Table 15 Sherwood number (Sh) at y = +1

G	I	II	III	IV	V	VI	VII
$1x10^2$	-13.66442	-4.35165	-2.33663	-1.13952	17.5951	13.58951	-15.95853
$2x10^2$	-54.21877	-8.01491	-7.80968	-5.14211	70.21468	55.59991	-63.84138
$-1x10^2$	-14.04267	-0.63777	-0.61882	-0.11269	18.59697	14.72046	-16.62602
$-2x10^2$	-54.97527	-6.58714	-5.37406	-5.24652	72.91384	57.86182	-65.17636
k	0.5	1.5	2.5	3.5	0.5	0.5	0.5
N	1	1	1	1	-0.5	-0.8	2

Table 16 Sherwood number (Sh) at y = +1

G	I	II	III	IV	V	VI	VII
$1x10^2$	-3.02025	-7.16231	-13.66442	-18.16560	20.81835	48.66371	-20.30183
$2x10^2$	-11.93973	-28.41439	-54.21877	-71.98674	83.10132	194.32800	-80.31210
$-1x10^2$	-3.44022	-7.57561	-14.04267	-18.47853	20.45685	48.46138	-20.53767
$-2x10^2$	-12.77967	-29.24098	-54.97527	-72.61261	82.37832	193.92340	-80.78378
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	-0.5	-1	1

Table 17 Sherwood number (Sh) at y = -1

G	I	II	III	IV	V
$1x10^2$	-14.29768	-13.33169	-16.02035	-29.12505	-41.75275
$2x10^2$	-54.91245	-51.02355	-61.80558	-65.1254	-79.0956
$-1x10^2$	-14.55506	-13.56410	-16.28017	-29.41346	-42.06879
$-2x10^2$	-55.42722	-51.48838	-62.32523	-66.1209	-80.1256
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2
α	2	2	2	4	6

Table 18 Sherwood number (Sh) at y = -1

G	I	II	III	IV	V	VI	VII
$1x10^2$	-14.29768	-3.90662	-1.41468	-0.25790	15.31475	12.13729	-17.09646
$2x10^2$	-54.91245	-10.91014	-7.59213	-5.47224	68.97286	54.80628	-65.20266
$-1x10^2$	-14.55506	-2.51222	-0.28805	-0.64468	15.28269	11.95107	-17.31727
$-2x10^2$	-55.42722	-8.12134	-5.33888	-6.24581	68.90874	54.43384	-65.64427
k	0.5	1.5	2.5	3.5	0.5	0.5	0.5
N	1	1	1	1	-0.5	-0.8	2

Table 19 Sherwood number (Sh) at y = -1

G	I	II	III	IV	V	VI	VII
$1x10^2$	-4.34972	-8.2555	-14.29768	-18.33151	18.48060	45.47777	-20.07877
$2x10^2$	-13.46850	-29.65995	-54.91245	-72.11906	80.36572	190.57960	-79.97672
$-1x10^2$	-4.37109	-8.36415	-14.55506	-18.71162	18.91478	46.40040	-20.53927
$-2x10^2$	-13.51124	-29.87718	-55.42722	-72.87928	81.23409	192.42490	-80.89772
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	-0.5	-1	1

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