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FINITE ELEMENT ANALYSIS OF CHEMICAL REACTION EFFECT ON NON-DARCY CONVECTIVE HEAT AND MASS TRANSFER FLOW THROUGH A POROUS MEDIUM IN VERTICAL CHANNEL WITH CONSTANT HEAT SOURCES

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ABSTRACT

We analyse the effect of chemical reaction on non-Darcy convective Heat and Mass transfer flow of a viscous electrically conducting fluid through a porous medium in a vertical channel with constant heat sources. The governing equations flow, heat and mass transfer are solved by using Galerkin finite element technique with quadratic polynomial approximations. The approximation solution is written directly as a linear combination of approximation functions with unknown nodal values as coefficients. Secondly, the approximation polynomials are chosen exclusively from the lower order piecewise polynomials restricted to contiguous elements. The velocity, temperature, concentration, shear stress and rate of Heat and Mass transfer are evaluated numerically for different values of G,M,D^{-1},N,Sc,γ and α.

Keywords: *Chemical Reaction, Heat and Mass Transfer, Porous Medium, Finite Element Analysis.*

1. 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 [1985] among others. Extensive effects are thus being made to include the inertia and viscous diffusion terms in the flow equations and to examine their effects in order to develop a reasonable accurate mathematical model for convective transport in porous media. The work of Vafai and Tien [1987] 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 [1983] presented analytical solutions for the velocity and temperature fields for the interface region using the Brinkman Forchheimer – extended Darcy equation. Detailed accounts of the recent efforts on non-Darcy convection have been recently reported in Tien and Hong [1978], Cheng [1985], and Kladias and Prasad [2002]. Here, we will restrict our discussion to the vertical cavity only. Poulikakos and Bejan [2000, 1990] investigated the inertia effects through the inclusion of Forchheimer's velocity squared term, and presented the boundary layer analysis for tall cavities. They also obtained numerical results for a few cases in order to verify the accuracy of their boundary layer analysis for tall cavities. They also obtained numerical results for a few cases in order to verify the accuracy of their boundary layer solutions. This result in reversal of flow regimes from boundary layer to asymptotic to conduction as the contribution of the inertia term increases in comparison with that of the boundary term. They also reported a criterion for the Darcy flow limit. Anwar Bég et.al [2011] have considered Viscoelastic flow and species transfer in a Dacian high-permeable channel. Makinde et al [2005] have discussed Heat transfer to MHD oscillatory flow in a channel filled with porous medium.

The Brinkman – Extended – Darcy modal was considered in Tong and Subramanian [1987], and Lauriat and Prasad [1988] to examine the boundary effects on free convection in a vertical cavity. While Tong and Subramanian performed a Weber – type boundary layer analysis, Lauriat and Prasad solved the problem numerically for A=1 and5. It was shown that for a fixed modified Rayleigh number, Ra, the Nusselt number; decrease with an increase in the Darcy number; the reduction being larger at higher values of Ra. A scale analysis as well as the computational data also showed that the transport term $(v.\nabla)v$, is of low order of magnitude compared to the diffusion plus buoyancy terms [1988]. A numerical study based on the Forchheimer-Brinkman-Extended Darcy equation of motion has also been reported recently by Beckerman et al [2006]. They demonstrated that the inclusion of both the inertia and boundary effects is important for convection in a rectangular packed – sphere cavity.

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Also in all the above studies the thermal diffusion effect (known as Soret effect) has been neglected. This assumption is true when the concentration level is very low. Therefore, so ever, exceptions. The thermal diffusion effects for instance, has been utilized for isotropic separation and in mixtures between gases with very light molecular weight (H_2.He)and the medium molecular weight (N_2, air)the diffusion – thermo effects was found to be of a magnitude just it can not be neglected [Hakiem2000]. In view of the importance of this diffusion – thermo effect, recently Jha and singh [2006] 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 [2005] studied the MHD free convection and mass transfer flow taking into account Soret effect. The analytical studies of Jha and singh and Kafousias [2006, 2005] were based on Laplace transform technique. Abdul Sattar and Alam [1999] have considered an unsteady convection 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. Malsetty et al [1985] have studied the effect of both the soret coefficient and Dufour coefficient on the double diffusive convective with compensating horizontal thermal and solutal gradients. Ruksana Begum et al. [2010] have considered a non-darcy convective heat transfer in a vertical channel with constant heat flux. Balasubrahmanyam et.al.[2010] have discussed non-darcy viscous electrically conducting heat and mass transfer flow in a vertical channel in the presence of heat sources.

In this paper we investigate effect of chemical reaction on non-Darcy convective het and Mass transfer flow of a viscous electrically conducting fluid through a porous medium in a vertical channel in the presence of constant heat source. The governing equations flow, heat and mass transfer are solved by using Galerkin finite element technique with quadratic polynomial approximations. The approximation solution is written directly as a linear combination of approximation functions with unknown nodal values as coefficients. Secondly, the approximation polynomials are chosen exclusively from the lower order piecewise polynomials restricted to contiguous elements. The velocity, temperature, concentration, shear stress and rate of Heat and Mass transfer are evaluated numerically for different variations of parameter

2. FORMULATION OF THE PROBLEM

Consider a fully developed laminar mixed convective heat and mass transfer flow of a viscous, electrically conducting fluid through a porous medium 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. A The walls are taken at $y=\pm L$. 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 Boussinesq 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 are

$$-\frac{\partial p}{\partial x}+(\frac{\mu}{\delta})\frac{\partial^2 u}{\partial y^2}-(\frac{\mu}{k})u-(\sigma\mu_e^2 H_o^2)u-\frac{\rho\delta F}{\sqrt{k}}u^2+\beta g(T-T_0)+\beta^{\bullet} g(C-C_0)=0 \quad (2.1)$$

$$\rho_0 C_p u\frac{\partial T}{\partial x}=k_f\frac{\partial^2 T}{\partial y^2}+Q \quad (2.2)$$

$$u\frac{\partial C}{\partial x}=D_1\frac{\partial^2 C}{\partial y^2}-K'(C-C_0) \quad (2.3)$$

The boundary conditions are

$$\begin{aligned} u=0 \quad , \quad T=T_1 \quad C=C_1 \qquad on \quad y=-L \\ u=0 \quad , \quad T=T_2 \quad C=C_2 \qquad on \quad y=+L \end{aligned} \quad (2.4)$$

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.

where u 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 ,k_f is the coefficient of thermal conductivity ,F is a function that depends on the Reynolds number and the microstructure of porous medium, J is the current density vector,

H is the magnetic field vector,σ is the electrical conductivity of the fluid,μ is the magnetic permeability of the medium, $\beta^{\bullet}$ is the volumetric coefficient of expansion with mass fraction concentration and D_1 is the chemical molecular diffusivity ,K is the chemical reaction coefficient and Q is the strength of the heat source. Here, the thermo physical 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.

We define the following non-dimensional variables as

$$u' = \frac{u}{(\nu / L)},\ (x', y') = (x, y)/L\ ,\quad p' = \frac{p\delta}{(\rho \nu^2 / L^2)}$$
$$\theta = \frac{T - T_2}{T_1 - T_2}\ ,\quad C' = \frac{C - C_2}{C_1 - C_2} \tag{2.5}$$

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

$$\frac{d^2u}{dy^2} = \pi + \delta(D^{-1} + M^2)u + \delta^2 \Delta u^2 - \delta G(\theta + NC) \tag{2.6}$$

$$\frac{d^2\theta}{dy^2} + \alpha = (PN_T)u \tag{2.7}$$

$$\frac{d^2C}{dy^2} - \gamma C = (Sc\, N_C)u \tag{2.8}$$

where

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

$G = \frac{\beta g(T_1 - T_2)L^3}{\nu^2}$ (Grashof Number) $D^{-1} = \frac{L^2}{k}$ (Darcy parameter)

$Sc = \frac{\nu}{D_1}$ (Schmidt number) $M^2 = \frac{\sigma \mu_e^2 H_o^2 L^2}{\nu^2}$ (Hartmann Number)

$N = \frac{\beta^{\bullet}(C_1 - C_2)}{\beta(T_1 - T_2)}$ (Buoyancy ratio) $P = \frac{\mu C_p}{\lambda}$ (Prandtl Number)

$\alpha = \frac{QL^2}{(T_1 - T_2)k_f}$ (Heat source parameter) $\gamma = \frac{K' L^2}{D_1}$ (Chemical reaction parameter)

$N_T = \frac{AL}{(T_1 - T_2)}$ (Temperature gradient) $N_C = \frac{BL}{(C_1 - C_2)}$ (Concentration gradient)

The corresponding boundary conditions are

$$u = 0\ ,\ \theta = 1\ ,\ C = 1\quad on\ y = -1$$
$$u = 0\ ,\ \theta = 0\ ,\ C = 0\quad on\ y = +1 \tag{2.9}$$

3. FINITE ELEMENT ANALYSIS

To solve these differential equations with the corresponding boundary conditions, we assume if u^i, θ^I , c^i are the approximations of u, θ and C we define the errors (residual) E_u^i, E_θ^i, E_c^i as

$$E_u^i = \frac{d}{d\eta}\left(\frac{du^i}{d\eta}\right) - \delta(D^{-1} + M^2)u^i + \delta^2 \Delta (u^i)^2 - \delta G(\theta^i + NC^i) \tag{3.1}$$

$$E_c^i = \frac{d}{dy}\left(\frac{dC^i}{dy}\right) - \gamma C^i - ScN_c u^i \tag{3.2}$$

$$E_\theta^i = \frac{d}{dy}\left(\frac{d\theta^i}{dy}\right) + \alpha - PN_T u^i \tag{3.3}$$

where

$$\left.\begin{aligned} u^i &= \sum_{k=1}^{3} u_k \psi_k \\ C^i &= \sum_{k=1}^{3} C_k \psi_k \\ \theta^i &= \sum_{k=1}^{3} \theta_k \psi_k \end{aligned}\right\} \tag{3.4}$$

These errors are orthogonal to the weight function over the domain of e^i under Galerkin finite element technique we choose the approximation functions as the weight function. Multiply both sides of the equations (3.1 – 3.3) by the weight function i.e. each of the approximation function ψ_j^i and integrate over the typical three nodded linear element (η_e, η_{e+1}) we obtain

$$\int_{\eta_e}^{\eta_{e+1}} E_u^i \psi_j^i dy = 0 \qquad (i = 1,2,3,4,) \tag{3.5}$$

$$\int_{\eta_e}^{\eta_{e+1}} E_c^i \psi_j^i dy = 0 \qquad (i = 1,2,3,4,) \tag{3.6}$$

$$\int_{\eta_e}^{\eta_{e+1}} E_\theta^i \psi_j^i dy = 0 \qquad (i = 1,2,3,4,) \tag{3.7}$$

where

$$\int_{\eta_e}^{\eta_{e+1}} \left(\frac{d}{d\eta}\left(\frac{du^i}{d\eta}\right) - \delta M_1^2 u^i + \delta^2 \Delta (u^i)^2 - \delta G(\theta^i + NC^i)\right) \psi_j^i dy = 0 \tag{3.8}$$

$$\int_{\eta_e}^{\eta_{e+1}} \left(\frac{d}{dy}\left(\frac{dC^i}{dy}\right) - \gamma C^i - ScN_c u^i\right) \psi_j^i dy = 0 \tag{3.9}$$

$$\int_{\eta_e}^{\eta_{e+1}} \left(\frac{d}{dy}\left(\frac{d\theta^i}{dy}\right) + \alpha - PN_T u^i\right) \psi_j^i d\eta = 0 \tag{3.10}$$

Following the Galerkin weighted residual method and integration by parts method to the equations [3.8] – [3.10] we obtain

$$\int_{\eta_e}^{\eta_{e+1}} \frac{d\Psi_j^i}{dy}\frac{d\psi^i}{dy} dy - \delta M_1^2 \int_{\eta_e}^{\eta_{e+1}} u^i \Psi_j^i dy + \delta^2 \Delta \int_{\eta_e}^{\eta_{e+1}} (u^i)^2 \Psi_j^i dy - \delta G \int_{\eta_e}^{\eta_{e+1}} (\theta^i + NC^i)\Psi_j^i dy = Q_{1,j} + Q_{2,j} \tag{3.11}$$

where – $Q_{1,j} = \Psi_j(\eta_e)\frac{du^i}{d\eta}(\eta_e)$

$$Q_{2,j} = \Psi_j(\eta_{e+1})\frac{du^i}{d\eta}(\eta_{e+1})$$

$$\int_{\eta_e}^{\eta_{e+1}} \frac{d\Psi_j^i}{dy}\left(\frac{dC^i}{dy}\right) dy - \gamma \int_{\eta_e}^{\eta_{e+1}} C^i \psi_j^i d\eta + \frac{ScSo}{N} - ScN_c \int_{\eta_e}^{\eta_{e+1}} u^i \psi_j^i d\eta = R_{1,j} + R_{2,j} \tag{3.12}$$

where – $R_{1,j} = \Psi_j(\eta_e)\frac{dC^i}{dy}(\eta_e)$

$$R_{2,j} = \Psi_j(\eta_{e+1})\frac{dC^i}{dy}(\eta_{e+1})$$

$$\int_{\eta_e}^{\eta_{e+1}} \frac{d\Psi_j^i}{dy}\frac{d\theta^i}{dy}dy - PN_T\int_{\eta_e}^{\eta_{e+1}} u^i\psi_j^i d\eta + \alpha\int_{\eta_e}^{\eta_{e+1}} \psi_j^i d\eta = \mathrm{S}_{1,\mathrm{j}} + \mathrm{S}_{2,\mathrm{j}} \tag{3.13}$$

where – $S_{1,j} = \Psi_j(\eta_e)\frac{d\theta^i}{dy}(\eta_e)$

$$S_{2,j} = \Psi_j(\eta_{e+1})\frac{d\theta^i}{dy}(\eta_{e+1})$$

Making use of equations [3.4] we can write above equations as

$$\sum_{k=1}^{3} u_k\int_{\eta_e}^{\eta_{e+1}} \frac{d\psi_j^i}{dy}\frac{d\psi_k}{dy}dy - \sum_{k=1}^{3}\delta M_1^2 u_k\int_{\eta_e}^{\eta_{e+1}}\psi_j^i\psi_k dy - \delta G(\sum_{k=1}^{3}\theta_k\int_{\eta_e}^{\eta_{e+1}}\psi_j^i\psi_k dy + NC_k\sum_{k=1}^{3}\psi_j^i\psi_k dy + \delta^2\Delta\sum_{k=1}^{3}u_k^2\int_{\eta_e}^{\eta_{e+1}}\left(\frac{d\psi_k}{d\eta}\right)^2\psi_j^i d\eta = Q_{1,j} + Q_{2,j} \tag{3.14}$$

$$\sum_{k=1}^{3} C_k\int_{\eta_e}^{\eta_{e+1}} \frac{d\psi_j^i}{dy}\frac{d\psi_k}{dy}dy - \gamma\sum_{k=1}^{3}C_k\int_{\eta_e}^{\eta_{e+1}}\psi_j^i\psi_k d\eta - ScN_c\sum_{k=1}^{3}C_k\int_{\eta_e}^{\eta_{e+1}}\psi_j^i\psi_k dy = R_{1,j} + R_{2.j} \tag{3.15}$$

$$\sum_{k=1}^{3}\theta_k\int_{\eta_e}^{\eta_{e+1}} \frac{d\psi_j^i}{dy}\frac{d\psi_k}{dy}dy + \alpha\sum_{k=1}^{3}\int_{\eta_e}^{\eta_{e+1}}\psi_j^i dy - PN_T\sum_{k=1}^{3}u_k\int_{\eta_e}^{\eta_{e+1}}\psi_k\psi_j^i dy = S_{1,j} + S_{2.j} \tag{3.16}$$

Choosing different Ψ_j^i's corresponding to each element η_e in the equation [3.14] yields a local stiffness matrix of order 3×3 in the form

$$(f_{i,j}^k)(u_i^k) - \delta G(g_{i.j}^k)(\theta_i^k + NC_i^k) + \delta M_1^2(m_{i.j}^k)(u_i^k) + \delta^2\Delta(n_{i.j}^k)(u_{i,j}^k) = (Q_{i,j}^k) + (Q_{2,j}^k) \tag{3.17}$$

Likewise the equation [3.15] & [3.16] gives rise to stiffness matrices

$$(e_{i,J}^k)(C_i^k) - PN_C(m_{i.j}^k)(u_i^k) = R_{1J}^k + R_{2J}^k \tag{3.18}$$

$$(l_{iJ}^k)(\theta_i^k) - P_rN_T(t_{iJ}^k)(\theta_i^k) = S_{1,J}^k + S_{2,J}^k \tag{3.19}$$

where $\left(f_{i,J}^k\right),\left(g_{i,J}^k\right),\left(m_{i,J}^k\right),\left(n_{i,J}^k\right),\left(e_{i,J}^k\right),\left(t_{iJ}^k\right)$ are3×3matrices and $\left(Q_{2,J}^k\right),\left(Q_{1,J}^k\right),\left(R_{2,J}^k\right),\left(R_{1J}^k\right),\left(S_{2J}^k\right)$ and $\left(S_{1J}^k\right)$ are 3×1 column matrices and such stiffness matrices (3.17) – (3.19) in terms of local nodes in each element are assembled using inter element continuity and equilibrium conditions to obtain the coupled global matrices in terms of the global nodal values of k, θ & C. In case we choose n-quadratic elements then the global matrices are of order 2n+1. The ultimate coupled global matrices are solved to determine the unknown global nodal values of the velocity, temperature and concentration in fluid region. In solving these global matrices an iteration procedure has been adopted to include the boundary and effects in the porous region.

The shape functions corresponding to

$$\Psi_1^1 = \frac{(y-4)(y-8)}{32} \qquad \Psi_2^1 = \frac{(y-12)(y-16)}{32} \qquad \Psi_3^1 = \frac{(y-20)(y-24)}{32}$$

$$\Psi_1^2 = \frac{(y-2)(y-4)}{8} \qquad \Psi_2^2 = \frac{(y-6)(y-8)}{8} \qquad \Psi_2^3 = \frac{(y-10)(y-12)}{8}$$

$$\Psi_1^3 = \frac{(3y-4)(3y-8)}{32} \qquad \Psi_2^3 = \frac{(3y-12)(3y-16)}{32} \qquad \Psi_3^3 = \frac{(3y-20)(3y-24)}{32}$$

$$\Psi_1^4 = \frac{(y-1)(y-2)}{2} \qquad \Psi_2^4 = \frac{(y-3)(y-4)}{2} \qquad \Psi_3^4 = \frac{(y-5)(y-6)}{2}$$

$$\Psi_1^5 = \frac{(5y-4)(5y-8)}{32} \qquad \Psi_2^5 = \frac{(5y-12)(5y-16)}{32} \qquad \Psi_3^5 = \frac{(5y-20)(5y-24)}{32}$$

4. STIFFNESS MATRICES

The global matrix for θ is

$$A_3 X_3 = B_3 \tag{4.1}$$

The global matrix for C is

$$A_4 X_4 = B_4 \tag{4.2}$$

The global matrix u is

$$A_5 X_5 = B_5 \tag{4.3}$$

In fact, the non-linear term arises in the modified Brinkman linear momentum equation (3.8) of the porous medium. The iteration procedure in taking the global matrices is as follows. We split the square term into a product term and keeping one of them say u_i's under integration, the other is expanded in terms of local nodal values as in (3.4), resulting in the corresponding coefficient matrix $(n_{i\ j}^{k}\ 's)$ in (3.17), whose coefficients involve the unknown u_i's . To evaluated (3.18) to begin with choose the initial global nodal values of u_i's as zeros in the zeroth approximation. We evaluate u_i's , θ_i's and C_i's in the usual procedure mentioned earlier. Later choosing these values of u_i's as first order approximation calculate θ_i's, C_i's. In the second iteration, we substitute for u_i's the first order approximation of and u_i's and the first approximation of θ_i's and C_i's obtain second order approximation. This procedure is repeated till the consecutive values of u_i's , θ_i's and C_i's differ by a preassigned percentage. For computational purpose we choose five elements in flow region.

Comparision with the earlier work:In the non-magnetic case [M=0] the results coinsides with that of kamalakar[2012].

5. DISCUSSION OF RESULTS

In this analysis we investigate the effect of chemical reaction on convective heat and mass transfer flow of a viscous electrically conducting fluid through a porous medium in a vertical channel maintained at constant temperature & concentration. The equations governing the flow of heat and mass transfer are solved numerically using Galerkin finite element analysis with quadratic approximation functions.

Figs.1 – 6 represent the variation of the axial velocity (u])with different variations of M, D^{-1}, α, Sc, N and γ. The variation of 'u' with Hart-man number M and Darcy parameter D^{-1} shows that higher the Lorentz force lesser the permeability of the porous medium smaller |u| in the entire flow region (fig 1 and 2). The variation of 'u' with heat source parameter α shows that a reversal flow is observed in the entire flow region in the case of heat sink and no such reversal flow any where in the flow region in the case of heat source |u| enhances with increase in the strength of heat source / sink (fig.3). The variation of 'u' with Schmidt number 'Sc' , S.T. lesser the molecular diffusivity smaller |u| in the entire flow region (fig.5). The variation of 'u' with buoyancy ration 'N' shows that the molecular buoyancy force dominates with the thermal buoyancy force |u| depreciates when the buoyancy forces act in the same direction and for the forces acting in opposite direction it enhances in the entire flow region (fig.5). The influence of chemical reaction on 'u' is exhibited in fig.6, it is found that the magnitude of u enhances in the degenerating chemical reaction case and depreciates in the generating chemical reaction case.

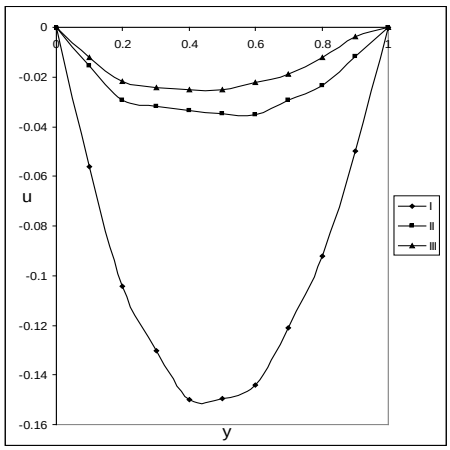

Fig.1 Variation of axial velocity(u) with M
$M=2, D^{-1}=10^2, \alpha=2$

	I	II	III
M	2	5	10

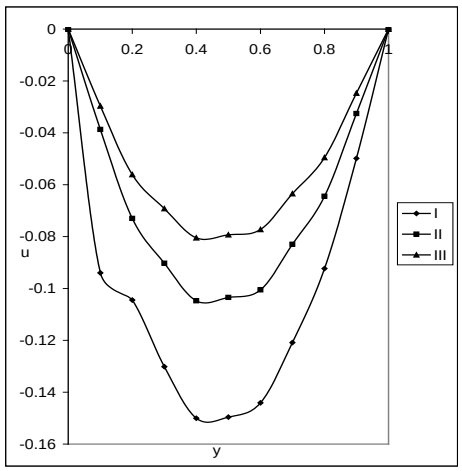

Fig.2 u with D^{-1}

	I	II	III
D^{-1}	10^2	$3x10^2$	$5x10^2$

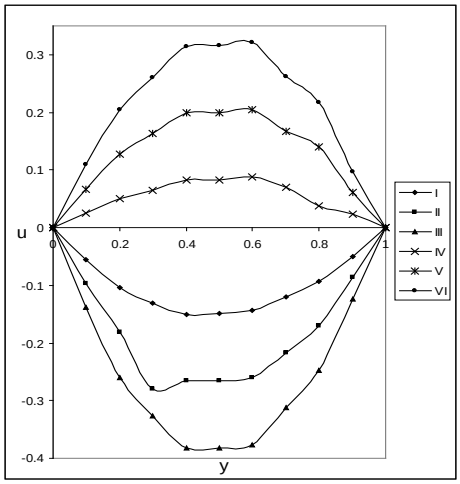

Fig.3 u with α

	I	II	III	IV	V	VI
α	2	4	6	-2	-4	-6

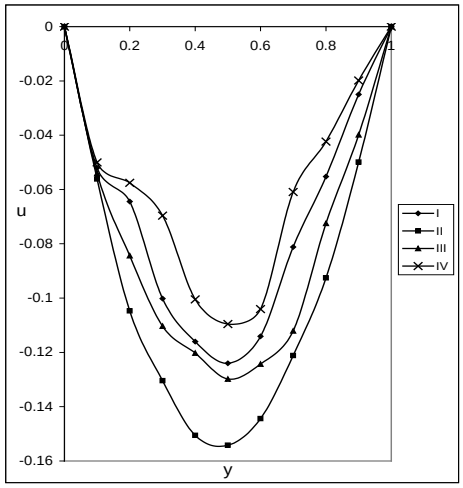

Fig.4 u with Sc

	I	II	III	IV
Sc	0.24	0.6	1.3	2.01

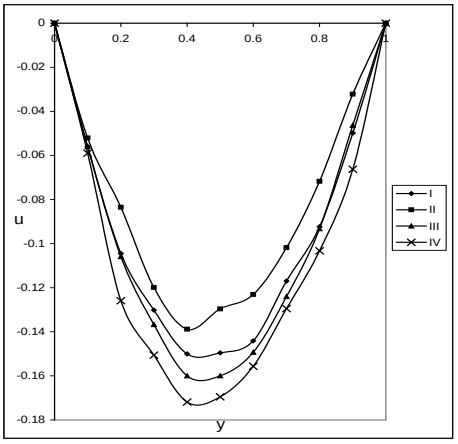

Fig.5 u with N

	I	II	III	IV
N	1	2	-0.5	-0.8

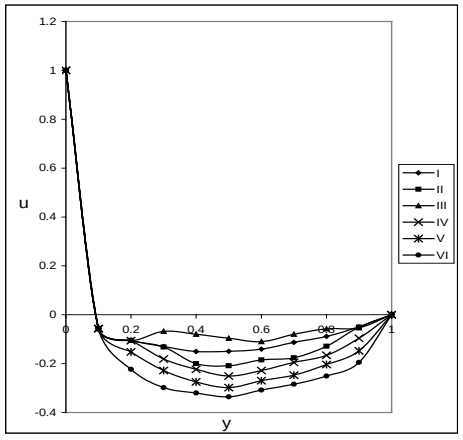

Fig.6 u with γ

	I	II	III	IV	V	VI
γ	0.5	1.5	2.5	-0.5	-1.5	-2.5

The non-dimensional temperature distribution 'θ' is shown in fig.7 – 12 for different parametric values. The variation of θ with M and D^{-1} shows that higher the Lorentz force / lesser the permeability of the porous medium smaller the actual temperature in the entire flow region (fig. 7 and 8). The variation of θ with heat source parameter α is shown in fig.9, it is found that the actual temperature enhances with increase actual temperature enhances with increase in $\alpha>0$ and depreciates with $\alpha<0$. The variation of θ with Schmidt number Sc shows that lesser the molecular diffusivity smaller the actual temperature in the flow region (fig.10). The variation of θ with buoyancy ration N shows that when the molecular buoyancy force dominates over the thermal buoyancy force the actual temperature depreciates irrespective of the directions of the buoyancy forces (fig.11). The influence of physical reaction on θ is shown in fig 12, it is found that the actual temperature enhances in the degenerating chemical reaction case and depreciates in the generating chemical reaction case.

The non-dimensional concentration (C) is shown in figs.13-18 for different parametric values. From figs.13 & 14, we found that the actual concentration enhances with increase in D^{-1} and depreciates with M. the variation of 'C' with Sc shows that lesser the molecular diffusivity smaller the concentration in the flow field (fig.15). From fig.16 we find that the actual concentration depreciates with increase in the strength of the heat source and enhances with heat sink. The variation of θ with buoyancy ratio N shows that the actual concentration enhances with N>0 and depreciates with N<0 every where in the flow region (fig.17). The influence of chemical reaction effect on 'C' is shown in fig.18. It is found that the actual concentration enhances in the degenerating chemical reaction k and depreciates in the generating chemical reaction case.

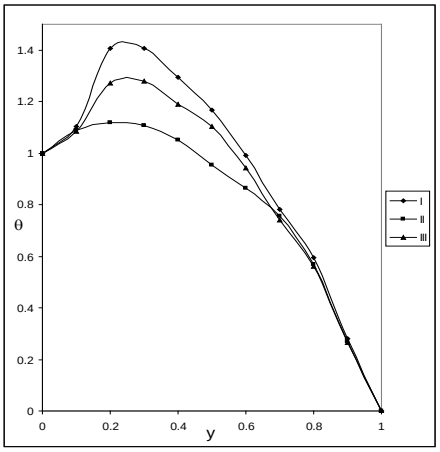

Fig.7 Variation of temperature (θ) with M
M=2, $D^{-1}=10^2$,α=2

	I	II	III
M	2	5	10

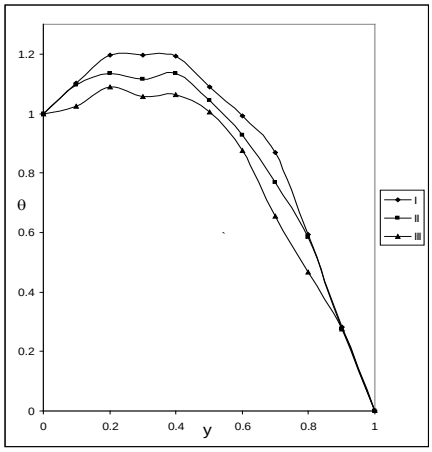

Fig.8 θ with D^{-1}

	I	II	III
D^{-1}	10^2	$3x10^2$	$5x10^2$

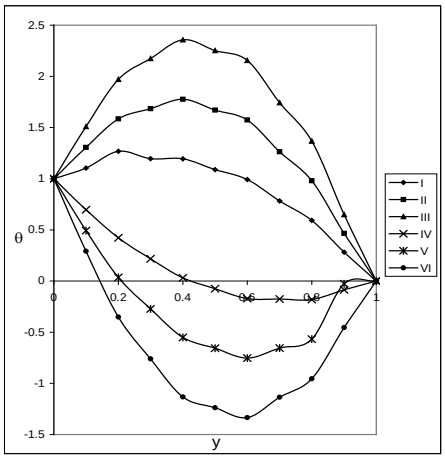

Fig.9 θ with α

	I	II	III	IV	V	VI
α	2	4	6	-2	-4	-6

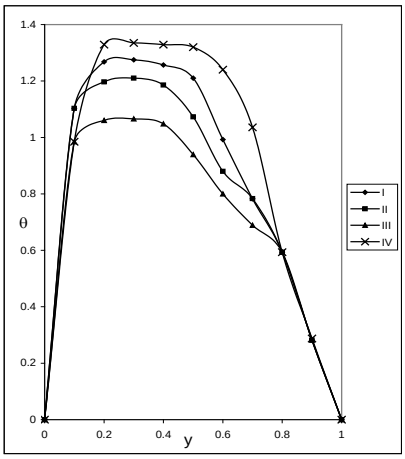

Fig.10 θ with Sc

	I	II	III	IV
Sc	0.24	0.6	1.3	2.01

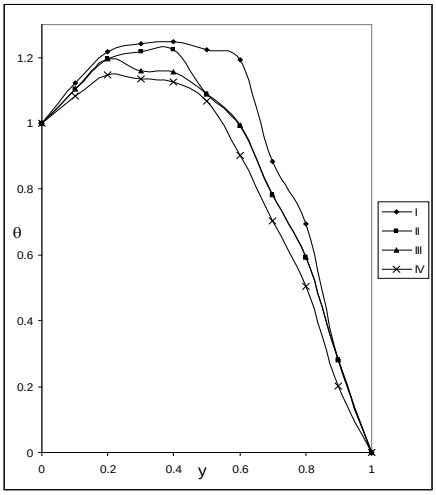

Fig.11 θ with N

	I	II	III	IV
N	1	2	-0.5	-0.8

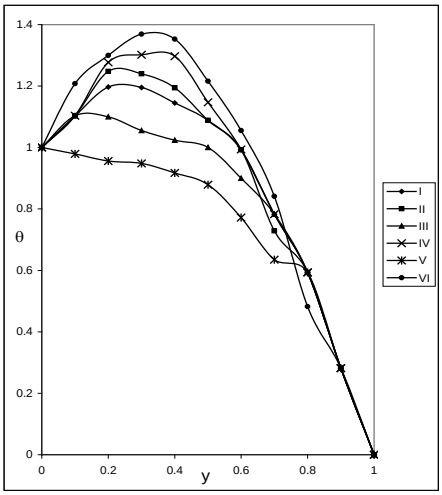

Fig.12 θ with γ

	I	II	III	IV	V	VI
γ	0.5	1.5	2.5	-0.5	-1.5	-2.5

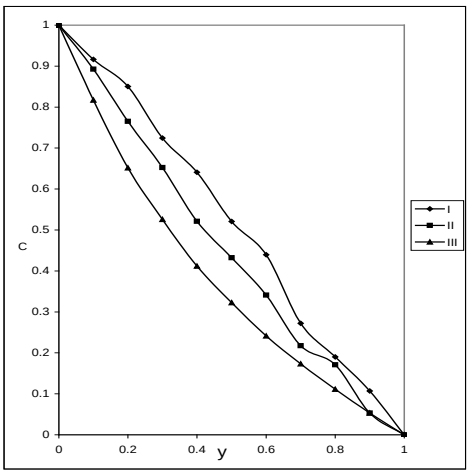

Fig.13 Variation of Concentration (C) with M

	I	II	III
M	2	5	10

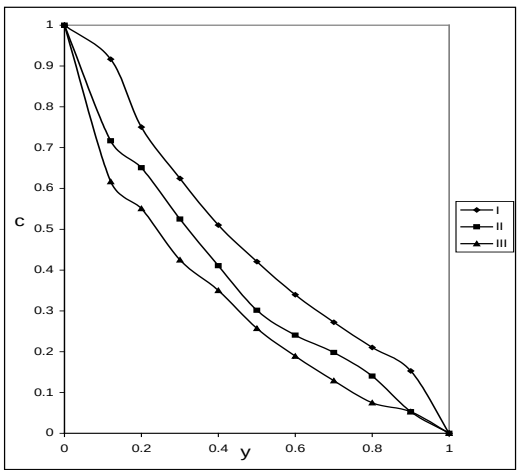

Fig.14 C with D^{-1}

	I	II	III
D^{-1}	10^2	$3x10^2$	$5x10^2$

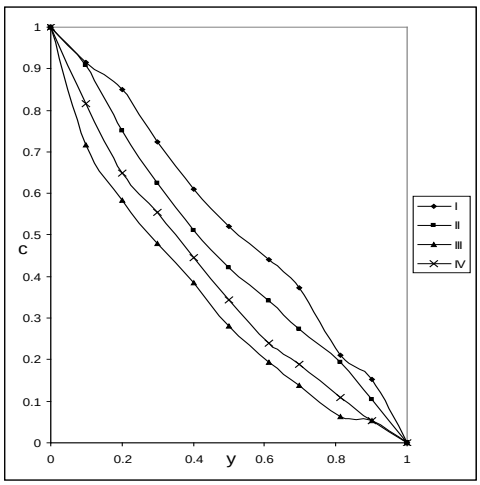

Fig.15 C with Sc

	I	II	III	IV
Sc	0.24	0.6	1.3	2.01

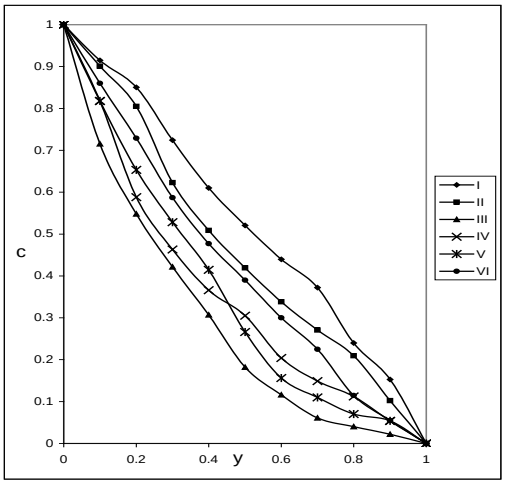

Fig.16 C with α

	I	II	III	IV	V	VI
α	2	4	6	-2	-4	-6

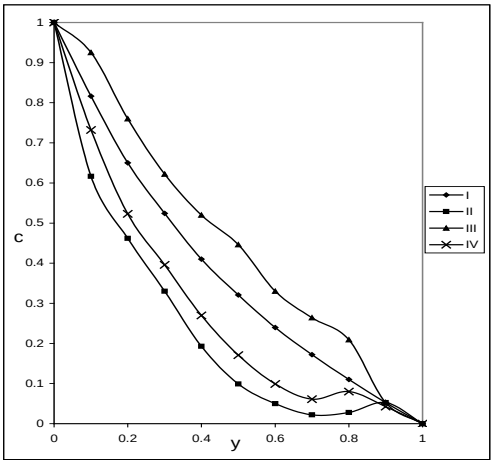

Fig.17 C with N

	I	II	III	IV
N	1	2	-0.5	-0.8

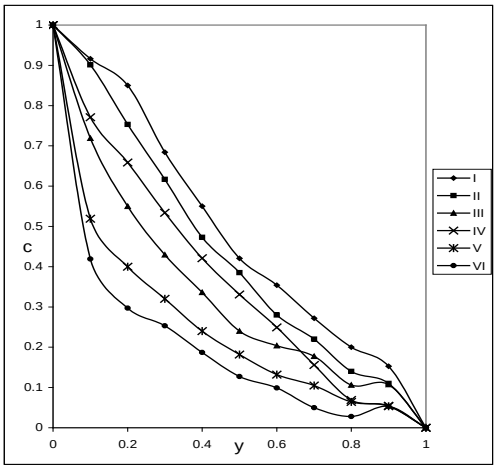

Fig.18 C with γ

	I	II	III	IV	V	VI
γ	0.5	1.5	2.5	-0.5	-1.5	-2.5

The rate of heat transfer at y = ± 1 is shown in tables 1 – 6 for different parametric values, it is found that the rate of heat transfer enhances with increasing |G| at y = ± 1 lesser the permeability of the porous medium smaller |Nu| at both the walls. The variation of Nu with Hartman number M shows that(tables 1 and 4) higher the lorentz force larger |Nu| in the heating case and smaller in the cooling case. The variation of Nu with buoyancy ratio N shows that(tables 1 and 4)when the molecular buoyancy force dominates the thermal buoyancy force, the rate of heat transfer experiences an enhancement when the buoyancy forces act in same direction and for the forces acting in opposite direction it depreciates in the magnitude at both the walls. The variation of Nu with heat source parameter α shows that(tables 2 and 5) the rate of heat transfer enhances with increase in strength of heat source / sink at y = ± 1 lesser the molecular diffusivity smaller |Nu| per G > 0 and larger |Nu| for G<0. The variation of Nu with chemical reaction γ shows that

(Table 6) |Nu| enhances in the degenerating chemical reaction case and depreciates in the generating chemical reaction case. In general we find that the rate of heat transfer at y= -1 is much greater than that at y = + 1.

Table: 1
Nusselt number [Nu] at y= +1

G	I	II	III	IV	V	VI	VII	VIII
10^3	39.3931	39.3434	39.3653	39.5076	39.5301	39.3932	39.3929	39.3928
$3X10^3$	39.4795	39.2016	39.2796	39.4089	39.3939	39.5045	39.5408	39.5295
-10^3	39.7326	39.6818	39.6537	39.6103	39.5377	39.7336	39.7327	39.7316
$-3X10^3$	40.0818	39.9271	39.8451	39.708	39.6067	40.0829	40.0816	40.0765
D^{-1}	10^3	$3x10^3$	$5x10^3$	10^3	10^3	10^3	10^3	10^3
M	2	2	2	4	8	2	2	2
N	1	1	1	1	1	2	-0.5	-0.8

Table: 2
Nusselt number [Nu] at y= +1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	39.3931	65.6944	91.9957	-13.2095	-39.5108	-65.8121	39.6805	39.5821	39.2042
$3X10^3$	39.4795	65.0326	91.0029	-12.8785	-38.8489	-64.8192	39.5589	39.5603	39.4795
-10^3	39.7326	66.3738	93.015	-13.5497	-40.1909	-66.8321	39.4239	39.5279	39.9434
$-3X10^3$	40.0818	67.0722	94.0625	-13.8989	-40.8893	-67.8796	39.1723	39.4739	40.7309
α	2	4	6	-2	-4	-6	2	2	2
Sc	1.3	1.3	1.3	1.3	1.3	1.3	0.24	0.6	2.02

Table: 3
Nusselt number [Nu] at y= +1

G	I	II	III	IV	V	VI
10^3	39.3931	40.1787	40.3361	41.7278	40.8008	40.8002
$3X10^3$	39.4795	40.3345	40.5945	42.9913	41.6426	41.3775
-10^3	39.7326	40.0246	40.0825	40.5685	40.3021	40.2473
$-3X10^3$	40.0818	39.8722	39.8336	39.5006	39.6784	39.7156
γ	0.5	1.5	2.5	-0.5	-1.5	-2.5

Table: 4
Nusselt number [Nu] at y= -1

G	I	II	III	IV	V	VI	VII	VIII
10^3	416.317	415.278	414.433	418.128	418.195	416.318	416.314	415.304
$3X10^3$	417.951	413.354	414.561	416.56	417.958	423.162	418.617	417.672
-10^3	421.57	420.784	420.349	417.818	418.597	422.669	421.57	420.37
$-3X10^3$	426.97	424.49	423.308	421.187	420.004	427.974	426.964	424.663
D^{-1}	10^3	$3x10^3$	$5x10^3$	10^3	10^3	10^3	10^3	10^3
M	2	2	2	4	8	2	2	2
N	1	1	1	1	1	2	-0.5	-0.8

Table: 5
Nusselt number [Nu] at y= -1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	416.317	823.066	1229.82	-397.183	-803.933	-1210.68	420.763	419.241	413.395
$3X10^3$	417.951	812.832	1214.46	-392.066	-793.698	-1195.33	419.03	418.966	417.951
-10^3	421.57	833.575	1245.58	-402.441	-814.447	-1226.45	416.793	418.403	424.832
$-3X10^3$	426.97	844.375	1261.78	-407.84	-825.245	-1242.65	412.9	417.568	437.002
α	2	4	6	-2	-4	-6	2	2	2
Sc	1.3	1.3	1.3	1.3	1.3	1.3	0.24	0.6	2.02

Table: 6
Nusselt number [Nu] at y= -1

G	I	II	III	IV	V	VI
10^3	416.317	425.029	426.766	433.697	433.697	431.967
$3X10^3$	417.951	427.424	430.732	461.507	444.182	440.786
-10^3	421.57	422.661	422.874	424.717	423.71	423.503
$-3X10^3$	426.97	428.319	429.054	408.509	406.187	409.375
γ	0.5	1.5	2.5	-0.5	-1.5	-2.5

The rate of mass transfer at $y = \pm 1$ is exhibited in tables 7 – 12. For different values of G, M, D^{-1}, N, α, Sc and γ. It is found that the rate of mass transfer enhances at y=+1 and depreciates at y = -1 with increase in |G|. The variation of Sh with Darcy parameter D^{-1} and Hartman number M shows that (tables 7 and 10)lesser the permeability of the porous medium smaller |Sh| at $y = \pm 1$ in the heating case and in the cooling case smaller at y =+1 and larger at y = -1, higher the lorentz force smaller |Sh| at = +1. For G>0 and for G<0, smaller at y = +1 and larger at y = -1. The variation of Sh with the buoyancy ratio N shows that(tables 7 and 10)when the molecular buoyancy forces dominates over the thermal buoyancy forces the rate of mass transfer depreciates at y = +1 and enhances at y = - 1 and for the forces acting tin opposite direction it enhances at y = + 1 and depreciates at y = -1. The variation of Sh with heat source parameter α shows that(tables 8 and 11) the rate of mass transfer at y=+1 depreciates with $\alpha>0$ in the heating case and enhances in the cooling case and at y = -1 it enhances with $\alpha>0$ in the heating case and reduces in the cooling case. We observe α reversed effect in the behaviour of |Sh| in the case of heat sink. The variation of Sh with Schmidt number Sc shows that (tables 8and 11) lesser the molecular diffusivity smaller |Sh| at y = + 1 and larger at y =- 1 in the heating case and in the cooling case larger |Sh| at y = + 1 and smaller at y = -1. The variation of Sh with chemical reaction parameter γ shows that (tables 9 and 12)the rate of mass transfer enhances at y = +1 and reduces at y = -1 in the degenerating chemical reaction and in the generating chemical reaction case it reduces at y = +1 and enhances at y = -1. In general we find that the rate of mass transfer at y = -1 is greater than that at y = +1.

Table: 7
Sherwood number [Sh] at y= +1

G	I	II	III	IV	V	VI	VII	VIII
10^3	13.0791	13.0609	13.0421	13.06638	13.0428	13.0691	13.0496	13.0590
$3X10^3$	13.0826	13.0712	13.0644	13.0797	13.0788	13.0653	13.0651	13..0874
-10^3	13.0931	13.092	13.0899	13.0874	13.0854	13.0831	13.0531	13.0931
$-3X10^3$	13.1076	13.1013	13.0978	13.0921	13.0878	13.0976	13.0736	13.1016
D^{-1}	10^3	$3x10^3$	$5x10^3$	10^3	10^3	10^3	10^3	10^3
M	2	2	2	4	8	2	2	2
N	1	1	1	1	1	2	-0.5	-0.8

Table: 8
Sherwood number [Sh] at y= +1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	13.0791	13.0721	13.0651	13.0931	13.1	13.107	13.0846	13.0827	13.07551
$3X10^3$	13.0826	13.0447	13.024	13.1068	13.1275	13.0648	13.0871	13.0892	0.0973
-10^3	13.0931	13.1002	13.1073	13.079	13.0719	13.0648	13.0871	13.0892	0.3973
$-3X10^3$	13.1076	13.1291	13.1506	13.0645	13.043	13.0214	13.0897	13.0956	13.1202
α	2	4	6	-2	-4	-6	2	2	2
Sc	1.3	1.3	1.3	1.3	1.3	1.3	0.24	0.6	2.02

Table: 9
Nusselt number [Nu] at y= +1

G	I	II	III	IV	V	VI
10^3	13.0791	13.0989	13.1116	13.1232	13.1064	13.1022
$3X10^3$	13.0826	13.0941	13.1088	13.1388	13.1113	13.1052
-10^3	13.0931	13.1036	13.1144	13.1088	13.1016	13.094
$-3X10^3$	13.1076	13.1082	13.1172	13.0956	13.0941	13.0926
γ	0.5	1.5	2.5	-0.5	-1.5	-2.5

Table: 10
Sherwood number [Sh] at y= -1

G	I	II	III	IV	V	VI	VII	VIII
10^3	14.4972	14.4949	14.4948	14.4934	14.492	14.5072	14.4973	14.4863
$3X10^3$	14.4928	14.4638	14.4211	14.4868	14.4831	14.4962	14.4923	14.4706
-10^3	14.4858	14.4875	14.4884	14.4866	14.4912	14.4928	14.4807	14.4752
$-3X10^3$	14.474	14.4796	14.482	14.4866	14.4911	14.484	14.4629	14.4519
D^{-1}	10^3	$3x10^3$	$5x10^3$	10^3	10^3	10^3	10^3	10^3
M	2	2	2	4	8	2	2	2
N	1	1	1	1	1	2	-0.5	-0.8

Table: 11
Sherwood number [Sh] at y= -1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	14.4972	14.503	14.5087	14.4858	14.4801	14.4743	14.4928	14.4943	14.5002
$3X10^3$	14.4928	14.5254	14.4745	14.4576	14.4406	14.4919	14.4921	14.4921	14.4928
-10^3	14.4858	14.48	14.442	14.4974	14.5032	14.509	14.4907	14.489	14.4824
$-3X10^3$	14.474	14.4563	14.4387	14.5092	14.5269	14.5445	14.4886	14.4837	14.4636
α	2	4	6	-2	-4	-6	2	2	2
Sc	1.3	1.3	1.3	1.3	1.3	1.3	0.24	0.6	2.02

Table: 12
Sherwood number [Sh] at y= -1

G	I	II	III	IV	V	VI
10^3	14.4972	14.4682	14.4185	14.4836	14.4993	14.5061
$3X10^3$	14.4928	14.472	14.4207	14.4711	14.4953	14.5037
-10^3	14.4858	14.4644	14.4163	14.4951	14.5032	14.5084
$-3X10^3$	14.474	14.4606	14.4142	14.5057	14.5068	14.5106
γ	0.5	1.5	2.5	-0.5	-1.5	-2.5

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