THERMO – DIFFUSION EFFECT ON MHD CONVECTIVE HEAT AND MASS TRANSFER THROUGH A POROUS MEDIUM IN A VERTICAL CHANNEL, MAINTAINED AT NON-UNIFORM TEMPERATURE

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Abstract

An attempt has been made to analyse the Soret effect on the hydromagnetic convective heat and mass transfer flow of an electrically conducting fluid through a porous medium confined in a vertical channel channel. The walls at y=±L are maintained at non-uniform temperature. The equations governing the flow, heat and mass transfer have been solved by a regular perturbation method with the slope δ *of the boundary temperature curve as a perturbation parameter. The velocity, temperature and concentration have been analysed computationally for different variations in G,D,R,N,Sc,*S_0 *and x. Also the Shear stress, the rate of heat and mass transfer are evaluated for different variations.*

Keywords
MHD, Heat and Mass Transfer, Vertical Channel, Non-Uniform Temperature, Thermo-Diffusion effect.

1.Introduction

Coupled heat and mass transfer driven by buoyancy due to temperature and concentration variation in a saturated porous medium has several important applications in geothermal and geophysical engineering such as the migration of moisture through the air contained in fibrous insulation, the extraction of geothermal energy, underground disposal of nuclear wastes and the spreading of chemical contaminants through water saturated soil. The study of dynamics of hot and salty springs of a sea where the combined convection of heat and mass transfer is involved has been analysed by Dragan(9).A systematic derivation of the governing equations with various types of approximations used in applications has been presented .Heat and mass transfer by free convection in a porous medium under boundary layer approximations has been studied by Bejan and Khair(3),Lai and Kulacki(17),Nakayama and Hossain (22) and Singh and Queeny(31).A review of combined heat and mass transfer by free convection in porous medium is given by Trevisan and Bejan (37).Recently Angirasa et al (2) have presented the analysis for combined heat and mass transfer by natural convection for aiding and opposing buoyancies in fluid saturated porous enclosures. In the theory of flow through porous medium, the role of momentum equations or force balance is occupied by the numerous experimental observations summerised mathematically as the Darcy's law. It is observed that the Darcy's law is applicable based on average grain(pore) diameter does not exceed a value between 1 and 10.But in general, the speed of specific discharge in the medium need not be always low. As the specific discharge increases ,the convective forces get developed and the internal stress generated in the fluid due to its viscous nature produces distributions in the velocity field. Also in the case of highly porous media such as fiber glass, pappus of dandilion … etc the viscous stress at the surface is able to penetrate into medium and produce flow near the surface even in the absence of the pressure gradient. Thus Darcy's law which specifies a linear relationship between the specific discharge and hydraulic gradient is inadequate in describing high speed flows or flows near surfaces which may either permeable or not. Hence consideration for non-Darcian description for the viscous flow through porous media is warranted. Saffman(29)employing a statistical method derived a general governing equation for the flow in a porous medium which takes into account the viscous stress. Later another modification has suggested by Brinkman(6)

$$0 = -\nabla p - (\frac{\mu}{k})\overline{V} + \mu\nabla^2\overline{V}$$

in which $\mu\nabla^2\overline{V}$ is intended to account for the distributions of the velocity profiles near the boundary. The same equation was derived analytically by Tam(36) to describe the viscous flow at low Reynolds number past a swam of small particles.A phenomenological theory of combined heat and mass transfer in porous media was previously established by Devries(10,11) and Philip and Devries(23) commonly known as Devries mechanism model ,its practical usefulness is widely recognized in describing the simultaneous heat and mass transfer with in a wide range of porous media .Experimental studies for mixed convection heat and mass transfer in the horizontal channel has been studied by Kamotani et al(15) and Maughan and Incorporeal (19).The heat and mass transfer through porous medium has been carried out by several authors(1,5,22,28,39,33,37)under different conditions.In the above mentioned investigations the boundary walls are maintained at constant temperature .However, these are 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. For example, in drawing optic glass fibres of extremely low loss and band width the processes of modified chemical vapour deposition(MCVD)(16,32)has been suggested in recent times . Performs from which these fibers are drawn are made by passing a gaseous mixture into a fused –silica tube which is heated locally, by an oxy-hydrogen flame .Particulate of So2-Geo2 composition are formed from the mixture and collect on the interior of the tube . Subsequently these are fined to form a vitreous deposit as the flame traversed along the tube. The deposition is carried out in the radial direction through the secondary flow created due to non-uniform wall temperature. The application of electromagnetic fields in controlling the heat transfer as in aerodynamic heating leads to the study of magneto hydrodynamics heat transfer. This MHD heat transfer has gained significance owing to advancement of space technology. The Mhd heat transfer can be divided into sections. One contains problems in which the heating is an incidental by product of the electromagnetic fields as in the MHD generators and pumps etc and the second contains of problems in which the primary use of electromagnetic fields is to control the heat transfer (20).With the fuel crisis deepening all over the world there is great concern to utilize the enormous power beneath the earth's crust in the geothermal region(34).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. Ravindra(26) has investigated the mixed convection flow of an electrically conducting viscous fluid through a porous medium in a vertical channel. Nagaraja (21) has investigated the combined heat and mass transfer effects on the flow of a viscous fluid through a porous medium in a vertical channel. Ravindra reddy(27) has analysed the effects of magnetic field on the combined heat and mass transfer in channels using finite element techniques. Since many industrially and environmentally relevant fluid 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. In the case of binary mixtures, species gradients can be established by the applied solute boundary conditions such as species rejection associated with alloys casting or can be induced by coupled transport mechanisms such as Soret(thermo) diffusion. In the case of Soret diffusion, gradients are established in an otherwise uniform concentration mixtures in accordance with the onsager reciprocal relationships. Recently some importance has been attended to the Benard problem in a two component system in which an initially homogeneous mixture is subjected to a temperature gradient. Then thermal diffusion known as Soret effect takes place and as a result of mass fraction distribution is established in the liquid layer(8).The sense of migration of the molecular species be determined by the sign of soret coefficient. Keeping this in view several authors have investigated the soret effect under varied conditions (4,7,12-14,18,24).Prasad(25) 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 analysed for different variations in the governing parameters. Srinivas Reddy(35) has analysed 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.

2.Formulation of the problem

We analyse the steady motion of viscous, electrically conducting incompressible fluid through a porous medium in a vertical channel bounded by flat walls which are maintained at a non-uniform wall temperature in the presence of a constant heat source and the concentration on these walls are taken to be constant. A uniform magnetic of strength H_0 is applied transverse to the walls. The Boussinesq approximation is used so that the density variation will be considered only in the buoyancy force. The thermo-diffusion effect has been taken into account. Also the kinematic viscosity ν, the thermal conductivity k are treated as constants. We choose a rectangular Cartesian

system 0(x ,y) with x-axis in the vertical direction and y-axis normal to the walls. The walls of the channel are at y = ± L. The equations governing the steady hydromagnetic flow , heat and mass transfer are
Equation of continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2.1}$$

Equation of linear momentum**:**

$$\rho_e(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y})=-\frac{\partial p}{\partial x}+\mu(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2})-\rho g-(\sigma\mu_e^2 H_0^2)u-(\frac{\mu}{k})u \tag{2.2}$$

$$\rho_e(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y})=-\frac{\partial p}{\partial y}+\mu(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2})-(\frac{\mu}{k})v \tag{2.3}$$

Equation of Energy:

$$\rho_e C_p(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y})=\lambda(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2})+Q \tag{2.4}$$

Equation of Diffusion:

$$(u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y})=D_1(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2})+k_{11}(\frac{\partial^2 \theta}{\partial x^2}+\frac{\partial^2 \theta}{\partial y^2}) \tag{2.5}$$

Equation of State:

$$\rho-\rho_e=-\beta\rho_e(T-T_e)-\beta^{\bullet}\rho_e(C-C_e) \tag{2.6}$$

where ρ_e is the density of the fluid in the equilibrium state, Te ,Ce are the temperature and Concentration in the equilibrium state,(u,v) are the velocity components along O(x ,y) directions, p is the pressure, T ,C are the temperature and Concentration in the flow region,ρis the density of the fluid,μ is the constant coefficient of viscosity , Cp is the specific heat at constant pressure, λ is the coefficient of thermal conductivity , k is the permeability of the porous medium, μ_e *is the magnetic* permeability , σ is the electrically conductivity and β is the coefficient of thermal expansion, $\beta^{\bullet}$ is the coefficient of expansion with mass fraction , D_1 is the molecular diffusivity,k_{11} is the cross diffusivity and Q is the strength of the constant internal heat source.
In the equilibrium state

$$0=-\frac{\partial p_e}{\partial x}-\rho_e g \tag{2.7}$$

Where $p=p_e+p_D, p_D$ being the hydrodynamic pressure.
The flow is maintained by a constant volume flux for which a characteristic velocity is defined as

$$Q=\frac{1}{2L}\int_{-L}^{L} u\,dy. \tag{2.8}$$

The boundary conditions for the velocity and temperature fields are

$$u = 0 \ , v = 0 \quad \text{on } y = \pm L$$
$$T-T_e=\gamma(\delta x/L) \quad \text{on } y = \pm L$$
$$C = C_1 \quad \text{on } y = -L$$
$$C = C_2 \quad \text{on } y = +L \tag{2.9}$$

γ is chosen to be twice differentiable function,δ is a small parameter characterizing the slope of the temperature variation on the boundary.
In view of the continuity equation we define the stream function ψ as

$$u = -\psi_y , v = \psi_x \tag{2.10}$$

the equation governing the flow in terms of ψ are

$$[\frac{\partial\psi}{\partial x}\frac{\partial(\nabla^2\psi)}{\partial y}-\frac{\partial\psi}{\partial y}\frac{\partial(\nabla^2\psi)}{\partial x}]=\nu(\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2})^2-\beta g\frac{\partial T}{\partial y}-$$
$$-\beta^\bullet g\frac{\partial C}{\partial y}-(\sigma\mu_e^2H_0^2)\frac{\partial^2\psi}{\partial y^2}-(\frac{\nu}{k})(\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}) \quad (2.11)$$

$$\rho_e C_p(\frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y})=\lambda\nabla^2\theta+Q \quad (2.12)$$

$$(\frac{\partial\psi}{\partial y}\frac{\partial C}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial y})=D_1(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2})+k_{11}(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}) \quad (2.13)$$

Introducing the non-dimensional variables in (2 .11)- (2.13) as

$$(x',\ y')=(x,y)/L,\ (u',v')=(u,v)/U,\theta=\frac{T-T_e}{\Delta T_e},C^\bullet=\frac{C-C_1}{C_2-C_1}$$
$$p'=\frac{p_D}{\rho_e U^2}\qquad ,\gamma'=\frac{\gamma}{\Delta T_e} \quad (2.14)$$

(under the equilibrium state $\Delta T_e=T_e(L)-T_e(-L)=\frac{QL^2}{\lambda}$)

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

$$R\frac{\partial(\psi,\nabla^2\psi)}{\partial(x,y)}=\nabla^4\psi+(\frac{G}{R}(\theta_y+NCy)-D^{-1}\nabla^2\psi-\mathrm{M}^2\frac{\partial^2\psi}{\partial y^2} \quad (2.15)$$

and the energy diffusion equations in the non-dimensional form are

$$PR(\frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y})=\nabla^2\theta+1 \quad (2.16)$$

$$RSc(\frac{\partial\psi}{\partial y}\frac{\partial C}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial y})=(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2})+\frac{ScSo}{N}(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}) \quad (2.17)$$

where

$R=\frac{UL}{\nu}$ (Reynolds number) $G=\frac{\beta g\Delta T_e L^3}{\nu^2}$ (Grashof number)

$\mathrm{P}=\frac{\mu c_p}{\lambda}$ (Prandtl number), $D^{-1}=\frac{L^2}{k}$ (Darcy parameter),

$E_c=\frac{\beta g L^3}{C_p}$ (Eckert number) $M^2=\frac{\sigma\mu_e^2H_0^2L^2}{\rho_0\nu}$ (Hartmann Number)

$N=\frac{\beta^\bullet\Delta C}{\beta\Delta T}$ (Buoyancy Number) $Sc=\frac{\nu}{D_1}$ (Schmidt number)

$So=\frac{k_{11}\beta^*}{\beta\nu}$ (Soret parameter)

The corresponding boundary conditions are

$$\psi(+1)-\psi(-1)=1$$
$$\frac{\partial\psi}{\partial x}=0,\ \frac{\partial\psi}{\partial y}=0\quad at\ y=\pm1 \quad (2.18a)$$
$$\theta(x,y)=f(\delta x)\qquad on\ \ y=\pm1 \quad (2.18b)$$

C= 0 on y = -1
C = 1 on y = 1 (2.18c)

$$\frac{\partial\theta}{\partial y}=0, \frac{\partial C}{\partial y}=0 \quad at \quad y=0 \tag{2.18d}$$

The value of ψ on the boundary assures the constant volumetric flow in consistent with the hyphothesis (2.8) .Also the wall temperature varies in the axial direction in accordance with the prescribed arbitrary function $\gamma(x)$.

3. Analysis of the flow

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

$$\bar{x}=\delta x$$

With this transformation the equations(2.15) - (2.17) reduce to

$$R\delta\frac{\partial(\psi,F^2\psi)}{\partial(x,y)}=F^4\psi+\frac{G}{R}(\theta_y+NC_y)-D^{-1}F^2\psi-M^2\frac{\partial^2\psi}{\partial y^2} \tag{3.1}$$

and the energy &diffusion equations in the non-dimensional form are

$$PR\delta(\frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y})=F^2\theta+1 \tag{3.2}$$

$$\delta RSc(\frac{\partial\psi}{\partial y}\frac{\partial C}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial y})=F^2C+\frac{ScSo}{N}F^2\theta \tag{3.3}$$

where

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

for small values of the slope δ,the flow develops slowly with axial gradient of order δ and hence we take

$$\frac{\partial}{\partial\bar{x}}\approx O(1)$$

We follow the perturbation scheme and analyse through first order as a regular perturbation problem at finite values of R,G,P ,Sc and D^{-1}

We introduce the asymptotic expansions as

$$\psi(x,y)=\psi_0(x,y)+\delta\psi_1(x,y)+\delta^2\psi_2(x,y)+\ldots\ldots$$
$$\theta(x,y)=\theta_0(x,y)+\delta\theta_1(x,y)+\delta^2\theta_2(x,y)+$$
$$C(x,y)=C_0(x,y)+\delta C_1(x,y)+\delta^2 C_2(x,y)+\ldots. \tag{3.4}$$

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

$$\psi_{0,yyyyy}-M_1^2\psi_{0,yy}=-\frac{G}{R}(\theta_{0,y}+NC_{0,y}) \tag{3.5}$$

$$\theta_{0,yy}=-1 \tag{3.6}$$

$$C_{0,yy}=-\frac{\mathrm{ScSo}}{\mathrm{N}}\theta_{0,yy} \tag{3.7}$$

with

$\psi_0(+1)-\Psi(-1)=1$,

$\psi_{0,y}=0$, $\psi_{0,x}=0$ at $y=\pm1$ (3.7a)

$\theta_0(\pm1)=\gamma(x)$ at $y=\pm1$

$C_0(-1)=0$ $C_0(+1)=1$ (3.7b)

and to the first order are

$$\psi_{1,yyyyy}-M_1^2\psi_{1,yy}=-\frac{G}{R}(\theta_{1,y}+NC_{1,y})+R(\psi_{0,y}\psi_{0,xyy}-\psi_{0,x}\psi_{0,yyy}) \tag{3.8}$$

$$\theta_{1,yy}=PR(\psi_{0,x}\theta_{0,y}-\psi_{0,y}\theta_{0,x}) \tag{3.9}$$

$$C_{1,yy}=RSc(\psi_{0,x}C_{0,y}-\psi_{0,y}C_{0,x})-\frac{ScSo}{N}\theta_{1,yy} \tag{3.10}$$

$\psi_{1(+1)} - \psi_{1(-1)} = 0$

$\psi_{1,y} = 0$, $\psi_{1,x} = 0$ at $y = \pm 1$ (3.11)

$\theta_1(\pm 1) = 0$ at $y = \pm 1$ (3.12)

$C_1(-1) = 0$, $C_1(+1) = 0$ (3.13)

4. Solution of the problem

Solving the equations (3.5)- (3.10) subject to the relevant boundary conditions we obtain

$$\theta_0 = 0.5(1-y^2) + \gamma(\bar{x})$$

$$C_0 = 0.5(y+1) + \frac{ScSo}{N}(y^2 - 1)$$

$$\psi_0 = a_4 Ch(M_1 y) + a_5 Sh(M_1 y) + a_6 y + a_7 + a_3 y^3 + d_2 y^2$$

$$\theta_1 = a_{24}(y^2-1) + a_{25}(y^3 - y) + a_{26}(y^4 - 1) + a_{27}(y^5 - y)$$

$$C_1 = a_{31}(y^2-1) + a_{32}(y^3-y) + a_{33}(y^4-1) + a_{34}(y^5-y) + a_{35}(y^6-1) + \\ + (a_{36} + y a_{38})(Ch(M_1 y) - Ch(M_1)) + a_{37}(Sh(M_1 y) - ySh(M_1)) + \\ + a_{39}(ySh(M_1 y) - Sh(M_1))$$

$$\psi_1 = b_8 Ch(M_1 y) + b_9 Sh(M_1 y) + b_{10} y + ba_{11} + \phi(y)$$

$$\phi(y) = a_{70} y^2 + a_{71} y^3 + a_{72} y^4 + a_{73} y^5 + a_{74} y^6 + a_{75} y^7 + \\ + (b_1 y + b_3 y^2 + b_5 y^3) Ch(M_1 y) + (b_2 y + b_4 y^2 + \\ + b_6 y^3) Sh(M_1 y) + b_7 y^4 Sh(M_1 y)$$

$$where\ a_1, a_2, ...a_{75}, b_1, b_2, ...b_7\ are\ cons\tan ts$$

The shear stress on the channel walls is given by

$$\tau = \mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)_{y=\pm L}$$

which in the non- dimensional form reduces to

$$\tau = \left(\frac{\tau}{\frac{\mu U}{a}}\right) = (\psi_{yy} - \delta^2 \psi_{xx})$$

$$= [\psi_{0,yy} + \delta\psi_{1,yy} + O(\delta^2)]_{y=\pm 1}$$

and the corresponding expressions are

$$(\tau)_{y=+1} = d_3 + d_5 + O(\delta^2)$$

$$(\tau)_{y=-1} = d_6 + \delta d_8 + O(\delta^2)$$

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

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

$$\theta_m = \int_{-1}^{1} \theta\, dy$$

and the corresponding expressions are

$$(Nu)_{y=+1} = \frac{d_{10} + \delta(d_{11} + d_{12})}{(d_8 + \delta d_9 - \gamma(x))}$$

$$(Nu)_{y=-1} = \frac{-d_{10} + \delta(d_{12} - d_{11})}{(d_8 + \delta d_{19} - 1)}$$

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

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

$$C_m = \int_{-1}^{1} C\,dy$$

and the corresponding expressions are

$$(Sh)_{y=+1} = \frac{0.5 + d_{15} + \delta(d_{17} + d_{16})}{(d_{13} + \delta d_{14} - 1)}$$

$$(Sh)_{y=-1} = \frac{0.5 - d_{15} + \delta(d_{17} - d_{16})}{(d_{13} + \delta d_{14})}$$

where $d_3, d_4, \ldots\ldots\ldots\ldots\ldots\ldots\ldots, d_{12}$ are constants.

5. Discussion of the numerical resultsresults

The aim of this analysis is to discuss the Soret effect on the hydro magnetic convective heat and mass transfer through a porous medium confined in a vertical channel on whose walls a non-uniform temperature is maintained .The analysis has been carried out at P=0.71.We note that the channel walls are heated or cooled according as the Grashof number G is positive or negative. The non-linear equations governing the flow have been solved by using by a regular perturbation method. The effect of different parameters governing the flow ,heat and mass transfer on the velocity, temperature and concentration distributions are analysed and exhibited if figures.1-27.The axial velocity is in the vertically downward direction and hence u negative is the actual velocity and u>0 represents the reversal flow .The axial velocity u is shown in figs.1-7.It is found from fig.1 that for │G│<$5x10^3$ there is reversal flow in the entire region and for │G│>$5x10^3$,we find reversal flow in a narrow region abutting the right boundary and for │G│=$5x10^3$ it occurs neat the left boundary. With increasing G the region of reversal flow shrinks in its size. For smaller and higher values of G the maximum u occurs at y=0.4,for G≤$3x10^3$ and for higher G≥$5x10^3$ the point shifts towards the left boundary while for │G│≤$3x10^3$ the point of maximum occurs at y=-0.4 and for higher │G│ it shifts towards the left wall and for still higher │G│ it shifts towards the midregion. We find that the magnitude of u reduces with │G│ except in the region -0.2≤y≤0.The effect of the porosity of the medium is exhibited in fig.2.For $D^{-1}\geq 10^3$.we find a reversal flow in the fluid region and the size of the reversal flow increases with increase in D^{-1}.It is found that the axial velocity increases in magnitude for $D^{-1}\geq 3x10^3$. Thus lesser the permeability of the porous medium smaller the magnitude of the velocity and for further lowering of the permeability we notice a remarkable enhancement in u in the entire flow region .It is found that the region of reversal flow which appears in the entire fluid region enlarges with increase in R.Also the magnitude of u increases with increase in R.The effect of the buoyancy ratio N on u shows that when the molecular buoyancy force dominates over the thermal buoyancy force the region of reversal flow reduces in its size when the buoyancy forces act in the same direction while it enlarges for the forces acting in opposite directions. Also the magnitude of u enhances with increase in N(>0) in the entire fluid region(fig.3) .Fig.4 shows that for Sc=0.24 the reversal flow occurs in the entire region except in -0.2≤y≤0 and for higher Sc it spreads to the entire fluid region. │u│ enhances with Sc. For an increase in │S_0│,│u│ experiences an enhancement and we find reversal flow for an increase in S_0 and no such reversal occurs for │S_0│(<0)(fig.5).Also u increases remarkably. The effect of the amplitude of the non-uniform boundary temperature is exhibited in fig.6.It is found that in a given porous medium reversal flow is observed in the entire region for α≤0.6 and the size of the reversal flow decreases marginally with increase in α and for higher α≥1.5 the reversal flow is confined to the regions adjacent to the boundaries. Also │u│ reduces marginally with α with maximum u occurring at y=0.6.Fig.7 shows that as we move along the axial direction we find a reversal flow in the fluid region and in this region │u│ enhances with x.

A secondary velocity v which is due to non-uniform temperature on the boundaries is analysed for different variations of G,D,R,N and x is shown in figs.8-11.We find that for all variations v is towards the midregion. From fig.8 it is found that │v│ increases with an increase in │G│ with a maximum at y=0.An increase in R decreases │u│ in the entire fluid region. From fig.9 it is noticed that lesser the permeability of the porous medium larger the magnitude of v in the entire fluid region. The variation of v with N shows that when the molecular buoyancy force dominates over the thermal buoyancy force │v│ enhances marginally when the forces act in the same direction and for the forces acting in opposite directions │v│ decreases with │N│(<0)(fig.10).The magnitude of v enhances marginally in the fluid region with an increase in the axial direction x≤π/2 and for x ≥ π we notice a marginal depreciation in the entire fluid region(fig.11).

The resultant velocity (Rt) is exhibited in figs.12&13.It is found that the profiles of the resultant velocity are almost bell shaped curves with maximum attained in the midregion.Rt decreases with │G│(<0>) and the resultant velocity in the heating case is greater than that in the cooling case in the left region(fig.12).From fig.13 it is noticed that lesser the permeability of the porous medium higher the resultant velocity near the boundaries with a dip in the midregion. The temperature distribution(θ) is exhibited in figs.14-19 for variations G,D,R,N,Sc,S_0,M,α and x .It is found that the temperature is positive for all variations in the governing parameters. The temperature gradually enhances from its prescribed value -1 on the left boundary ,attains its maximum in the mideregion and later falls to its prescribed value 1 on the right boundary. It is found that the temperature depreciates in the heating of the channel walls and enhances in the cooling of walls(fig.14).An increase in R depreciates the temperature in the fluid region. Also we find that the temperature decreases in the left region and enhances in the right region with increase in D^{-1}.Thus lesser the permeability of the porous medium larger the temperature in the left region and smaller the temperature in the right region(fig.15).The variation of θ with the buoyancy ratio N shows that when the molecular buoyancy ratio dominates over the thermal buoyancy force the temperature reduces with N when the forces act in the same direction and for the forces acting in opposite directions the temperature depreciates in the fluid region.(fig.16).An increase in S_0(>0) depreciates θ in the entire fluid region and it enhances with increase in │S_0│(<0)(figs.17&18).Also an increase in M decreases θ in the left region and enhances in the right region. The effect of the non-uniformity of the boundary is to enhance θ in the entire region with α(fig.19).As we move along the channel walls the temperature increases with x≤π/2 and depreciates with x≥ π(fig.20).

The concentration distribution (C) is depicted in figs.21-27 for different variations of the parameters. It is observed that the concentration is positive in the entire fluid region for G>0 in the left region and positive in the right region.. The magnitude of C enhances with increase in│G│(fig.21).Fig.23corresponds to the variation of C with R.It is observed that for an increase in R≤70 we notice an enhancement in the entire region except in the midregion where it experiences a depreciation .For further increase in R≥140,the concentration reduces in the left region and enhances in the right region.. From fig.22 we find that lesser the permeability of the porous medium larger the magnitude of the concentration in the left region and smaller the concentration. In the right region. When the molecular buoyancy force dominates over the thermal buoyancy force it enhances when the forces act in the same direction and for the forces acting in opposite directions the concentration depreciates in the fluid region(fig.23).Fig.24 corresponds to the variation of C with Soret parameter S_0. It is noticed that an increase in S_0(>0) depreciates C and enhances with increase in │S_0│(<0).Also the concentration enhances with M. The effect of the non-uniformity of the boundary temperature on the concentration shows that an increase in the amplitude α≤0.7 increases C in the left region and depreciates in the right region(fig.26).As we move along the axial direction the concentration depreciates in the left region and enhances in the right region for x≤π/2 and for higher x≥π the concentration enhances in the fluid region except in the midregion (fig.27 The rate of heat transfer (Nu) on y=±1 is exhibited in tables.13-18 for different variations. It is noticed that the rate of heat transfer on y=1 experiences an enhancement with increase in R for G>0 and decreases for G<0.An enhancement in │G│(<0>) leads to a reduction in │τ│ .In the case of heating of the channel walls the stress decreases with D^{-1} .Thus lesser the permeability of the porous medium smaller the magnitude of Nu(tab.13).For10^3≤G≤3x10^3 and for │G│≤10^3 we find a marginal decrease in Nu with increase in M(tab.14),From table.10 it is found that the rate of heat transfer increases with N(>0) and enhances with │N│(<0) (tab.14).Table.15 shows that lesser the molecular diffusivity smaller the magnitude of Nu at y=1.An increase in S_0(>0) reduces │Nu│ and for │S_0│(<0) we find an enhancement in │Nu│ (tab.16).Also │Nu│ depreciates with increase in the amplitude α of the boundary temperature(tab.17).For x≤π the magnitude of Nu enhances as we move along the axial direction while for further moving along the axial direction x≥π we notice a depreciation in │Nu│ for all │G│ except for G≤3x10^3 (tab.18).The rate of heat transfer on the left boundary y =-1 shows that │Nu│ enhances with │G│(<0>)and R .Also from table.19 we notice that lesser the permeability of the porous medium smaller the magnitude of Nu. hen

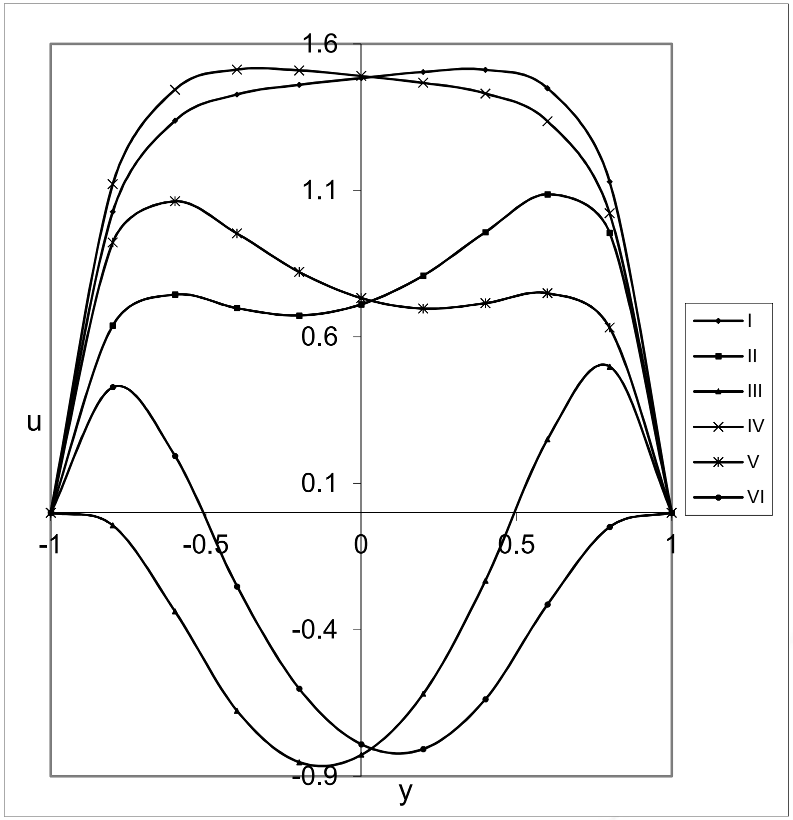

Fig.1 Profiles for u with G
D^{-1} = $2x10^3$, R = 35

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

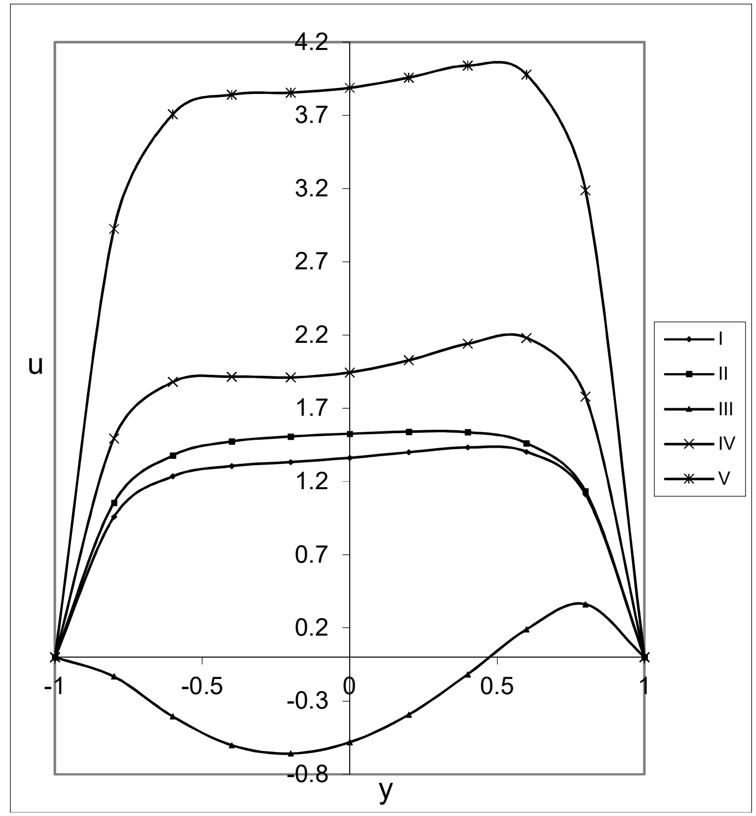

Fig.2 u with D &R
G= $3x10^3$,N=1,Sc=1.3,S_0=0.5

	I	II	III	IV	V
R	70	140	35	35	35
D^{-1}	$2x10^3$	$2x10^3$	10^3	$3x10^3$	10^4

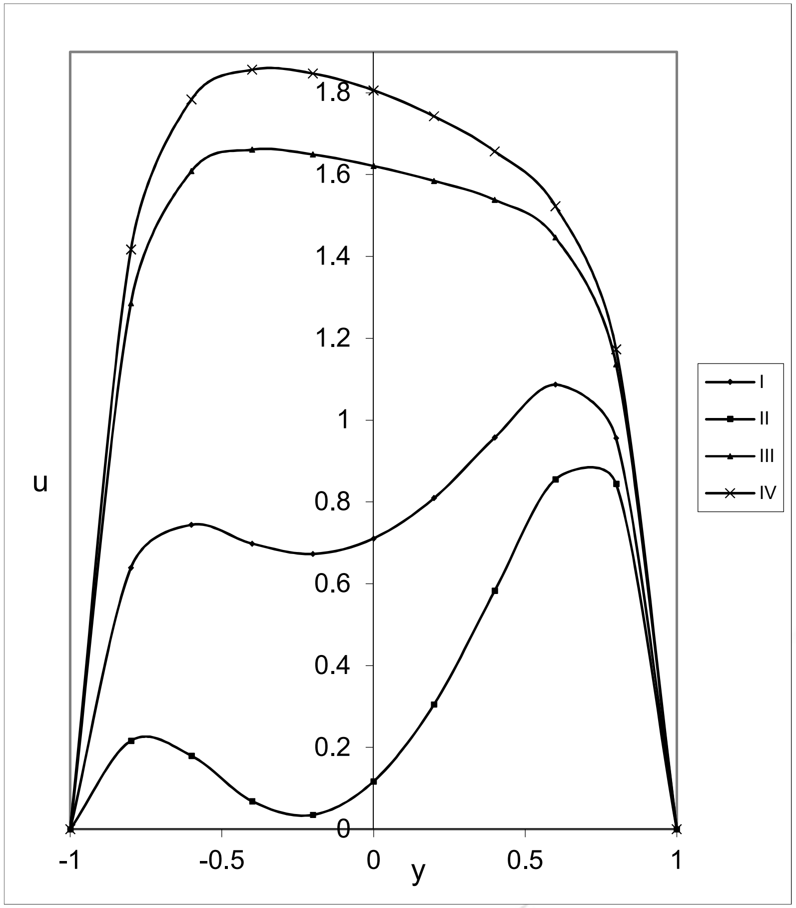

Fig.3 u with N

	I	II	III	IV
N	1.0	2.0	-0.5	-0.8

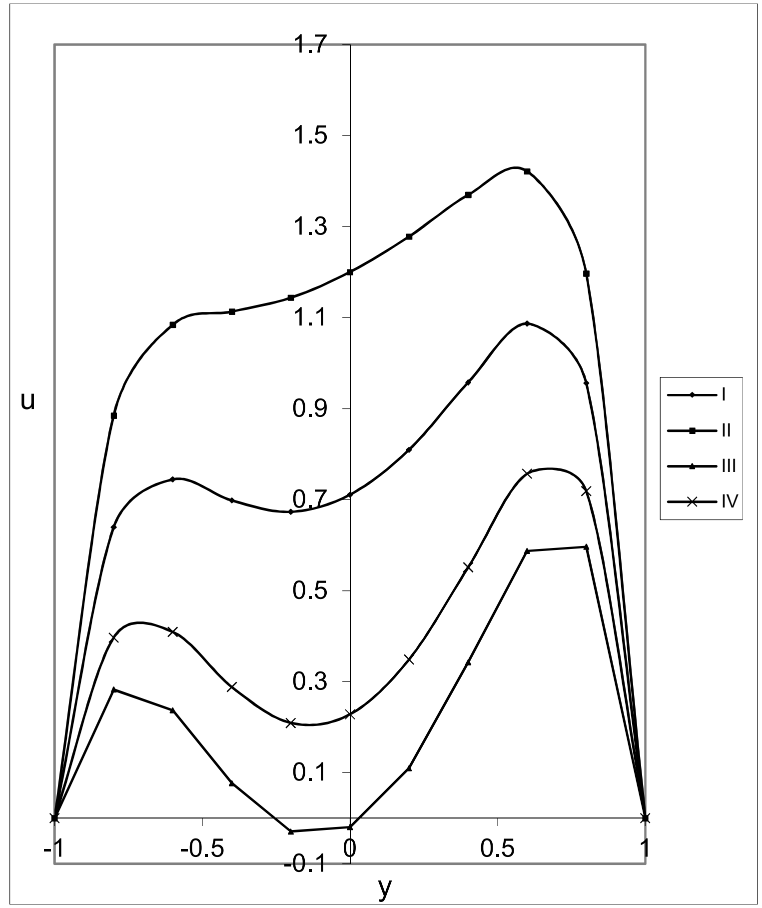

Fig.4 u with Sc

	I	II	III	IV
Sc	1.3	2.01	0.24	0.6

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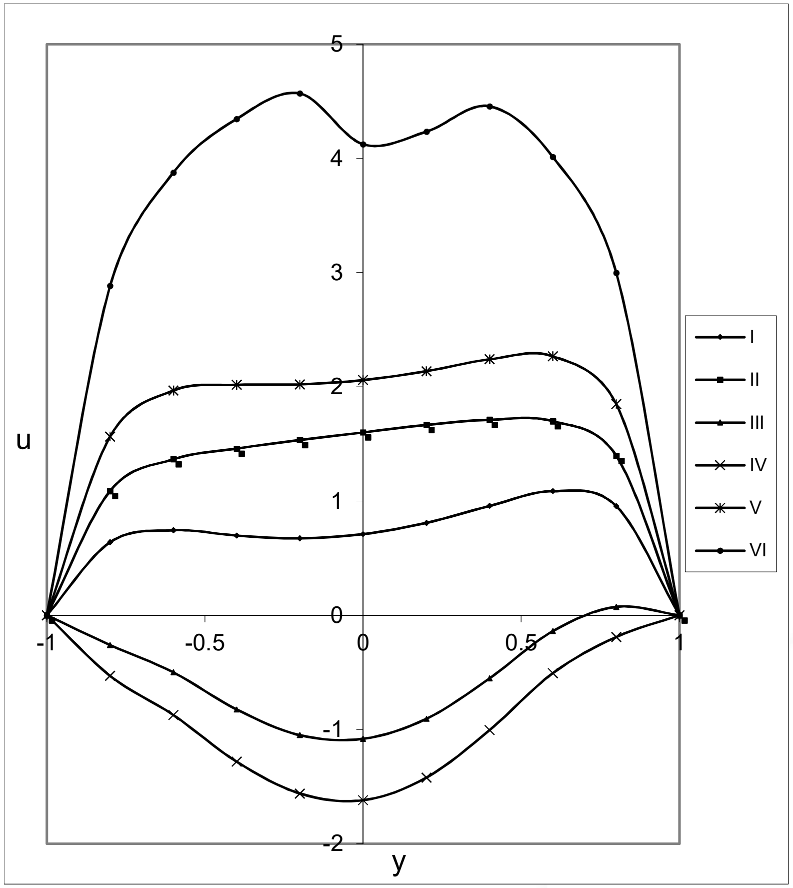

Fig.5 u with S_0& M

	I	II	III	IV	V	VI
S_o	0.5	1.0	-0.5	-1.0	0.5	0.5
M	2	2	2	2	4	6

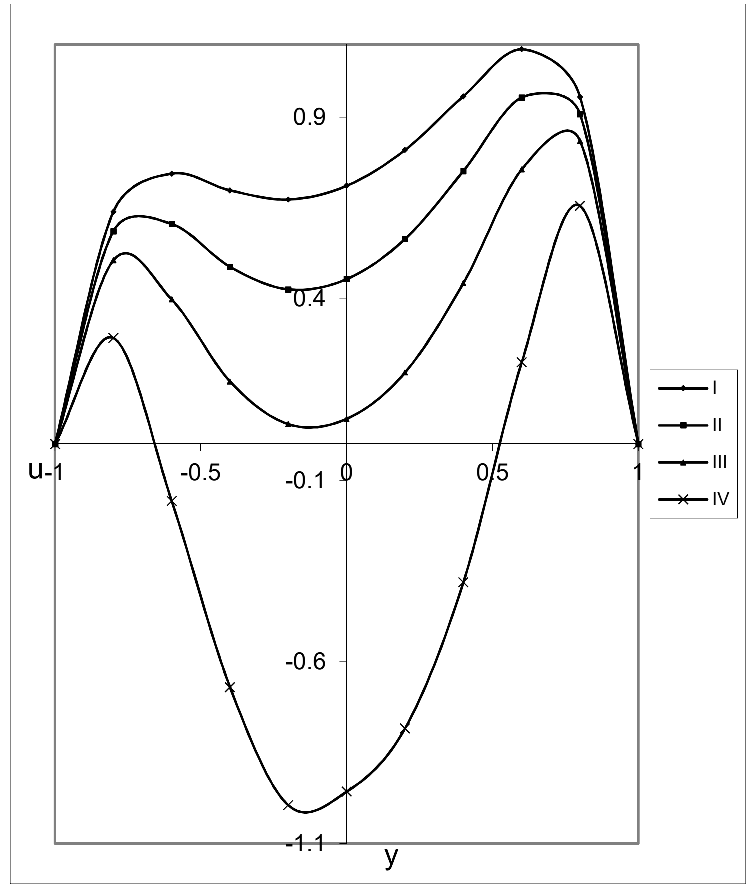

Fig.6 u with α

	I	II	III	IV
α	0.2	0.4	0.6	1.5

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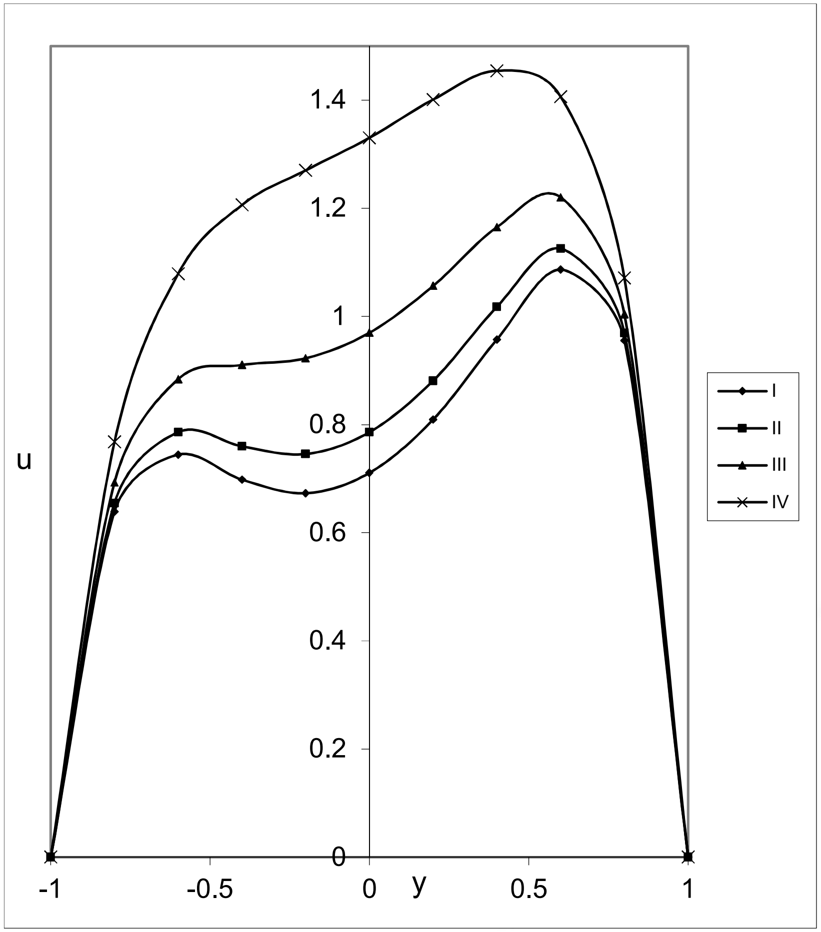

Fig.7 u with x

	I	II	III	IV
x	π/4	π/3	π/2	π

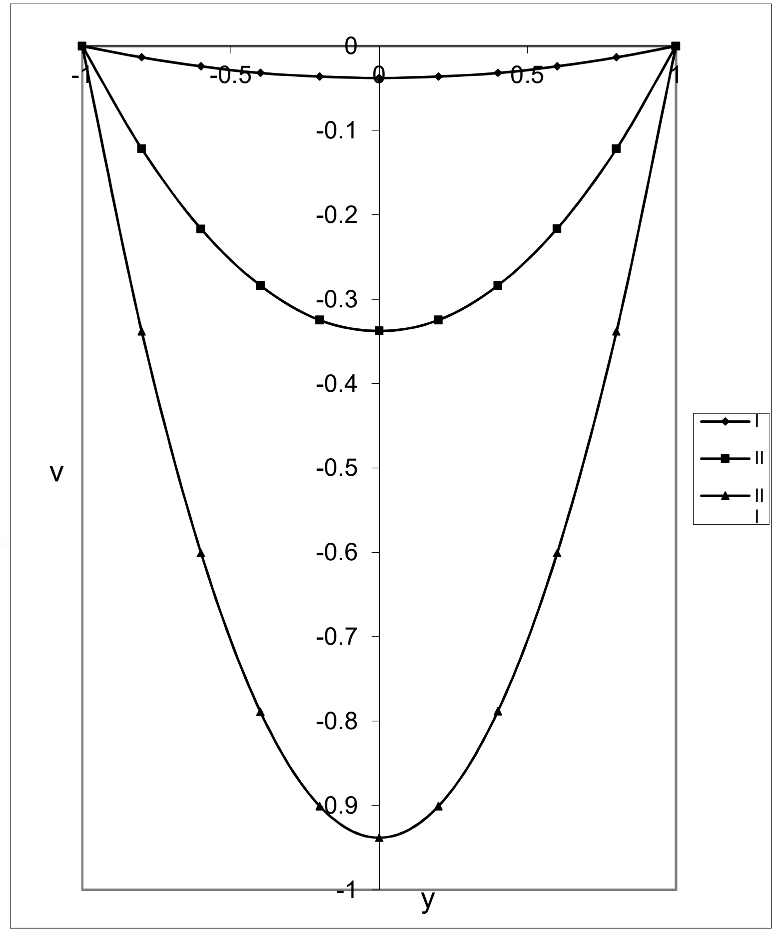

Fig.8 Profiles of secondary velocity (v) with G

	I	II	III
G	10^3	$3x10^3$	$5x10^3$

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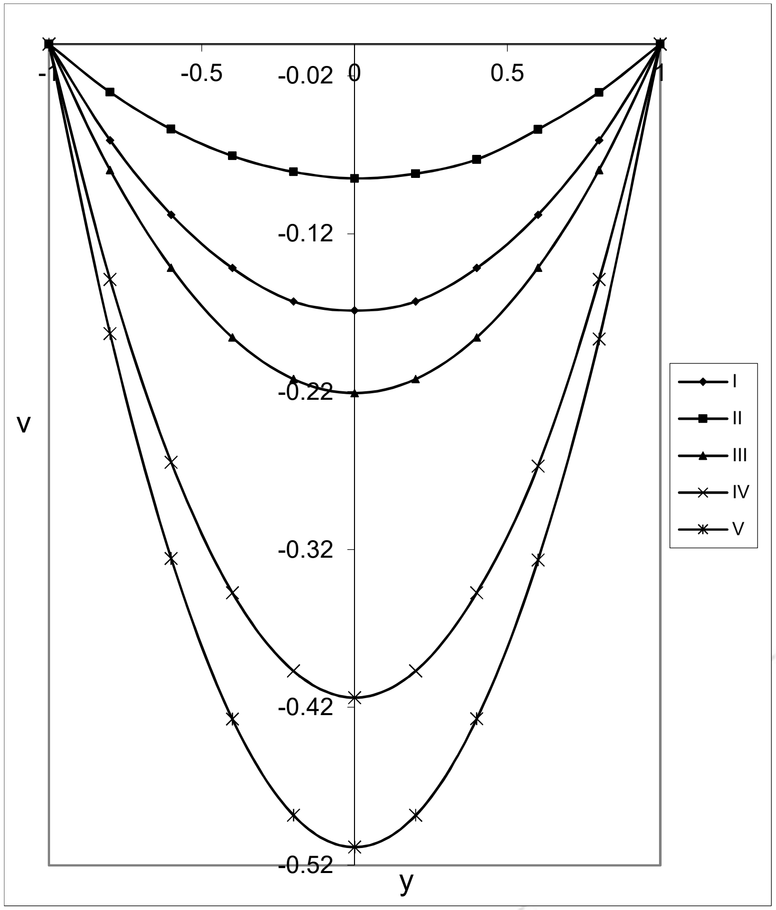

Fig.9 V with R& D
G =3x10^3 ,Sc =1.3
I II III IV
N 1 2 -0.5 -0.8

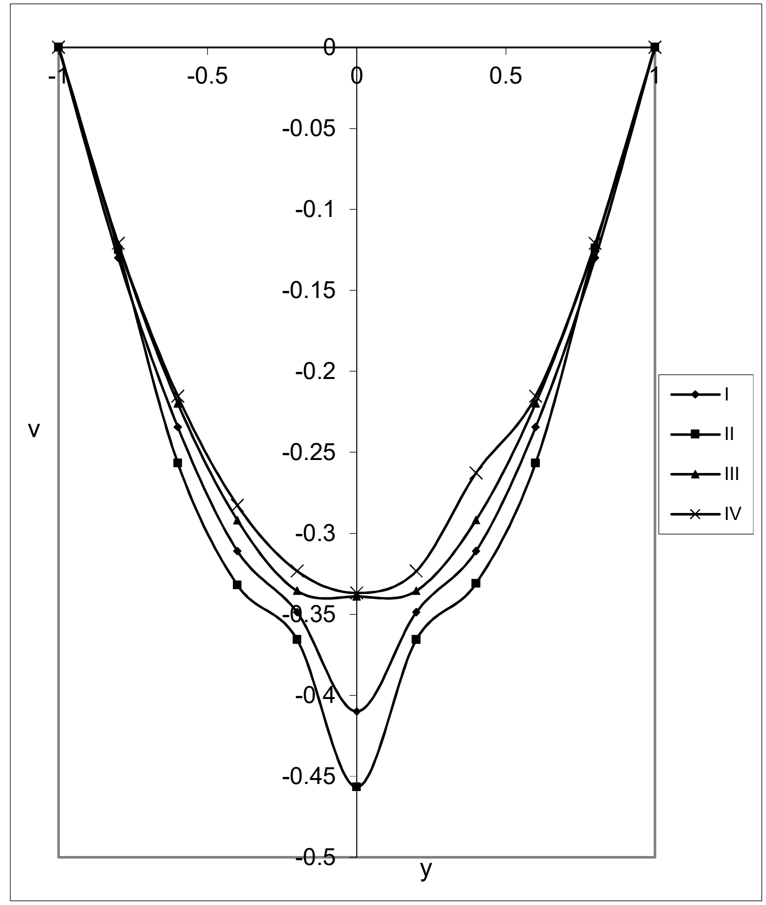

Fig.10 V with N
I II III IV
N 1 2 -0.5 -0.8

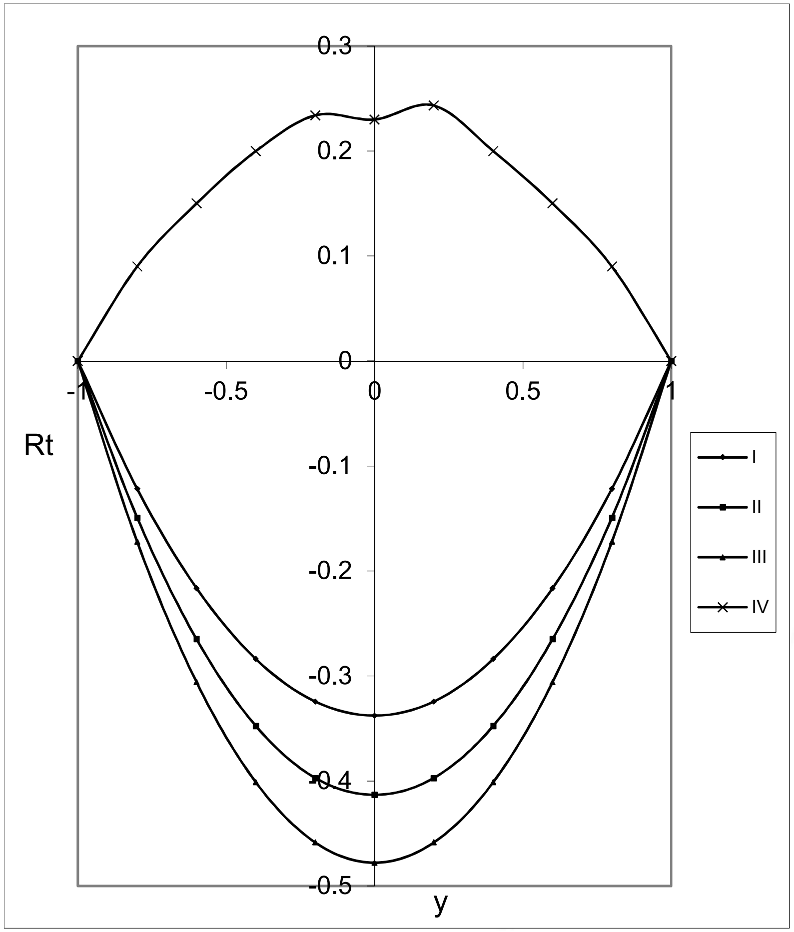

Fig.11 v with x

	I	II	III	IV
x	π/4	π/3	π/2	π

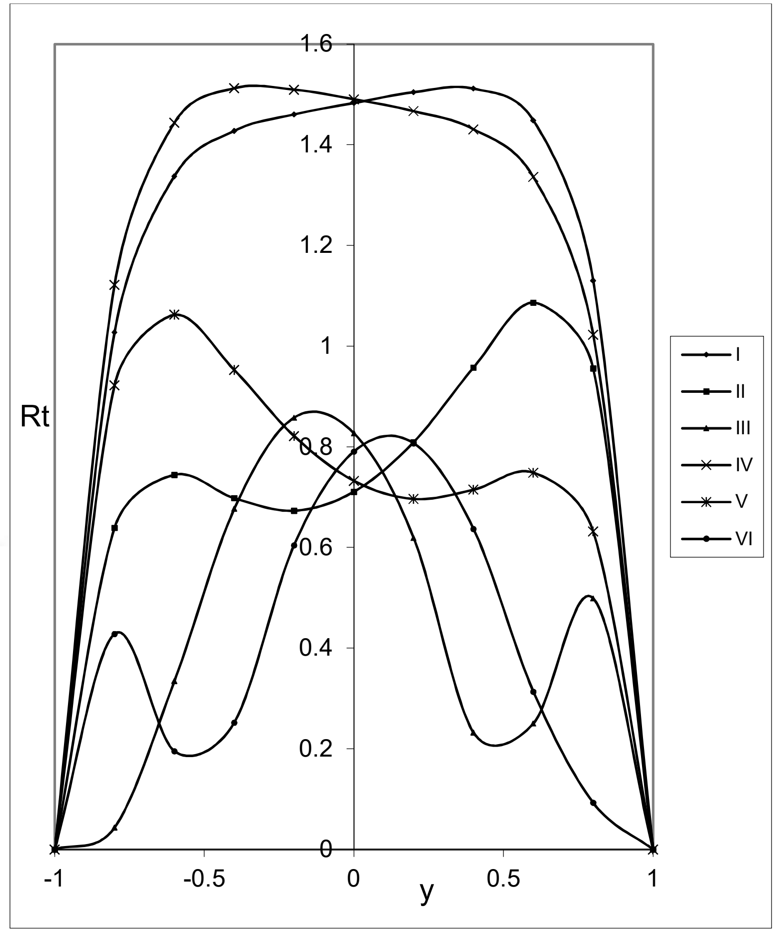

Fig.12 Variation of Resultant Velocity(Rt) with G

	I	II	III	IV	V	VI
Rt	10^3	$3x10^3$	$5x10^3$	-10^3	$-3x10^3$	$-5x10^3$

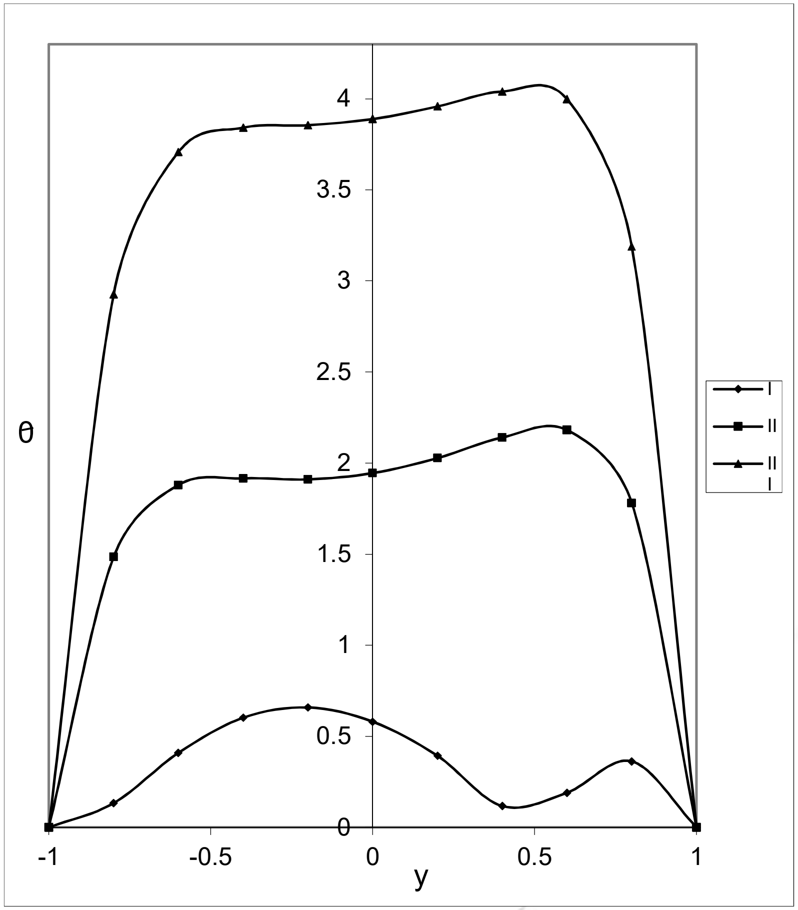

Fig.13 Rt with D^{-1}

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

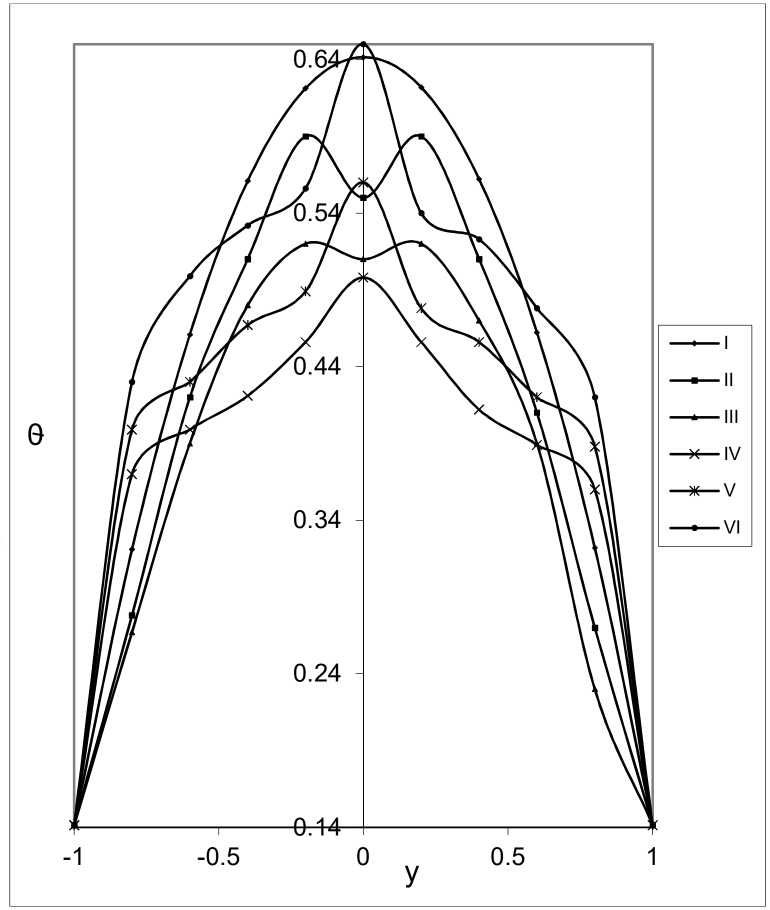

Fig.14 Variation of temperature(θ) with G

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

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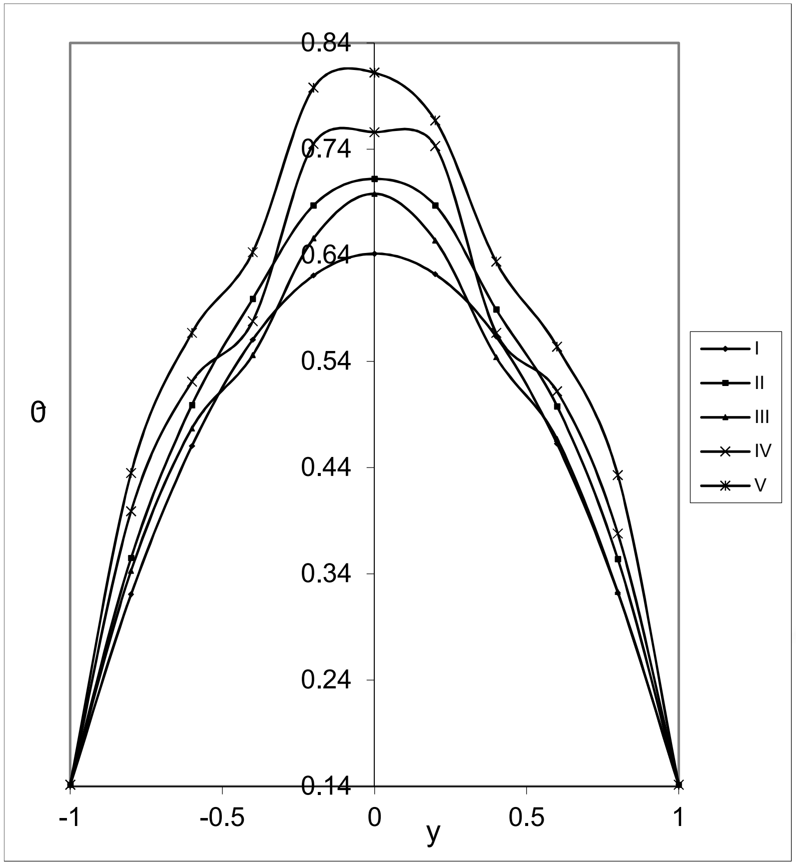


Fig.15 θ with R&D

	I	II	III	IV	V
R	35	70	140	35	35
D^{-1}	$2x10^3$	$2x10^3$	$2x10^3$	10^3	$3x10^3$

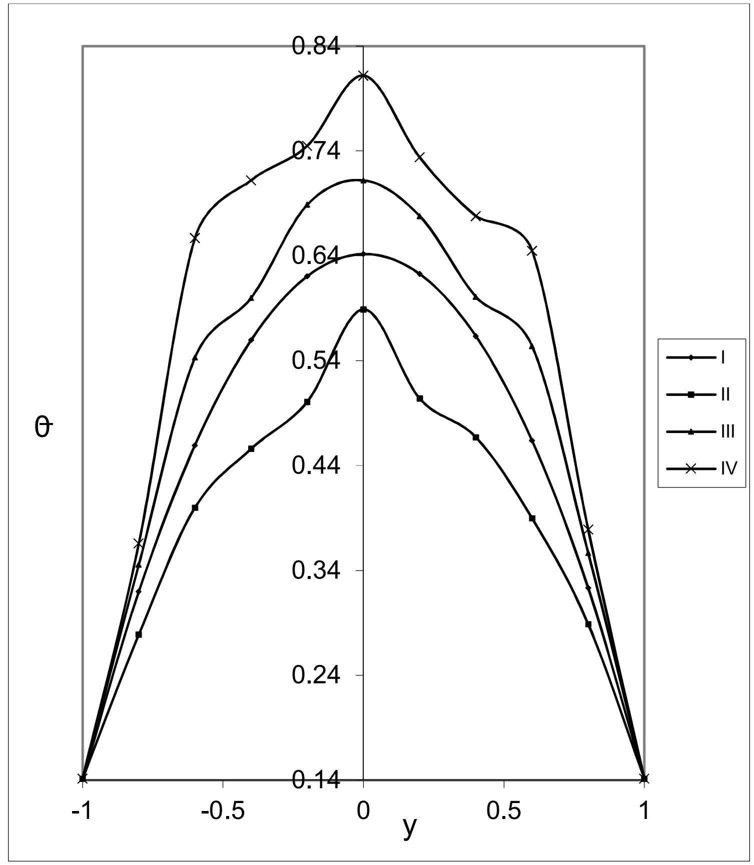


Fig.16 θ with N

	I	II	III	IV
N	1	2	-0.5	-0.8

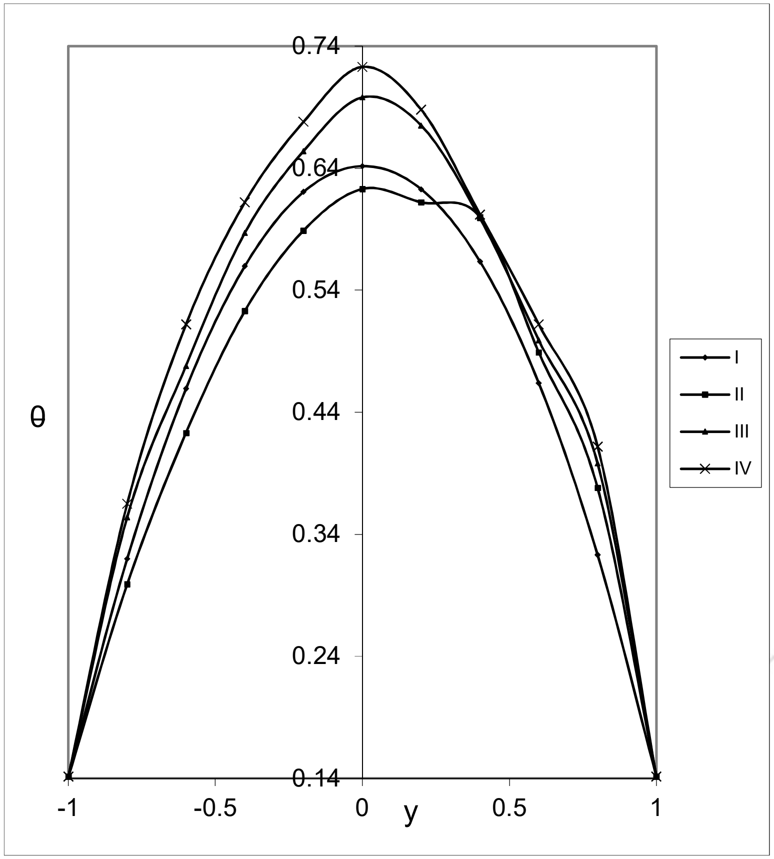


Fig.17 θ with Sc
S_0=0.4,N=1,R=35

	I	II	III	IV
1. Sc	1.3	2.01	0.24	0.6

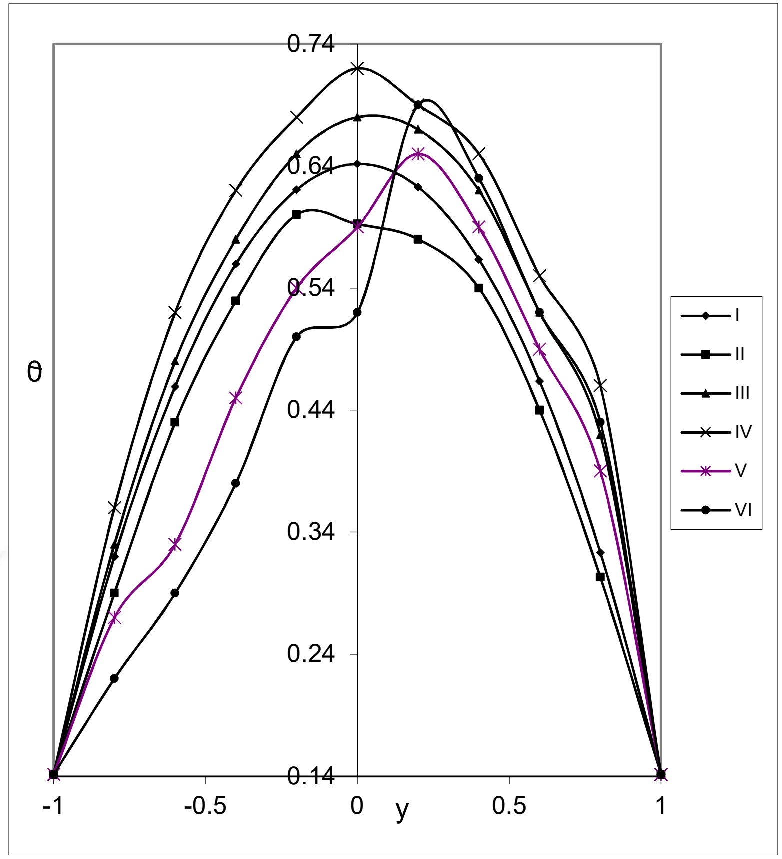
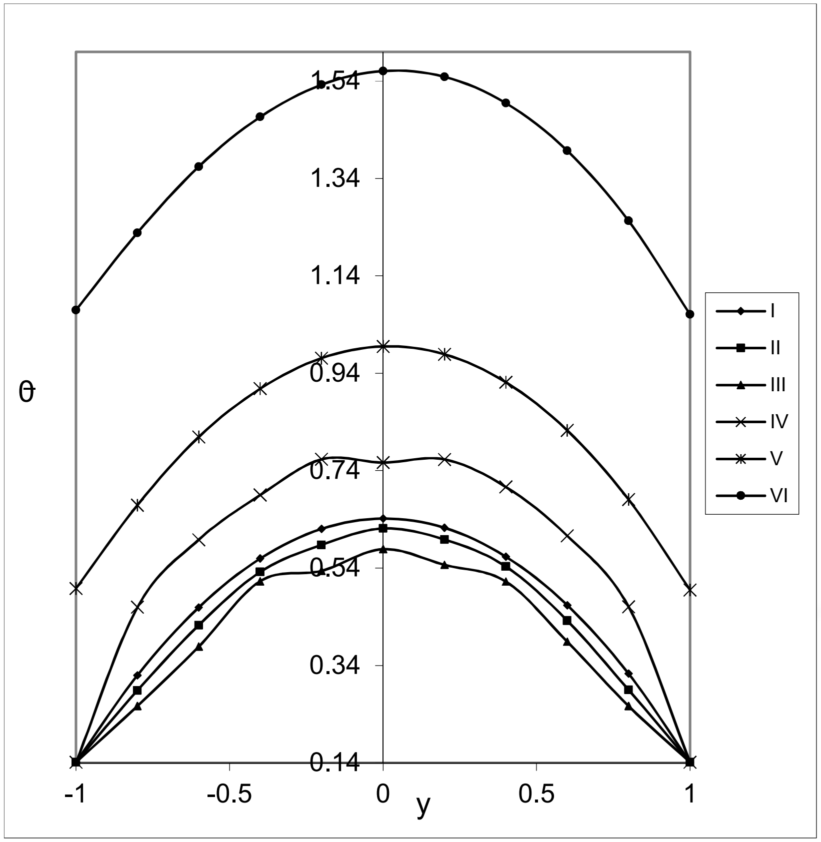
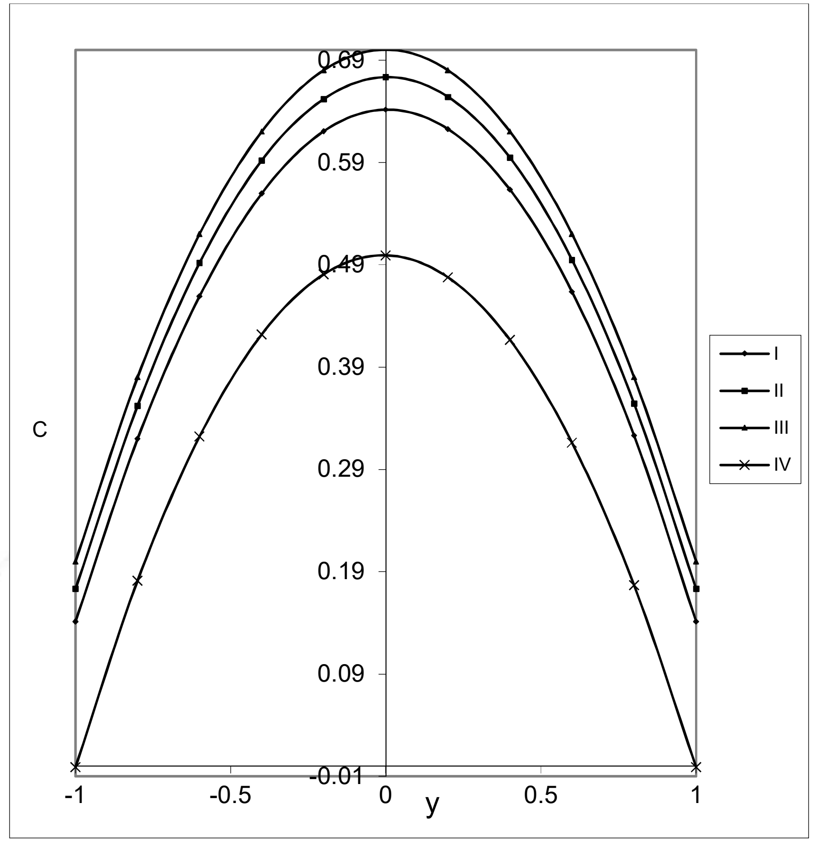


Fig.18 θ with S_0& M

	I	II	III	IV	V	VI
S_0	0.5	1.0	-0.5	-1.0	0.5	0.5
M	2 2	2	2	4	6	





with α

Fig.20 θ with x

	I	II	III	IV
α	0.2	0.4	0.7	1.5

	I	II	III	IV
x	π/4	π/3	π/2	π

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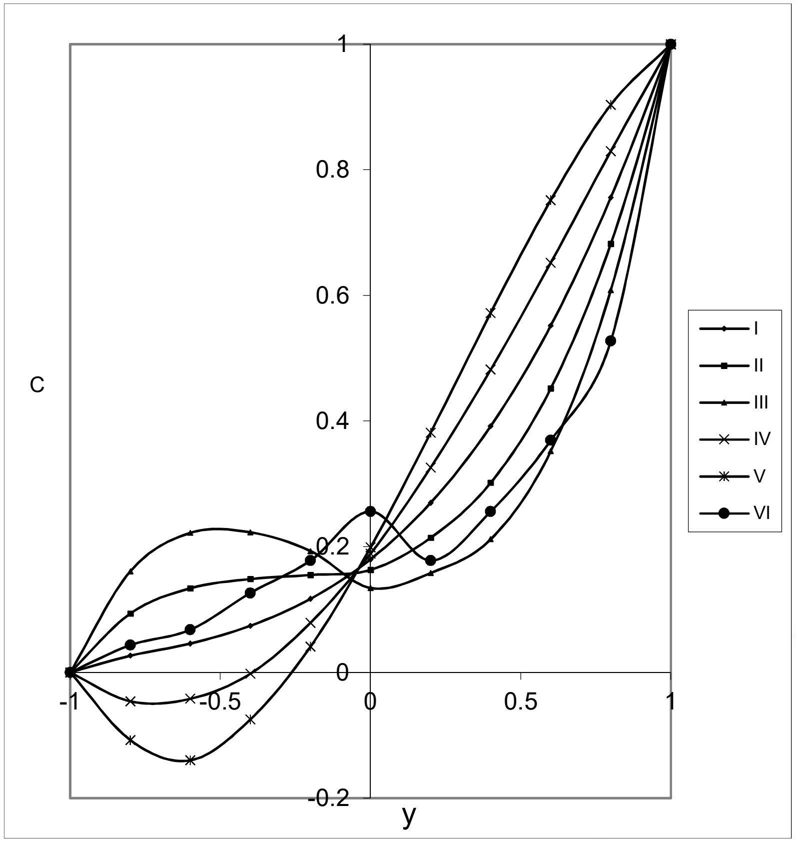

Fig.21 Variation of Concentration(c) with G
$D^{-1}=2x10^3$,N=1,Sc=1.3

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

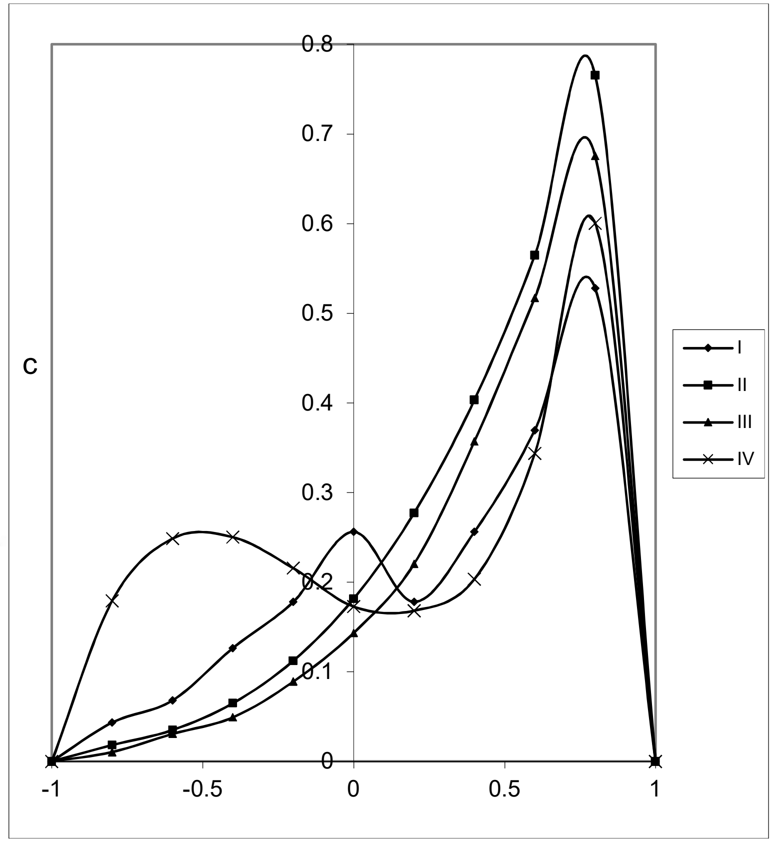

Fig.22 C with R&D
$G=3x10^3$,N=1,R=35,Sc=1.3

	I	II	III	IV
R	70	140	35	35
D^{-1}	$2x10^3$	$2x10^3$	10^3	$3x10^3$

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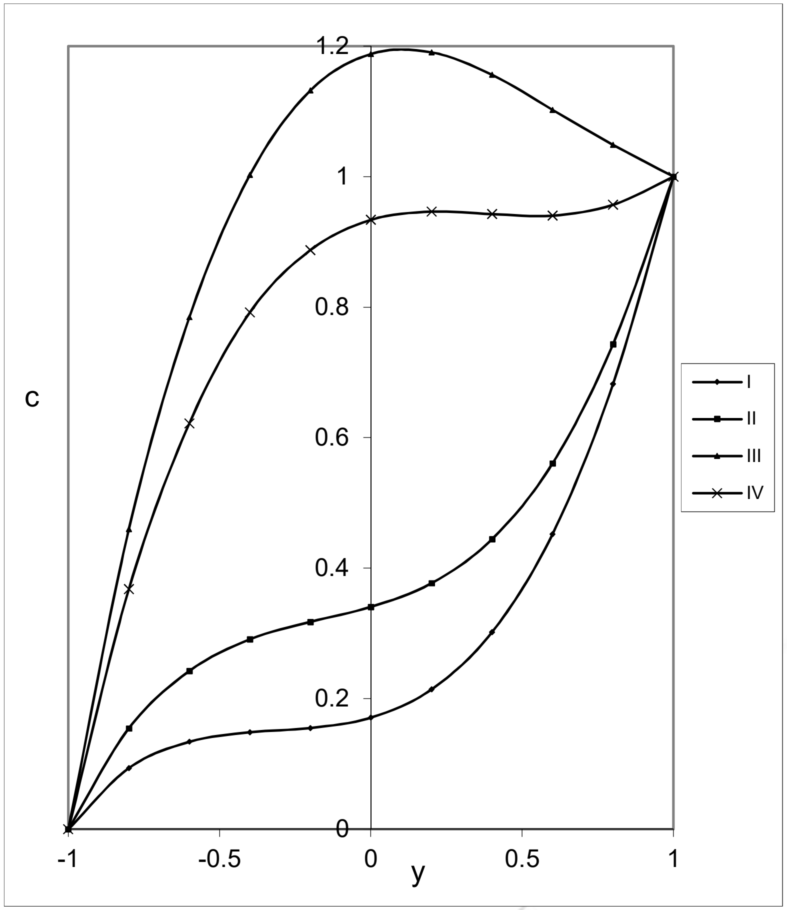

Fig.23 C with N
$S_0 = 0.5, R=35, D^{-1}=2x10^3$

	I	II	III	IV
N	1	2	-0.5	-0.8

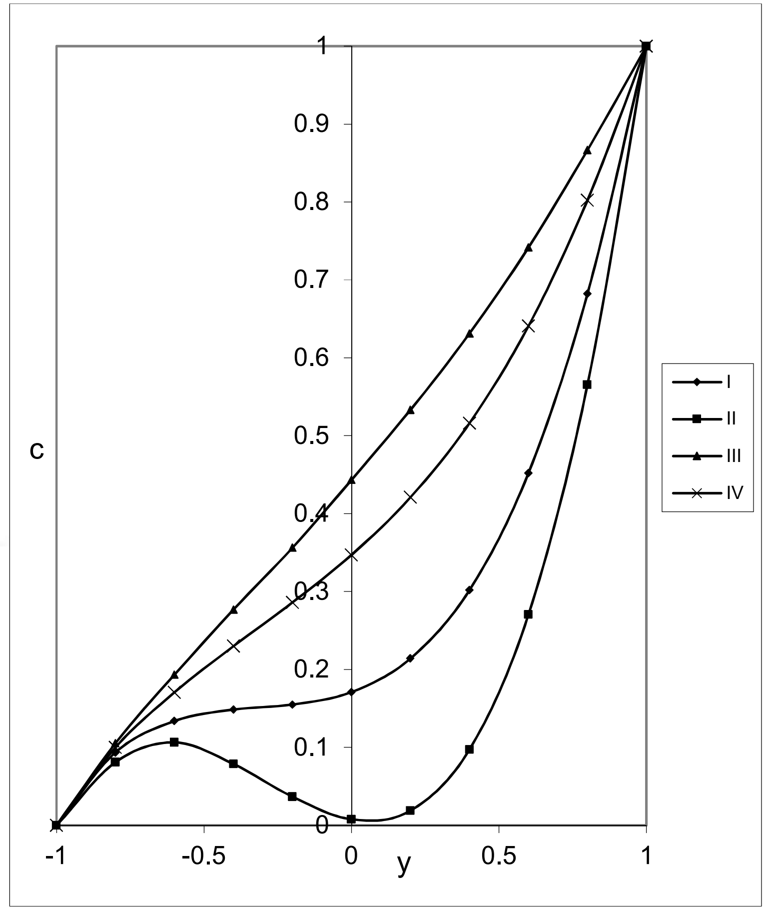

Fig.24 C with Sc

	I	II	III	IV
Sc	1.3	2.01	0.24	0.6

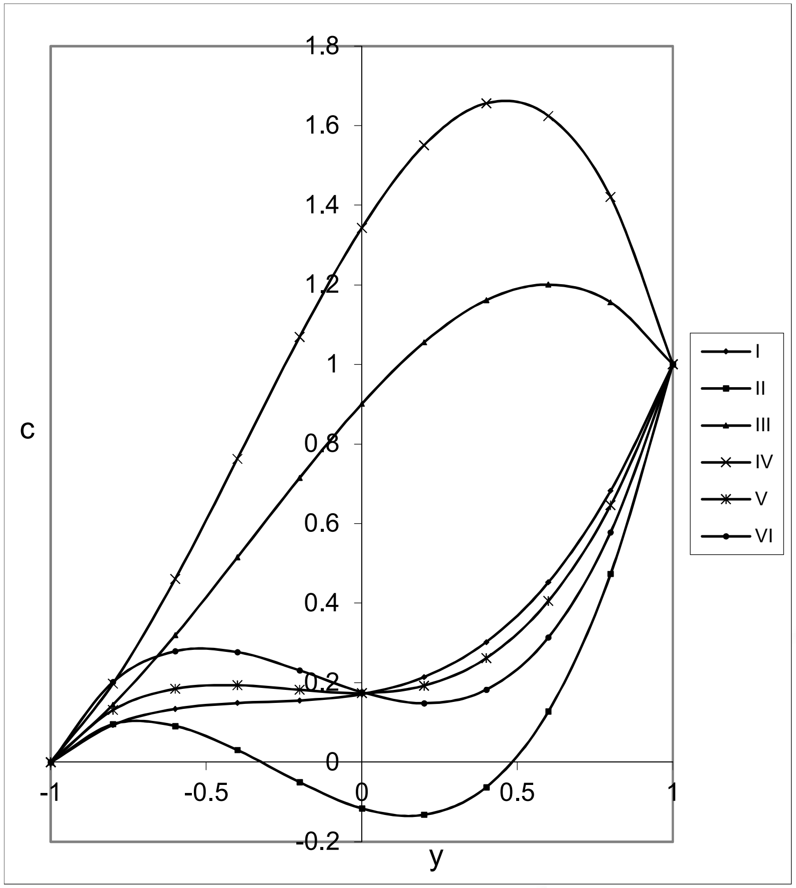

Fig.25 C with S_0&M

	I	II	III	IV	V	VI
S_0	0.5	1.0	-0.5	-1.0	0.5	0.5
M	2	2 2		2	4	6

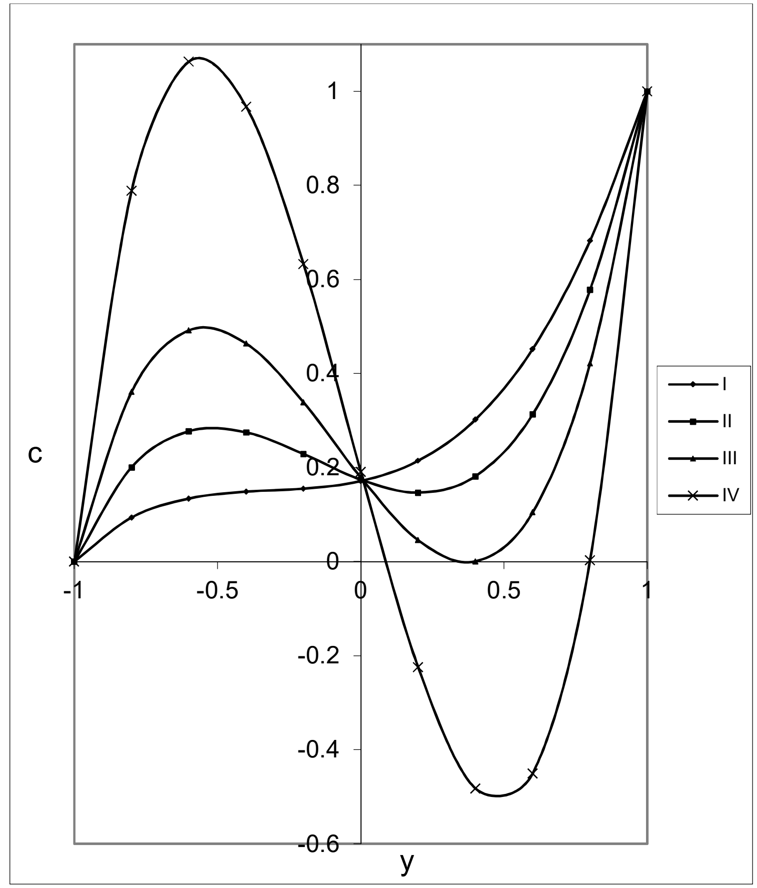

Fig.26 C with α

	I	II	III	IV
α	0.2	0.4	0.7	1.5

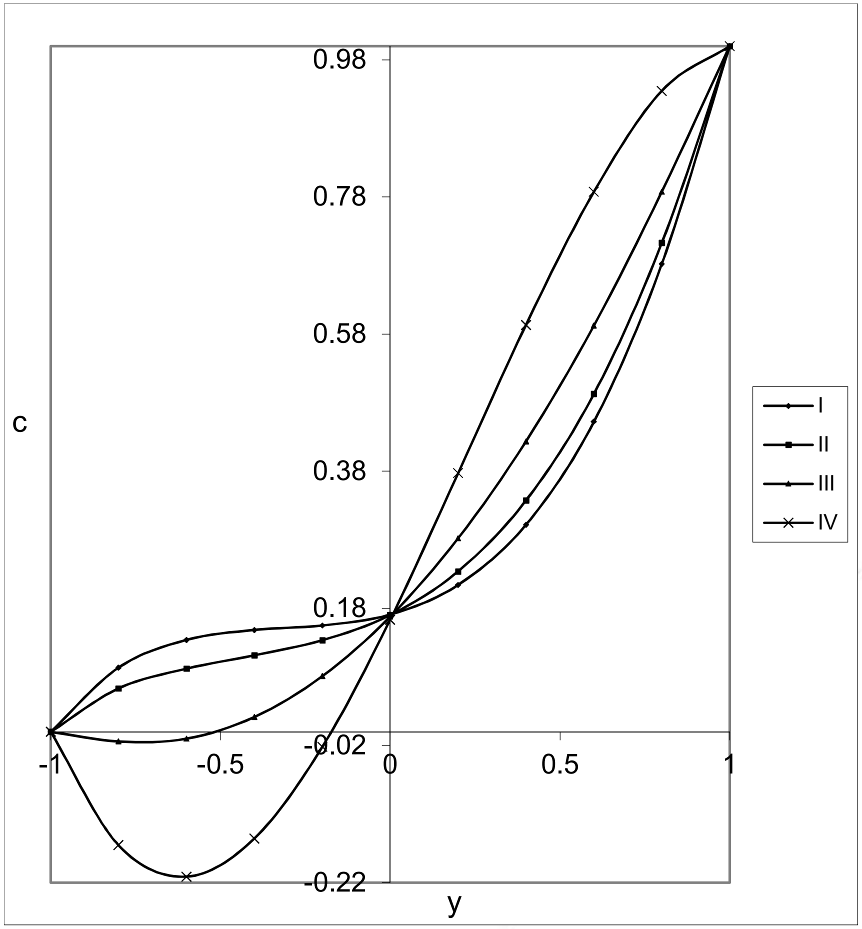

Fig.27 C with x

	I	II	III	IV
X	π/4	π/3	π/2	π

Table.1
Average Nusselt Number(Nu) at y= -1
P=0.71,Sc=1.3,S=0.5,N=1

G\Nu	I	II	III	IV	V	VI
10^3	-0.1127	-0.2871	-0.3424	-0.1661	-0.1428	-0.0472
$3x10^3$	-0.0195	-0.0726	-0.0984	-0.0267	-0.0239	-0.0125
$5x10^3$	-0.0853	-0.0363	-0.0535	-0.0109	-0.0111	-0.0059
-10^3	-0.9273	0.3563	0.3385	-2.4034	-2.3752	-0.1315
$-3x10^3$	-0.0221	0.2209	0.1361	-0.0423	-0.0346	-0.0039
$-5x10^3$	-0.0058	1.0153	0.0986	-0.0126	-0.0098	0.0017

	I	II	III	IV	V	VI
D^{-1}	$3x10^3$	$3x10^3$	$3x10^3$	10^3	$2x10^3$	$5x10^3$
R	35	70	140	35	35	35

Table.2
Average Nusselt Number(Nu) at y= -1
P=0.71,Sc=1.3,S=0.5,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV	V	VI
10^3	-0.1127	-0.0985	0.2829	0.3756	0.0838	-0.0651
$3x10^3$	-0.0195	-0.0182	-0.1281	-0.1747	-0.0154	-0.0126
$5x10^3$	-0.0853	-0.0081	-0.0208	-0.0245	-0.0071	-0.0061
-10^3	-0.9273	-0.3553	-0.1194	-0.1785	-0.3191	-0.1331
$-3x10^3$	-0.0221	-0.0117	-0.0254	-0.0401	-0.0101	-0.0036
$-5x10^3$	-0.0058	-0.0021	-0.0116	-0.0193	-0.0017	-0.0004

	I	II	III	IV	V	VI
N	1	2	-0.5	-0.8	1	1
M	2	2	2	2	4	6

Table.3
Average Nusselt Number(Nu) at y = -1
P=0.71,M=2,S=0.5,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV
10^3	-0.1127	-0.1039	-0.1292	-0.1231
$3x10^3$	-0.0195	-0.0183	-0.0221	-0.0209
$5x10^3$	-0.0853	-0.0081	-0.0093	-0.0091
-10^3	-0.9273	-1.3578	-0.6292	-0.7064
$-3x10^3$	-0.0221	-0.0219	-0.0226	-0.0225
$-5x10^3$	-0.0058	-0.0056	-0.0061	-0.0059

	I	II	III	IV
Sc	1.3	2.01	0.24	0.6

Table.4
Average Nusselt Number(Nu) at y = -1
P=0.71,M=2,Sc=1.3,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV
10^3	-0.1127	-0.0975	0.1639	-0.2121
$3x10^3$	-0.0195	-0.0175	-0.0255	-0.0321
$5x10^3$	-0.0853	-0.0077	-0.0108	-0.0125
-10^3	-0.9273	-2.2099	-0.4288	-0.3379
$-3x10^3$	-0.0221	-0.0215	-0.0232	-0.0239
$-5x10^3$	-0.0058	-0..0055	-0.0064	-0.0068

	I	II	III	IV

S_0	0.5	1.0	-0.5	-1.0

Table.5
Average Nusselt Number(Nu) at y = -1
P=0.71,M=2,Sc=1.3,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV
10^3	-0,.1289	-0.1007	-0.0876	-0.0731
$3x10^3$	-0.0232	-0.0172	-0.0148	-0.0126
$5x10^3$	-0.0101	-0.0076	-0.0067	-0.0059
-10^3	2.4676	-0.3774	-0.1927	-0.1001
$-3x10^3$	-0.0386	-0.0145	-0.0086	-0.0038
$-5x10^3$	-0.0103	-0.0035	-0.0016	0.0002

	I	II	III	IV
α_1	0.3	0.7	0.9	1.5

Table.6
Average Nusselt Number(Nu) at y = -1
P=0.71,M=2,Sc=1.3,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV
10^3	-0.1127	-0.1256	-0.1765	-1.1827
$3x10^3$	-0.0195	-0.0221	-0.0359	0.0386
$5x10^3$	-0.0853	-0.0096	-0.0156	0.0081
-10^3	-0.9273	7.8849	0.3577	0.1422
$-3x10^3$	-0.0221	-0.0327	-0.0409	0.0292
$-5x10^3$	-0.0058	-0.0089	-0.0468	0.0136

	I	II	III	IV
x	π/4	π/3	π/2	π

Table.7
Average Nusselt Number(Nu) at y= 1
P=0.71,Sc=1.3,S=0.5,N=1

G\Nu	I	II	III	IV	V	VI
10^3	-0.1127	-0.2871	-0.3424	0.1661	-0.1428	-0.0647
$3x10^3$	-0.0195	-0.0726	-0.0984	0.0267	-0.0239	-0.0124
$5x10^3$	-0.0853	-0.0363	-0.0535	-0.0109	-0.0111	-0.0059
-10^3	-0.9273	0.3563	0.3385	-2.4034	-2.3752	-0.1315
$-3x10^3$	-0.0221	0.2209	0.1361	-0.0423	-0.0346	-0.0039
$-5x10^3$	-0.0058	1.0153	0.0986	-0.0126	-0.0098	0.0017

	I	II	III	IV	V	VI
D^{-1}	$3x10^3$	$3x10^3$	$3x10^3$	10^3	$2x10^3$	$5x10^3$
R	35	70	140	35	35	35

Table.8
Average Nusselt Number(Nu) at y = 1
P=0.71,Sc=1.3,S=0.5,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV	V	VI
10^3	-0.1127	-0.0985	0.2829	0.3756	0.0838	-0.0651
$3x10^3$	-0.0195	-0.0181	-0.1281	-0.1747	-0.0154	-0.0126
$5x10^3$	-0.0853	-0.0081	-0.0208	-0.0245	-0.0071	-0.0061
-10^3	-0.9273	-0.3553	-0.1194	-0.1785	-0.3191	-0.1331
$-3x10^3$	-0.0221	-0.0117	-0.0254	-0.0401	-0.0101	-0.0036
$-5x10^3$	-0.0058	-0.0021	-0.0116	-0.0192	-0.0017	-0.0004

	I	II	III	IV	V	VI

N	1	2	-0.5	-0.8	1	1
M	2	2	2	2	4	6

Table.9
Average Nusselt Number(Nu) at y = 1
P=0.71,M=2,S=0.5,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV
10^3	-0.1127	-0.1039	-0.1292	-0.1231
$3x10^3$	-0.0195	-0.0181	-0.0221	-0.0209
$5x10^3$	-0.0853	-0.0081	-0.0093	-0.0091
-10^3	-0.9273	-1.3578	-0.6292	0.7064
$-3x10^3$	-0.0221	-0.0219	-0.0226	-0.0225
$-5x10^3$	-0.0058	-0.0056	-0.0061	-0.0059

	I	II	III	IV
Sc	1.3	2.01	0.24	0.6

Table.10
Average Nusselt Number(Nu) at y = 1
P=0.71,M=2,Sc=1.3,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV
10^3	-0.1127	-0.0975	-0.1639	-0.2121
$3x10^3$	-0.0195	-0.0175	-0.0255	-0.0301
$5x10^3$	-0.0853	-0.0077	-0.0108	-0.0125
-10^3	-0.9273	-2.2099	-0.4288	-0.3379
$-3x10^3$	-0.0221	-0.02165	-0.0232	-0.0239
$-5x10^3$	-0.0058	-0.0055	-0.0064	-0.0068

	I	II	III	IV
S_0	0.5	1.0	-0.5	-1.0

Table.11
Average Nusselt Number(Nu) at y = 1
P=0.71,M=2,Sc=1.3,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV
10^3	-0.1287	-0.1007	-0.0876	-0.0731
$3x10^3$	-0.0132	-0.0172	-0.0148	-0.0126
$5x10^3$	-0.0101	-0.0076	-0.0067	-0.0059
-10^3	2.4676	-0.3774	-0.1927	-0.1001
$-3x10^3$	-0.0386	-0.0145	-0.0086	-0.0038
$-5x10^3$	-0.0103	-0.0035	-0.0016	0.0002

	I	II	III	IV
α_1	0.3	0.7	0.9	1.5

Table.12
Average Nusselt Number(Nu) at y = 1
P=0.71,M=2,Sc=1.3,$D^{-1}=3x10^3$

G\Nu	I	II	III	IV
10^3	-0.1127	-0.1256	-0.1765	-1.1827
$3x10^3$	-0.0195	-0.0221	-0.0359	0.0386
$5x10^3$	-0.0853	-0.0096	-0.01569	0.0081
-10^3	-0.9273	7.8849	0.3577	0.1422
$-3x10^3$	-0.0221	-0.0327	-0.0492	0.0292
$-5x10^3$	-0.0058	-0.0087	-0.0467	0.0136

	I	II	III	IV

x	π/4	π/3	π/2	π

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