International Journal of Mathematical Archive-4(4), 2013, 197-207
IJMA Available online through www.ijma.info ISSN 2229 – 5046

TRANSIENT CONVECTIVE HEAT AND MASS TRANSFER THROUGH A POROUS MEDIUM IN A VERTICAL CHANNEL WITH SORET EFFECTS

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(Received on: 10-03-13; Revised & Accepted on: 03-04-13)

ABSTRACT

We analyze the unsteady free connective heat and mass transfer flow through a porous medium in a vertical channel with the unsteadiness in the flow is due to the travelling thermal wave imposed on the wall $y = L$. The coupled equations governing the flow, heat and mass transfer have been solved by using a perturbation technique with the aspect ratio as perturbation parameter. The expression for the velocity, the temperature, the concentration ,the shear stress and the rate of heat and mass transfer are derived and are analysed for different variations of the governing parameters G,N,Sc,So,α and γ.

Key words: *Convective heat and mass transfer, Soret effect, Porous medium, Vertical Channel etc.*

INTRODUCTION:

The time dependent thermal convection flows have applications in Chemical engineering, Space technology etc. These flows can also be achieved by either time dependent movement of the boundary or unsteady temperature of the boundary. Flows which arise due to the interaction of the gravitational force and density differences caused by the simultaneous diffusion of thermal energy and chemical species have many applications in geophysics and engineering. Such thermal and mass diffusion plays a dominant role in a number of technological and engineering systems [3, 6, 9]. Convection fluid flows generated by travelling thermal waves have also received attention due to applications in physical problems. The linearised analysis of these flows has shown that a travelling thermal wave cal generate a mean shear flow within a layer of fluid, and the induced mean flow is proportional to the square of the amplitude of the wave. From a physical point of view, the motion induced by travelling thermal waves is quite interesting as a purely fluid-dynamical problem and can be used as a possible explanation for the observed four-day retrograde zonal motion of the upper atmosphere of Venus. Also, the heat transfer results will have a definite bearing on the design of oil-or gas–fired boilers. Several authors Ravindra [16], Vajravelu and Debnath [18], Purushotham Reddy [14] Naga Leela Kumari and Sarojamma [13] have studied convection with respect to different conditions.

Channels are frequently used in various applications in designing ventilating and heating of buildings, cooling electronic components, drying several types of agriculture products grain and food, and packed bed thermal storage. Convective flows in channels driven by temperature differences of bounding walls have been studied and reported, extensively in literature. Applied magnetic field on transient free convective flow of an incompressible viscous dissipative fluid in a vertical channel was analyzed by Ananda Rao and Srinivasa Raju [1]. Madhusudhan Reddy and Prasada Rao [12] studied the effect of thermo diffusion and chemical reaction on non darcy convective heat and mass transfer flow in a vertical channel with radiation. Devi *et at*. [7] looked the effect of chemical reaction on double-diffusive flow in a non uniformly heated vertical channel. Dileep Singh and Priyanka Rastogi [8] examined the radiation effects on natural convection MHD flow in a rotating vertical porous channel partially filled with a porous medium. Reddaiah and Prasada Rao [17] discussed the effect of radiation on unsteady hydromagnetic convective heat transfer flow of a viscous fluid through a porous medium in a vertical channel with traveling thermal waves and heat sources. Ananda Rao and Prabhakar Reddy [2] studied the numerical solution of mass transfer in MHD free convective flow of a viscous fluid through a vertical channel. Atul Kumar Singh [4] discussed the effects of mass transfer on MHD free convective flow of a viscous fluid through vertical channel. Jafarunnisa *et al.* [10] examined the effect of chemical reaction and radiation absorption on unsteady double diffusive flow in a vertical channel with heat generating sources.

In all these problems the Soret effect has been neglected. This is possible if the flow takes place at low concentration levels. But there are some solutions where we have to take Soret effect into consideration. Ramana Reddy *et al.* [15]

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discussed the unsteady MHD free convective mass transfer flow past an infinite vertical porous plate with variable suction and Soret effect. Jha and Singh [11] analyzed Soret effects on free-convection and mass transfer flow in the Stokes problem for an infinite vertical plate.

In this paper we analyse the convective heat and mass transfer through a porous medium in a vertical channel with Soret effect. The equations governing the flow, heat and mass transfer have been solved by using a regular perturbation technique. The effect of various governing parameters on velocity, temperature, concentration, shear stress, the rate of heat and mass transfer is analyzed.

2. FORMULATION OF THE PROBLEM

We consider the motion of viscous, incompressible fluid through a porous medium in a vertical channel bounded by flat walls. The thermal buoyancy in the flow field is created by a travelling thermal wave imposed on the boundary wall at y = L while the boundary at y = -L is maintained at constant temperature T_1.and concentration C_1.The viscous and Darcy dissipations are neglected in the energy equation. Also the kinematic viscosity ν, the thermal conducting k are treated as constants. We choose a rectangular Cartesian system O(x, y) with x-axis in the vertical direction and y-axis normal to the walls. The equations governing the unsteady flow, heat and mass transfer in terms of stream function ψ under Brinkman model (5) are

$$\partial[(\nabla^2\psi)_t+\psi_x(\nabla^2\psi)_y-\psi_y(\nabla^2\psi)_x]=\nu\nabla^4\psi-\beta g(T-T_0)_y-\beta^* g(C-C_0)_y-\left(\frac{\nu}{k}\right)\nabla^2\psi \tag{1}$$

$$\rho_e C_p\left(\frac{\partial\theta}{\partial t}+\frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y}\right)=\lambda\nabla^2\theta+Q \tag{2}$$

$$\left(\frac{\partial C}{\partial t}+\frac{\partial\psi}{\partial y}\frac{\partial C}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial y}\right)=D_1\nabla^2 C+k_{11}\nabla^2\theta \tag{3}$$

The flow is maintained by a constant volume flux for which a characteristic velocity is defined as

$$Q=\frac{1}{2L}\int_{-L}^{L}u\,dy\,. \tag{4}$$

The boundary conditions for the velocity and temperature fields are

$$\left.\begin{aligned}&u=0,\ v=0,\ T=T_1,\ C=C_1 && on\ y=-L\\ &u=0,\ v=0,\ T=T_2+\Delta T_e Sin(mx+nt),\ C=C_2\ on\ y=L&&\end{aligned}\right\} \tag{5}$$

where $u=-\psi_y\,,\ v=\psi_x$ (6)

Introducing the non-dimensional variables in (1)- (3) as

$$x'=mx,\ y'=y/L,t'=t\nu m^2,\psi^1=\psi/\nu,\theta=\frac{T-T_e}{\Delta T_e}\ ,C=\frac{C-C_1}{C_1-C_2} \tag{7}$$

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

The governing equations (1) in the non-dimensional form (after dropping the dashes) are

$$\delta R\left(\delta(\nabla_1^2\psi)_t+\frac{\partial(\psi,\nabla_1^2\psi)}{\partial(x,y)}\right)=\nabla_1^4\psi+\left(\frac{G}{R}\right)\theta_y-D^{-1}\nabla_1^2\psi \tag{8}$$

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

$$\delta P\left(\delta\frac{\partial\theta}{\partial t}+\frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y}\right)=\nabla_1^2\theta+\alpha \tag{9}$$

$$\delta Sc\left(\delta\frac{\partial C}{\partial t}+\frac{\partial\psi}{\partial y}\frac{\partial C}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial y}\right)=\nabla_1^2 C+\frac{ScSo}{N}\nabla_1^2\theta \tag{10}$$

where

$$\left.\begin{array}{l} R=\dfrac{UL}{v}, G=\dfrac{\beta g\Delta T_e L^3}{v^2},\ P=\dfrac{\mu c_p}{k_1},\ D^{-1}=\dfrac{L^2}{k},\ \delta=mL \\ \gamma=\dfrac{n}{vm^2},\ \nabla_1^2=\delta^2\dfrac{\partial^2}{\partial x^2}+\dfrac{\partial^2}{\partial y^2}, Sc=\dfrac{v}{D}, N=\dfrac{\beta\Delta C}{\beta\Delta T}, So=\dfrac{K_{11}^*\beta^*}{\beta v} \end{array}\right\} \quad (11)$$

The corresponding boundary conditions are

$$\left.\begin{array}{l} \psi(+1)-\psi(-1)=1 \\ \dfrac{\partial\psi}{\partial x}=0, \dfrac{\partial\psi}{\partial y}=0\, at\ y=\pm 1 \\ \theta(x,y)=1, C=0\ on\ y=-1 \\ \theta(x,y)=\sin(x+\gamma t),\ C=0\ on\ y=1 \\ \dfrac{\partial\theta}{\partial y}=0, \dfrac{\partial C}{\partial y}=0\ at\ y=0 \end{array}\right\} \quad (12)$$

The value of ψ on the boundary assumes the constant volumetric flow in consistent with the hypothesis (10). Also the wall temperature varies in the axial direction in accordance with the prescribed arbitrary function t.

3. ANALYSIS OF THE FLOW

The perturbation analysis is carried out by assuming that the aspect ratio δ to be small.

We adopt the perturbation scheme and write

$$\left.\begin{array}{l} \psi(x,y)=\psi_0(x,y)+\delta\psi_1(x,y)+\delta^2\psi_2(x,y)+\ldots\ldots \\ \theta(x,y)=\theta_0(x,y)+\delta\,\theta_1(x,y)+\delta^2\theta_2(x,y)+\ldots\ldots \\ C(x,y)=C_0(x,y)+\delta\,C_1(x,y)+\delta^2 C_2(x,y)+\ldots\ldots \end{array}\right\} \quad (13)$$

On substituting (13) in (8) - (10) and separating the like powers of δ the equations and respective conditions to the zeroth order are

$$\psi_{0,\,yyyyy}-M_1^2\psi_{0,\,yy}=-G(\theta_{0,y}+NC_{0,y}) \quad (14)$$

$$\theta_{o,yy}+\alpha=0 \quad (15)$$

$$C_{o,yy}=-\frac{ScSo}{N}\theta_{o,yy} \quad (16)$$

With

$$\left.\begin{array}{ll} \psi_0(+1)-\psi(-1)=1 & \\ \psi_{0,y}=0, \psi_{0,x}=0 & at\ \ y=\pm 1 \\ \theta_0=1, C_0=0 & on\ \ y=-1 \\ \theta_0=Sin(x+\gamma t),\ C_0=1\ on\ \ y=1 & \end{array}\right\} \quad (17)$$

and to the first order are

$$\psi_{1,\,yyyyy}-M_1^2\psi_{1,\,yy}=-G\theta_y+(\psi_{0,\,y}\,\psi_{0,\,xyy}-\psi_{0,\,x}\,\psi_{0,yyy}) \quad (18)$$

$$\theta_{1,yy}=(\psi_{0,x}\theta_{o,y}-\psi_{0,y}\theta_{ox}) \quad (19)$$

$$C_{1,yy}=(\psi_{0,x}C_{o,y}-\psi_{0,y}C_{ox})-\frac{ScSo}{N}\theta_{0,yy} \quad (20)$$

With

$$\left.\begin{array}{l}\psi_1(+1)-\psi_1(-1)=0\\ \psi_{1,y}=0,\ \psi_{1,x}=0 \quad at\ y=\pm 1\\ \theta_1(\pm 1)=0,\ C_1(\pm 1)=0\ at\ y=\pm 1\end{array}\right\} \qquad (21)$$

The equations (14)-(16) and (18)-(20) have been solved subject to the boundary conditions (17) and (21)

4. SHEAR STRESS AND NUSSELT NUMBER

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

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

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

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

$$Nu=\frac{1}{\theta_m-\theta_w}\left(\frac{\partial\theta}{\partial y}\right)_{y=\pm 1}$$ where $\theta_m=0.5\int_{-1}^{1}\theta\,dy$ and the corresponding expressions are

$$(Nu)_{y=+1}=\frac{(m_1+Ecm_2+\delta m_3)}{(m_4+Ec\,m_5+\delta m_6)}$$

$$(Nu)_{y=-1}=\frac{(m_7+Ec\,m_8+\delta m_9)}{(m_{10}+Ecm_5+\delta m_6)}$$

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

$$Sh=\frac{1}{C_m-C_w}\left(\frac{\partial C}{\partial y}\right)_{y=\pm 1}$$ where $C_m=0.5\int_{-1}^{1}C\,dy$ and the corresponding expressions are

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

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

where d_1,………..d_{16} are constants …

6. DISCUSSION OF THE RESULTS

The aim of the this analysis is to discuss the Soret effect on the convective heat and mass transfer of a viscous fluid through a porous medium in a vertical channel bounded by flat walls on which a travelling thermal wave is imposed. For computational purpose we take P = 0.71 and δ = 0.01. . It is observed that the temperature variation on the boundary effects contributes substantially to the flow field. This contribution may be represented as perturbations over the mixed convection flow generated in the state of uniform wall temperature and So = 0. These perturbations not only depend on the wall temperature but also on the nature of the mixed convection flow. In general we note that the creation of the reversal flow in the flow field depends on whether the free convection effect dominates over the forced flow or vice-versa. If the free convection effects are sufficiently large as to create reversal flow the variation in the wall temperature effects the flow remarkably.

The velocity u is exhibited in figures (1)-(4) for different variations in the governing parameters G, D, N, So. In the case of heating of the walls the actual moment of the fluid in the left and in the right region is in the vertical upward direction, while in the case of cooling of the walls the fluid in the left region is in the upward direction and the fluid in the right region is in the direction of the buoyancy force. Such movement in the opposite directions takes place for $G \geq 10^3$. These opposing regions in the right mid half get widened with increase in $|G|$ (<0>) (fig. 1). The magnitude of u increases with $|G|$ (<0>) and with maximum u occurring at y = 0.6 for G>0 and at y = -0.6 for G<0.

From fig. 2 we find that the reversed flow occurs for $D^{-1} \geq 5\times10^2$ and the region of reversed flow gradually shrinks and the reversal flow disappears for $D^{-1} \geq 5\times10^3$. The velocity u depreciates in magnitude with increase in $D^{-1} \leq 3\times10^3$ and for higher values of $D^{-1} \geq 5\times10^3$, $|u|$ enhances in the region -0.8≤ y ≤ -0.4 and decreases in the region 0 ≤ y ≤ 0.8.

Fig. 3 depicts the variation of u with Soret parameter So. It is found that when So increases through positive values the velocity u experiences an enhancement in the region abutting the left boundary and in the remaining region -0.4≤y≤ 0.8, u depreciates with So while for So < 0, u enhances everywhere in the fluid region except in the vicinity of the left boundary with increase in $|So|$ (<0).

The variation of u with the buoyancy ratio N is shown in fig. 4. The buoyancy ratio N measures the relative importance of the concentration buoyancy over the thermal buoyancy. N>=<1 corresponds to the concentration buoyancy being either greater, equal or less than the thermal buoyancy. N is negative, positive or zero according as the concentration buoyancy either opposes or absent or acting in the direction of the thermal buoyancy. It is found that when the molecular buoyancy force dominates over the thermal buoyancy force we find a reversal flow in the region abutting the left wall and the velocity experiences enhanced speeds in the entire fluid region, when the forces act in the same direction. On the other hand when the two buoyancy forces act in opposing directions the fluid moves with lower velocities. The region of reversed velocity widened with N and shrinks with $|N|$ (<0) (fig. 4).

The secondary velocity V is plotted in figs. 5-8 for different variations in the governing parameters. It is observed that the profiles for V are asymmetric bell shaped curves with maximum at y = -0.4. The secondary velocity (V) is directed towards the boundary in the heating case and is towards the mid region in the cooling case. The magnitude of V increases with an increases in $|G|$ (fig 5). It is noticed that the magnitude of V in the heating case is always greater than in the cooling case. The variations of V with D show that for all values of D^{-1} the velocity V is always towards the boundary and V decreases with increase in D^{-1}. Thus, the lesser permeability of the porous medium smaller the magnitude of the velocity. (fig. 6)

Fig. 7 shows the variation of V with Soret parameter So. We notice that V for an increases in S_0 (>0), V decreases in the lower half and increases in the upper half while a reversed effect is observed for an increase in $|So|$(<0). Fig. 8 shows the influence of V with buoyancy ratio N. We find that irrespective of the directions of the buoyancy forces the secondary velocity V reduces with increase in $|N|$ (><0).

The behavior of the temperature distribution for Prandtl number P = 0.71 is exhibited in figs. (9)-(13). The perturbed temperature in general is positive and hence contributes to the enhancement of the actual temperature in the field.

Fig. 9 depicts the temperature θ for different G (<0>). The temperature profiles exhibit that for all G (<0>) the temperature gradually enhances from its prescribed values on the left boundary to attain its maximum at y = -0.4 and later falls to its prescribed value at y =1. From fig. 10 we find that θ reduces for $D^{-1} \leq 10^3$ except in a narrow region adjacent to the left boundary and for higher $D^{-1} \geq 3\times10^3$, we find an enhancement in θ except in the vicinity of the right boundary y = 1.The temperature enhances in the heating case and reduces in the cooling case. Thus lesser the permeability of the porous medium smaller the temperature in the entire fluid region and for further lowering of the permeability θ enhances except in the vicinity of y = 1. An increase in So enhances θ in the left region and decreases it in the right region while a reversed effect is noticed for an increase in $|So|$ (<0) (fig. 11). Irrespective of the directions of the buoyancy forces the temperature enhances with increase in the buoyancy ratio $|N|(><0)$ (fig. 12).

The concentration distribution (C) for different variations in the governing parameters is exhibited in figs. (13)-(16). We find that the concentration is positive for all variations. This means that the actual concentration is greater than the equilibrium concentration. The magnitude of C decreases in the heating case and enhances in the cooling case with maximum attained at y = 0.4 (fig. 13). As the permeability of the porous medium decreases C enhances in the entire fluid region (fig. 14). An increase in the Soret parameter So enhances C in the fluid region while it enhances in the left region and decreases in the right region for an increase in│So │ (<0) (fig. 15). The concentration is positive for N >0 and negative for N < 0. │C│ decreases with │N│ (<0>) irrespective of the directions of the buoyancy forces (fig. 6).

The average Nusselt number (Nu) which measures the local rate of heat transfer is shown in tables.14-22 for variations in G, D, N, So, and x + γ t. The magnitude of Nu reduces with│G│(><0) in both the cases of heating and cooling of the channel walls. │Nu│ at y = ± 1 enhances with D^{-1}. Thus lesser the permeability of the porous medium larger the magnitude of │Nu│. With increase in the strength of the heat sources we find that the magnitude of Nu at y = -1 increases for any │G│$\leq 10^3$ and enhances for │G│$\geq 3 \times 10^3$ while at y=+1 Nu enhances in both heating and cooling cases table (tables. 17, 23).

From tables 1, 2 & 5, 6 in the find that │Nu│ periodically varies with increase in the phase x + γ t of the travelling thermal wave. The variation of N u with D shows that the Nusselt number at y = -1 enhances with increase in $D^{-1} \leq 3\times10^3$ and for further increase in $D^{-1} \geq 5\times10^3$. Nu experiences depreciation in the heating case and enhances with $D^{-1} \geq 10^3$ in the cooling of the channel walls. At y = 1 the Nusselt number reduces with $D^{-1} \leq 3\times10^3$ and enhances with $D^{-1} \geq 5\times10^3$ in both heating and cooling cases. When the molecular buoyancy force dominates over the thermal buoyancy force Nu at y = -1 depreciates when the forces act in the same direction and enhances when they act in opposite directions while at y = 1 a reversed effect is observed (tables.1, 5). An increase in Schmidt number enhances │Nu│ at both walls (tables.15, 31). An increase in Soret parameter │So│ enhances N u at y= -1 in the heating case and depreciates it in the cooling case while at y = + 1while for │So│ (<0) we notice a reversed effect (tables.2, 6).

The Sherwood number (Sh) which measures the rate of mass transfer is exhibited in tables (3, 4)-(7, 8) for variations in G, D, N, Sc, So & x +γ t. We find that in a given porous medium the rate of mass transfer at y = ± 1 decreases in the heating case and increases in the cooling of the channel walls while a reversed effect is noticed at y = + 1. Also lesser the permeability of the porous medium larger the magnitude of Sh at y = ± 1. When the molecular buoyancy force dominates over the thermal buoyancy force, │Nu| at y = -1 depreciates irrespective of the directions of the buoyancy forces. At y = +1, N u enhances with N for G $\leq 10^3$ and decreases with N for G$\geq 3\times10^3$ when the buoyancy forces act in the same direction, while in the case of forces acting in opposite directions, the magnitude of Nu decreases with │N│ for G $\leq 10^3$ and for higher │G│ $\geq 3\times10^3$,│N u│ enhances with │N│ (tables.3, 7).

The variation of Nu with Soret parameter So shows that an increase in So (>0) enhances│N u│ and in │So│ (<0) depreciates it at y = -1 while at y = 1 for G > 0, $|Nu|$ enhances with So and depreciates it for G < 0 and for an increase in │So│ (< 0). We find an enhancement in |Sh| (tables.4, 8). Also, an increase in the phase x+γ t the magnitude of Sh. fluctuates. This is in view of the traveling thermal wave impressed on the walls.

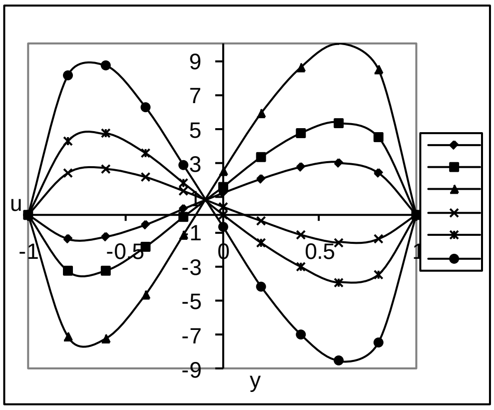

Fig. 1: Variation of u with G
$D^{-1}=2x10^3$, Sc=1.3, So=0.5, N=1

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

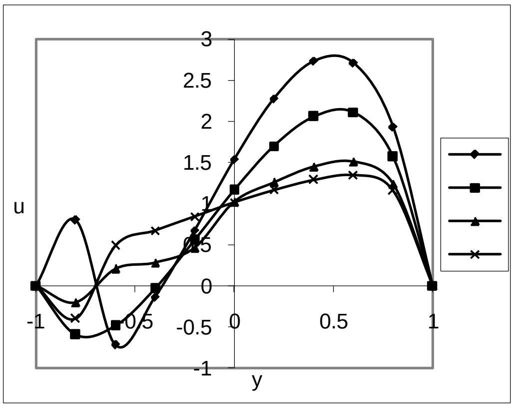

Fig. 2: Variation of u with D^{-1}
$G=10^3$, Sc=1.3, So=0.5, N=1

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

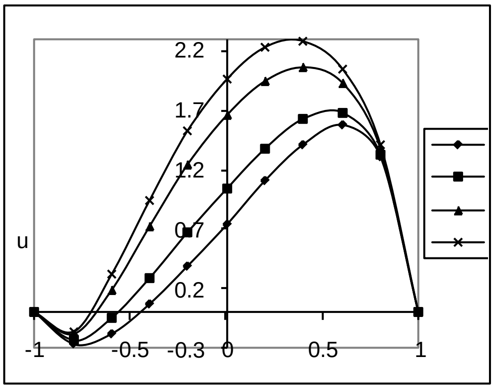

Fig. 3: Variation of u with S_0

N=1, Sc=1.3

	I	II	III	IV
$S_{0.}$	0.5	1	-0.5	-1

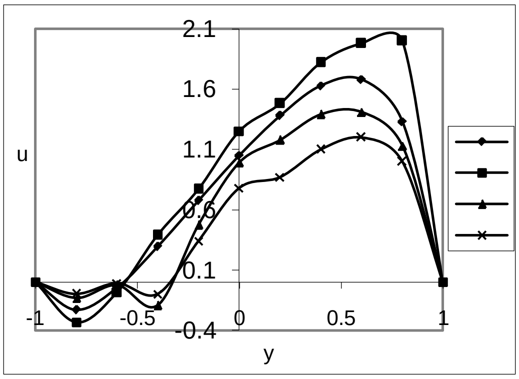

Fig. 4: Variation of u with N

$G=10^3$, $D^{-1}=2x10^3$, Sc=1.3, So=0.5

	I	II	III	IV
N	1	2	-0.5	-0.8

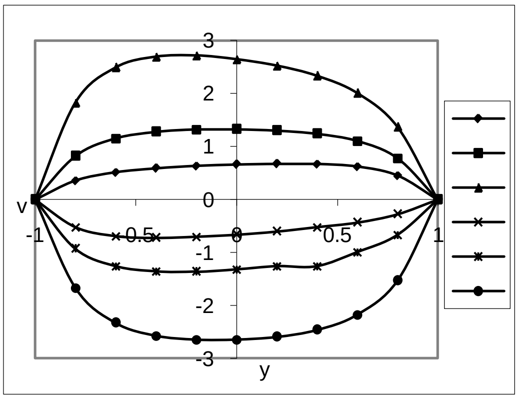

Fig. 5: Variation of V with G

$D^{-1}=2x10^3$, N=1, α=2

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

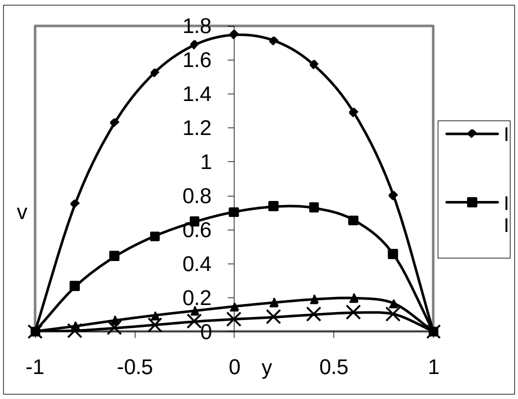

Fig. 6: Variation of V with D^{-1}

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

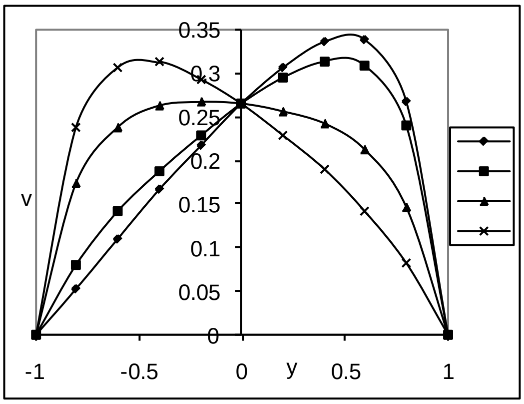

Fig. 7: Variation of v with S_0

N=1, Sc=1.3

	I	II	III	IV
S_0	0.5	1	-0.5	-1

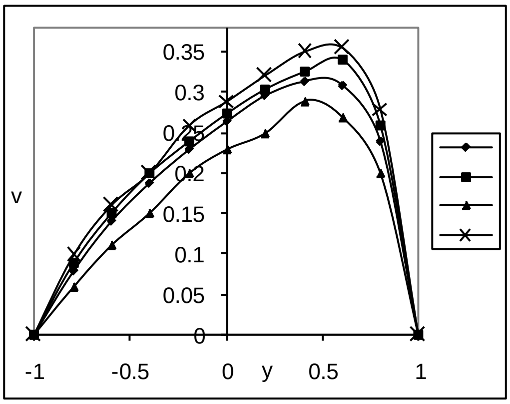

Fig. 8: Variation of v with N

$G=10^3$, $D^{-1}=2x10^3$, Sc=1.3, So=0.5

	I	II	III	IV
N	1	2	-0.5	-0.8

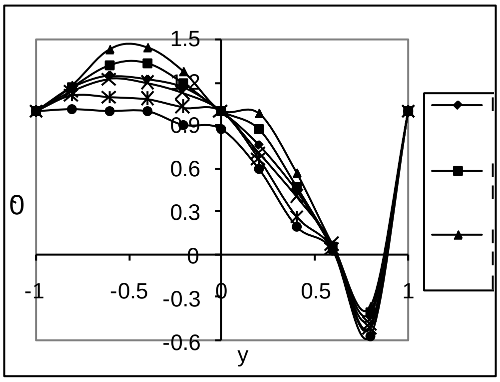

Fig. 9: Variation of θ with G
$D^{-1}=2x10^3$, N=1, Sc=1.3, So=0.5, α=2, x=π/4, γ=5

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

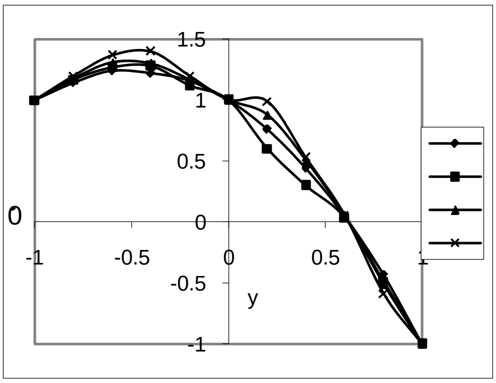

Fig. 10: Variation of θ with D^{-1}
G = 10^3, N=1, Sc=1.5, So=0.5

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

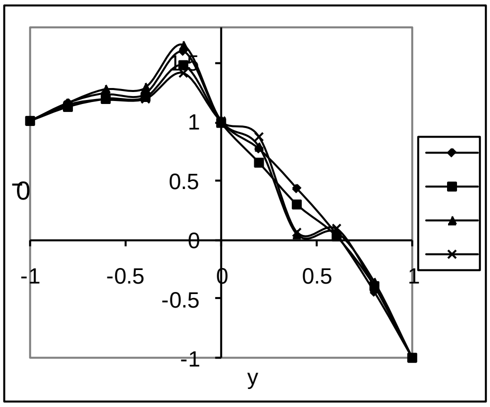

Fig. 11: Variation of θ with S_0

	I	II	III	IV
So	0.5	1	-0.5	-1

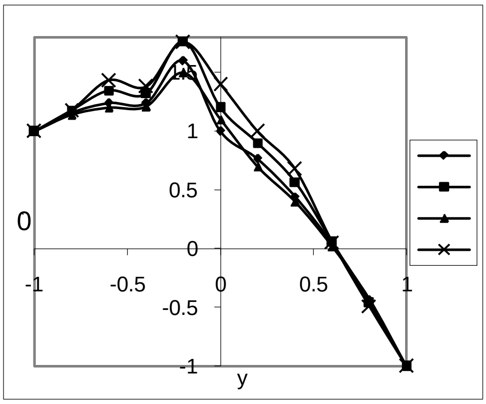

Fig. 12: Variation of θ with N

	I	II	III	IV
N	1	2	-0.5	-0.8

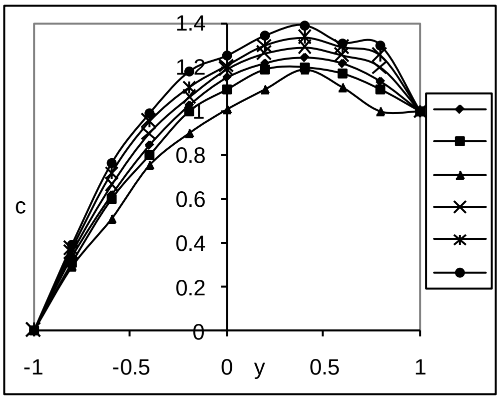

Fig. 13: Variation of c with G
$D^{-1}=2x10^3$, Sc=1.3, So=0.5

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

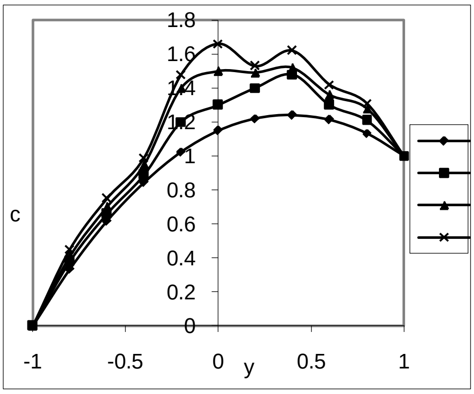

Fig.14: Variation of c with D^{-1}
G=10^3, Sc=1.3, So=0.

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

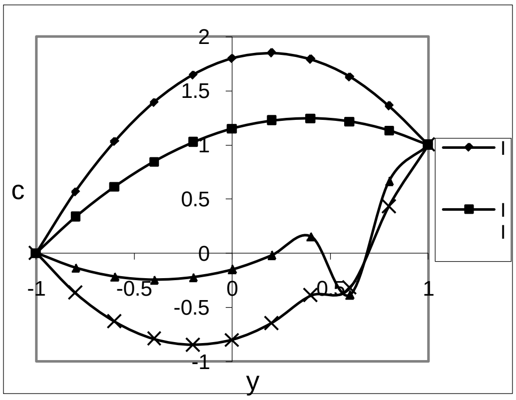

Fig.15: Variation of c with So

	I	II	III	IV
S_0	0.5	1	-0.5	-1

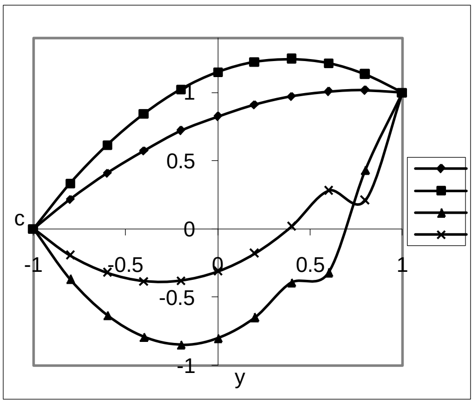

Fig.16: Variation of c with N

	I	II	III	IV
N	1	2	-0.5	-0.8

Table.1

Average Nusselt Number (Nu) at y = -1, P=0.71,Sc=1.3

Nu\G	I	II	III	IV	V	VI	VII	VIII
10^3	-1.9049	-3.0176	-1.8049	-1.9249	-1.9449	-1.8848	-1.6234	-1.7846
$3x10^3$	-1.2387	-3.0181	-1.2087	-1.2487	-1.2638	-1.2087	-1.1639	-1.2649
$5x10^3$	-0.9951	-3.0189	-0.9051	-1.0951	-0.2951	-0.9652	-0.8652	-0.9756
-10^3	-1.9354	-2.4794	-1.9154	-1.9654	-2.0354	-1.9654	-0.9956	-1.1207
$-3x10^3$	-1.2405	-1.6697	-1.2205	-1.2605	-1.3405	-1.2653	-1.0453	-1.0969
$-5x10^3$	-0.9941	-1.4489	-0.8941	-1.0141	-1.1941	-1.0642	-0.9243	-0.9647

Table.2

Average Nusselt Number (Nu) at y = 1, P=0.71,Sc=1.3

Nu\G	I	II	III	IV	V	VI	VII	VIII
10^3	3.2188	2.9781	3.3188	3.2088	3.2188	3.2467	3.1187	2.9956
$3x10^3$	3.6641	2.9785	3.7641	3.6041	3.5641	3.8645	3.4657	3.2578
$5x10^3$	3.7786	2.9793	3.8786	3.7086	3.6786	3.9634	3.6753	3.4321
-10^3	3.2072	3.1009	3.2672	3.1671	3.1272	3.6623	2.9678	3.1486
$-3x10^3$	3.6595	3.4386	3.7595	3.6095	3.5096	3.8512	3.2523	3.5643
$-5x10^3$	3.7761	3.5007	3.8761	3.7261	3.6761	3.9456	3.5546	3.7534

Table.3

Sherwood Number (Sh) at y = -1, P=0.71,Sc=1.3

Nu\G	I	II	III	IV	V	VI	VII	VIII
10^3	0.7729	1.4983	0.7129	1.0033	1.1132	0.8825	0.7052	0.6426
$3x10^3$	-0.4051	1.4973	0.0641	2.3205	1.6588	-0.6052	-0.3551	-0.3052
$5x10^3$	-1.3277	1.4954	-0.0011	1.1974	1.0541	-1.3629	-1.3072	-1.2856
-10^3	0.8081	1.3167	0.7421	1.0493	1.1576	0.8625	0.7815	0.7615
$-3x10^3$	-0.4177	0.7135	0.0621	2.2514	1.6291	-0.5276	-0.3917	-0.3129
$-5x10^3$	-1.5171	0.5974	-0.0151	1.7522	1.0411	-1.7275	-1.3175	-1.2152

Table.4

Sherwood Number (Sh) at y = 1, P=0.71,Sc=1.3

Nu\G	I	II	III	IV	V	VI	VII	VIII
10^3	-1.1412	-1.4892	-1.3922	-0.7644	-0.6891	-1.2512	-1.1321	-1.1467
$3x10^3$	-3.0562	-1.4884	9.7421	-9.1012	-10.312	-1.1462	-1.0064	-1.1274
$5x10^3$	-0.8784	-1.4863	-0.0023	-2.1921	-2.4552	-0.9786	-0.7784	-0.9863
-10^3	-1.1682	-1.4972	-1.4021	-0.8159	-0.7455	-1.1482	-1.1564	-1.2678
$-3x10^3$	-1.3052	-1.1755	3.9463	-3.8532	-4.3632	-1.2152	-1.2092	-1.3562
$-5x10^3$	-0.8572	-2.2552	-0.0321	-2.0953	-2.3421	-0.6523	-0.7564	-0.9173

	I	II	III	IV	V	VI	VII	VIII
D^{-1}	$2x10^3$	$5x10^3$	$2x10^3$	$2x10^3$	$2x10^3$	$2x10^3$	$2x10^3$	$2x10^3$
N	1	1	2	-0.5	-0.8	1	1	1
So	0.5	0.5	0.5	0.5	0.5	1.0	-0.5	-1.0

Table.5

Average Nusselt number(Nu) at y = -1, P=0.71,Sc=1.3,So=0.5,N=1

Nu\G	I	II	III	IV	V
10^3	-1.4022	-1.9031	-1.8753	-1.7025	-1.7911
$3x10^3$	-1.2976	-1.2512	-1.2413	-0.9941	-1.1362
$5x10^3$	-1.1671	-1.3092	-1.0784	-0.8944	-1.0363
-10^3	-1.4031	-1.9301	-1.8982	-1.7394	-1.8188
$-3x10^3$	-1.2965	-1.2207	-1.1672	-0.9993	-1.0808
$-5x10^3$	-1.1651	-0.9608	-0.9204	-0.8876	-0.9184

Table.6

Average Nusselt number (Nu) at y = 1, =0.71, Sc=1.3,So=0.5,N=1

Nu\G	I	II	III	IV	V
10^3	1.9414	3.1761	2.8991	2.0163	2.3599
$3x10^3$	1.8174	3.4837	2.6919	1.4219	1.8208
$5x10^3$	1.6431	3.4635	2.5239	1.3411	1.7196
-10^3	1.9426	3.1668	2.8905	2.0417	2.3721
$-3x10^3$	1.8162	3.5084	2.6125	1.3982	1.7183
$-5x10^3$	1.6406	3.5389	2.2661	1.2935	1.5075

Table.7

Sherwood Number (Sh) y = -1, P=0.71, Sc=1.3,So=0.5,N=1

Nu\G	I	II	III	IV	V
10^3	-2.5324	0.7724	0.7701	0.7636	0.7655
$3x10^3$	-4.6112	-0.4048	-0.3979	-0.3774	-0.3843
$5x10^3$	-21.2282	-1.2707	-0.9879	-0.6571	-0.7276
-10^3	-2.5748	0.9079	0.8061	0.7998	0.8019
$-3x10^3$	-5.1351	-0.4153	-0.4043	-0.3827	-0.3881
$-5x10^3$	-66.0316	-1.4373	-1.0765	-0.6914	-0.7676

Table.8

Sherwood Number (Sh) at y = 1, P=0.71,Sc=1.3,So=0.5,N=1

Nu\G	I	II	III	IV	V
10^3	14.7986	-1.1412	-1.1363	-1.1242	-1.1283
$3x10^3$	-13.3541	-9.3273	7.3983	1.9943	2.5443
$5x10^3$	-4.3621	-0.9219	-1.3901	9.6652	-7.7942
-10^3	16.2231	-1.1673	-1.1632	-1.1512	-1.1543
$-3x10^3$	-10.6543	-1.7794	1.1773	2.2435	2.9741
$-5x10^3$	-3.8974	-0.9017	-1.3321	2.7863	-5.4763

	I	II	III	IV	V
$x+\gamma t$	$3\pi/2$	$19\pi/2$	$7\pi/8$	$9\pi/4$	4π

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Source of support: Nil, Conflict of interest: None Declared

