UNSTEADY FREE CONVECTIVE HEAT TRANSFER THROUGH A POROUS MEDIUM IN A HORIZONTAL WAVY CHANNEL WITH TRAVELLING THERMAL WAVE AND RADIATION EFFECT

[1]N. VIMALA* AND [2]P. M. V. PRASAD
[1]Lecturer in Mathematics, Sri Krishnadevaraya University College of Engineering and Technology, S. K. University, Anantapur - 515 003, (A.P.), India.
[2]Reader in Mathematics, Department of Mathematics, S. V. G. S. Degree College, Nellore, (A.P.), India.

Abstract : We would like to discuss the unsteady thermal convection flow through a porous medium due to the imposed traveling thermal boundary waves on horizontal channel bounded by non-uniform walls. The effect of free convection on the flow has been discussed by solving the governing unsteady non-linear equations under perturbation scheme. The Shear stress and the average Nusselt number on the boundaries have been evaluated for different variations of the governing parameters.

Key words: Heat Transfer, Porous medium, Radiation effect.

1. INTRODUCTION

The study of unsteady thermal convection flows has gained importance in view of its applications in several technological fields like chemical engineering aerospace technology and design of heat exchangers etc. The unsteadiness in the flow may be due to time dependent free stream osicillations, dependent convection flows may be generated due to heat transfer in an oscillatory fluid flow bounded by wall maintained at periodically varying temperatures. Such convection flows generated by a periodic boundary thermal wave has received attention in the recent years due to its applications in the design of oil or gas fired boilers and a few other physical phenomena. It has been shown that a traveling thermal wave can generate a mean shear flow with in a layer of fluid and also give rise to a significant secondary flow in the field. This analysis of convection flows generated due to these traveling thermal waves has been studied by Nanda and Purushothaman [6]. The perturbation technique is used to obtain the mean and the perturbed flow under longwave approximation for four different possible configurations at the wavy channel. However, this study of convection flows due to imposed thermal boundry waves has not been done in horizontal channel flows bounded by uniform or non-uniform horizontal waves. Ravindra [8] has analyzed mixed convection effects on the flow of an incompressible, viscous fluid through a porous medium in a vertical channel with traveling thermal waves imposed on one wall. Eswaraiah Setty [4] has analyzed unsteady free convection flow through a horizontal wavy channel with traveling thermal waves imposed on the walls.

In the content of space technology and in the processes involving high temperatures, the effects of radiation are of vital importance. The unsteady flow past a moving plate in the presence of free convection and radiation were studied by Mansour [5], Raptis and Perdikis [7] studied the effects of thermal radiation and free convective flow past moving plate. Das et al [3] analyzed the radiation effects on the flow past an impulsively started infinite isothermal vertical plate. Chamkha et al [2] considered the effect of radiation on free convective flow past a semi-infinite vertical plate with mass transfer.Recently Bharathi [1] has discussed the mixed convective heat and mass transfer through a porous medium in a vertical channel with traveling thermal wave imposed on the boundaries.

2. FORMULATION OF THE PROBLEM

We consider the unsteady flow of an incompressible viscous fluid through a porous medium confined in a horizontal channel bounded by corrugated walls in the presence of a constant heat source. The Boussinesque approximation is used so that the density variation will be retained only in the buoyancy force. The viscous dissipation is neglected in comparison to the flow by conduction and convection. We choose the rectangular Cartesian coordinates system O(x,y,z) with x-axis in the direction of motion and y-axis in the vertical direction and walls are taken at $y = \pm Lf(\delta x / L)$,where 2L is the distance between the walls, f is a twice differentiable function and δ is a small parameter proportional to the boundary slope. A linear density temperature variation is assumed with ρ_e and Te being the density and temperature of the fluid in the equilibrium state.

Equation of linear momentum

$$\rho_e(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}) = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) - \rho g - (\frac{\mu}{k})u \quad (2.1)$$

$$\rho_e(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}) = -\frac{\partial p}{\partial y} + \mu(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}) - (\frac{\mu}{k})v \quad (2.2)$$

Equation of continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2.3)$$

Equation of energy

$$\rho_e C_p(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}) = k_1(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) - \frac{\partial (q_r)}{\partial y} \quad (2.4)$$

Equation of state

$$\rho - \rho_e = -\beta\rho_e(T - T_e) \quad (2.5)$$

Invoking Rosseland approximation for radiation (9)

$$q_r = -(\frac{4\sigma^*}{3\beta_r})\frac{\partial T'^4}{\partial y} \quad (2.6)$$

Expanding T'^4 in Taylor series about Te and neglecting higher order terms (8a)

$$T'^4 \approx 4T_e^3 T - 3T_e^4 \quad (2.7)$$

where βr is the mean absorption coefficient and σ^* is the Stefan-Boltzmann constant. ρ_e is the density of the fluid in the equilibrium state, Te is the temperature in the equilibrium state,(u,v) are the velocity components along O(x,y) directions, p is the pressure, T is the temperature 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,k_1 is the coefficient of thermal conductivity, k is the permeability of the porous medium and β is the coefficient of thermal expansion.

In the equilibrium state

$$0 = -\frac{\partial p_e}{\partial x} - \rho_e g \quad (2.8)$$

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

$$Q = \frac{1}{2L}\int_{-L}^{L} u\, dy. \quad (2.9)$$

The boundary conditions for the velocity and temperature fields are

$u = 0$, $v = 0$, $T=T_1$ on $y = -L$

$u=0,\ v=0, T = T_2 + \Delta T_e\, Sin(mx+nt)$ on $y = L$ (2.10)

where $\Delta T_e = T_2 - T_1$ and $Sin(mx+nt)$ is the imposed traveling thermal wave

In view of the continuity equation we define the stream function ψ as

$u = -\psi_y$, $v = \psi_x$ (2.11)

Eliminating pressure p from equations (2.1)&(2.2) the equations governing the flow in terms of ψ are

$$[(\nabla^2\psi)_t + \psi_x(\nabla^2\psi)_y - \psi_y(\nabla^2\psi)_x] = \nu\nabla^4\psi - \beta g(T - T_0)_y - (\frac{\nu}{k})\nabla^2\psi \quad (2.12)$$

$$\rho_e C_p(\frac{\partial\theta}{\partial t} + \frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x} - \frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y}) = \lambda\nabla^2\theta + \frac{\partial(q_r)}{\partial y} \quad (2.13)$$

Introducing the non-dimensional variables in (2 .12)- (2.13) as

$$x' = mx,\ y' = y/L, t' = t\nu m^2, \Psi' = \Psi/\nu, \theta = \frac{T - T_e}{\Delta T_e} \quad (2.14)$$

(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

$$\delta R(\delta(\nabla_1^2\psi)_t + \frac{\partial(\psi, \nabla_1^2\psi)}{\partial(x,y)}) = \nabla_1^4\psi + (\frac{G}{R})\theta_y - D^{-1}\nabla_1^2\psi \quad (2.15)$$

The energy equation in the non-dimensional form is

$$\delta P(\delta\frac{\partial\psi}{\partial t} + \frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x} - \frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y}) = \nabla_1^2\theta + \frac{4}{3N_1}\frac{\partial^2\theta}{\partial y^2} \quad (2.16)$$

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

$P = \frac{\mu c_p}{k_1}$ (Prandtl number), $D^{-1} = \frac{L^2}{k}$ (Darcy parameter),

$\delta = mL$ (Aspect ratio) $\gamma = \frac{n}{\nu m^2}$ (non-dimensional thermal wave velocity)

$N_1 = \frac{\beta_R k_1}{4\sigma^{\bullet} T_e^3}$ (Radiation parameter)

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

The corresponding boundary conditions are

$\psi(+1) - \psi(-1) = 1$

$\frac{\partial\psi}{\partial x} = 0,\ \frac{\partial\psi}{\partial y} = 0$ at $y = \pm 1$ (2.17)

$\theta(x,y) = 1$ on $y = -1$

$\theta(x,y) = Sin(x + \gamma t)$, on $y = 1$

$\frac{\partial\theta}{\partial y} = 0$ at $y = 0$ (2.18)

The value of ψ on the boundary assumes the constant volumetric flow in consistant with the hypothesis (2.9) .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 the aspect ratio δ is small. In order that the convection effects is felt at the zeroth order in the perturbed analysis we choose the thermal buoyancy parameter G is of order. δ so that $\hat{G} = G\delta \approx O(1)$

Introducing the transformation $\eta = \frac{y}{f(x)}$ and substituting the expansions for ψ and θ as

$$\psi(x,\eta,t) = \psi_0(x,\eta,t) + \delta\psi_1(x,\eta,t) + \delta^2\psi_2(x,\eta,t) + \ldots\ldots$$

$$\theta(x,\eta,t) = \theta_0(x,\eta,t) + \delta\theta_1(x,\eta,t) + \delta^2\theta_2(x,\eta,t) + \ldots\ldots\ldots \qquad (3.1)$$

On substituting (3.1) in (2.15) - (2.16) and separating the like powers of δ the equations and respective conditions to the zeroth order are

$$\psi_{0,\eta\eta\eta\eta} - \beta_1^2\psi_{0,\eta\eta} = -(\hat{G}f^3/R)(\theta_{0,x}) \qquad (3.2)$$

$$\theta_{o,\eta\eta} = 0 \qquad (3.3)$$

with

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

$\psi_{0,\eta} = 0$, $\psi_{0,x} = 0$ at $\eta = \pm 1$ (3.4)

$\theta_o = 1$ on $\eta = -1$

$\theta_o = Sin(x+\gamma t)$ on $\eta = 1$ (3.5)

and to the first order are

$$\psi_{1,\eta\eta\mu\mu} - \beta_1^2\psi_{1,\eta\eta} = -(\hat{G}f^3/R)(\theta_{1,x}) + Rf(\psi_{0,\eta}\psi_{0,x\eta\eta} - \psi_{0,x}\psi_{0,\eta\eta\eta}) \qquad (3.6)$$

$$\theta_{1,\eta\eta} = (P1f)(\psi_{0,x}\theta_{o,\eta} - \psi_{0,\eta}\theta_{ox}) \qquad (3.7)$$

With

$\psi_1(+1) - \psi_1(-1) = 0$

$\psi_{1\eta} = 0, \psi_{1,x} = 0$ at $\eta = \pm 1$ (3.8)

$\theta_1(\pm 1) = 0$, at $\eta = \pm 1$ (3.9)

where $P1 = \frac{3N_1P}{3N_1+4}$

4. SHEAR STRESS AND NUSSELT NUMBER

The shear stress on the channel walls is given by

$$\tau = \frac{(f^2(1+f'^2)\psi_{0,\eta\eta} + \delta(f^2(1-f'^2)\psi_{1,\eta\eta} - (2f'/f)\psi_{0,x\eta}) + O(\delta^2)}{(1+f'^2)}$$

and the corresponding expressions are

$$(\tau)_{\eta=1} = \frac{(f^2(1+f'^2)d_{28} + \delta(f^2(1-f'^2)d_{12} - (2f'/f)d_{24}) + O(\delta^2)}{(1+f'^2)}$$

$$(\tau)_{\eta=-1} = \frac{(f^2(1+f'^2)d_{32} + \delta(f^2(1-f'^2)d_{20} - (2f'/f)d_{24}) + O(\delta^2)}{(1+f'^2)}$$

The rate of heat transfer (Nusselt Number) on the channel walls has been calculated using the formula

$$Nu = \frac{1}{f(\theta_m - \theta_w)}\left(\frac{\partial\theta}{\partial\eta}\right)_{\eta=\pm1}$$

where

$$\theta_m = 0.5\int_{-1}^{1}\theta\, d\eta$$

and the corresponding expressions are

$$(Nu)_{\eta=1} = \frac{1}{f(d_{39} + \delta d_{43} - SinD_1)}(0.5 + \delta\, d_{36})\ \_\ (Nu)_{\eta=-1} = \frac{1}{f(d_{39} + \delta d_{43} - SinD_1)}(0.5 + \delta\, d_{39})$$

where $d_1, d_2, \ldots\ldots\ldots d_{43}$ are constants

5. RESULTS AND DISCUSSION

We analyze the effect of radiation on the unsteady convective heat transfer of a viscous incompressible fluid in a horizontal channel bounded by wavy walls. The perturbation analysis is carried out making use of the wall slope δ as a small parameter.Forcomputationalpurposewechoose $f(x) = 1 + \beta e^{-x^2}$ .The non uniformity in boundary curve gives rise to a secondary flow in the transverse direction. In order that the thermal buoyancy influence is felt at the zeroth order. We insist the Grashoff number G~O(δ^{-1})

The variation of u for different G(><0) in the dilated constricted channel. It is found that for all |G|(><0) the reversal flow appears in the lower half in the dilated channel while it appears in the entire fluid for (β<0). The region on reversed flow grows in size with increase in |G| for β>0 while for β<0 it reduces in its size(Fig.1). The maximum u occurs in the vicinity of the lower boundary In both the configurations the variation of u with R, α,γ, D^{-1} has been depicted in figures 2,3&4 and 10. It is found that reversal flow appears in the lower half for all R, γ, D^{-1} in a dilated channel. The region of reversed flow increases with R≤70 (and γ≤10) and for higher values of R≥140 & (γ≥15) it grows in size. Also lower the permeability of the porous medium larger the magnitude of u. In constricted case the reversal flow appears in the region -0.6≤η≤0.4. It enlarges to the entire flow region for higher R≥70. (Figs.2,3&4)

The secondary velocity (v) which arises due to the non-uniformity of the boundaries is represented in Figs.5-8 for β>0. It is found that in dilated channel the fluid in the lower half is directed towards the boundary and in upper half it is directed towards the midregion in the heating case while in the cooling case the fluid in the lower half is towards the midregion and is towards the boundary in the upper half. The magnitude of v enhances with |G|(<>0). (Fig.5). The variation of R, D^{-1} and γ is shown in Figs.6,7&8 It is found that for β>0 an increase in R depreciates the magnitude of v. Also lower the permeability of the porous medium higher the magnitude of v in both the configurations. The variation with thermal velocity γ shows that for β>0 an increase in γ≤10 enhances |v| in the lower half and reduces it in the upper half and for higher γ≥15 we notice a reversed effect in |v|. The variation of v with β shows that higher the dilation/constriction larger the magnitude of v in the flow region (Fig.6,7&8).

The Non dimensional temperature distribution (θ) is exhibited in Figs.9&10 for β(><0) for different G,R, γ,β. The peturbed temperature in general is positive and hence contributes to the enhancement of the actual temperature in the fluid region. Fig.9 depicts the variation of θ with |G|(<>0). We notice that in a dilated channel the temperature increases/decreases in the region -0.8≤y≤0.4 according as as G>0 or G<0. In the remaining region a reversed effect is noticed in θ. The variation θ with reference to R,σ, and γ is given in Figs.9&10. In a dilated case θ is positive and in constricted case θ is positive in lower half and negative in the upper half we find that θ decreases with in the region -0.8≤ή≤0.4 and enhances in the remaining region for β>0(Fig.10)

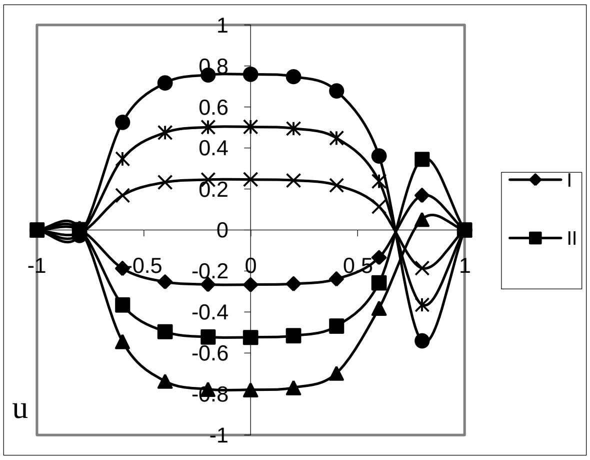

Fig.1. Profile for Velocity (u) with G
$m_1=2$, $D^{-1}=10$, R=10

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

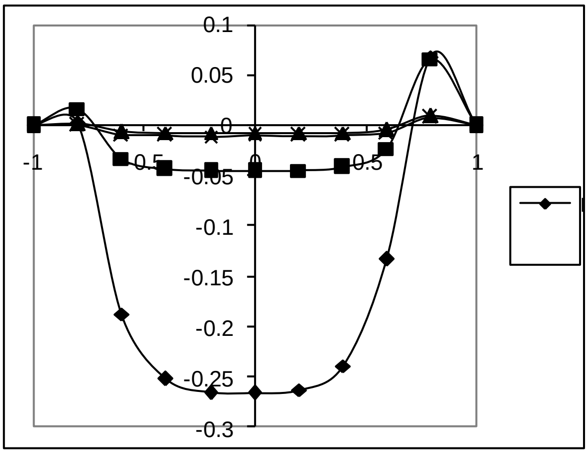

Fig.2. Profile for Velocity (u) with D^{-1}
$m_1=2$, R=10, $G=10^2$

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

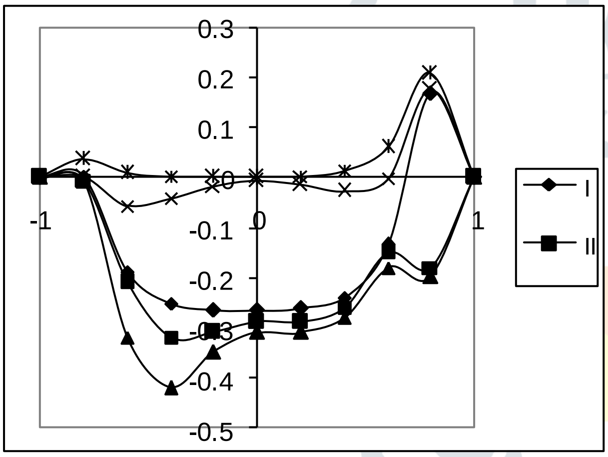

Fig. 3 Profile for velocity (u) with α and γ
$m_1=2$, ,G=100 $D^{-1}=10$, R=10

	I	II	III	IV	V
α	2	4	6	2	2
γ	2	2	2	4	6

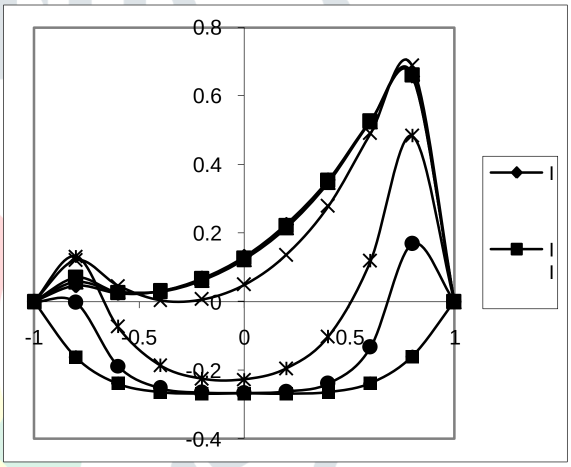

Fig.4 Profile for velocity (u) with R
$m_1=2$, $D^{-1}=10$, G=100

	I	II	III	IV	V	VI	VII
R	0.1	0.3	0.5	1.5	5	10	100

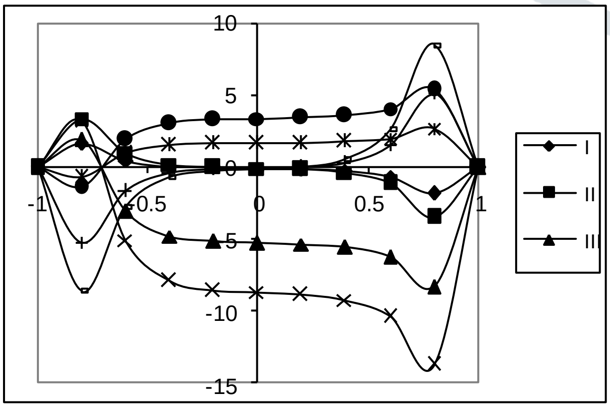

Fig. 5 Profile for velocity (v) with G
$m_1=-1$, $D^{-1}=10$, R=10

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

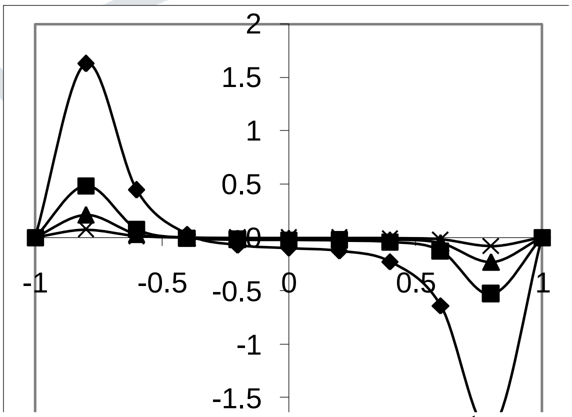

Fig. 6 Profile for velocity (v) with D^{-1}
$m_1=-1$, R=10, $G=10^2$

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

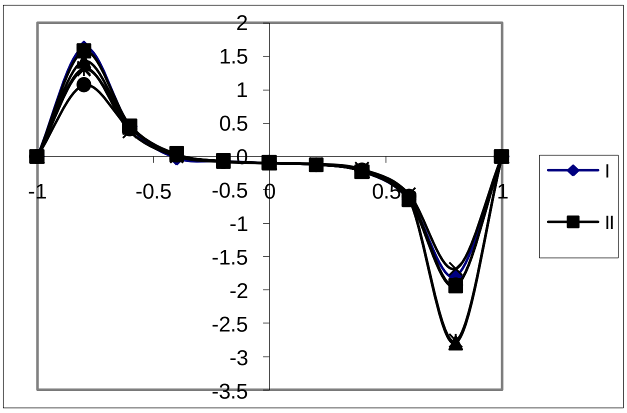

Fig. 7 Profile for velocity (v) with α and γ

m_1=-1 , D^{-1}=10, R=10, G=100

	I	II	III	IV	V	VI
γ	2	3	4	6	2	2
α	2	2	2	2	4	6

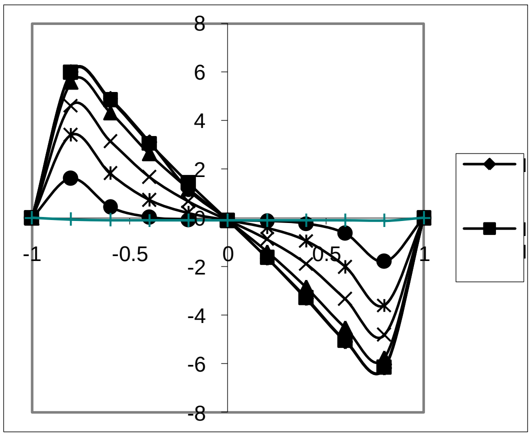

Fig.8 Profile for velocity (v) with R

m_1 =-1, D^{-1}=10, G=10^2

	I	II	III	IV	V	VI	VII
R	0.3	0.5	1.5	3	5	10	100

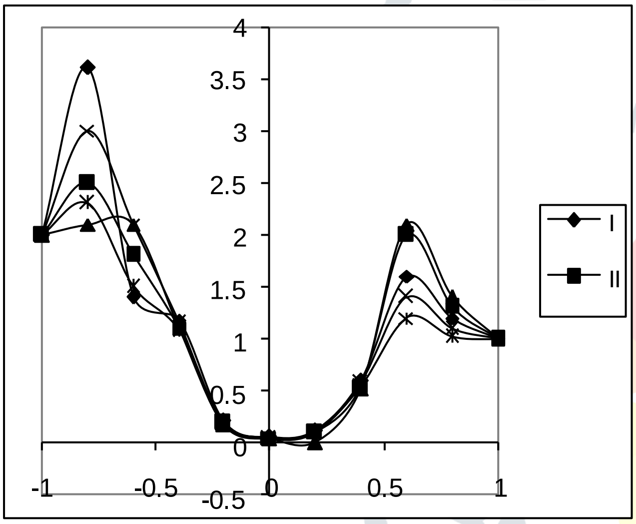

Fig. 9 Profile for temperature (θ) with α and γ

m_1=2 , D^{-1}=10, G=10^2

	I	II	III	IV	V
α	2	4	6	2	2
γ	2	2	2	3	4

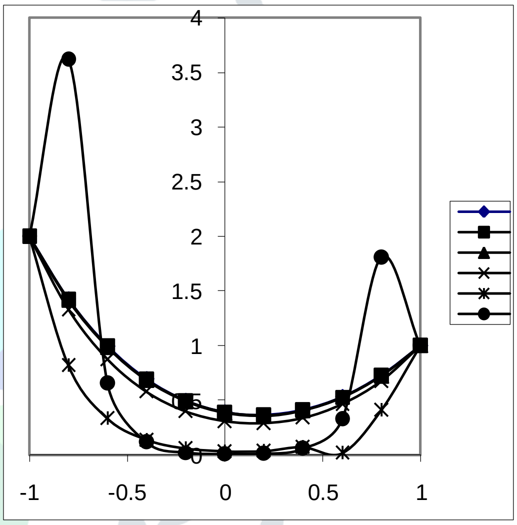

Fig.10 Profile for temperature (θ) with R

m_1 =2, D^{-1}=10, α=2

	I	II	III	IV	V	VI	VII
R	0.3	0.5	0.5	1.5	3	5	100

The shear stress has been evaluated at the boundaries for different variations in G,R,D^{-1}, β, γ and N_1 and are given in tables for β>0 or β<0. The shear stress at the both the plates η=±1 decrease in magnitude with increase in G>0 and enhances with increase in |G|(<0) fixing the other parameters. An increase in R leads to an enhancement in the magnitude of τ. Also lesser the permeability of porous medium smaller the magnitude of τ and for further lowering of the permeability we find an enhancement |τ| (Table 1). From Table.2 we notice that higher the dilation β≤0.7 larger |τ| and for further increase in β≥0.9, |τ| enhances at η=1, Also an increase in thermal wave velocity γ≤4 leads to an enhancement in |τ| and for higher γ≥6 it reduces at η=1, for all |G| while at η=-1 |τ| enhances with γ in the heating of the channel and in the case of cooling |τ| enhances with γ≤4 and reduces with higher γ≥6. In a constricted channel the magnitude of τ is positive for all variations. It is found that the stress at η=1 increases with increase in G>0 and reduces with increase in |G| (<0) while a reversed effect is observed at the lower plate η= -1. An increase in R reduces τ at η=1 and enhances at η=-1 in the heating case, while it enhances τ at η=1 and reduces at η=-1 in the cooling case. (table 3&4).

Table.1 Shear stress (τ) at y= 1 P=0.71,γ=2,β=0.5

G	I	II	III	IV	V
10^3	12.9003	12.9017	12.9025	-2.2383	0.3420
2×10^3	12.8943	12.8988	12.9010	-2.4566	0.3424
3×10^3	12.8884	12.8958	12.8995	-2.5035	0.3416
-10^3	12.9062	12.9047	12.9040	-2.4524	0.3439
-2×10^3	12.9121	12.9077	12.9054	-2.5074	0.3446
-3×10^3	12.91805	12.9106	12.9069	-2.5949	0.3453
R	35	70	35	140	35
D^{-1}	3×10^2	3×10^2	10^2	3×10^2	2×10^2

Table.2 Shear stress (τ) at y= 1 P=0.71,R=35,N_1=4.0

G	I	II	III	IV	V
10^3	9.8631	14.0044	11.0688	12.2104	11.5332
2×10^3	9.8613	14.1890	11.0331	12.2004	11.5447
3×10^3	9.8594	14.1735	10.9974	12.1905	11.5561
-10^3	9.8649	14.2198	11.1047	12.2203	11.5215
-2×10^3	9.8668	14.2353	11.1407	12.2303	11.5103
-3×10^3	9.8686	14.2508	11.1769	12.2402	11.4989
β	0.3	0.7	0.9	0.5	0.5
γ	2	2	2	4	6

Table.3 Shear stress (τ) at y=1P=0.71,R=35,γ=2,β=0.5

G	I	II	III	IV	V
10^3	12.9803	12.9431	12.9363	12.9106	12.9003
2×10^3	12.8943	12.8723	12.8543	12.8343	12.8143
3×10^3	12.8884	12.8724	12.8544	12.8384	12.8184
-10^3	12.9062	12.9234	12.9482	12.9602	12.9882
-2×10^3	12.9631	12.9764	12.984	12.932	13.024
-3×10^3	12.9386	12.9532	12.9708	12.9934	13.0125
N1	0.5	1	5	10	100

Table.4 Shear stress (τ) at y= -1 P=0.71,β= 0.5,γ=2

G	I	II	III	IV	V
10^3	11.5970	12.1827	12.4756	26.447	1.4069
2×10^3	9.2541	11.0113	11.8899	28.6118	1.0794
3×10^3	6.9113	9.8399	11.3042	29.044	0.7631
-10^3	13.9399	13.3542	13.0613	28.749	1.7121
-2×10^3	16.2828	14.5256	13.6470	29.487	2.0284
-3×10^3	18.6256	15.6970	14.2328	30.584	2.3447
R	35	70	140	35	35
D^{-1}	3×10^2	3×10^2	3×10^2	10^2	2×10^2

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