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NON-DARCY CONVECTIVE HEAT AND MASS TRANSFER FLOW IN VERTICAL CHANNEL WITH TEMPERATURE DEPENDENT HEAT SOURCE, RADIATION AND DISSIPATION

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ABSTRACT

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

Key Words: *Heat and mass transfer, radiation effect and heat generating sources.*

1. INTRODUCTION

The phenomenon of heat and mass transfer has been the object of extensive research due to its applications in Science and Technology. Such phenomena are observed in buoyancy induced motions in the atmosphere, in bodies of water, quasi solid bodies such as earth and so on.

Non–Darcy effects on natural convection in porous media have received a great deal of attention in recent years because of the experiments conducted with several combinations of solids and fluids covering wide ranges of governing parameters which indicate that the experimental data for systems other than glass water at low Rayleigh numbers, do not agree with theoretical predictions based on the Darcy flow model. This divergence in the heat transfer results has been reviewed in detail in Cheng (5) and Prasad *et al.* (16) among others. Extensive effects are thus being made to include the inertia and viscous diffusion terms in the flow equations and to examine their effects in order to develop a reasonable accurate mathematical model for convective transport in porous media.

The Brinkman – Extended – Darcy modal was considered in Tong and Subramanian (20), and Lauriat and Prasad (23) to examine the boundary effects on free convection in a vertical cavity. A numerical study based on the Forchheimer-Brinkman-Extended Darcy equation of motion has also been reported recently by Beckerman *et al* (3).

Also in all the above studies the thermal diffusion effect (known as Soret effect) has been neglected. This assumption is true when the concentration level is very low. The thermal diffusion effects for instance has been utilized for isotropic separation and in mixtures between gases with very light molecular weight (H_2, He) and the medium molecular weight (N_2, air) the diffusion – thermo effects was found to be of a magnitude just it can not be neglected (6). In view of the importance of this diffusion – thermo effect, recently Jha and Singh (7) studied the free convection and mass transfer flow in an infinite vertical plate moving impulsively in its own plane taking into account the Soret effect. Kafousias (8) studied the MHD free convection and mass transfer flow taking into account Soret effect. The analytical studies of Jha and singh (7) and Kafousias (8) were based on Laplace transform technique. Abdul Sattar and Alam(1) have considered an unsteady convection and mass transfer flow of viscous incompressible and electrically conducting fluid past a moving infinite vertical porous plate taking into the thermal diffusion effects. Similarity equations of the momentum energy and concentration equations are derived by introducing a time dependent length scale. Malsetty *et al* (12) have studied the effect of both the soret coefficient and Dufour coefficient on the double diffusive convective with compensating horizontal thermal and solutal gradients.

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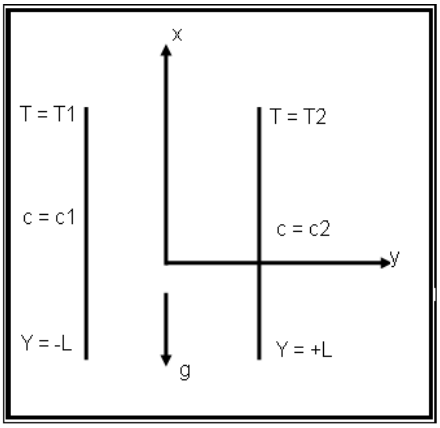
2. FORMULATION OF THE PROBLEM

We consider a fully developed laminar convective heat and mass transfer flow of a viscous fluid through a porous medium confined in a vertical channel bounded by flat walls. We choose a Cartesian co-ordinate system O(x, y, z) with x- axis in the vertical direction and y-axis normal to the walls. The walls are taken at y= ± 1.The walls are maintained at constant temperature and concentration. The temperature gradient in the flow field is sufficient to cause natural convection in the flow field. A constant axial pressure gradient is also imposed so that this resultant flow is a mixed convection flow. The porous medium is assumed to be isotropic and homogeneous with constant porosity and effective thermal diffusivity. The thermo physical properties of porous matrix are also assumed to be constant and Boussinesq approximation is invoked by confining the density variation to the buoyancy term. In the absence of any extraneous force the flow is unidirectional along the x-axis which is assumed to be infinite.



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

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

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

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

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

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

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

Since the flow is unidirectional, the continuity of equation (2.1) reduces to

$\frac{\partial u}{\partial x} = 0$, where u is the axial velocity implies u = u(y)

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

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

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

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

The boundary conditions are

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

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

Invoking Rosseland approximation for radiation flux we get

$$q_r = -\frac{4\sigma^{\bullet}}{\beta_R}\frac{\partial (T'^4)}{\partial y} \tag{2.10}$$

and linearising T'^4 about Te by using Taylor's expansion and neglecting higher order terms we get

$$T'^4 \cong 4T_e^3 T - 3T_e^4 \tag{2.11}$$

Where σ^* is the Stefan-Boltzman constant and β_R is the mean absorption coefficient.

We define the following non-dimensional variables as

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

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

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

$$\frac{d^2\theta}{dy^2} - \alpha\,\theta + \frac{4}{3N_1}\frac{d^2\theta}{dy^2} = (PN_T)u \tag{2.14}$$

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

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

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

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

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

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

3. SOLUTION OF THE PROBLEM

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

$$\begin{aligned} &u = u_0 + \delta u_1 + \delta^2 u_2 + \ldots\ldots\ldots\ldots \\ &\theta = \theta_0 + \delta\theta_1 + \delta^2\theta_2 + \ldots\ldots\ldots \\ &C = C_0 + \delta\, C_1 + \delta^2 C_2 + \ldots\ldots\ldots \end{aligned} \tag{3.1}$$

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

$$\frac{d^2u_0}{dy^2}=\pi \tag{3.2}$$

$$\frac{d^2\theta_0}{dy^2}-\alpha_1\theta_0=(P_1N_T)u \tag{3.3}$$

$$\frac{d^2C_0}{dy^2}+\frac{ScSo}{N}\frac{d^2\theta_0}{dy^2}=(ScN_C)u_0 \tag{3.4}$$

The equations to the first order are

$$\frac{d^2u_1}{dy^2}-M_1^2u_1=-G(\theta_0+NC_0) \tag{3.5}$$

$$\frac{d^2\theta_1}{dy^2}-\alpha_1\theta_1=(P_1N_T)u_1 \tag{3.6}$$

$$\frac{d^2C_1}{dy^2}+\frac{ScSo}{N}\frac{d^2\theta_1}{dy^2}=(ScN_C)u_1 \tag{3.7}$$

The equations to the second order are

$$\frac{d^2u_2}{dy^2}-M_1^2u_2=-G(\theta_1+NC_1)-\mathrm{A}u_0^2 \tag{3.8}$$

$$\frac{d^2\theta_2}{dy^2}-\alpha_1\theta_2=(P_1N_T)u_2 \tag{3.9}$$

$$\frac{d^2C_2}{dy^2}+\frac{ScSo}{N}\frac{d^2\theta_2}{dy^2}=(ScN_C)u_2 \tag{3.10}$$

The corresponding conditions are

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

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

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

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

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

$$\theta_0=a_7\left(y^2-\frac{Ch(\beta_1y)}{Ch(\beta_1)}\right)-a_6\left(\frac{Ch(\beta_1y)}{Ch(\beta_1)}-1\right)+0.5\left(\frac{Ch(\beta_1y)}{Ch(\beta_1)}-\frac{Sh(\beta_1y)}{Sh(\beta_1)}\right)+a_8\left(y^4-\frac{Ch(\beta_1y)}{Ch(\beta_1)}\right)$$

$$C_0=\frac{a_{15}}{\beta_1^2}(Ch(\beta_1y)-Ch(\beta_1))+\frac{a_{16}}{\beta_1^2}(Sh(\beta_1y)-ySh(\beta_1))+0.5(1-y)$$
$$+\frac{a_{14}}{12}(y^4-1)+\frac{a_{13}}{2}(y^2-1)+0.5\,(1-y)$$

$$u_1 = a_{25}\left(1-\frac{Ch(M_1 y)}{Ch(M_1)}\right) - a_{27}\left(\frac{Ch(M_1 y)}{Ch(M_1)} - y^2\right) + a_{28}\left(Ch(\beta_1 y) - Ch(\beta_1)\frac{Ch(M_1 y)}{Ch(M_1)}\right).$$
$$+ a_{26}\left(y - \frac{Sh(M_1 y)}{Sh(M_1)}\right) + a_{27}\left(y^2 - \frac{Ch(M_1 y)}{Ch(M_1)}\right) + a_{29}\left(Sh(\beta_1 y) - Sh(\beta_1)\frac{Sh(M_1 y)}{Sh(M_1)}\right)$$
$$+ a_{30}\left(yCh(\beta_1 y) - Ch(\beta_1)\frac{Sh(M_1 y)}{Sh(M_1)}\right) - a_{30}\left(ySh(\beta_1 y) - Sh(\beta_1)\frac{Ch(M_1 y)}{Ch(M_1)}\right)$$

$$u_2 = a_{60}\left(\frac{Ch(\beta_2 y)}{Ch(\beta_2)}Ch(\beta_1) - Ch(\beta_1 y)\right) + a_{62}\left(\frac{Ch(\beta_2 y)}{Ch(\beta_2)}Sh(\beta_1) - ySh(\beta_1 y)\right)$$
$$+ a_{64}\left(\frac{Ch(\beta_2 y)}{Ch(\beta_2)}Sh(\beta_2) - ySh(\beta_2 y)\right) + a_{66}\left(\frac{Ch(\beta_2 y)}{Ch(\beta_2)} - y^4\right) - a_{68}\left(\frac{Ch(\beta_2 y)}{Ch(\beta_2)} - y^2\right)$$
$$+ a_{70}\left(\frac{Ch(\beta_2 y)}{Ch(\beta_2)} - 1\right) + a_{61}\left(\frac{Sh(\beta_2 y)}{Sh(\beta_2)}Sh(\beta_1) - ySh(\beta_1 y)\right) - a_{63}\left(\frac{Sh(\beta_2 y)}{Sh(\beta_2)}Ch(\beta_2) - yCh(\beta_2 y)\right)$$
$$- a_{65}\left(\frac{Sh(\beta_2 y)}{Sh(\beta_2)}Ch(\beta_1) - yCh(\beta_1 y)\right) - a_{67}\left(\frac{Sh(\beta_2 y)}{Sh(\beta_2)} - y^3\right) - a_{69}\left(\frac{Sh(\beta_2 y)}{Sh(\beta_2)} - y\right)$$

$$\theta_1 = a_{53}\left(1-\frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) + a_{54}\left(y - \frac{Sh(\beta_1 y)}{Sh(\beta_1)}\right) + a_{55}\left(y^2 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) - a_{56}\left(y^3 - \frac{Sh(\beta_1 y)}{Sh(\beta_1)}\right)$$
$$- a_{57}\left(y^4 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) + a_{58}\left(Ch(M_1 y) - Ch(M_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) + a_{59}\left(Sh(M_1 y) - Sh(M_1)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}\right)$$
$$+ a_{60}\left(yCh(M_1 y) - Ch(M_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) + a_{61}\left(ySh(M_1 y) - Sh(M_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right)$$
$$+ a_{62}\left(y^2 Ch(M_1 y) - Ch(M_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) + a_{63}\left(y^2 Sh(M_1 y) - Sh(M_1)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}\right)$$
$$+ a_{64}\left(yCh(\beta_1 y) - Ch(\beta_1)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}\right) + a_{65}\left(ySh(\beta_1 y) - Sh(\beta_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right)$$
$$+ a_{66}(y^2-1)Ch(\beta_1 y) + a_{67}(y^2-1)Sh(\beta_1 y) + a_{68}\left(y^3 Ch(\beta_1 y) - \; - Ch(\beta_1)\frac{Sh(\beta_1 y)}{Sh(\beta_1)}\right)$$
$$+ a_{69}\left(y^3 Sh(\beta_1 y) - Sh(\beta_1)\frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) + a_{70}(y^4-1)Ch(\beta_1 y) + a_{71}(y^2-1)Sh(\beta_1 y)$$

$$C_1 = a_{89}(y^2-1) + a_{90}(y^3-y) + a_{91}(y^4-1) + (a_{92} + ya_{95})(Ch(M_1 y) - Ch(M_1))$$
$$+ a_{93}(Sh(M_1 y) - ySh(M_1)) + a_{94}(ySh(M_1 y) - Sh(M_1)) + (a_{96} + ya_{98} + y^2 a_{100}$$
$$+ y^3 a_{102} + y^4 a_{104}))Ch(\beta_1 y) - Ch(\beta_1 y)) + (a_{97} + ya_{99} + y^2 a_{101} + y^3 a_{103} + y^4 a_{105})(Sh(\beta_1 y) - ySh(\beta_1))$$

$$C_2 = (b_{10} + yb_{18})(Ch(\beta_1 y) - Ch(\beta_1)) + b_{19}(ySh(\beta_1 y) - Sh(\beta_1)) + (b_{20} + yb_{22})x$$
$$+ (Ch(\beta_2 y) - Ch(\beta_2)) + b_{23}(ySh(\beta_2 y) - Sh(\beta_2)) + b_{24}(y^2-1) + b_{17}(Sh(\beta_1 y)$$
$$- ySh(\beta_1)) + b_{21}(Sh(\beta_2 y) \_ Sh(\beta_2))$$

$$\theta_2 = a_{71}(Ch(\beta_2 y) - Ch(\beta_2)) + a_{74}\left(ySh(\beta_2 y) - Sh(\beta_2)\frac{Ch(\beta_2 y)}{Ch(\beta_2)} \right)$$
$$+a_{75}\left(ySh(\beta_1 y) - Sh(\beta_1)\frac{Ch(\beta_2 y)}{Ch(\beta_2)} \right) - a_{79}(y^2-1)Ch(\beta_1 y)$$
$$+a_{79}(y^4-1) + a_{81}(y^2-1) + a_{83}\left(1 - \frac{Ch(\beta_1 y)}{Ch(\beta_1)}\right) + a_{72}\left(Sh(\beta_2 y) - \frac{Sh(\beta_1 y)}{Sh(\beta_1)}Sh(\beta_2) \right)$$
$$+a_{73}\left(yCh(\beta_1 y) - \frac{Sh(\beta_1 y)}{Sh(\beta_1)}Ch(\beta_2) \right) + a_{76}\left(yCh(\beta_1 y) - \frac{Sh(\beta_1 y)}{Sh(\beta_1)}Ch(\beta_1) \right)$$
$$+a_{78}(y^2-1)Sh(\beta_1 y) + a_{80}\left(y^3 - \frac{Sh(\beta_1 y)}{Sh(\beta_1)} \right) + a_{82}\left(y - \frac{Sh(\beta_1 y)}{Sh(\beta_1)} \right)$$

SHEAR STRESS, NUSSELT NUMBER AND SHERWOOD NUMBER

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

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

which in the non-dimensional form is

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

and the corresponding expressions are

$$\tau_{y=+1} = \pi + \delta b_1 + ...$$
$$\tau_{y=-1} = \pi + \delta b_2 + ...$$

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

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

5. DISCUSSION OF THE NUMERICAL RESULTS

The primary aim of this analysis is to investigate the effect of Thermo-diffusion, radiation and dissipation on the Non-Darcy convective heat and mass transfer in a vertical channel in the presence of heat generating sources. The velocity and temperature are discussed for different values of N, α, S_0, N_1, Ec.

Fig. (1) represents when the molecular buoyancy force dominates over the thermal buoyancy force |u| depreciates when the buoyancy forces act in the same direction and for the forces acting in opposite directions |u| enhances everywhere in the region.

The effect of thermo-diffusion on u is shown in fig. 2. It is found that |u| enhances with increase in $S_0 > 0$ and reduces with $|S_0|$.

An increase in the strength of the heat source results in a depreciation in |u| in the entire flow region (fig. 3). With reference to radiation parameter N_1 it is found that the magnitude of u reduces with increase in $N_1 \le 2.5$ and enhances with higher $N_1 \ge 5$ (fig. 4).

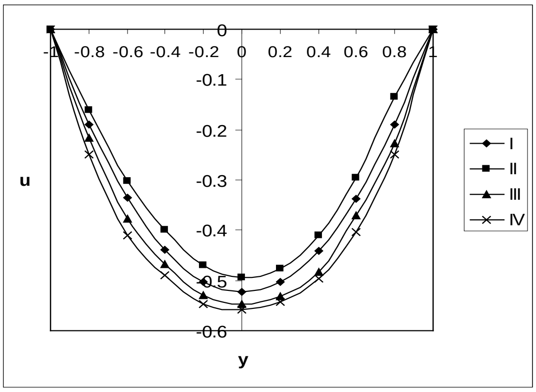


Fig. - 1: Variation of u with N
$\alpha = 2$, Sc = 1.30, $S_0 = 0.50$, $N_1 = 1.50$ Ec = 0.01

	I	II	III	IV
N	1	2	-0.50	-0.80

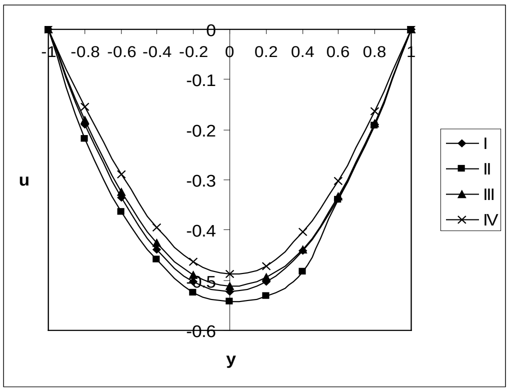


Fig. - 2: Variation of u with S_0
$\alpha = 2$, Sc = 1.30, N = 1.00, $N_1 = 1.50$ Ec = 0.01

	I	II	III	IV
S_0	0.50	1.00	-0.50	-1.00

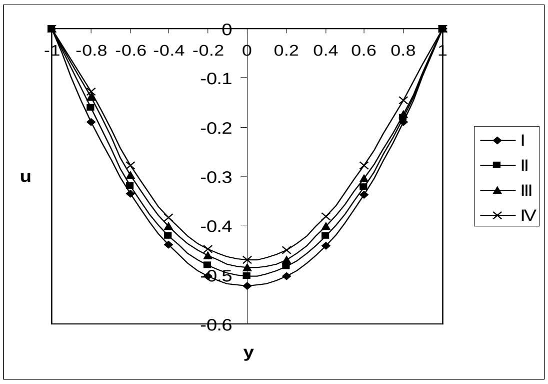


Fig. - 3: Variation of u with α
Sc = 1.30, $S_0 = 0.50$, N = 1.00, $N_1 = 1.50$ Ec = 0.01

	I	II	III	IV
α	2	4	6	10

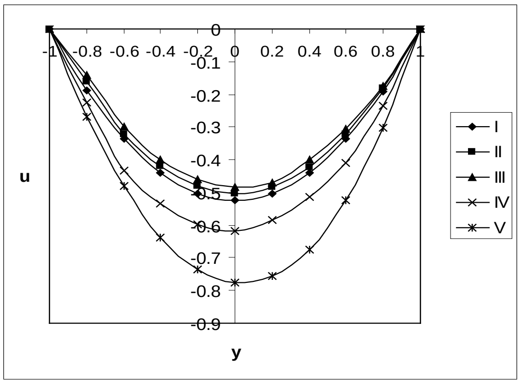


Fig. - 4: Variation of u with N_1
$\alpha = 2$, Sc = 1.30, $S_0 = 0.50$, N = 1.00, Ec = 0.01

	I	II	III	IV	V
N_1	1.50	2.50	5.00	10.00	100.00

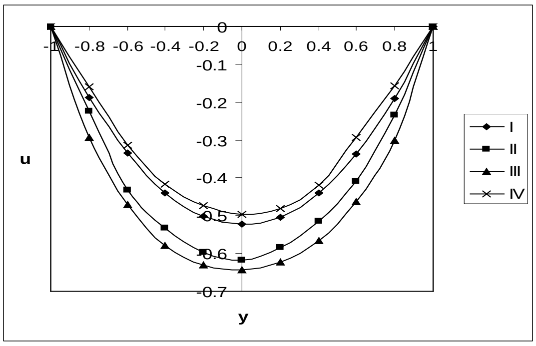


Fig. - 5: Variation of u with Ec
$\alpha = 2$, Sc = 1.30, $S_0 = 0.50$, N = 1.00, $N_1 = 1.50$

	I	II	III	IV
Ec	0.01	0.03	0.05	0.07

The stress at $y = \pm 1$ is shown in tables 1-3 for different values of G, D^{-1}, Sc, S_0, N, N_1 and Sc. It is found that the stress at $y = \pm 1$ enhances with increase in $|G|$ and D^{-1} and depreciates with Sc. Thus lesser the permeability of the porous medium larger the stress, also lesser the molecular diffusivity smaller the stress at $y = \pm 1$. Also the stress depreciates with increase in $S_0 > 0$ and enhances with $|S_0|$ at $y = \pm 1$ (table.1).

Table - 1: Shear stress (τ) at y = +1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	2.8099	3.7069	4.2791	4.2582	3.7663	1.8398	1.0337	6.3623	8.1764
$3x10^3$	10.4297	13.1209	14.8373	14.7745	13.2989	7.5195	5.1011	21.0868	26.4154
-10^3	-4.8099	-5.7069	-6.2791	-6.2582	-5.7663	-3.8398	-3.0337	-8.3623	-10.1385
$-3x10^3$	-12.4297	-15.1209	-16.8373	-16.7745	-15.2989	-9.5195	-7.1011	-23.0868	-28.4154
D^{-1}	10^2	$3x10^2$	$5x10^2$	10^2	10^2	10^2	10^2	10^2	10^2
Sc	1.3	1.3	1.3	0.24	0.6	2.01	1.3	1.3	1.3
S_0	0.5	0.5	0.5	0.5	0.5	0.5	1	-0.5	-1

The variation of τ with buoyancy ratio N shows that when the molecular buoyancy force dominates over the thermal buoyancy force the stress depreciates when the buoyancy forces act in the same direction and for the forces acting in opposite directions, it enhances at both the walls. With reference to radiation parameter we find an increasing tendency with increase in N_1 (table. 2). The variation of τ with Ec shows that higher the dissipative effects smaller |τ| at y = ±1 (table. 3).

Table - 2: Shear stress (τ) at y = +1

G	I	II	III	IV	V	VI	VII
10^3	2.8099	2.2509	3.6484	3.8161	2.8814	4.0145	6.7684
$3x10^3$	10.4297	8.7527	12.9452	13.4483	10.6442	14.0435	22.3053
-10^3	-4.8099	-4.2509	-5.6484	-5.8161	-4.8814	-6.0145	-8.7684
$-3x10^3$	-12.4297	-10.7527	-14.9452	-15.4483	-12.6442	-16.0435	-24.3054
N	1	2	-0.5	-0.8	1	1	1
N_1	1.5	1.5	1.5	1.5	2.5	5	10

Table - 3: Shear stress (τ) at y = +1

G	I	II	III	IV
10^3	2.8099	2.7422	2.3359	1.9974
$3x10^3$	10.4297	10.2266	9.0078	7.9922
-10^3	-4.8099	-4.7422	-4.3359	-3.9974
$-3x10^3$	-12.4297	-12.2266	-11.0078	-9.9922
Ec	0.005	0.01	0.03	0.05

Table - 4: Shear stress (τ) at y = -1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	-2.2148	-3.3221	-4.1842	-2.5033	-2.4054	-2.0216	-1.8609	-2.9225	-3.2764
$3x10^3$	-8.6448	-11.9663	-14.5526	-9.5101	-9.2161	-8.0647	-7.5829	-10.7675	-21.8291
-10^3	4.2148	5.3221	6.1842	4.5033	4.4054	4.0215	3.8609	4.9225	5.2763
$-3x10^3$	10.6445	13.9663	16.5526	11.5101	11.2161	10.0647	9.5829	12.7675	13.8291
D^{-1}	10^2	$3x10^2$	$5x10^2$	10^2	10^2	10^2	10^2	10^2	10^2
Sc	1.3	1.3	1.3	0.24	0.6	2.01	1.3	1.3	1.3
S_0	0.5	0.5	0.5	0.5	0.5	0.5	1	-0.5	-1

Table - 5: Shear stress (τ) at y = -1

G	I	X	XI	XII	XIII	XIV	XV
10^3	-2.2148	-1.6558	-3.0533	-3.2211	-2.1607	-2.9728	-5.0984
$3x10^3$	-8.6448	-6.9675	-11.1599	-11.6631	-8.4821	-10.9183	-17.2954
-10^3	4.2148	3.6558	5.0533	5.2211	4.1607	4.9728	7.0984
$-3x10^3$	10.6445	8.9675	13.1599	13.6631	10.4821	12.9183	19.2954
N	1	2	-0.5	-0.8	1	1	1
N_1	1.5	1.5	1.5	1.5	2.5	5	10

The Nusselt number (Nu) at y = ±1 is shown in tables 4-6 for different parametric values. It is found that the rate of heat transfer depreciates at y = +1 and enhances at y = -1 with G>0 and a reversed effect is noticed with increase in |G|. The variation of Nu with Darcy parameter D^{-1} shows that lesser the permeability of the porous medium smaller Nu in the heating case and enhances in the cooling case at y = ±1. With reference to Sc we find that lesser the molecular diffusivity larger |Nu| at y = +1 and reduces at y = -1. The variation of Nu with Soret parameter S_0 shows that higher the thermo-diffusion effects smaller |Nu| at both the walls (table. 4). When the molecular buoyancy force dominates over the thermal buoyancy force the rate of heat transfer enhances for G>0 and reduces for G<0 when the buoyancy forces act in the same direction and for the forces acting in opposite directions |Nu| depreciates in the heating case and enhances in the cooling case at both the walls. An increase in N_1 shows that higher the radiative heat flux larger the rate of heat transfer at y = ±1 (table 5).

From table 6 we find that higher the dissipative effects smaller the Nusselt number at both the walls.

Table - 6: Shear stress (τ) at y = -1

G	I	II	III	IV
10^3	-2.2148	-2.1576	-1.8642	-1.5279
$3x10^3$	-8.6448	-8.4727	-7.4425	-6.5839
-10^3	4.2148	4.1576	3.8142	3.5279
$-3x10^3$	10.6445	10.4728	9.4425	.5839
Ec	0.005	0.01	0.03	0.05

The Sherwood number (Sh) which measures the rate of mass transfer at y = ±1 is shown in tables 7-9 for different parametric values. It is found that the rate of mass transfer enhances with increase in |G| and D^{-1} at both the walls. Also an in increase in S_0 results in a depreciation in |Sh| at y = ±1. The effect of thermo- diffusion an Sh is shown in table. 7. It is found that an increase in S_0 > 0 reduces |Sh| at y = +1 and enhances at y = -1 while it enhances with $|S_0|$ at y = ±1. The variation of Nu with buoyancy ratio N shows that the rate of mass transfer reduces at y = +1 and enhances the mass transfer at y = -1when the buoyancy forces act in the same direction and for the forces acting in opposite directions, it enhances at y = +1 and reduces at y = -1 for all G.

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

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	0.2379	0.2344	0.2275	0.2361	0.2367	0.2391	0.2401	0.2335	0.2314
$3x10^3$	0.2328	0.2239	0.2062	0.2275	0.2293	0.23637	0.2393	0.2197	0.2131
-10^3	0.2430	0.2449	0.2487	0.2448	0.2442	0.2418	0.2408	0.2474	0.2496
$-3x10^3$	0.2481	0.2554	0.2701	0.2535	0.2517	0.2445	0.2416	0.2612	0.2678
D^{-1}	10^2	$3x10^2$	$5x10^2$	10^2	10^2	10^2	10^2	10^2	10^2
Sc	1.3	1.3	1.3	0.24	0.6	2.01	1.3	1.3	1.3
S_0	0.5	0.5	0.5	0.5	0.5	0.5	1	-0.5	-1

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

G	I	II	III	IV	V	VI	VII
10^3	0.2379	0.2386	0.2367	0.2365	0.7601	1.9417	4.1972
$3x10^3$	0.2328	0.2351	0.2294	0.2287	0.7556	1.9368	4.1904
-10^3	0.2430	0.2423	0.2442	0.2443	0.7645	1.9466	4.2039
$-3x10^3$	0.2481	0.2458	0.2515	0.2522	0.7689	1.9515	4.2108
N	1	2	-0.5	-0.8	1	1	1
N_1	1.5	1.5	1.5	1.5	2.5	5	10

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

G	I	II	III	IV
10^3	0.2379	0.2243	0.1946	0.1709
$3x10^3$	0.2328	0.1999	0.1306	0.0794
-10^3	0.2430	0.2487	0.2586	0.2625
$-3x10^3$	0.2481	0.2730	0.3225	0.3541
Ec	0.005	0.01	0.03	0.05

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