EFFECT OF NON-LINEAR DENSITY TEMPERATURE VARIATION ON CONVECTIVE HEAT AND MASS TRANSFER FLOW OF A VISCOUS DISSIPATIVE FLUID IN A RECTANGULAR CAVITY

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Abstract: In this paper an attempt has been made to discuss the combined influence of radiation and dissipation on the convective heat and mass transfer flow of a viscous fluid through a porous medium in a rectangular cavity using Darcy model with non-linear density temperature variation. Making use of the incompressibility the governing non-linear coupled equations for the momentum, energy and diffusion are derived in terms of the non-dimensional stream function, temperature and concentration. The Galerkin finite element analysis with linear triangular elements is used to obtain the Global stiffness matrices for the values of stream function, temperature and concentration. These coupled matrices are solved using iterative procedure and expressions for the stream function, temperature and concentration are obtained as a linear combinations of the shape functions. The behaviour of temperature, concentration, Nusselt number and Sherwood number are discussed computationally for different values of the governing Parameters N_1 and Ec.

Keywords : Dissipation, Porous medium, Radiation and Viscous fluid.

Introduction: Convective heat transfer in a Rectangular porous duct whose vertical walls are maintained at two different temperatures and horizontal walls insulated, is a problem which has received attention by many investigators. The investigation of heat transfer in enclosures containing porous media began with the experimental work of Verschoor and Greebler [10].. Teomann Ay Han et. al., [8] have considered heat transfer and flow structure in a rectangular channel with wing-type Vortex Generator. Chitti Babu et. al., [3] has discussed convective flow in a porous rectangular duct with differentially heated side wall using Brinkman model.

When heat and mass transfer occur simultaneously, it leads to complex fluid motion called double-diffusive convection. Double-diffusion occurs in a wide range of scientific fields such as oceanography, astrophysics, geology, biology and chemical processes. Ostrich [4] and Viskanta et. al., [11] reported complete reviews on the subject. Bejan [2] reported fundamental study of scale analysis relative to heat and mass transfer with in cavities submitted to horizontal combined and pure temperature and concentration gradients. unsteady double-diffusive convection in a rectangular enclosure with aiding and opposing temperature and concentration gradients that were in good agreement with reported experimental results.

Literature suggests that the effect of viscous dissipation on heat transfer as been studied for different geometries. The study showed that the viscous dissipation effect on natural convection in a porous cavity and found that the heat transfer rate at hot surface decreases with increase of viscous dissipation parameter. Thermal radiation plays a significant role in the overall surface heat transfer where convective heat transfer is small. Recently Padmavathi [5] has analyzed the conductive heat transfer through a porous medium in a rectangular cavity with heat sources and dissipation under varied conditions. By using Galerkine finite element analysis, the governing equations are solved. Reddaih et. al., [6] have analyzed the effect of viscous dissipation on convective heat and mass transfer flow of a viscous fluid in a duct of rectangular cross section by employing Galerkin finite element analysis. Recently Shanti [7] has investigated double diffusive flow in a rectangular cavity with linear density temperature variation.

In this paper an attempt has been made to discuss the combined influence of radiation and dissipation on the convective heat and mass transfer flow of a viscous fluid through a porous medium in a rectangular cavity using Darcy model with non-linear density temperature variation. Making use of the incompressibility the governing non-linear coupled equations for the momentum, energy and diffusion are derived in terms of the non-dimensional stream function, temperature and concentration. The Galerkin finite element analysis with linear triangular elements is used to obtain the Global stiffness matrices for the values of stream function, temperature and concentration. These coupled matrices are solved using iterative procedure and expressions for the stream function, temperature and concentration are obtained as a linear combinations of the shape functions. The behaviour of temperature, concentration, Nusselt number and Sherwood number are discussed computationally for different values of the governing Parameters N_1 and Ec.

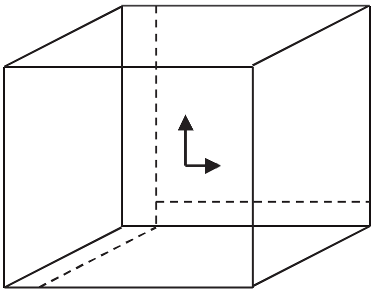

Fig. I
SCHEMATIC DIAGRAM OF THE FLOW MODEL

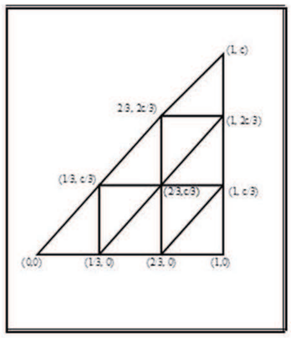

Fig. ii.
SCHEMATIC DIAGRAM OF THE CONFIGURATION

2. Formulation:

We consider the mixed convective heat and mass transfer flow of a viscous incompressible fluid in a saturated porous medium confined in the rectangular duct (Fig. 1) whose base length is a and height b. The heat flux on the base and top walls is maintained constant.

We assume that

i) The convective fluid and the porous medium are everywhere in local thermodynamic equilibrium.

ii) There is no phase change of the fluid in the medium.

iii) The properties of the fluid and of the porous medium are homogeneous and isotrophic.

iv) The porous medium is assumed to be closely packed so that Darcy's momentum law is adequate in the porous medium.

v) The Boussinesq approximation is applicable.

Under these assumption the governing equations are given by

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

(2.1)

$$u' = -\frac{k}{\mu}\left(\frac{\partial p'}{\partial x'}\right)$$

(2.2)

$$v' = -\frac{k}{\mu}\left(\frac{\partial p'}{\partial y'} + \rho' g\right)$$

(2.3)

$$\rho_\sigma c_p\left(u'\frac{\partial T'}{\partial x'} + v'\frac{\partial T'}{\partial y'}\right) = K_1\left(\frac{\partial^2 T'}{\partial x'^2} + \frac{\partial^2 T'}{\partial y'^2}\right) + \left(\frac{\mu}{K}\right)(u^2 + v^2)$$

(2.4)

$$\rho_\sigma c_p\left(u'\frac{\partial C}{\partial x'} + v'\frac{\partial C}{\partial y'}\right) = D_1\left(\frac{\partial^2 C}{\partial x'^2} + \frac{\partial^2 C}{\partial y'^2}\right)$$

(2.5)

$$\rho' = \rho_0\left\{1 - \beta_0(T' - T_0) - \beta_1(\mathrm{T} - \mathrm{T}_0)^2 - \beta^\bullet(C' - C_0)\right\}$$

(2.6)

$$T_0 = \frac{T_h + T_c}{2}, C_0 = \frac{C_h + C_c}{2}$$

where u′ and v′ are Darcy velocities along θ(x, y) direction. T′, C,p′ and g′ are the temperature, Concentration, pressure and acceleration due to gravity, T_c ,Cc and T_h ,C_h are the temperature and Concentration on the cold and warm side walls respectively. ρ′, μ, ν, and β are the density, coefficients of viscosity, kinematic viscosity and thermal expansion of he fluid, k is the permeability of the porous medium, K_1 is the thermal conductivity, C_p is the specific heat at constant pressure, β* is the volume coefficient of expansion with mass fraction concentration and q_r is the radiative heat flux..

The boundary conditions are

u′ = v′ = o

on the boundary of the duct

$T' = T_c$,$C=C_c$

on the side wall to the left

$T' = T_h$,$C=C_h$

on the side wall to the right (2.7)

$$\frac{\partial T'}{\partial y} = 0 \ , \ \frac{\partial C}{\partial y} = 0$$

on the top (y = o) and bottom

$$u = v = 0$$

walls(y = o)which are insulated.

We now introduce the following non-dimensional variables

x′ = ax; ; y′ = by ;
c = b/a

u′ = (ν/a) u ; v′ = (ν/a)v ;
$p' = (\nu^2\rho/a^2)p$

$T' = T_o + \theta\,(T_h - T_c)$ $C' = C_o + \phi\,(T_h - T_c)$ (2.8).

The governing equations in the non-dimensional form are

$$u = -\left(\frac{K}{a^2}\right)\frac{\partial p}{\partial x} \tag{2.9}$$

$$v = -\frac{k}{a^2}\frac{\partial p}{\partial y} - \frac{kag}{\nu^2} + \frac{kag\beta_0(T_h - T_c)\theta}{\nu^2} + \frac{kag\beta_1(T_h - T_c)^2\theta^2}{\nu^2} + \frac{kag\beta_1^*(C_h - C_c)\phi}{\nu^2} \tag{2.10}$$

$$P\left(u\frac{\partial\theta}{\partial x} + v\frac{\partial\theta}{\partial y}\right) = \left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2}\right) + E_C\left(u^2 + v^2\right) \tag{2.11}$$

$$Sc\left(u\frac{\partial\phi}{\partial x} + v\frac{\partial\phi}{\partial y}\right) = \left(\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2}\right) \tag{2.12}$$

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

$$u = \frac{\partial\psi}{\partial y}\ ; \quad v = -\frac{\partial\psi}{\partial x} \tag{2.13}$$

Eliminating p from the equation (2.9) and (2.10) and making use of (2.13) the equations in terms of ψ and θ are

$$\nabla^2\psi - M_1^2\frac{\partial^2\psi}{\partial x^2} = -Ra\left(\frac{\partial\theta}{\partial x} + N\frac{\partial\phi}{\partial x}\right) \tag{2.14}$$

$$P\left(\frac{\partial\psi}{\partial y}\frac{\partial\theta}{\partial x} - \frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial y}\right) = \left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2}\right) + E_C\left(\left(\frac{\partial\psi}{\partial y}\right)^2 + \left(\frac{\partial\psi}{\partial x}\right)^2\right) \tag{2.15}$$

$$Sc\left(\frac{\partial\psi}{\partial y}\frac{\partial\phi}{\partial x} - \frac{\partial\psi}{\partial x}\frac{\partial\phi}{\partial y}\right) = \left(\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2}\right) \tag{2.16}$$

where

$$G = \frac{g\beta(T_h - T_c)a^3}{\nu^2}$$

(Grashof number)

$P = \mu\, c_p / K_1$

(Prandtl number)

$$Ra = \frac{\beta g\left(T_g - T_c\right)Ka}{\nu^2}$$

(Rayleigh Number)

$$Sc = \frac{\nu}{D}$$

(Schmidt Number)

$$N = \frac{\beta^*(C_h - C_c)}{\beta(T_h - T_c)}$$

(Buoyancy ratio)

$$Ec = \left(\frac{a^4}{\mu K K_1 \Delta T}\right)$$

(Eckert number)

$$\gamma = \frac{\beta_1 \Delta T}{\beta_0}$$

(Density ratio)

The boundary conditions are

$$\frac{\partial\psi}{\partial x} = 0,\ \frac{\partial\psi}{\partial y} = 0 \ on \quad x = 0\ \&\ 1 \tag{2.17}$$

$$\theta = 1 \quad \phi = 1 \quad on \quad x = 0$$
$$\theta = 0 \quad \phi = 0 \quad on \quad x = 1 \tag{2.18}$$

3. Finite Element Analysis and Solution of the Problem:

The region is divided into a finite number of three node triangular elements, in each of which the element equation is derived using Galerkin weighted residual method. In each element f_i the approximate solution for an unknown f in the variational formulation is expressed as a linear combination of shape function. $\left(N_k^i\right) k = 1,2,3,$ which are linear polynomials in x and y.

Let ψ^i , θ^i and ϕ^i be the approximate values of ψ ,θ and φ in an element θ_i.

$$\psi^i = N_1^i\ \psi_1^i + N_2^i\ \psi_2^i + N_3^i\ \psi_3^i \tag{3.1a}$$

$$\theta^i = N_1^i\ \theta_1^i + N_2^i\ \theta_2^i + N_3^i\ \theta_3^i \tag{3.1b}$$

$$\phi = N_1^i\ \phi_1^i + N_2^i\ \phi_2^i + N_3^i\ \phi_3^i = \tag{3.1c}$$

Substituting the approximate value ψ^i , θ^i and ϕ^i for ψ ,θ and φ respectively in (2.13),

Repeating the above process with each of s elements, we obtain sets of such matrix equations. Introducing the global coordinates and global values for θ_p^i and making use of inter element continuity and boundary conditions relevant to the problem the above stiffness matrices are assembled to obtain a global matrix equation. This global matrix is r x r square matrix if there are r distinct global nodes in the domain of flow considered.

Similarly substituting ψ^i ,θ^i and ϕ^i in (2.12) and defining the error

and following the Galerkin method we obtain

$$\int_{\Omega} E_3^i \psi_j^i d\Omega = 0 \quad (3.2)$$

In the problem under consideration, for computational purpose, we choose uniform mesh of 10 triangular element (Fig. ii). The domain has vertices whose global coordinates are (0,0), (1,0) and (1,c) in the non-dimensional form. Let $e_1, e_2 \ldots\ldots e_{10}$ be the ten elements and let $\theta_1, \theta_2, \ldots\ldots \theta_{10}$ be the global values of θ and $\psi_1, \psi_2, \ldots\ldots \psi_{10}$ be the global values of ψ at the ten global nodes of the domain (Fig. ii).

The 3x3 matrix equations are assembled using connectivity conditions to obtain a 8x8 matrix equations for the global nodes ψ_p, θ_p and ϕ_p.The global matrix equations are coupled and are solved under the following iterative procedures The three equations are thus solved under iteration process until two consecutive iterations differ by a preassigned percentage.

The domain consists three horizontal levels and the solution for Ψ & θ at each level may be expressed in terms of the nodal values as follows,

In the horizontal strip $0 \le y \le \frac{c}{3}$

$$\Psi = (\Psi_1 N^1_1 + \Psi_2 N^1_2 + \Psi_7 N^1_7)\, H(1-\tau_1)$$

$$= \Psi_1 (1-4x) + \Psi_2 4(x - \frac{y}{c}) + \Psi_7 (\frac{4y}{c}) (1-\tau_1) \quad (0 \le x \le \frac{1}{3})$$

$$\Psi = (\Psi_2 N^3_2 + \Psi_3 N^3_3 + \Psi_6 N^3_6)\, H(1-\tau_2)$$

$$+ (\Psi_2 N^2_2 + \Psi_7 N^2_7 + \Psi_6 N^2_6) H(1-\tau_3) \quad (\frac{1}{3} \le x \le \frac{1}{3})$$

$$= (\Psi_2 2(1-2x) + \Psi_3 (4x - \frac{4y}{c} - 1) + \Psi_6 (\frac{4y}{c}))H(1-\tau_2)$$

$$+ (\Psi_2 (1 - \frac{4y}{c}) + \Psi_7 (1 + \frac{4y}{c} - 4x) + \Psi_6 (4x-1))H(1-\tau_3)$$

$$\Psi = (\Psi_3 N^5_3 + \Psi_4 N^5_4 + \Psi_5 N^5_5)\, H(1-\tau_3)$$

$$+ (\Psi_3 N^4_3 + \Psi_5 N^4_5 + \Psi_6 N^4_6) H(1-\tau_4) \quad (\frac{2}{3} \le x \le 1)$$

$$= (\Psi_3 (3-4x) + \Psi_4 2(2x - \frac{2y}{c} - 1) + \Psi_6 (\frac{4y}{c} - 4x + 3))H(1-\tau_3)$$

$$+ \Psi_3 (1 - \frac{4y}{c}) + \Psi_5 (4x-3) + \Psi_6 (\frac{4y}{c}))H(1-\tau_4)$$

Along the strip $\frac{c}{3} \le y \le \frac{2c}{3}$

$$\Psi = (\Psi_7 N^6_7 + \Psi_6 N^6_6 + \Psi_8 N^6_8)\, H(1-\tau_2) \quad (\frac{1}{3} \le x \le 1)$$

$$+ (\Psi_6 N^7_6 + \Psi_9 N^7_9 + \Psi_8 N^7_8)\, H(1-\tau_3) + (\Psi_6 N^8_6 + \Psi_5 N^8_5 + \Psi_9 N^8_9)\, H(1-\tau_4)$$

$$\Psi = (\Psi_7 2(1-2x) + \Psi_6 (4x-3) + \Psi_8 (\frac{4y}{c} - 1))H(1-\tau_3)$$

$$+ \Psi_6 (2(1 - \frac{2y}{c}) + \Psi_9 (\frac{4y}{c} - 1) + \Psi_8 (1 + \frac{4y}{c} - 4x))H(1-\tau_4)$$

$$+ \Psi_6 (4(1-x) + \Psi_5 (4x - \frac{4y}{c} - 1) + \Psi_9 2(\frac{2y}{c} - 1))H(1-\tau_5)$$

Along the strip $\frac{2c}{3} \le y \le 1$

$$\Psi = (\Psi_8 N^9_8 + \Psi_9 N^9_9 + \Psi_{10} N^9_{10})\, H(1-\tau_6) \quad (\frac{2}{3} \le x \le 1)$$

$$= \Psi_8 (4(1-x) + \Psi_9 4(x - \frac{y}{c}) + \Psi_{10} 2(\frac{4y}{c} - 3))H(1-\tau_6)$$

where $\tau_1 = 4x$, $\tau_2 = 2x$, $\tau_3 = \frac{4x}{3}$, $\tau_4 = 4(x - \frac{y}{c})$, $\tau_5 = 2(x - \frac{y}{c})$, $\tau_6 = \frac{4}{3}(x - \frac{y}{c})$

and H represents the Heaviside function.

The expressions for θ are

In the horizontal strip $0 \le y \le \frac{c}{3}$

$$\theta = [\theta_1 (1-4x) + \theta_2\, 4(x - \frac{y}{c}) + \theta_7 (\frac{4y}{c}))\, H(1-\tau_1) \quad (0 \le x \le \frac{1}{3})$$

$$\theta = (\theta_2 (2(1-2x) + \theta_3 (4x - \frac{4y}{c} - 1) + \theta_6 (\frac{4y}{c}))\, H(1-\tau_2)$$

$$+ \theta_2 (1 - \frac{4y}{c}) + \theta_7 (1 + \frac{4y}{c} - 4x) + \theta_6 (4x-1))H(1-\tau_3) \quad (\frac{1}{3} \le x \le \frac{2}{3})$$

$$\theta = \theta_3 (3-4x) + 2\,\theta_4 (2x - \frac{2y}{c} - 1) + \theta_6 (\frac{4y}{c} - 4x + 3)\, H(1-\tau_3)$$

$$+ (\theta_3 (1 - \frac{4y}{c}) + \theta_5 (4x-3) + \theta_6 (\frac{4y}{c}))\, H(1-\tau_4) \quad (\frac{2}{3} \le x \le 1)$$

Along the strip $\frac{c}{3} \le y \le \frac{2c}{3}$

$$\theta = (\theta_7 (2(1-2x) + \theta_6 (4x-3) + \theta_8 (\frac{4y}{c} - 1))\, H(1-\tau_3) \quad (\frac{1}{3} \le x \le \frac{2}{3})$$

$$+ (\theta_6 (2(1 - \frac{2y}{c}) + \theta_9 (\frac{4y}{c} - 1) + \theta_8 (1 + \frac{4y}{c} - 4x))\, H(1-\tau_4)$$

$+(\theta_6(4(1-x)+\theta_5(4x-\frac{4y}{c}-1)+\theta_9\, 2(\frac{4y}{c}-1))\, H(1-\tau_5)$

Along the strip $\frac{2c}{3}\le y\le 1$

$\theta = (\theta_8 4(1-x) + \theta_9 4(x-\frac{y}{c})+\theta_{10}(\frac{4y}{c}-3)\, H(1-\tau_6)$

$(\frac{2}{3}\le x\le 1)$

The expressions for ϕ are

$\phi = [\phi_1(1-4x)+ \phi_2\, 4(x-\frac{y}{c})+ \phi_7\, (\frac{4y}{c}))\, H(1-\tau_1)$

$(0\le x\le\frac{1}{3})$

$\phi = (\phi_2(2(1-2x)+ \phi_3\, (4x-\frac{4y}{c}-1)+ \phi_6(\frac{4y}{c}))\, H(1-\tau_2)$

$+\phi_2(1-\frac{4y}{c})+ \phi_7(1+\frac{4y}{c}-4x)+ \phi_6(4x-1))H(1-\tau_3)$

$(\frac{1}{3}\le x\le\frac{2}{3})$

$\phi = \phi_3(3-4x) +2\, \phi_4(2x-\frac{2y}{c}-1)+ \phi_6(\frac{4y}{c}-4x+3)\, H(1-\tau_3)$

$+(\phi_3(1-\frac{4y}{c})+ \phi_5(4x-3)+ \phi_6(\frac{4y}{c}))\, H(1-\tau_4)\quad(\frac{2}{3}\le x\le 1)$

Along the strip $\frac{c}{3}\le y\le\frac{2c}{3}$

$\phi = (\phi_7(2(1-2x)+ \phi_6(4x-3)+ \phi_8(\frac{4y}{c}-1))\, H(1-\tau_3)$

$(\frac{1}{3}\le x\le\frac{2}{3})$

$+(\phi_6(2(1-\frac{2y}{c})+ \phi_9(\frac{4y}{c}-1)+ \phi_8(1+\frac{4y}{c}-4x))\, H(1-\tau_4)$

$+(\phi_6(4(1-x)+ \phi_5(4x-\frac{4y}{c}-1)+ \phi_9\, 2(\frac{4y}{c}-1))\, H(1-\tau_5)$

Along the strip $\frac{2c}{3}\le y\le 1$

$\phi = (\phi_8 4(1-x) + \phi_9 4(x-\frac{y}{c})+ \phi_{10}(\frac{4y}{c}-3)\, H(1-\tau_6)$

$(\frac{2}{3}\le x\le 1)$

The dimensionless Nusselt numbers(Nu) and Sherwood Numbers (Sh) on the non-insulated boundary walls of the rectangular duct are calculated using the formula

$Nu = (\frac{\partial\theta}{\partial x})_{x=1}$ and $Sh = (\frac{\partial\phi}{\partial x})_{x=1}$

Nusselt Number on the side wall x=1in different regions are

$Nu_1=2-4\theta_3 \quad (0\le y\le h/3)$

$Nu_2=2-4\theta_5 \quad (h/3\le y\le 2h/3)$

$Nu_3=2-4\theta_7 \quad (2h/3\le y\le h)$

Sherwood Number on the side wall x=1in different regions are

$Sh_1=2-4\phi_3 \quad (0\le y\le h/3)$

$Sh_2=2-4\phi_5 \quad (h/3\le y\le 2h/3)$

$Sh_3=2-4\phi_7 \quad (2h/3\le y\le h)$

For $\gamma = 0$ the results are in good agreement with Shanthi (7).

4. Discussion of The Numerical Results:

In this analysis we investigate the effect of non-linear density temperature variation on double diffusive convective heat transfer flow of the viscous fluid through a porous medium in a rectangular cavity in the presence of constant heat source with radiation. The equations governing the flow heat and mass transfer are solved by employing by a finite element Galerkin method with three noded triangular element.

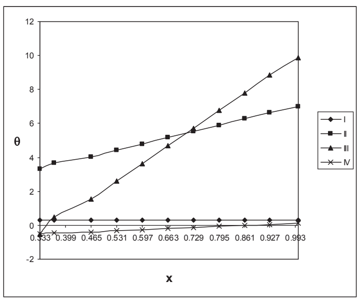

Fig. 1 : Variation of θ with N_1 at $y=\frac{h}{3}$ level

	I	II	III	IV
N_1	0.01	0.03	0.05	0.07

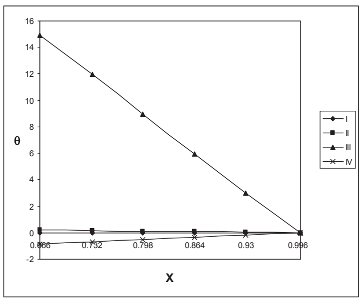

Fig. 2 : Variation of θ with N_1 at $y=\frac{2h}{3}$ level

	I	II	III	IV
N_1	0.01	0.03	0.05	0.07

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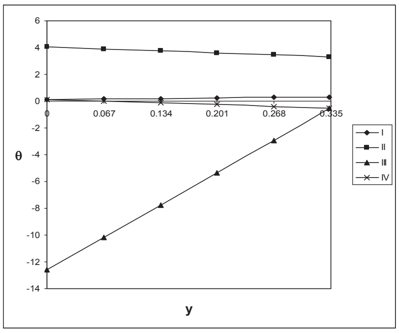

Fig.3 : Variation of θ with N_1 at $x = \frac{1}{3}$ level

	I	II	III	IV
N_1	0.01	0.03	0.05	0.07

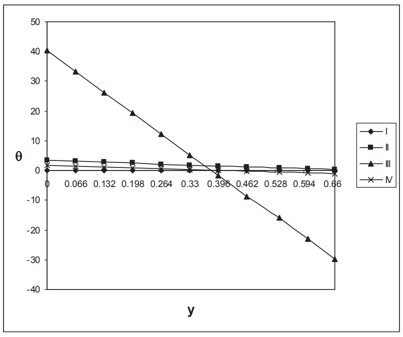

Fig 4 : Variation of θ with N_1 at $x = \frac{2}{3}$ level

	I	II	III	IV
N_1	0.01	0.03	0.05	0.07

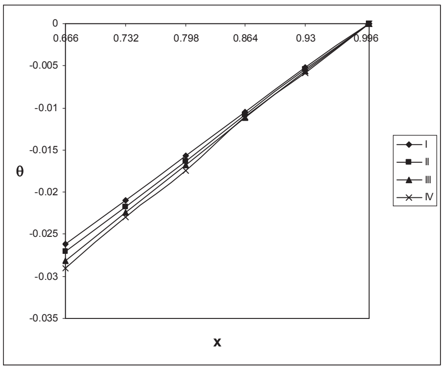

Fig.5 : Variation of θ with Ec at $y = \frac{h}{3}$ level

	I	II	III	IV
Ec	0.001	0.003	0.005	0.007

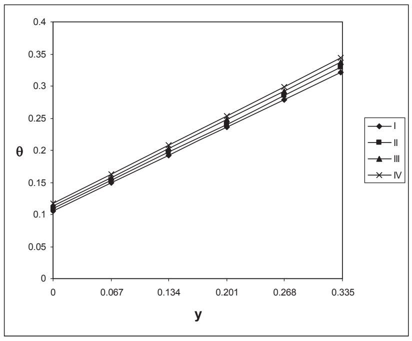

Fig. 6 : Variation of θ with Ec at $x = \frac{1}{3}$ level

	I	II	III	IV
Ec	0.001	0.003	0.005	0.007

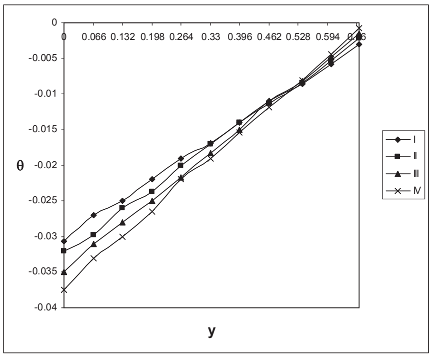

Fig7 : Variation of θ with Ec at $x = \frac{2}{3}$ level

	I	II	III	IV
Ec	0.001	0.003	0.005	0.007

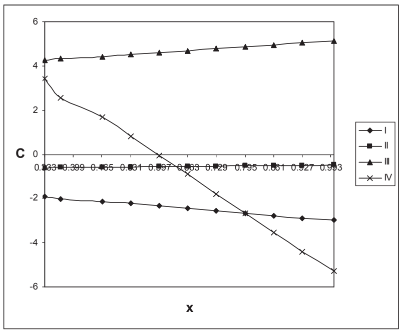

Fig. 8: Variation of C with N_1 at $y = \frac{h}{3}$ level

	I	II	III	IV
N_1	0.01	0.03	0.05	0.07

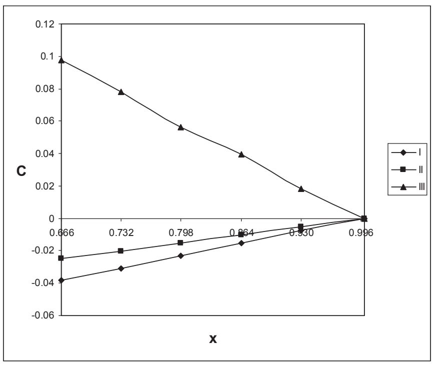

Fig. 9 : Variation of C with N_1 at $y = \frac{2h}{3}$ level

	I	II	III	IV
N_1	0.01	0.03	0.05	0.07

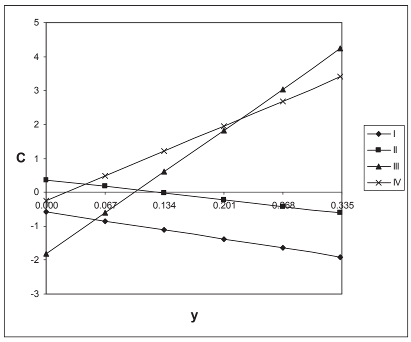

Fig. 10: Variation of C with N_1 at $x = \frac{1}{3}$ level

	I	II	III	IV
N_1	0.01	0.03	0.05	0.07

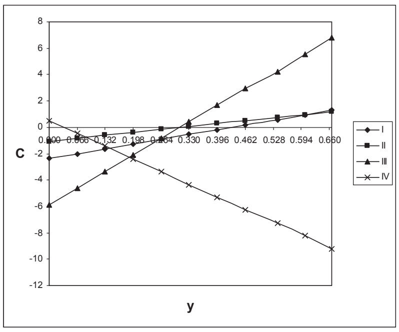

Fig. 11 : Variation of C with N_1 at $x = \frac{2}{3}$ level

	I	II	III	IV
N_1	0.01	0.03	0.05	0.07

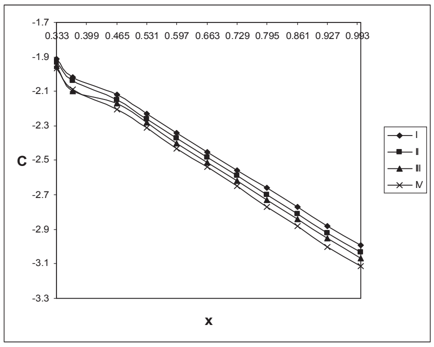

Fig.12: Variation of C with Ec at $y = \frac{h}{3}$ level

	I	II	III	IV
Ec	0.001	0.003	0.005	0.007

The temperature distribution (θ) is shown in figures 1 –7 for different values of radiation parameter N_1 , and Eckert number Ec at different horizontal and vertical levels The influence of radiative heat flux on θ is shown in figures 1-4 .An increase in $N_1 \leq 0.05$ results in an enhancement in actual temperature and reduces with higher $N_1 \geq 0.07$ at all horizontal levels . While at vertical level x = 1/3 the actual temperature enhances with $N_1 \leq 0.03$ and reduces at $N_1 = 0.05$ and again enhances with $N_1 = 0.07$ and at the higher vertical level x = 2/3 the actual temperature enhances with $N_1 \leq 0.05$ and depreciates with higher $N_1 \geq 0.07$ (fig.4). The effect of viscous dissipation on θ is shown in figures 5-7. It is observed that the actual temperature enhances at y = h/3 level and depreciates at y = 2h/3 level. While it enhances at x = 1/3 level and depreciates at x = 2/3 level . The non-dimensional concentration C is shown in figures 8-12 for a different parametric values at horizontal and vertical levels . It is found that at both the horizontal levels the actual concentration enhances with increase in $N_1 \leq 0.05$ and depreciates with higher $N_1 \geq 0.07$ (figures 8 & 9). While at the vertical levels the actual concentration enhances with increase in $N_1 \leq 0.05$ and with higher $N_1 \geq 0.07$ the actual concentration enhances at X = 1/3 level and depreciates at X = 2/3 level (figures 10 & 11).

Figure 12 represents the variation of C with Eckert number Ec. It is found that the actual concentration experiences a depreciation with increase in Ec with all levels . Thus the greater the dissipative heat smaller the actual concentration in the flow region .

Table – 1
Nusselt Number (Nu) at x=1

	I	II	III	IV	V	VI	VII
Nu_1	2.12293	-11.7616	-15.3216	-4.41056	0.67912	0.651136	0.623036
Nu_2	2.06762	-5.40572	-18.8721	0.74653	0.750204	0.72464	0.699704
Nu_3	2.01231	0.95015	12.5776	5.90362	0.820696	0.79815	0.77637
N_1	0.01	0.03	0.05	0.07	0.01	0.01	0.01
Ec	0.001	0.001	0.001	0.001	0.003	0.005	0.007

Table – 2
Sherwood number (Sh) at x=1

	I	II	III	IV	V	VI	VII
Sh_1	11.481	6.22932	12.6391	13.027152	9.73188	9.81812	9.91372
Sh_2	4.16126	1.76094	3.241536	19.4076	11.92632	12.04908	12.18536
Sh_3	-3.1584	-2.7074	-25.156	38.84236	14.12072	14.28008	14.457
N_1	0.01	0.03	0.05	0.07	0.01	0.01	0.01
Ec	0.001	0.001	0.001	0.001	0.003	0.005	0.007

The Nusselt number (Nu) at X = 1 is shown in tables 1 at different levels. The variation of Nu with radiation parameter N_1 and Eckert number Ec is exhibited in table-1 . It is observed that the rate of heat transfer enhances with increase in the radiation parameter $N_1 \leq 0.05$ and depreciates with N_1

≥ 0.07 at all three quadrants where an increase in Ec reduces Nu at all three quadrants .

The rate of mass transfer (Sh) at X = 1 at all different levels is shown in Table 2 for different values of N_1 and Ec The variation of Sh with radiation parameter N_1 shows that the rate of mass transfer at all the quadrants depreciates with $N_1 \leq 0.03$ and enhances with higher $N_1 \geq 0.03$. Also Sh reduces in the first quadrant with Ec ≤ 0.03 and enhances with Ec ≥ 0.05 while at the second and upper quadrants Sh experiences an enhancement with increase in Ec (table 2).

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