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EFFECT OF THERMO-DIFFUSION AND THERMAL RADIATION ON NON-DARCY CONVECTIVE HEAT AND MASS TRANSAFER FLOW IN A CYLINDRICAL ANNULUS WITH CHEMICAL REACTION

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ABSTRACT

We investigate the mixed convective heat and mass transfer flow with radiation, Soret effects and chemical reaction in a circular annulus where the boundaries are maintained at constant temperature and Concentration. By using Galerkin finite element technique the non-linear coupled equations governing the flow have been solved. The effect of Radiation parameter Rd, Soret parameter S_0 and Chemical reaction parameter γ on all the flow characteristics have been investigated.

Key Words: *Finite element method,Mixed convection, Non-Darcy, thermo-diffusion, Thermal radiation and Chemical reaction.*

1. INTRODUCTION:

Combined heat and mass transfer problems with chemical reaction are important in many processes and have, therefore, received a considerable amount of attention in recent years. In processes such as drying, evaporation at the surface of a water body, energy transfer in a wet cooling tower and the flow in a desert cooler, heat and mass transfer occur simultaneously. Possible applications of this type of flow can be found in many industries. For example, in the power industry, among the methods of generating electric power is one of in which electrical energy is extracted directly from a moving conducting fluid. Obviously, the understanding of this transport process is desirable in order to effectively control the overall transport characteristics.

The increasing cost of energy has led technologists to examine measures which could considerably reduce the usage of the natural source energy. Thermal insulations will continue to find increased use as engineers seek to reduce cost. Heat transfer in porous thermal insulation within vertical cylindrical annuli provide us insight into the mechanism of energy transport and enable engineers to use insulation more efficiently. Convection through annulus region under steady slate conditions has also been discussed with two cylindrical surface kept at different temperatures [14]. This work has been extended in temperature dependent convection flow [7, 8, 9] as well as convection flows through horizontal porous channel whose inner surface is maintained at constant temperature while the other surface is maintained at circumferentially varying sinusoidal temperature [25]. Free convection flow and heat transfer in hydromagnetic case is important in nuclear and space technology [15, 20, 23]. In particular, such convection flow in a vertical annulus region in the presence of radial magnetic field has been studied by Sastry and Bhadram [21]. Leppinen *et al.* [10] examined free convection in a shallow annular cavity filled with a porous medium. Jha[9] studied free convection flow through an annular porous medium. Non-Darcian thermal stability of a heat generating fluid in a porous annulus was investigated by Saravanan and Kandaswamy[25]. Charrier Mojtabi[4] studied numerical simulation of two-and three dimensional free convection flows in a horizontal porous annulus using a pressure and temperature formulation. Chmaissem et al[5] reported numerical study of a Boussinesq model of natural convection in an annular space having a horizontal axis bounded by circular and elliptical isothermal cylinders. Chen and Yuh [6] have investigated the heat and mass transfer characteristics of natural convection flow along a vertical cylinder under the combined buoyancy effects of thermal and

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species diffusion, Sivanjaneya Prasad [24] has investigated the free convection flow of an incompressible, viscous fluid through a porous medium in the annulus between the porous concentric cylinders under the influence of a radial magnetic field. Antonio [2] has investigated the laminar flow, heat transfer in a vertical cylinder duct by taking into account both viscous dissipation and the effect of buoyancy, the limiting case of fully developed natural convection in porous annuli is solved analytically for steady and transient cases by E. Sharawi and Al-Nimir [22] and Al-Nimir [1]. Philip [17] has obtained solutions for the annular porous media valid for low modified Reynolds number. Chamkha *et al.* [3] studied the effect of radiation on combined heat and mass transfer by non-Darcy natural convection about an impermeable horizontal cylinder embedded in porous medium. Sreevani [26] has studied the convective heat and mass transfer through a porous medium in cylindrical annulus under radial magnetic field with Soret effect. Prasad [18] has analyzed the convective heat and mass transfer in an annulus in the presence of heat generating source under radial magnetic field, Reddy [27,28] has discussed the Soret effect on mixed convective heat and mass transfer though a porous cylindrical annulus. For natural convection, the existence of large temperature differences between the surfaces is important. Sudheer Kumar *et al.*, [29] have studied the effect of radiation on natural convection over a vertical cylinder in a porous media. Padmavathi [16] has analyzed the convective heat transfer in a cylindrical annulus by using finite element method. Madhusudhan Reddy [12] has investigated the convective heat and mass transfer flow of a viscous fluid through a porous medium in a vertical annulus with cylinder maintained at constant temperature and constant concentration. Sudarsana Reddy *et al.* [27, 28] have discussed the convective heat and mass transfer flow of a viscous fluid in a concentric cylindrical annulus with Soret and Dufour effect. Mallikarjuna *et al.* [13] have investigated the mixed convective heat and mass transfer flow through a porous medium in a vertical cylindrical annulus with Soret and Dufour effects. Mahusudan *et al.* [11] have discussed the effect thermal radiation on mixed convective heat and mass transfer in a circular annulus with chemical radiation.

In this paper, we analyse the combined influence of thermal radiation, thermo-diffusion and chemical reaction on non-Darcy free and forced convection flow of a viscous electrically conduction fluid through a porous medium in a Co-axial cylindrical duct where the boundaries are maintained at constant temperature Tw and Concentration Cw. The behaviour of velocity, temperature and concentration is analyzed at different axial positions. The shear stress and the rate of heat and mass transfer have also been obtained for variations in the governing parameters.

2. FORMULATION OF THE PROBLEM:

We consider the mixed convection flow in a vertical circular annulus region through a porous medium whose walls are maintained at a constant heat and concentration .Both the fluid and porous region have constant physical properties and the flow is a mixed convection flow taking place under thermal and molecular buoyancies and uniform axial pressure gradient. The Boussinesq approximation is invoked so that the density variation is confined to the thermal and molecular buoyancy forces. Also the flow is unidirectional along the axial direction of the cylindrical annulus. Making use of the above assumptions the governing equations are

$$-\frac{\partial p}{\partial z}+\frac{\nu}{\delta}\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}\right)-\left(\frac{\nu}{k}\right)u-\frac{\sigma\mu_e^2 H_0^2}{r^2}-\frac{\delta F}{\sqrt{k}}u^2+\rho\beta(T-T_i)+\rho\beta^\bullet(C-C_i)=0 \quad (1)$$

$$\rho C_p u\frac{\partial T}{\partial z}=k_f\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right)+Q_H(T-T_0)-\frac{\partial(q_R)}{\partial y} \quad (2)$$

$$u\frac{\partial C}{\partial z}=D_B\left(\frac{\partial^2 C}{\partial r^2}+\frac{1}{r}\frac{\partial C}{\partial r}\right)-k_c'C+\frac{D_B K_T}{T_s}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right) \quad (3)$$

where u is the axial velocity in the porous region, T , C are the temperature and concentration of the fluid, k is the permeability of porous medium, k_f is the thermal diffusivity, F is a function that depends on Reynolds number, the microstructure of the porous medium and D_B is the molecular diffusivity, β is the coefficient of the thermal expansion, $\beta^\bullet$ is the coefficient of the volume expansion Q_H is the heat source coefficient, Q_1' is the radiation absorption coefficient, C p is the specific heat, ρ is density and g is gravity.

The relevant boundary conditions are

$$u=0,\quad T=T_w,\quad C=C_w \quad \text{at} \quad r = a\&a+s \quad (4)$$

Following Tao(31), Das et al(7) we assume that the temperature and concentration of the both walls is $T_w = T_0 + Az$, $C_w = C_0 + Bz$ where A and B are the vertical temperature and concentration gradients which are positive for buoyancy –aided flow and negative for buoyancy –opposed flow, respectively, T_0 and C_0 are the upstream reference wall temperature and concentration, respectively. For the fully developed laminar flow in the presences of radial magnetic field, the velocity

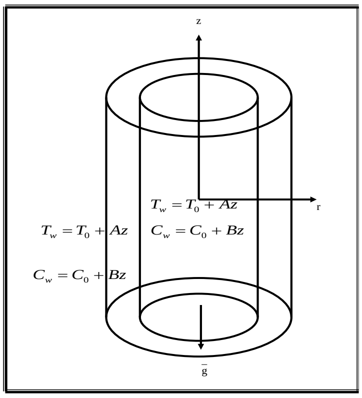

Fig.1 : CONFIGURATION OF THE PROBLEM

depend only on the radial coordinate and all the other physical variables except temperature, concentration and pressure are functions of r and z, z being the vertical co-ordinate .The temperature and concentration inside the fluid can be written as

$$T = T^{\bullet}(r) + Az, \qquad C = C^{\bullet}(r) + Bz \tag{5}$$

By applying Rosseland approximation the energy equation reduces to

$$\rho C_p u \frac{\partial T}{\partial z} = k_f \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} \right) + Q_H (T - T_0) + \frac{16\sigma^{\bullet} T_e^3}{3\beta_R} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} \right) \tag{6}$$

We now define the following non-dimensional variables

$$z^* = \frac{z}{a}, \quad r^* = \frac{r}{a}, \quad u^* = \left(\frac{a}{\nu}\right) u$$

$$p^* = \frac{pa\delta}{\rho \nu^2}, \quad \theta^*(r^{\bullet}) = \frac{T^{\bullet} - T_0}{Aa}, \quad C^*(r^{\bullet}) = \frac{C^{\bullet} - C_0}{Ba}, \quad s^* = \frac{s}{a}$$

Introducing these non-dimensional variables, the governing equations in the non-dimensional form are (on removing the stars)

$$\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} \right) = 1 + \delta \left(D^{-1} + \frac{M^2}{r^2} \right) u + \delta^2 (D^{-1})^{1/2} \Lambda u^2 - \delta G(\theta + NC) \tag{7}$$

$$\left(1 + \frac{4Rd}{3}\right)\left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r} \right) = u + \frac{\alpha}{\Pr}\theta \tag{8}$$

$$\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\frac{\partial C}{\partial r} \right) - \gamma C = Sc\, u + ScSr \left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r} \right) \tag{9}$$

where $\Delta = FD^{-1}$(Inertia parameter or Forchhimer number)

$G = \frac{g\beta(T_e - T_i)a^3}{\nu^2}$ (Grashof number), $D^{-1} = \frac{a^2}{k}$ (Inverse Darcy parameter)

$M^2 = \frac{\sigma \mu_e^2 H_0^2}{a\nu}$ (Hartmann number), $P_r = \frac{\mu C_p}{k_f}$ (Prandtl number)

$Sc = \frac{\nu}{D_B}$ (Schmidt number), $S_r = \frac{D_b K_T (T_o - T_i)}{T_s (C_o - C_i)}$ (Soret Parameter)

$\gamma = \frac{k_c^1 a^2}{D_B}$ (Chemical Reaction parameter), $Rd = \frac{4\sigma^{\bullet} T_e^3}{\beta_R k_f}$ (Radiation parameter)

The corresponding non-dimensional conditions are

$$u = 0, \quad \theta = 0, \; C=0 \quad \text{at} \quad r=1 \text{ and } 1+s \tag{10}$$

3. FINITE ELEMENT ANALYSIS

The finite element analysis with quadratic polynomial approximation functions is carried out along the radial distance across the circular duct. The behavior of the velocity, temperature and concentration profiles has been discussed computationally for different variations in governing parameters. The Gelarkin method has been adopted in the variational formulation in each element to obtain the global coupled matrices for the velocity, temperature and concentration in course of the finite element analysis.

Choose an arbitrary element e_k and let u^k, θ^k and C^k be the values of u, θ and C in the element e_k. We define the error residuals as

$$E_p^k = \frac{d}{dr}\left(r\frac{du^k}{dr} \right) + \delta G(\theta^k) - \delta \left(D^{-1} + \frac{M^2}{r^2} \right) r u^k - \delta^2 \Lambda r (u^k)^2 \tag{11}$$

$$E^k{}_\theta = \frac{(1+4Rd/3)}{\Pr}\frac{d}{dr}\left(r\frac{d\theta^k}{dr}\right) - ru^k + \frac{\alpha}{P_r}r\theta \tag{12}$$

$$E^k{}_c = \frac{d}{dr}\left(r\frac{dC^k}{dr}\right) - rScu^k - \gamma C^k + ScSr\frac{d}{dr}\left(r\frac{d\theta^k}{dr}\right) \tag{13}$$

where u^k, θ^k & C^k are values of u, θ & C in the arbitrary element e_k. These are expressed as linear combinations in terms of respective local nodal values.

$$u^k = u_1^k\psi_1^k + u_2^k\psi_1^k + u_3^k\psi_3^k$$

$$\theta^k = \theta_1^k\psi_1^k + \theta_2^k\psi_2^k + \theta_3^k\psi_3^k$$

$$C^k = C_1^k\psi_1^k + C_2^k\psi_2^k + C_3^k\psi_3^k \tag{14}$$

where ψ_1^k, ψ_2^k ……etc are Lagrange's quadratic polynomials. Substituting (14) and shape functions in equations (11)-(13) and evaluating the resulting integrals we get the coupled stiffness matrices, which have been solved by iteration process.

4. SHEAR STRESS, NUSSELT NUMBER AND SHERWOOD NUMBER

The shear stress (τ) is evaluated using the formula $\tau = \left(\frac{du}{dr}\right)_{r=1,1+s}$

The rate of heat transfer (Nusselt number) is evaluated using the formula $Nu = -\left(\frac{d\theta}{dr}\right)_{r=1,1+s}$

The rate of mass transfer (Sherwood number) is evaluated using the formula $Sh = -\left(\frac{dC}{dr}\right)_{r=1,1+s}$

5. COMPARISON

In the absence of thermo-diffusion(S_0=0) the results are in good agreement with Madhusudan *et al.* [11].

Parameters			Madhusudana et al(11)				Present results(So=0)			
N	Rd	γ	Nu(1)	Nu(2)	Sh(1)	Sh(2)	Nu(1)	Nu(2)	Sh(1)	Sh(2)
1	0.5	0.5	0.10673	1.7335	12.3727	14.5232	0.10669	1.7336	12.36987	14.52289
2	0.5	0.5	0.11549	1.74131	12.3734	14.5233	0.11538	1.741299	12.37299	14.52319
-0.5	0.5	0.5	0.01152	1.74152	12.3718	14.5237	0.011492	1.741499	12.3714	14.52299
-1.5	0.5	0.5	0.01156	1.74162	12.3712	14.5138	0.01151	1.74155	12.3706	14.5136
1	1.5	0.5	0.2225	3.3518	12.3721	14.5237	0.22239	3.35168	12.3719	14.5231
1	5.0	0.5	0.30165	4.5736	12.3713	14.5239	0.30159	4.57345	12.3709	14.52301
1	0.5	1.5	0.11552	1.74131	13.0332	14.4276	0.115499	1.74131	13.03289	14.4266
1	0.5	-0.5	0.11554	1.741525	13.3226	14.4516	0.115035	1.741499	13.32189	14.4516
1	0.5	-1.5	0.115432	1.741625	12.1728	14.4526	0.115437	1.741587	12.17187	14.4522

6. RESULTS AND DISCUSSION

The coupled equations governing the flow, heat and mass transfer have been solved by using Galerkin finite method with quadratic approximation functions. In order to get physical insight into the problem we have carried out numerical calculations for non-dimensional velocity, temperature and spices concentration, skin-friction, Nusselt number and Sherwood number by assigning some specific values to the parameters entering into the problem with G=10,M=2, D^{-1}=0.2, Pr=0.71, Sc=1.3.

The coupled equations governing the flow, heat and mass transfer have been solved by using Galerkin finite method with quadratic approximation functions. The velocity, temperature and concentration have been analysed for different parametric variations. The important results of this analysis are

- The velocity and the concentration reduces and the temperature enhances in the flow region with increase in N>0 when the buoyancy forces are in the same directions and for the forces acting in opposite directions, they reduce in the flow region(figs.2,7,12).The Nusselt number decreases, Sherwood number enhances with increases in N>0 and for N<0,wee find a reversed effect in Nu and Sh. The skin friction enhances with increase in N>0 while it reduces with N<0 on r=1&2(table.1).
- With respect to Schmidt number Sc, we find that lesser the molecular diffusivity, larger the velocity, temperature and smaller the concentration in the flow region in the flow region(figs.7&12).

- With reference to the chemical reaction parameter γ, we find that the velocity, temperature and concentration enhance in the flow region in the degenerating chemical reaction case while in the generating chemical reaction case, the velocity enhances, the temperature and concentration reduces in the flow region(figs.4, 9, 14). The skin friction enhance in the degenerating chemical reaction case while in generating case a reversed effect is noticed on the cylinders. The rate of heat transfer reduces for $\gamma>0$ and enhance on r=1 & 2. The Sherwood number reduces on r=1 and enhances on r=2 for $\gamma>0$ and for $\gamma<0$, it enhances on r=1 and reduces on r=2(table.1).
- With reference to the Soret parameter S_0, the velocity and concentration increases while the temperature reduces with S_0 in the flow region (figs.5, 10). As S_0 increases the skin friction, the rate of heat and mass transfer experiences an enhancement on both the cylinders (table.1).

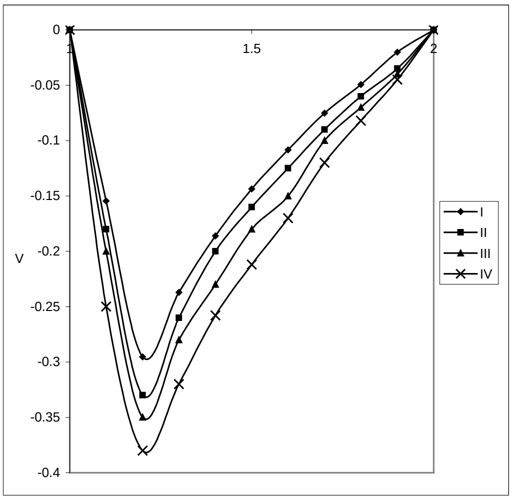

Fig.2 Variation of u with N
G=10,M=2,A=0.5,N1=0.5,So=0.5,D^{-1}=0.2,Sc=1.3

	I	II	III	IV
N	1	2	-0.5	-1.5

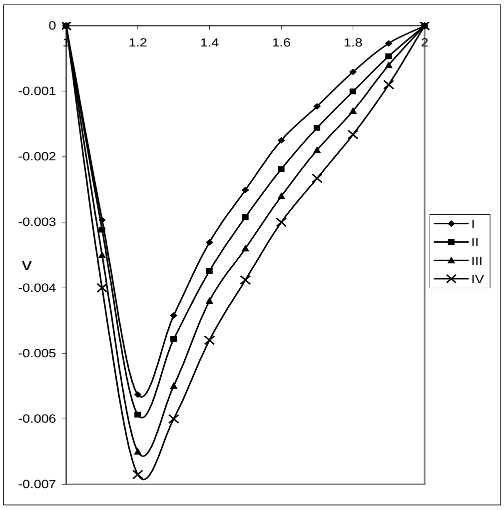

Fig.3 Variation of u with N1
N=1,A=0.5;M=2,So=0.5,D^{-1}=0.2,Sc=1.3

	I	II	III	IV
N1	0.5	1.5	3.5	5

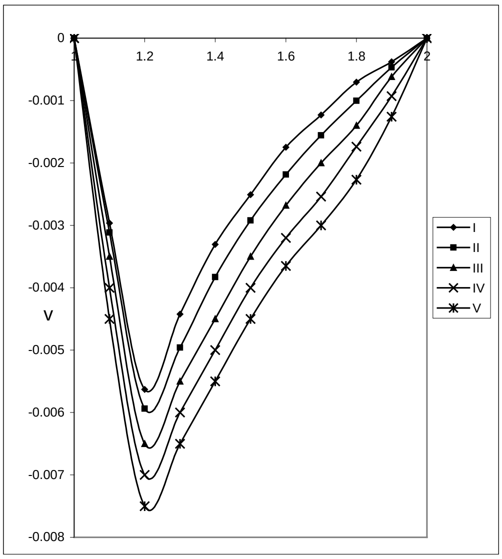

Fig.4 Variation of u with γ
N=1, A=0.5,N1=0.5,So=0.5,D^{-1}=0.2,Sc=1.3

	I	II	III	IV	V
γ	0.5	1.5	2.5	-0.5	-1.5

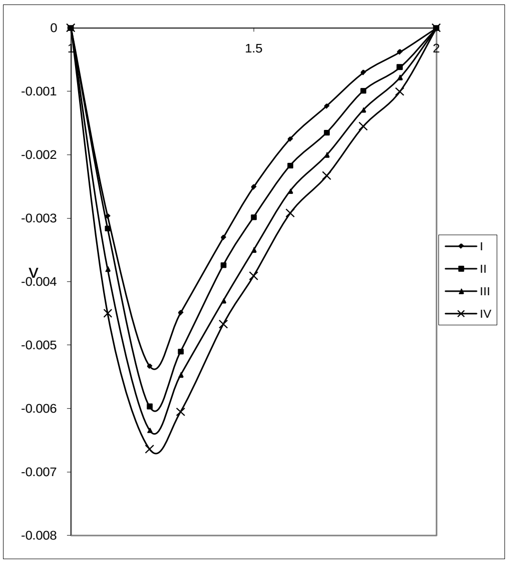

Fig.5 Variation of u with S_0
N=1, A=0.5,N1=0.5,M=2,D^{-1}=0.2,Sc=1.3

	I	II	III	IV
S_0	0.5	1.5	2.5	3.5

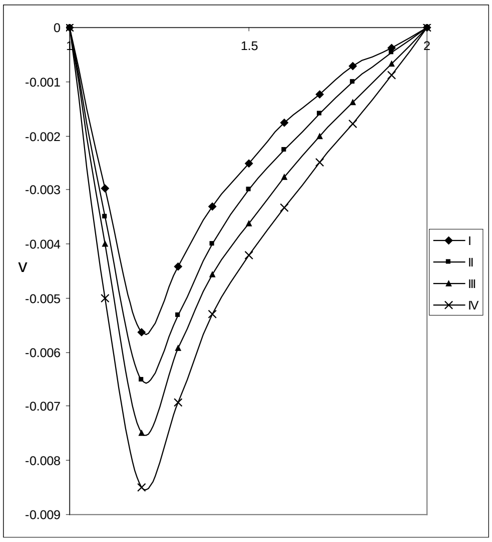

Fig.6 Variation of u with A
N=1,M=2,N1=0.5,So=0.5,D^{-1}=0.2,Sc=1.3

	I	II	III	IV
A	0.71	1.71	3.71	7

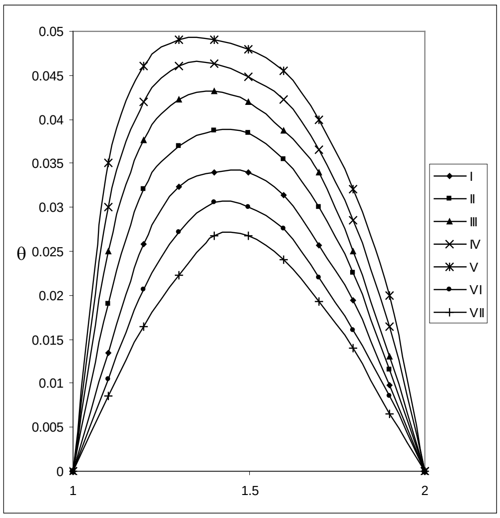

Fig.7 Variation of θ with Sc &N
N=1, A=0.5,N1=0.5,So=0.5,D^{-1}=0.2,M=2

	I	II	III	IV	V	VI	VII
Sc	0.24	0.66	1.3	2.01	0.24	0.24	0.24
N	0.5	0.5	0.5	0.5	1.5	-0.5	-1.5

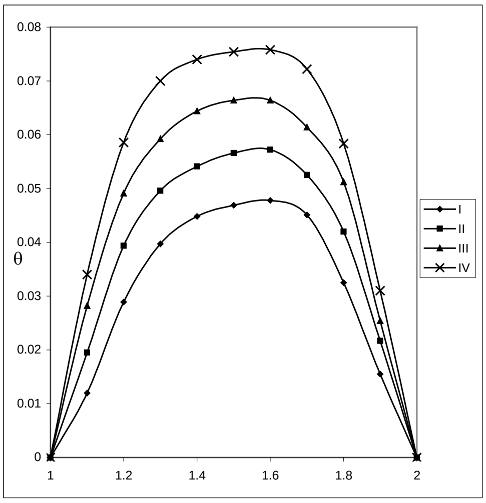

Fig.8 Variation of θ with N1
N=1, A=0.5,M=2,So=0.5,D^{-1}=0.2,Sc=1.3

	I	II	III	IV
N1	0.5	1.5	3.5	5

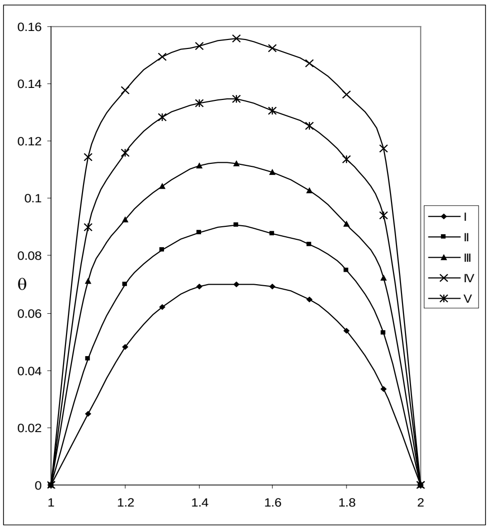

Fig.9 Variation of θ with γ
N=1, A=0.5,M=2,So=0.5,D^{-1}=0.2,Sc=1.3

	I	II	III	IV	V
γ	0.5	1.5	2.5	-0.5	-1.5

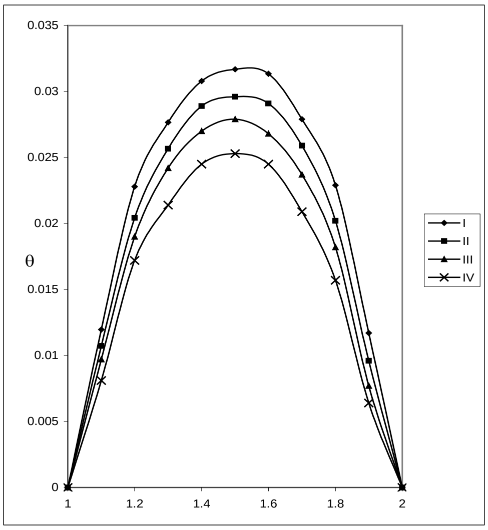

Fig.10 Variation of θ with S_0
N=1, A=0.5,M=2,G=10,D^{-1}=0.2,Sc=1.3

	I	II	III	IV
S_0	0.5	1.5	2.5	3.5

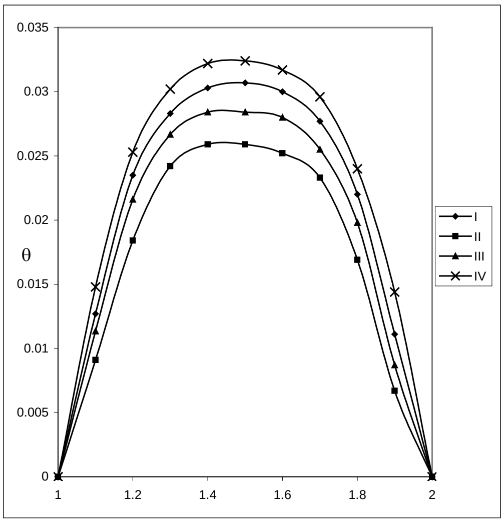

Fig.11 Variation of θ with A
N=1, A=0.5,M=2,So=0.5,D^{-1}=0.2,Sc=1.3 ,N1=0.5

	I	II	III	IV
A	0.71	1.71	3.71	7.0

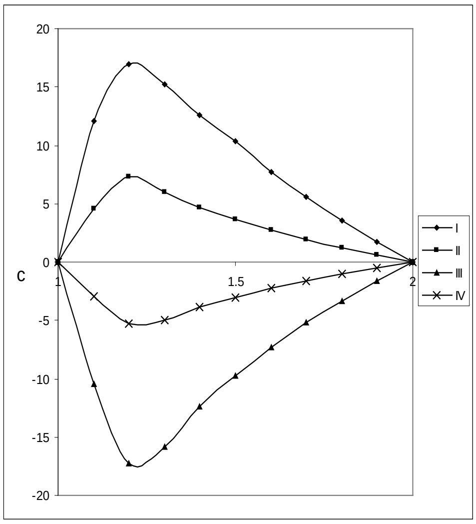

Fig.12 Variation of C with N
N1=0.5, A=0.5,M=2,So=0.5,D^{-1}=0.2,Sc=1.3

	I	II	III	IV
N	1	2	-0.5	-1.5

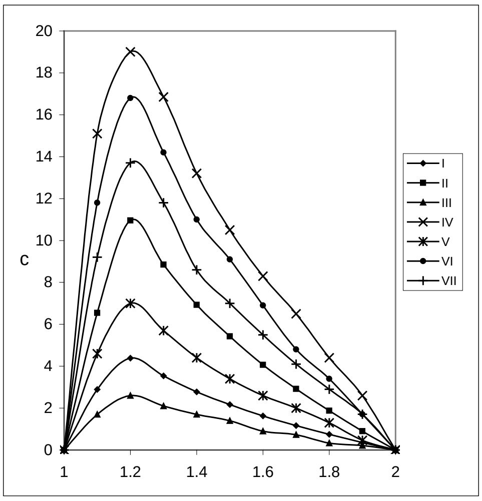

Fig.13 Variation of C with Sc&N1
N=1, A=0.5,M=2,So=0.5,G=10,N1=0.5

	I	II	III	IV	V	VI	VII
Sc	0.24	0.66	1.3	2.01	0.24	0.24	0.24
N1	0.5	0.5	0.5	0.5	1.5	3.5	5

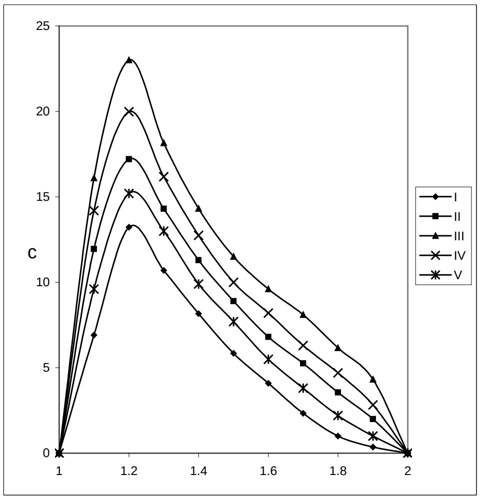

Fig.14 Variation of C with γ
N=1, A=0.5,M=2,So=0.5,G=10,Sc=1.3

	I	II	III	IV	V
γ	0.5	1.5	2.5	-0.5	-1.5

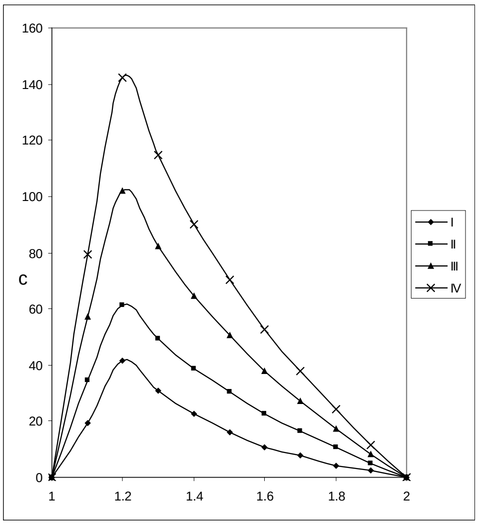

Fig.15 Variation of C with S_0
N=1, A=0.5,M=2,N1=0.5,G=10,Sc=1.3

	I	II	III	IV
S_0	0.5	1.5	2.5	3.5

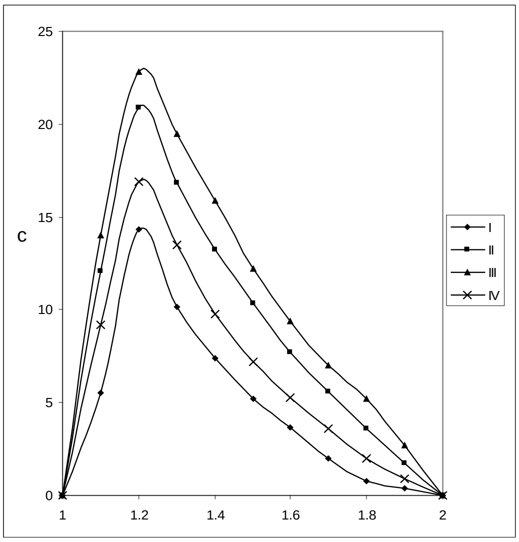

Fig.16 Variation of C with A
N=1,N1=0.5,M=2,So=0.5,G=10,Sc=1.3

	I	II	III	IV
A	0.71	1.71	3.71	7.0

- An increase in Forchheimer parameter (Δ) enhances the velocity in the entire channel (fig.6). This shows that inclusion of inertial and boundary effects leads to a enhancement in the thickness of the momentum boundary layer which in turn results in an increment in the velocity. An increase in the Forchheimer parameter Δ<1.5) decreases the actual temperature and for still higher Δ>5.0, we notice an enhancement in the actual temperature in the flow region (fig.11). The actual concentration increases withy increase in $\Delta \leq 1.5$ and reduces with higher $\Delta \geq 5.0$ (fig.16). As the Forchheimer number A increases (Δ<1.5) the skin friction reduces and for further higher Δ>3.5, we notice an enhancement in skin friction on r=1 & 2. The variation of Nu with A shows that an increase in Δ<1.5 reduces the rate of heat transfer and for further smaller values of Δ>3.5 larger the rate of heat transfer on both the cylinders. As the Forchheimer (Δ<1.5) increases we notice an enhancement in Sh on r=2 and depreciates on r=1 and for still higher Δ>3.5, we notice an enhancement in Sh on r = 1 & 2.

Table – 1

Parameter		τ (1)	τ (2)	Nu(1)	Nu(2)	Sh(1)	Sh(2)
N	0.5	-0.03257	0.427635	0.11225	1.71697	1.6685	-1.28805
	1.5	-0.03261	0.437624	0.11224	1.71696	0.9969	-2.23574
	-0.5	-0.03257	0.417654	0.11221	1.71698	-1.0645	3.2834
	-1.5	-0.03256	0.407681	0.11228	1.71701	-0.8976	2.7596
N_1	0.5	-0.03257	0.427635	0.112225	1.71697	1.6685	-1.28805
	1.5	-0.03261	0.431093	0.216353	3.32733	1.7096	-1.29028
	5.0	-0.03265	0.433717	0.295346	4.54893	1.7245	-1.29196
S_0	0.5	-0.03257	0.427635	0.112225	1.71697	1.6685	-1.28805
	1.0	-0.03336	0.748694	0.112271	1.71709	3.9692	-3.86352
	1.5	-0.03363	0.861064	0.112288	1.71713	4.5182	-4.91022
γ	0.5	-0.0325	0.427719	0.11225	1.71697	1.6685	-1.28805
	1.5	-0.0493	0.432069	0.11215	1.70987	1.3635	-1.29025
	-0.5	-0.0505	0.416785	0.11195	1.70765	1.5075	-1.27685
	-1.5	-0.0452	0.404956	0.11267	1.71786	1.1638	-1.26986
A	0.5	-0.03257	0.427635	0.112225	1.71697	1.6685	-1.28805
	1.5	-0.03184	0.362457	0.112196	1.71692	1.2705	-1.28875
	3.5	-0.03198	0.453698	0.118729	1.73897	1.3686	-1.28907

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