Effect of Chemical Reaction and Radiation on Convective Heat and Mass Transfer Flow in Vertical Wavy Channel with Hall Effects

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ABSTRACT:

We analyse the effect of chemical reaction and radiation on mixed convective heat and mass transfer flow of a viscous, electrically conducting fluid through a porous medium in a vertical wavy channel under the influence of an inclined magnetic fluid with heat sources. The equations governing the flow, heat and mass transfer are solved by employing perturbation technique with aspect ratio δ as perturbation parameter. The velocity, temperature and concentration distributions are investigated for different values of m, M, β, N_1, λ, k & R. The rate of heat and mass transfer are numerically evaluated for different variations of the governing parameters.

KEYWORDS: Hall Effects, Heat and Mass Transfer, Wavy Channel, Chemical Reaction, Thermal Radiation

1.INTRODUCTION

Combined heat and mass transfer problems with chemical reaction are of importance in many processes and have, therefore, received a considerable amount 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 in which electrical energy is extracted directly from a moving conducting fluid.

We are particularly interested in cases in which diffusion and chemical reaction occur at roughly the same speed. When diffusion is much faster than chemical reaction, then only chemical factors influence the chemical reaction rate; when diffusion is not much faster than reaction, the diffusion and kinetics interact to produce very different effects. The study of heat generation or absorption effects in moving fluids is important in view of several physical problems, such as fluids undergoing exothermic or endothermic chemical reaction. Due to the fast growth of electronic technology, effective cooling of electronic equipment has become warranted and cooling of electronic equipment ranges from individual transistors to main frame computers and from energy suppliers to telephone switch boards and thermal diffusion effect has been utilized for isotopes separation in the mixture between gases with very light molecular weight (hydrogen and helium) and medium molecular weight.

Muthucumaraswamy and Ganesan [32] studied effect of the chemical reaction and injection on flow characteristics in an in steady upward motion of an unsteady upward motion of an isothermal plate. Deka et at. [13] studied the effect of the first order homogeneous chemical reaction on the process of an unsteady flow past an infinite vertical plate with a constant beat and mass transfer. Chamkha [5] studies the MHD flow of a numerical of uniformly stretched vertical permeable surface in the presence of heat generation/absorption and a chemical reaction. The effect of foreign mass on the free-convection flow past a semi-infinite vertical plate were studied by Gebhart et al[19]. Chamkha [5] assumed that the plate is embedded in a uniform porous medium and moves with a constant velocity in the flow direction in the presence of a transverse magnetic field. Raptis and Perdikis [41] studied the unsteady free convection flow of water near 4 C in the laminar boundary layer over a vertical moving porous plate.

In the theory of flow through porous medium, the role of momentum equations or force balance is occupied by the numerous experimental observations summerised mathematically as the Darcy's law. It is observed that the Darcy's law is applicable as long as the Reynolds number based on average grain(pore) diameter does not exceed a value between 1 and 10.But in general ,the speed of specific discharge in the medium need not be always low. As the specific discharge increases, the convective forces get developed and the internal stress generated in the fluid due to its viscous nature produces distortions in the velocity field. Also in the case of highly porous media such as fibre glass, pappus of dandilion etc., the viscous stress at the surface is able to penetrate into media and produce flow near the surface even in the absence of the pressure gradient. Thus Darcy's law which specifies a linear relationship between the specific discharge and hydraulic gradient is inadequate in describing high speed flows or flows near surfaces which may be either permeable or not. Hence consideration for non-Darcian description for the viscous flow through porous media is warranted. Saffman[26] employing statistical method derived a general governing equations for the flow in a porous medium which takes into account the viscous stress. Later another modification has suggested by Brinkman(3)

$$o = -\nabla p - (\frac{\mu}{k})\bar{v} + \mu \nabla^2 \bar{v}$$

in which $\mu \nabla^2 \bar{v}$ is intended to account for the distortions of the velocity profiles near the boundary. The same equation was derived analytically by Tam[55] to describe the viscous flow at low Reynolds number past a swam of small particles. The generalization of the above study was presented by Yamamoto and Iwamura [66]. The steady two-dimensional flow of viscous fluid through a porous medium bounded by porous surface subjected to a constant suction velocity by taking account of free convection currents (both velocity and temperature fields are constant along x-axis)was studied by Raptis et al [42] Combarnous and Borris[10],Chang [7,8] and Combarnous [9[have recently proved extensive reviews of state of the art of free convection in fluid saturated porous medium.

There is an extensive literature on free convection in porous media, i.e., flows through a porous media under gravitational fields that are driven by gradients of fluid density caused by temperature gradient. Many studies,including most of the earlier work, have dealt with systems heated from below [20,32,37]. Some attention has also been given to investigations of free convection in porous media introduced by a temperature gradient normal to the gravitational field. Raptis [43] has investigated unsteady free convective flow through a porous medium.

Convection fluid flows generated by traveling thermal waves have also received attention due to applications in physical problems. The linearised analysis of these flows has shown that a traveling thermal wave can generate a mean shear flow within a layer of fluid, and the induced mean flow is proportional to the square of the amplitude of the wave. From a physical point of view, the motion induced by traveling thermal waves is quite interesting as a purely fluid-dynamical problem and can be used as a possible explanation for the observed four-day retrograde zonal motion of the upper atmosphere of Venus. Also, the heat transfer results will have a definite bearing on the design of oil-or gas –fired boilers. Vajravelu and Debnath[57] have made an interesting and a detailed study of non-linear convection heat transfer and fluid flows, induced by traveling thermal waves. The traveling thermal wave problem was investigated both analytically and experimentally by White head [59] by postulating series expansion in the square of the aspect ratio(assumed small) for both the temperature and flow fields. White head[59] obtained an analytical solution for the mean flow produced by a moving source theoretical predictions regarding the ratio of the mean flow velocity to the source speed were found to be in good agreement with experimental observations in Mercury which therefore justified the validity of the asymptotic expansion a posterior

Heat generation in a porous media due to the presence of temperature dependent heat sources has number of applications related to the development of energy resources. It is also important in engineering processes pertaining to flows in which a fluid supports an exothermic chemical or nuclear reaction. Proposal of disposing the radioactive waste material b burying in the ground or in deep ocean sediment is another problem where heat generation in porous medium occurs, Foroboschi and Federico [18] have assumed volumetric heat generation of the type

$$\theta = \theta_o (T - T_0) \quad \text{for} \quad T \geq T_0$$
$$= 0 \quad \text{for} \quad T < T_0$$

David Molean [14] has studied the effect of temperature dependent heat source $\theta = 1/ a + bT$ such as occurring in the electrical heating on the steady state transfer within a porous medium. Chandrasekahr [6], Palm [38] reviewed the extensive work and mentioned about several authors who have contributed to the force convection with heat generating source. Mixed convection flows have been studied extensively for various enclosure shapes and thermal boundary conditions. Due to the super position of the buoyancy effects on the main flow there is a secondary flow in the form of a vortex recirculation pattern.

In all these investigations, the effects of Hall currents are not considered. However, in a partially ionized gas, there occurs a Hall current [4] when the strength of the impressed magnetic field is very strong. These Hall effects play a significant role in determining the flow features. Sato [48], Yamanishi [60], Sherman and Sutton [51] have discussed the Hall effects on the steady hydromagnetic flow between two parallel plates. These effects in the unsteady cases were discussed by Pop [39]. Debnath [56,58] has studied the effects of Hall currents on unsteady hydromagnetic flow past a porous plate in a rotating fluid system and the structure of the steady and unsteady flow is investigated. Alam *et. al.*,[1] have studied unsteady free convective heat and mass transfer flow in a rotating system with Hall currents, viscous dissipation and Joule heating. Taking Hall effects in to account Krishan *et. al.*,[12,13] have investigated Hall effects on the unsteady hydromagnetic boundary layer flow. Rao *et. al.*, [44] have analyzed Hall effects on unsteady Hydromagnetic flow. Siva Prasad *et. al.*, [44) have studied Hall effects on unsteady MHD free and forced convection flow in a porous rotating channel. Recently Seth *et. al.*, [50] have investigated the effects of Hall currents on heat transfer in a rotating MHD channel flow in arbitrary conducting walls. Sarkar *et. al.*, [46] have analyzed the effects of mass transfer and rotation and flow past a porous plate in a porous medium with variable suction in slip flow region.

In this paper we investigate the effect of chemical reaction on mixed convective heat and mass transfer flow of a viscous , electrically conducting fluid through a porous medium in a vertical wavy channel under the influence of an inclined magnetic fluid with heat sources. The equations governing the flow , heat and mass transfer are solved by employing perturbation technique with aspect ratio δ as perturbation parameter. The velocity , temperature and concentration distributions are investigated for different values of m, M, β, N_1, λ, k & R. The rate of heat and mass transfer are numerically evaluated for different variations of the governing parameters.

2.FORMULATION AND SOLUTION OF THE PROBLEM

We consider the unsteady flow of an incompressible, viscous ,electrically conducting fluid confined in a vertical channel bounded by two wavy walls under the influence of an inclined magnetic field of intensity Ho lying in the plane (x-z).The magnetic field is inclined at an angle α_1 to the axial direction and hence its components are $(0, H_0Sin(\alpha_1), H_0Cos(\alpha_1))$.In view of the traveling thermal wave imposed on the wall $x = +Lf(mz)$ the velocity field has components(u,0,w)The magnetic field in the presence of fluid flow induces the current($(J_x, 0, J_z)$.We choose a rectangular cartesian co-ordinate system O(x,y,z) with z-axis in the vertical direction and the walls at $x = \pm Lf(mz)$.

When the strength of the magnetic field is very large we include the Hall current so that the generalized Ohm's law is modified to

$$\overline{J} + \omega_e \tau_e \overline{J} x \overline{H} = \sigma(\overline{E} + \mu_e \overline{q} x \overline{H}) \quad (1)$$

where $\overline{q}$ is the velocity vector. $\overline{H}$ is the magnetic field intensity vector. $\overline{E}$ is the electric field, J is the current density vector, ω_e is the cyclotron frequency, τ_e is the electron collision time,σ is the fluid conductivity and μ_e is the magnetic permeability.

Neglecting the electron pressure gradient, ion-slip and thermo-electric effects and assuming the electric field E=0,equation (1) reduces

$$j_x - mH_0 J_z Sin(\alpha_1) = -\sigma\mu_e H_0 w Sin(\alpha_1) \quad (2)$$

$$J_z + mH_0 J_x Sin(\alpha_1) = \sigma\mu_e H_0 u\, Sin(\alpha_1) \quad (3)$$

where m= $\omega_e \tau_e$ is the Hall parameter.

On solving equations (2)&(3) we obtain

$$j_x = \frac{\sigma\mu_e H_0 Sin(\alpha_1)}{1 + m^2 H_0^2 Sin^2(\alpha_1)}(mH_0 Sin(\alpha_1) - w) \quad (4)$$

$$j_z = \frac{\sigma\mu_e H_0 Sin(\alpha_1)}{1 + m^2 H_0^2 Sin^2(\alpha_1)}(u + mH_0 w\, Sin(\alpha_1)) \quad (5)$$

where u,w are the velocity components along x and z directions respectively,

The Momentum equations are

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}) + \mu_e(-H_0 J_z Sin(\alpha_1)) - (\frac{\mu}{k})u \quad (6)$$

$$\frac{\partial w}{\partial t}u\frac{\partial W}{\partial x}+w\frac{\partial W}{\partial z}=-\frac{\partial p}{\partial z}+\mu(\frac{\partial^2 W}{\partial x^2}+\frac{\partial^2 W}{\partial z^2})+\mu_e(H_0 J_x Sin(\alpha_1))-(\frac{\mu}{k})w \qquad (7)$$

Substituting J_x and J_z from equations (4)&(5)in equations (6)&(7) we obtain

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}+\mu(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial z^2})+$$
$$-(\frac{\mu}{k})u \quad -\frac{\sigma\mu_e H_{00}^2 Sin^2(\alpha_1)}{1+m^2H_0^2Sin^2(\alpha_1)}(u+mH_0wSin(\alpha_1))-\rho g \qquad (8)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial W}{\partial x}+w\frac{\partial W}{\partial z}=-\frac{\partial p}{\partial z}+\mu(\frac{\partial^2 W}{\partial x^2}+\frac{\partial^2 W}{\partial z^2})-(\frac{\mu}{k})w$$
$$-\frac{\sigma\mu_e H_0^2 Sin^2(\alpha_1)}{1+m^2H_0^2Sin^2(\alpha_1)}(w-mH_0uSin(\alpha_1)) \qquad (9)$$

The energy equation is

$$\rho C_p(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+w\frac{\partial T}{\partial z}=k_f(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial z^2})+Q(T_0-T) \qquad (10)$$

The diffusion equation is

$$(\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+w\frac{\partial C}{\partial z}=D_{1f}(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial z^2})-k_1(C-C_0) \quad (11)$$

The equation of state is

$$\rho-\rho_0=-\beta(T-T_o)-\beta^\bullet(C-C_0)) \qquad (12)$$

Where T,C are the temperature and concentration in the fluid. k_f is the thermal conductivity, Cp is the specific heat constant pressure, k is the permeability of the porous medium, β is the coefficient of thermal expansion, $\beta^\bullet$ is the volumetric coefficient of expansion with mass fraction coefficiemnt,$D_1$is the molecular diffusivity, Q is the strength of the heat source,k_{11} is the cross diffusivity,k1 is the chemical reaction coefficient.
The flow is maintained by a constant volume flux for which a characteristic velocity is defined as

$$q=\frac{1}{L}\int_{-Lf}^{Lf} wdz \qquad (13)$$

The boundary conditions are

u= 0 ,w=0 T=T_1 ,C=C_1 on $x=-Lf(mz)$ (14)

w=0, w=0, T=T_2 +((T_1-T_2)Sin(mz+nt),C=C_2 on $x=-Lf(mz)$ (15)

diffusivity..

Eliminating the pressure from equations(8)&(9) and introducing the Stokes Stream function ψ as

$$u=-\frac{\partial\psi}{\partial z} \quad , \; w=\frac{\partial\psi}{\partial x} \qquad (18)$$

the equations (8),(9) ,(11)&(17) in terms of ψ are

$$\frac{\partial(\nabla^2\psi)}{\partial t}-\frac{\partial\psi}{\partial z}\frac{\partial(\nabla^2\psi)}{\partial x}+\frac{\partial\psi}{\partial x}\frac{\partial(\nabla^2\psi)}{\partial z}=\mu\nabla^4\psi+\beta g\frac{\partial(T-T_e)}{\partial x}$$
$$+\beta^\bullet g\frac{\partial(C-C_e)}{\partial x}-(\frac{\sigma\mu_e^2H_0^2Sin^2(\alpha_1)}{1+m^2H_0^2\,Sin^2(\alpha_1)})\nabla^2\psi \qquad (19)$$

$$\rho C_p(\frac{\partial T}{\partial t}+\frac{\partial \psi}{\partial x}\frac{\partial T}{\partial z}-\frac{\partial \psi}{\partial z}\frac{\partial T}{\partial x}=k_f(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial z^2})+Q(T-T_e) \quad (20)$$

$$(\frac{\partial C}{\partial t}+\frac{\partial \psi}{\partial x}\frac{\partial c}{\partial z}-\frac{\partial \psi}{\partial z}\frac{\partial C}{\partial x}=D_1(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial z^2})-k_1(C-C_0) \quad (21)$$

On introducing the following non-dimensional variables

$$(x',z')=(x,mz/L),\psi'=\frac{\psi}{qL},\ \theta=\frac{T-T_2}{T_1-T_2},C'=\frac{C-C_2}{C_1-C_2}$$

the equation of momentum and energy in the non-dimensional form are

$$\nabla^4\psi-M_1^2\nabla^2\psi+\frac{G}{R}(\frac{\partial\theta}{\partial z}+N\frac{\partial C}{\partial z})=\delta R(\delta\frac{\partial}{\partial t}(\nabla^2\psi)+ (\frac{\partial\psi}{\partial z}\frac{\partial(\nabla^2\psi)}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial(\nabla^2\psi)}{\partial z}) \quad (22)$$

$$\delta P(\delta\frac{\partial\theta}{\partial t}+\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial\theta}{\partial x})=(\frac{\partial^2\theta}{\partial x^2}+\delta^2\frac{\partial^2\theta}{\partial z^2})-\alpha\theta \quad (23)$$

$$\delta Sc(\delta\frac{\partial C}{\partial t}+\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial C}{\partial x})=(\frac{\partial^2 C}{\partial x^2}+\delta^2\frac{\partial^2 C}{\partial z^2})-KC \quad (24)$$

$$\nabla^2=\frac{\partial}{\partial x^2}+\delta^2\frac{\partial}{\partial z^2}$$

where $G=\frac{\beta g\,\Delta T_e L^3}{\nu^2}$ (Grashof Number), $\delta=mL$ (Aspect ratio)

$M^2=\frac{\sigma\mu_e^2 H_o^2 L^2}{\nu^2}$ (Hartman Number), $D^{-1}=\frac{L^2}{k}$ (Darcy Number)

$M_1^2=\frac{M^2 Sin^2(\alpha_1)}{1+m^2}$, $R=\frac{qL}{\nu}$ (Reynolds Number)

$P=\frac{\mu C_p}{K_f}$ (Prandtl Number), $\alpha=\frac{QL^2}{K_f(T_1-T_2)}$ (Heat Source Parameter)

$Sc=\frac{\nu}{D_1}$ (Schmidt Number), $N=\frac{\beta^\bullet(C_1-C_2)}{\beta(T_1-T_2)}$ (Buoyancy ratio)

$K=\frac{k_1L^2}{D_1}$ (Chemical reaction parameter)

The corresponding boundary conditions are

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

$$\frac{\partial\psi}{\partial z}=0,\frac{\partial\psi}{\partial x}=0,\theta=1,C=1 \quad at\ x=-f(z)$$

$$\frac{\partial\psi}{\partial z}=0,\frac{\partial\psi}{\partial x}=0,\theta=Sin(z+\gamma t),\ C=0\ \ at\ x=+f(z) \quad (25)$$

3.ANALYSIS OF THE FLOW

On introducing the transformation

$$\eta=\frac{x}{f(z)} \quad (26)$$

The equations(22)-(24) reduce to

$$F^4\psi-(M_1^2f^2)F^2\psi+(\frac{Gf^3}{R})(\frac{\partial\theta}{\partial z}+N\frac{\partial C}{\partial z})=(\delta Rf)(\delta\frac{\partial}{\partial t}(F^2\psi)+ (\frac{\partial\psi}{\partial z}\frac{\partial(F^2\psi)}{\partial\eta}-\frac{\partial\psi}{\partial\eta}\frac{\partial(F^2\psi)}{\partial z}) \tag{27}$$

$$(\delta Pf)(\delta\frac{\partial\theta}{\partial t}+\frac{\partial\psi}{\partial\eta}\frac{\partial\theta}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial\theta}{\partial\eta})=(\frac{\partial^2\theta}{\partial\eta^2}+\delta^2f^2\frac{\partial^2\theta}{\partial z^2})-(\alpha f^2)\theta \tag{28}$$

$$(\delta Scf)(\delta f^2\frac{\partial C}{\partial t}+\frac{\partial\psi}{\partial\eta}\frac{\partial C}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial C}{\partial\eta})=(\frac{\partial^2C}{\partial\eta^2}+\delta^2f^2\frac{\partial^2C}{\partial z^2})-(Kf^2)C \tag{29}$$

Assuming the aspect ratio δ to be small we take the asymptotic solutions as

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

$$\theta(x,z,t)=\theta_o(x,z,t)+\delta\theta_1(x,z,t)+\delta^2\theta_2(x,z,t)+.................. \tag{30}$$

$$C(x,z,t)=C_o(x,z,t)+\delta C_1(x,z,t)+\delta^2C_2(x,z,t)+.........$$

Substituting (30) in equations (26)-(28) and equating the like powers of δ the equations and the respective boundary conditions to the zeroth order are

$$\frac{\partial^2\theta_0}{\partial\eta^2}-(\alpha f^2)\theta_o=0 \tag{31}$$

$$\frac{\partial^2C_0}{\partial\eta^2}-(kf^2)C_0=0 \tag{32}$$

$$\frac{\partial^4\psi_0}{\partial\eta^4}-(M_1^2f^2)\frac{\partial^2\psi_0}{\partial\eta^2}=-(\frac{Gf^3}{R})(\frac{\partial\theta_0}{\partial z}+N\frac{\partial C_0}{\partial z}) \tag{33}$$

with

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

$$\frac{\partial\psi_0}{\partial\eta}=0,\ \frac{\partial\psi_0}{\partial\bar{z}}=0,\quad \theta_0=1,\ C_0=1\ at\ \ \eta=-1 \tag{34}$$

$$\frac{\partial\psi_0}{\partial\eta}=0,\ \frac{\partial\psi_0}{\partial\bar{z}}=0,\quad \theta_0=Sin(z+\gamma t),\ C_0=0\ \ at\ \ \eta=+1$$

and to the first order are

$$\frac{\partial^2\theta_1}{\partial\eta^2}-(\alpha f^2)\theta_1=(PRf)(\frac{\partial\psi_0}{\partial\eta}\frac{\partial\theta_0}{\partial\bar{z}}-\frac{\partial\psi_0}{\partial\bar{z}}\frac{\partial\theta_0}{\partial\eta}) \tag{35}$$

$$\frac{\partial^2C_1}{\partial\eta^2}-(kf^2)C_1=(ScRf)\left(\frac{\partial\psi_0}{\partial\mu}\frac{\partial C_0}{\partial\bar{z}}-\frac{\partial\psi_0}{\partial\bar{z}}\frac{\partial C_0}{\partial\eta}\right) \tag{36}$$

$$\frac{\partial^4\psi_1}{\partial\eta^4}-(M_1^2f^2)\frac{\partial^2\psi_1}{\partial\eta^2}=-(\frac{Gf^3}{R})(\frac{\partial\theta_1}{\partial z}+N\frac{\partial C_1}{\partial z})+ +(Rf)(\frac{\partial\psi_0}{\partial\eta}\frac{\partial^3\psi_0}{\partial z^3}-\frac{\partial\psi_0}{\partial\bar{z}}\frac{\partial^3\psi_0}{\partial\eta\partial z^2}) \tag{37}$$

with

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

$$\frac{\partial\psi_1}{\partial\eta}=0,\ \frac{\partial\psi_1}{\partial\bar{z}}=0,\quad \theta_1=0,\ C_1=0\ \ at\ \ \eta=-1 \tag{38}$$

$$\frac{\partial\psi_1}{\partial\eta}=0,\ \frac{\partial\psi_1}{\partial\bar{z}}=0,\quad \theta_1=0,\ C_1=0\ \ at\ \ \eta=+1$$

4.SOLUTIONS OF THE PROBLEM

Solving the equations(31)- (33) and (35) – (37) subject to the boundary conditions (34) & (38) we obtain

$$\theta_{0_0}=0.5\alpha(x^2-1)+0.5Sin(z+\gamma t)(1+x)+0.5(1-x)$$
$$C_0=0.5\left(\frac{Ch(\beta_1 x)}{Ch(\beta_1)}-\frac{sh(\beta_1 x)}{sh(\beta_1)}\right)+a_3\left(\frac{Ch(\beta_1 x)}{Ch(\beta_1)}-1\right)$$
$$\psi_0=a_9Cosh(M_1x)+a_{10}Sinh(M_1x)+a_{11}x+a_{12}+\phi_1(x)$$
$$\phi_1(x)=-a_6x+a_7x^2-a_8x^3$$

Similarly the solutions to the first order are

$$\theta_1=a_{36}(x^2-1)+a_{37}(x^3-x)+a_{38}(x^4-1)+a_{39}(x^5-x)+a_{40}(x^6-1)+$$
$$+(a_{41}+xa_{43})(Ch(M\ \ x)-Ch(M_1)+a_{42}(Sh(M_1x)-xSh(M_1))+$$
$$+a_{44}(xSh(M_1x)-Sh(M_1))$$
$$C_1=a_{47}\left(1-\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+a_{48}\left(x-\frac{Sh(\beta_1x)}{Sh(\beta_1)}\right)+a_{49}\left(x^2-\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+$$
$$+a_{50}\left(x^3-\frac{Sh(\beta_1x)}{Sh(\beta_1)}\right)+a_{51}\left(x^4-\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+a_{52}\left(Ch(M_1x)-Ch(M_1)\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+$$
$$+a_{53}\left(Sh(M_1x)-Sh(M_1)\frac{Sh(\beta_1x)}{Sh(\beta_1)}\right)+a_{54}\left(xCh(M_1x)-Ch(M_1)\frac{Sh(\beta_1x)}{Sh(\beta_1)}\right)+$$
$$+a_{55}\left(xSh(M_1x)-Sh(M_1)\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+b_3\left(Sh(\beta_2x)-Sh(\beta_2)\frac{Sh(\beta_1x)}{Sh(\beta_1)}\right)+$$
$$+b_4\left(Sh(\beta_3x)-Sh(\beta_3)\frac{Sh(\beta_1x)}{Sh(\beta_1)}\right)+b_5\left(Ch(\beta_2x)-Ch(\beta_2)\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+$$
$$+b_6\left(Ch(\beta_3x)-Ch(\beta_2)\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+b_7\left(xSh(\beta_1x)-Sh(\beta_1)\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+$$
$$+b_8\left(x^2Sh(\beta_1x)-Sh(\beta_1)\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+b_9\left(x^3Sh(\beta_1x)-Sh(\beta_1)\frac{Ch(\beta_1x)}{Ch(\beta_1)}\right)+$$

$$+b_{11}(xCh(\beta_1 x)-Ch(\beta_1)\frac{Sh(\beta_1 x)}{Sh(\beta_1)})+b_{12}(x^2Ch(\beta_1 x)-Ch(\beta_1))+$$

$$+b_{13}(x^3Ch(\beta_1 x)-Ch(\beta_1)\frac{Sh(\beta_1 x)}{Sh(\beta_1)})$$

$$\psi_1 = d_2Cosh(M_1x)+d_3Sinh(M_1x)+d_4x+d_5+\phi_4(x)$$

$$\phi_4(x) = b_{65}x+b_{66}x^2+b_{67}x^3+b_{68}x^4+b_{69}x^5+b_{70}x^6+b_{71}x^7+(b_{72}x+$$

$$+b_{74}x^2+b_{77}x^3)Cosh(M_1x)+(b_{73}x+b_{75}x^2+b_{76}x^3)Sinh(M_1x)+$$

$$+b_{78}Cosh(\beta_1 x)+b_{79}Sinh(\beta_{1x}x)$$

5.NUSSELT NUMBER and SHERWOOD NUMBER

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

$$Nu = \frac{1}{(\theta_m-\theta_w)}(\frac{\partial\theta}{\partial x})_{x=\pm 1}$$

where $\theta_m = 0.5\int_{-1}^{1}\theta\, dx$

$$(Nu)_{x=+1} = \frac{1}{\theta_m - Sin(z+\gamma t)}(b_{24}+\delta b_{22}) \qquad (Nu)_{x=-1} = \frac{1}{(\theta_m-1)}(b_{25}+\delta b_{23})$$

$$\theta_m = b_{26}+\delta b_{27}$$

The rate of mass transfer (Sherwood Number) on the walls has been calculated using the formula

$$Sh = \frac{1}{(C_m-C_w)}(\frac{\partial C}{\partial x})_{x=\pm 1} \qquad \text{where} \qquad C_m = 0.5\int_{-1}^{1}C\, dx$$

$$(Sh)_{x=+1} = \frac{1}{C_m}(b_{18}+\delta b_{16}) \qquad (Sh)_{x=-1} = \frac{1}{(C_m-1)}(b_{19}+\delta b_{17})$$

$$C_m = b_{20}+\delta b_{21}$$

where $a_1,a_2,\ldots\ldots\ldots,a_{90},b_1,b_2,\ldots\ldots\ldots,b_{79}$ are constants.

6.RESULTS AND DISCUSSION OF THE NUMERICAL RESULTS

In this analysis we investigate the effect of Hall Currents and radiation on mixed convective heat and mass transfer flow of a viscous, electrically conducting fluid through a porous medium in a vertical wavy channel with traveling thermal wave imposed on the wall in the presence of heat generating source under an inclined magnetic field..

The axial velocity (w) is shown in Figs1-5 for different values of m, M, β, N_1, λ, k & R. The variation of w with M and m shows that higher the Lorentz force smaller |w| in the flow region. An increase in the Hall parameter m leads to an enhancement in w(fig2.). The effect of surface geometry (β) on w is shown in fig.2. It is found that higher the dilation of the channel walls larger w in the flow region (fig.3). The effect of radiation on W is shown in fig.8. It is found that |w| enhances with increase in the radiation parameter N_1 an increase in the inclination of the magnetic field ($\lambda\le\pi/2$) leads to an enhancement in |w| and for further higher inclination ($\lambda=\pi$), it depreciates and for still higher λ , we notice an enhancement in

|w| in the entire flow region(fig.4). Fig.5 represents w with chemical reaction parameter k. It is found that W exhibits a reversal flow for k=3.5 and |w| enhances with increase in k.

The secondary velocity (u) which arises due to the waviness of the boundary is shown in figs(6-10) for different parametric values. The variation of u with M and m shows that higher the Lorentz force smaller |u| in the flow region(fig.6). An increase in the Hall parameter m leads to a depreciation u (fig.6). From fig.7 we find that |u| enhances with increase in and β. Thus higher the dilation of the channel walls larger |u| in the flow region. The effect of radiative heat flux on u is shown in fig.8. We find that higher the radiative heat flux larger u in the flow region (fig.8). From fig.9 we find that |u| depreciates with increase in $\lambda \le \pi$ and enhances marginally with higher $\lambda = 2\pi$. The variation f u with chemical reaction parameter k shows that u is towards the boundary force $k \le 2.5$ and for higher $k \ge 3.0$, u is towards the midregion in the left half and is towards the buoynacy in the right half of the channel (fig.10)

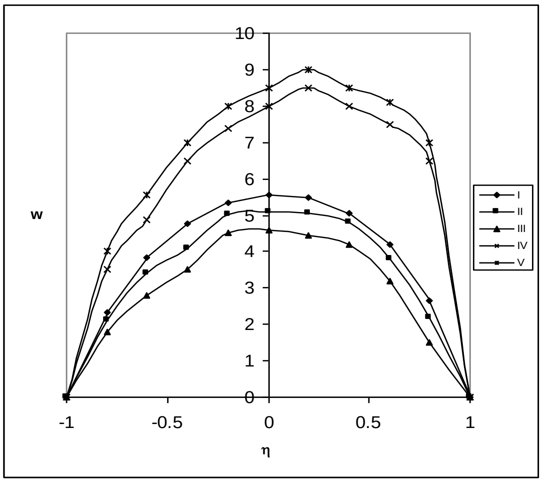

Fig.1 W with M&m
G= 10^3, $D^{-1}=10^2$, Sc=1.3, $\alpha=2$, $\beta = 0.5$

	I	II	III	IV	V
M	2	5	10	2	2
m	0.5	0.5	0.5	1.5	2.5

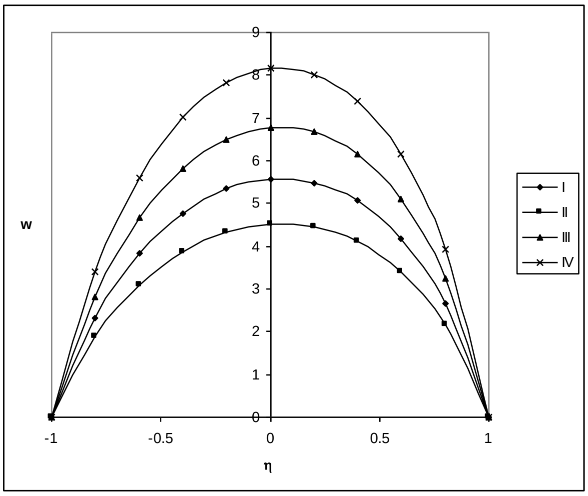

Fig.2 W with β
G= 10^3, $D^{-1}=10^2$, Sc=1.3, $\alpha=2$, k=0.5

	I	II	III	IV
β	0.3	0.5	0.7	0.9

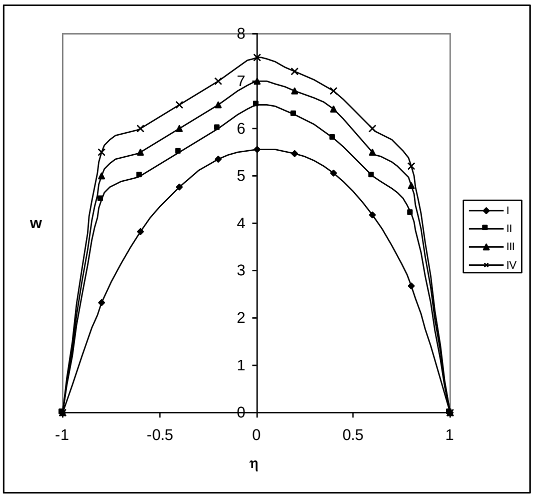

Fig.3 W with N1
G= 10^3, $D^{-1}=10^2$, Sc=1.3, $\alpha=2$, $\beta = 0.5$, k=0.5

	I	II	III	IV
N1	1.5	5	10	100

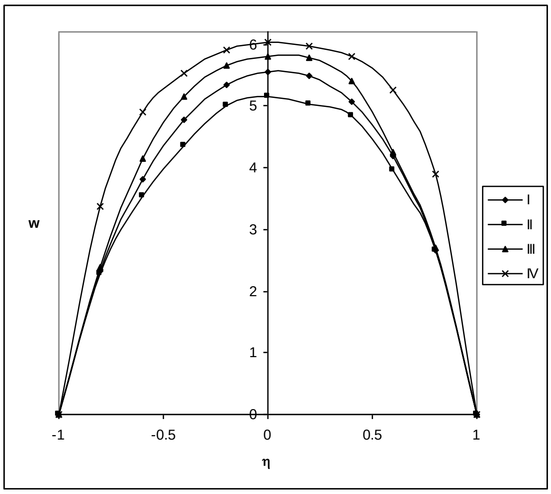

Fig.4 W with λ
M=2, m=0.5, $D^{-1}=10^2$, Sc=1.3, $\alpha=2$, $\beta = 0.5$

	I	II	III	IV
λ	$\pi/4$	$\pi/2$	π	2π

The non-dimensional temperature(θ)is shown in figs.11-14 for different variations. An increase in the Hall parameter m≤1.5 leads to an enhancement in the actual temperature in the left half and reduces in the right half while for higher m≥2.5 it depreciates in the entire flow region(fig.11). With respect to the chemical reaction parameter k≤1.5 we find that the actual temperature reduces in the left half and enhances in the right half and for higher k≥2.5 we find a depreciation in the entire flow region(fig.12). The influence of surface geometry on θ is shown in fig.13. It is observed that higher the dilation of the channel walls larger the actual temperature and for higher dilation we notice a depreciation in the left half and an enhancement in the right half of the channel. An increase in the inclination λ of the magnetic field results in an enhancement in the actual temperature in the left half and depreciates in the right half (fig.14).

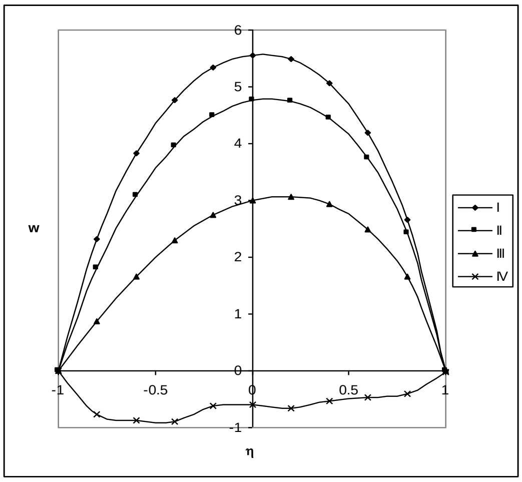

Fig.5 W with k
$G= 10^3$, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5
I II III IV
k 0.5 1.5 2.5 3.5

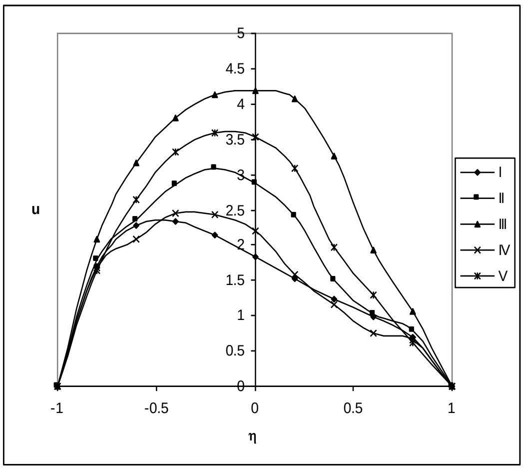

Fig.6 u with M&m
$G= 10^3$, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5
I II III IV V
M 2 5 10 2 2

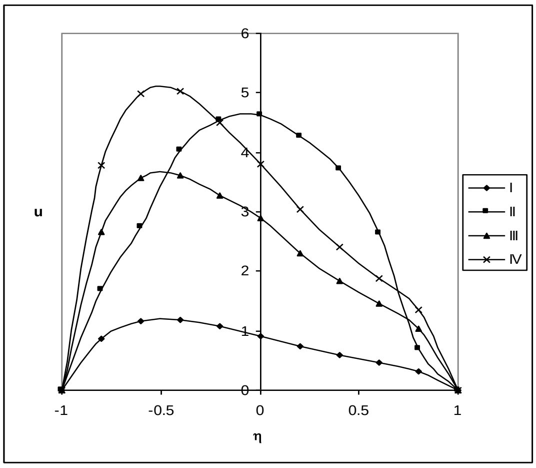

Fig.7 u with β
$G= 10^3$, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5
I II III IV
β 0.3 0.5 0.7 0.9

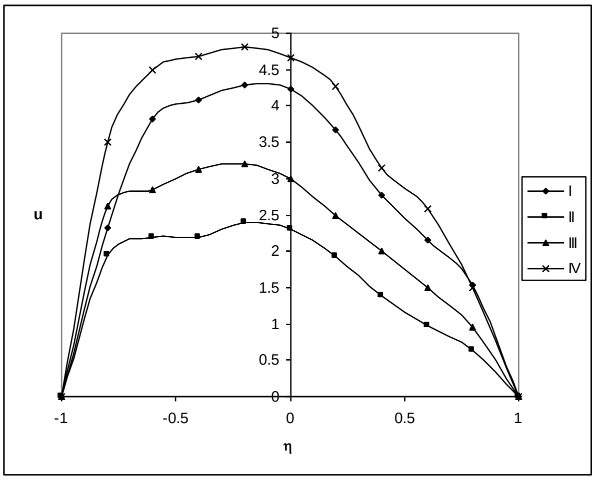

Fig.8 u with N1
$G= 10^3$, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5
I II III IV
N1 1.5 5 10 100

The concentration distribution(C) is shown in figs.15-18 for different variations of the parameters. An increase in R≤70 depreciates C in the left half and enhances in the right half while for R≥140 we notice a reversed effect in |C|. An increase in the Hall parameter m reduces the concentration in the left half and enhances in the right half(fig.15). An increase in the chemical reaction parameter k results in a depreciation in the actual concentration in the entire flow region(fig.16). The variation of C with β shows that higher the dilation of the channel walls smaller the actual concentration in the left half and larger in the right half (fig.17).With increase in λ≤π/2 the actual concentration reduces in the lefct half and enhances in the right half while for higher λ≥π,the actual concentration enhances in the left half and reduces in the right half of the channel(fig.18).

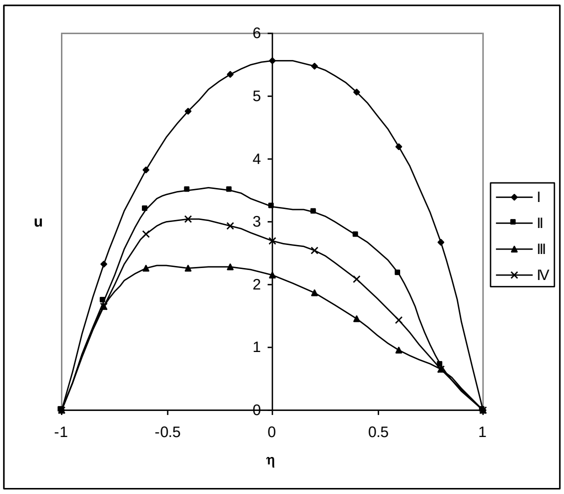

Fig.9 u with λ
M=2, m=0.5, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5

	I	II	III	IV
λ	π/4	π/2	π	2π

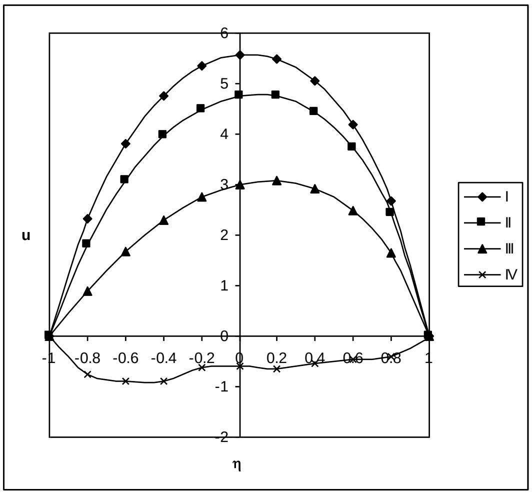

Fig.10 u with k
G= 10^3, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5

	I	II	III	IV
k	0.5	1.5	2.5	3.5

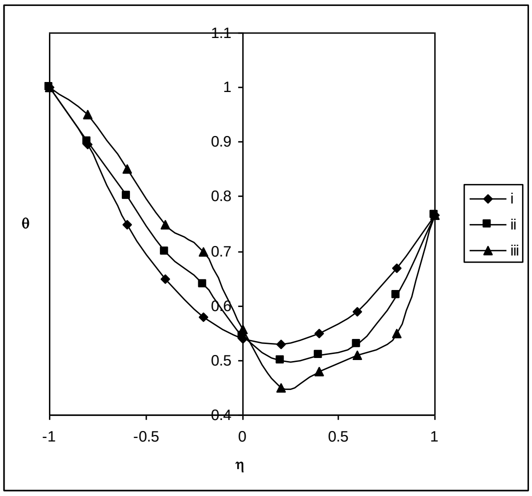

Fig.11 θ with m
G= 10^3, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5

	I	II	III
m	0.5	1.5	2.5

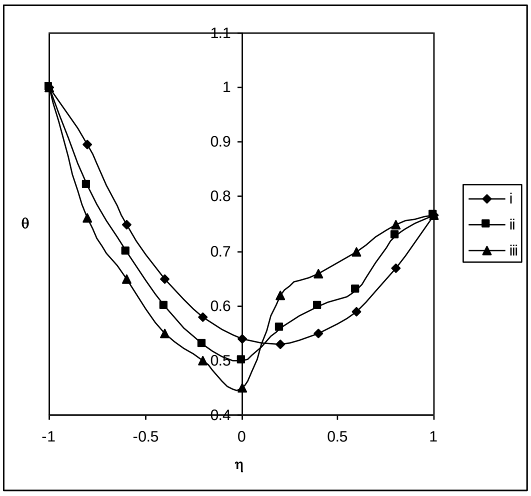

Fig.12 θ with k
M=2, m=0.5, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5

	I	II	III
k	0.5	1.5	2.5

The rate of heat transfer(Nusselt Number) at η=±1 is shown in tables.1 & 2 for different variations of m, β, λ, k. At η=+1, |Nu| reduces with m≤1.5 for G>0 and enhances for G<0 and for higher m≥2.5,we notice a depreciation in ,|Nu| for all G.At η=-1, ,|Nu|reduces with increase in the Hall parameter m for all G. With reference to the chemical reaction parameter k we find an enhancement in ,|Nu| with increase in k≤1.5 and depreciates with higher k≥2.5 at both the walls. Higher the dilation of the channel walls larger ,|Nu| at η=±1. The variation of Nu with λ shows that an increase in λ through smaller and higher values of λ(λ=π/2 &2π) we notice an enhancement for G>0 and depreciation for G<0 and for moderate values of λ=π, |Nu|depreciates for G>0 and enhances for G<0 at η=+1 and at η= -1,it enhances for G>0 and reduces for G<0 for λ=π/2 and for higher λ=π,it depreciates for G>0 and enhances for G<0 and for still higher λ=2π, |Nu| reduces for all G

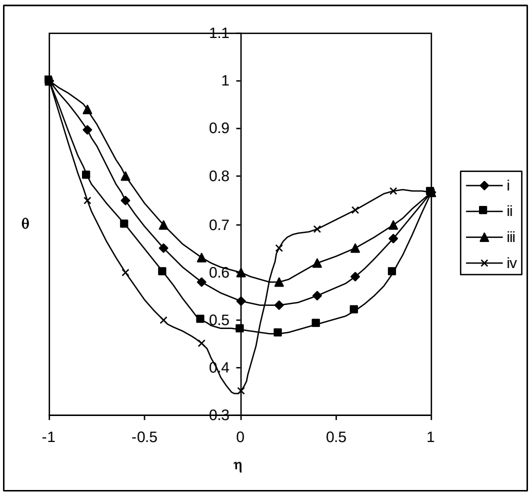

Fig.13 θ with λ

$G= 10^3$, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5

	I	II	III	IV
λ	π/4	π/2	π	2π

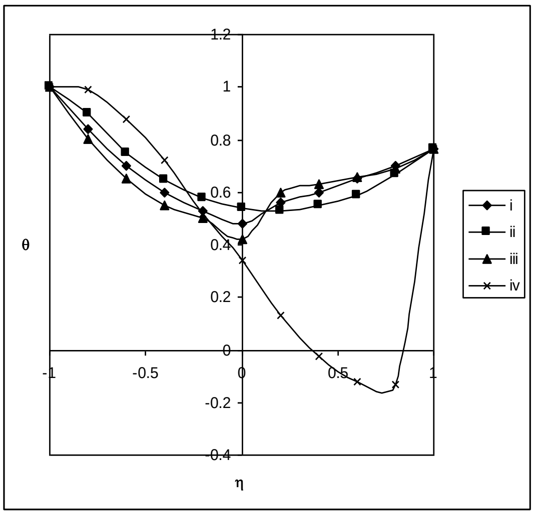

Fig.14 θ with β

M=2, m=0.5, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5

	I	II	III	IV
β	0.3	0.5	0.7	0.9

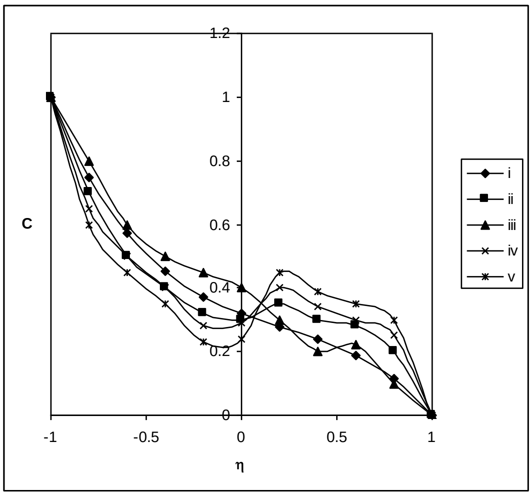

Fig.15 C with R & m

$G= 10^3$, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5

	I	II	III	IV	V
R	35	70	140	35	35
m	0.5	0.5	0.5	1.5	2.5

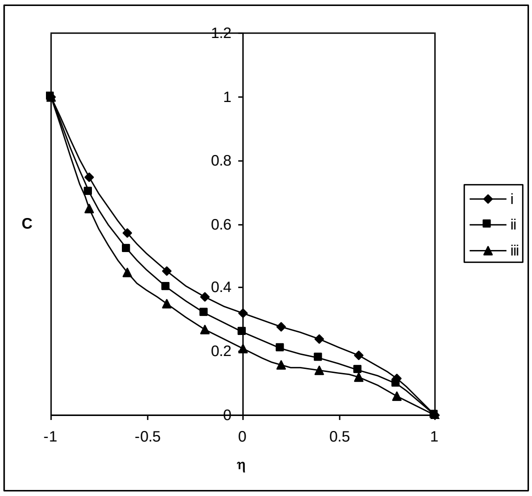

Fig.16 C with k

$G= 10^3$, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5

	I	II	III
k	0.5	1.5	2.5

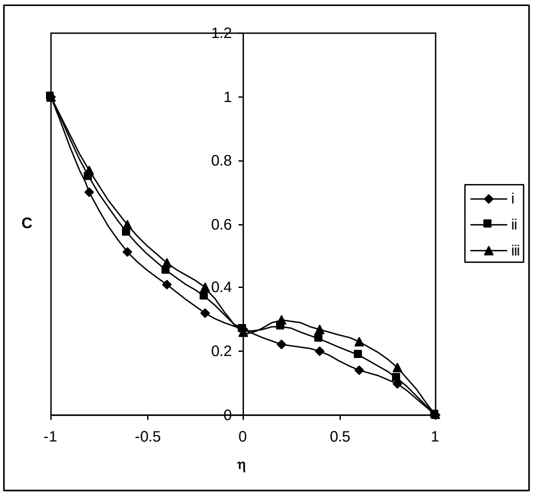

Fig.17 C with β

M=2, m=0.5, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5,R=35

	I	II	III
β	0.3	0.5	0.7

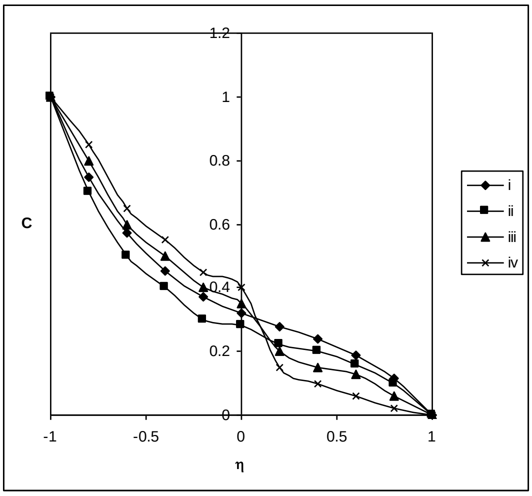

Fig.18 C with λ

$G= 10^3$, $D^{-1}=10^2$, Sc=1.3, α=2, β = 0.5, k=0.5

	I	II	III	IV
λ	π/4	π/2	π	2π

The rate of mass transfer (Sherwood Number) at the boundaries $\eta=\pm1$ is shown in tables.3 & 4 for different variations of the governing parameters. It is found that the rate of mass transfer at $\eta=+1$ reduces with G>0 and enhances with G<0.At $\eta=-1$, ,|Sh| reduces with ,|G|. The rate of mass transfer with Hall parameter m shows that Sh at $\eta=1$ enhances with m for G>0 and reduces for G<0. At $\eta=-1$, Higher the dilation of the channel walls larger ,|Sh| at both the walls. With respect t to chemical reaction parameter k we find that ,|Sh| reduces at both the walls with increase in $k\le1.5$ and for higher $k\ge2.5$,we find an enhancement at $\eta=\pm1$ for all G. An increase in the inclination $\lambda\le\pi/2$ depreciates at $\eta=1$,enhances with higher $\lambda\ge\pi$ and again depreciates with $\lambda=2\pi$.At $\eta=-1$, ,|Sh| depreciates with $\lambda\le\pi/2$ and enhances with higher $\lambda\ge\pi$.

Table.1

Average Nusselt Number(Nu) at $\eta=+1$

G/Nu	I	II	III	IV	V	VI	VII	VIII	IX	X
10^3	0.2192	0.1785	0.1418	0.5058	0.2123	0.6902	0.6613	0.5663	0.2303	0.1972
$3x10^3$	1.0275	0.9952	0.9751	1.1842	0.9057	1.4652	1.3799	1.0933	0.7421	0.6406
-10^3	2.4351	2.4412	2.4419	2.5129	2.2647	2.7707	2.8066	2.1222	2.4137	2.8836
$-3x10^3$	1.7416	1.7353	1.7489	1.8869	1.6274	2.1518	2.1864	2.4383	2.7738	2.9812
m	0.5	1.5	2.5	3.5	0.5	0.5	0.5	0.5	0.5	0.5
K	0.5	0.5	0.5	0.5	1.5	2.5	0.5	0.5	0.5	0.5
β	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.7	0.5	0.5
λ	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/2$	π

Table.2

Average Nusselt Number(Nu) at $\eta=-1$

G/Nu	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
10^3	2.4666	2.4751	2.4714	2.4711	2.5323	2.2616	2.6909	2.9577	2.5149	2.2520	2,3265
$3x10^3$	2.2825	2.3008	2.3015	2.3009	2.2923	1.9722	2.4517	2.7757	2.2801	2.2082	2.2354
-10^3	1.8793	1.8733	1.8669	1.8635	2.0674	1.7203	1.9519	2.5463	1.8017	2.0727	1.9903
$-3x10^3$	2.0845	2.0832	2.0827	2.0809	2.1945	1.9155	2.2076	2.6926	2.0442	2.1511	2.1248
m	0.5	1.5	2.5	3.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
K	0.5	0.5	0.5	0.5	1.5	2.5	0.5	0.5	0.5	0.5	0.5
β	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.7	0.5	0.5	0.5
λ	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/2$	π	2π

Table.3

Sherwood Number(Sh) at $\eta=+1$

G/Nu	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
10^3	-47.060	-48.435	-47.750	-47.875	-2.9588	-52.9188	5.6377	-6.2429	-8.8005	-11.7197	-6.4492
$3x10^3$	-2.6361	-2.6387	-2.6411	-2.6424	-1.1695	-2.8695	-1.8714	-3.0899	-2.6297	-2.6442	-2.6433
-10^3	-0.3688	-0.3643	-0.3619	-0.3609	-.2951	-2.4151	-0.2592	-0.5181	-0.3674	-0.3797	-0.3602
$-3x10^3$	-0.8191	-0.8191	-0.8167	-0.8198	0.7123	-2.7168	-0.5326	-1.2958	-0.8183	-0.8199	-0.8168
m	0.5	1.5	2.5	3.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
K	0.5	0.5	0.5	0.5	1.5	2.5	0.5	0.5	0.5	0.5	0.5
β	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.7	0.5	0.5	0.5
λ	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/2$	π	2π

Table.4

Sherwood Number(Sh) at $\eta=-1$

G/Nu	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
10^3	16.5867	16.5017	43.4746	54.465	1.1007	2.9988	10.0625	-1.9378	35.2031	45.6689	76.5602
$3x10^3$	-2.0187	-2.0264	-2.0314	-2.0338	-0.5031	2.1831	-1.1058	-2.7752	-2.0092	-2.0371	-2.0455
-10^3	3.7976	3.9187	3.9871	4.0190	-1.3504	5.0405	1.9355	8.3006	3.7774	4.0562	4.0389
$-3x10^3$	2.5767	2.5773	2.5678	2.5682	-1.1795	3.4624	1.4888	4.5067	2.5638	2.5649	2.5651
m	0.5	1.5	2.5	3.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
K	0.5	0.5	0.5	0.5	1.5	2.5	0.5	0.5	0.5	0.5	0.5
β	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.7	0.5	0.5	0.5
λ	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/4$	$\pi/2$	π	2π

7.CONCLUSIONS:

1. An increase in the Hall parameter m leads to an enhancement in w.
2. It is found that higher the dilation of the channel walls larger w in the flow region
3. It is found that |w| enhances with increase in the radiation parameter N_1 .
4.An increase in the inclination of the magnetic field ($\lambda\leq\pi/2$) leads to an enhancement in |w| and for further higher inclination ($\lambda=\pi$), it depreciates and for still higher λ , we notice an enhancement in |w| in the entire flow region
5.W exhibits a reversal flow for k=3.5 and |w| enhances with increase in k.
6.An increase in the Hall parameter m leads to a depreciation u
7.|u| enhances with increase in and β. Thus higher the dilation of the channel walls larger |u| in the flow region.
8.Higher the radiative heat flux larger u in the flow region
9. An increase in the Hall parameter $m\leq1.5$ leads to an enhancement in the actual temperature in the left half and reduces in the right half while for higher $m\geq2.5$ it depreciates in the entire flow region.
10. the actual temperature reduces in the left half and enhances in the right half for k<1.5 and for higher $k\geq2.5$ we find a depreciation in the entire flow region.
11. Higher the dilation of the channel walls larger the actual temperature and for higher dilation we notice a depreciation in the left half and an enhancement in the right half of the channel.
12. An increase in the Hall parameter m reduces the concentration in the left half and enhances in the right half.
13.An increase in the chemical reaction parameter k results in a depreciation in the actual concentration in the entire flow region.
14. |Nu| reduces with $m\leq1.5$ for G>0 and enhances for G<0 and for higher $m\geq2.5$,we notice a depreciation in ,|Nu| for all G.At $\eta=-1$, ,|Nu|reduces with increase in the Hall parameter m for all G.
15.|Nu| enhances with increase in $k\leq1.5$ and depreciates with higher $k\geq2.5$ at both the walls.
16.Higher the dilation of the channel walls larger ,|Nu| at $\eta=\pm1$.
17. The rate of mass transfer with Hall parameter m shows that Sh at $\eta=1$ enhances with m for G>0 and reduces for G<0.
18.Higher the dilation of the channel walls larger ,|Sh| at both the walls.
19.|Sh| reduces at both the walls with increase in $k\leq1.5$ and for higher $k\geq2.5$,we find an enhancement at $\eta=\pm1$ for all G.

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