Effect Of Chemical Reaction And Radiation Absorption On Unsteady Convective Heat And Mass Transfer Flow Of A Viscous Electrically Conducting Fluid In A Vertical Wavy Channel With Traveling Thermal Waves And Hall Effects

N.S. Rajasekhar*, Dr. P.M.V. Prasad, Prof. D. R.V. Prasada Rao*****
*(Department of Mathematics, Audi Sankara Institute of Technology, Gudur, Nellore Dt., A.P. India)
**(Department of Mathematics, S.V.G.S. Degree College, Nellore, A.P. India)
***(Department of Mathematics, Sri Krishnadevaraya University, Anantapur, AP, India)

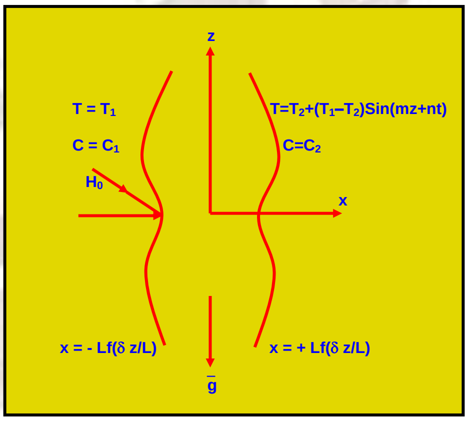
ABSTRACT
In this paper we investigate the effect of chemical reaction, Hall currents on unsteady mixed convective heat and mass transfer flow of a viscous, electrically conducting fluid in a vertical channel under the influence of an inclined magnetic fluid with heat sources. The equations governing 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, Q_1, k, β, λ. The rate of heat and mass transfer are numerically evaluated for different variations of the governing parameters.
Keywords : **Hall effect, Chemical reaction, Radiation absorption, Wall wavyness, Inclined magnetic filed**.

I. INTRODUCTION
There are many physical processes in which buoyancy forces resulting from combined thermal and species diffusion play an important role in the convective transfer of heat and mass. The engineering applications include the chemical distillatory processes, formation and dispersion of fog, design of heat exchangers, channel type solar energy collectors, and thermo-protection systems. Therefore, the characteristics of natural convection heat and mass transfer are relatively important. Convection flows driven by temperature and concentration differences have been studied extensively in the past.

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[32] 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 Whitehead [35] by postulating series expansion in the square of the aspect ratio(assumed small) for both the temperature and flow fields. Whitehead [35] 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. Recently Muthuraj et al[20] have discussed mixed convective heat and mass transfer in a vertical w3avy channel with traveling thermal waves and porous medium.

The study of heat and mass transfer from an irregular surface has many applications. It is often encountered in heat transfer devices to enhance heat transfer. For examples, flat-plate solar collectors and flat-plate condensers in refrigerators. The natural convective heat transfer from an isothermal vertical wavy surface was first studied by Yao[36,37]. Vajravelu and Nayfeh [33] have investigated the influence of the wall waviness on friction and pressure drop of the generated coquette flow. Vajravelu and Sastry [31] have analysed the free convection heat transfer in a viscous, incompressible fluid confined between long vertical wavy walls in the presence of constant heat source. Later Vajravelu and Debnath [32] have extended this study to convective flow in a vertical wavy channel in four different geometrical configurations. This problem has been extended to the case of wavy walls by McMichael and Deutsch [18], Deshikachar et al [10], Rao et al [23,24] and Sree Ramachandra Murthy [30]. Hyan Goo Kwon et al[12] have analyzed that the Flow and heat/mass transfer in a wavy duct with various corrugation angles in two dimensional flow regimes. Kumar[16] has studied heat transfer with radiation and temperature dependent heat source in MHD free convection flow confined between two vertical wavy walls.

Mahdy [17] have studied the mixed convection heat and mass transfer on a vertical wavy plate embedded in a saturated porous media (PST/PSE). Comini et al [5] have analyzed the Convective heat and mass transfer in wavy finned-tube exchangers. Jer-Huan Jang et al[13] have analyzed that the Mixed convection heat and mass transfer along a vertical wavy surface. Cheng[3,4] has investigated coupled heat and mass transfer by natural convection flow along a wavy conical surface and vertical wavy surface in a porous medium.
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. Muthucumaraswamy and Ganesan [19] 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. [7] 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 [2] 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[11]. Chamkha [2] 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 [22] studied the unsteady free convection flow of water near 4^0 C in the laminar boundary layer over a vertical moving porous plate.
In all these investigations, the effects of Hall currents are not considered. However, in a partially ionized gas, there occurs a Hall current [6] when the strength of the impressed magnetic field is very strong. These Hall effects play a significant role in determining the flow features. Sato [26], Yamanishi [38], Sherman and Sutton [28] have discussed the Hall effects on the steady hydromagnetic flow between two parallel plates. These effects in the unsteady cases were discussed by Pop [21]. Debnath [8,9] 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.*,[14,15] have investigated Hall effects on the unsteady hydromagnetic boundary layer flow. Rao *et. al.*, [24] have analyzed Hall effects on unsteady Hydromagnetic flow. Sivapasad *et. al.*[29] have studied Hall effects on unsteady MHD free and forced convection flow in a porous rotating channel. Recently Seth *et. al.*, [27] have investigated the effects of Hall currents on heat transfer in a rotating MHD channel flow in arbitrary conducting walls. Sarkar *et. al.*, [25] 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. Recently Suneela et al[34] have investigated the effect of Hall currents on convective heat and mass transfer flow of a viscous electrically conducting fluid in a vertical wavy channel with internal heat sources.
In this paper, we investigate the effect of chemical reaction, Hall currents on unsteady mixed convective heat and mass transfer flow of a viscous , electrically conducting fluid in a vertical 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, Q_1, k, β, λ. The rate of heat and mass transfer are numerically evaluated for different variations of the governing parameters.



Configuration of the Problem

II. 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 $(0, H_0 Sin(\alpha_1), H_0 Cos(\alpha_1))$.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

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

where $\bar{q}$ is the velocity vector. $\bar{H}$ is the magnetic field intensity vector. $\bar{E}$ 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

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

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

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

Substituting J_x and J_z from equations (3)&(4)in the Momentum equations we obtain

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}) + \quad (4)$$

$$-\frac{\sigma\mu_e H_{0\,0}^2 Sin^2(\alpha_1)}{1 + m^2 H_0^2 Sin^2(\alpha_1)}(u + mH_0 w Sin(\alpha_1)) - \rho g$$

$$\frac{\partial w}{\partial t} + u\frac{\partial W}{\partial x} + w\frac{\partial W}{\partial z} = -\frac{\partial p}{\partial z} + \mu(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial z^2}) \quad (5)$$

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

The energy equation is

$$\rho C_p(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + w\frac{\partial T}{\partial z} = k_f(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}) + Q + Q_1'(C - C_0) \quad (6)$$

The diffusion equation is

$$(\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} = D_1(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}) - k_1(C - C_0) \quad (7)$$

The equation of state is

$$\rho - \rho_0 = -\beta(T - T_o) - \beta^\bullet(C - C_0)) \quad (8)$$

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,k1 is the chemical reaction coefficient, Q_1' is the radiation absorption coefficient. The flow is maintained by a constant volume flux for which a characteristic velocity is defined as

$$q = \frac{1}{L}\int_{-Lf}^{Lf} w dz \quad (9)$$

The boundary conditions are

u= 0 ,w=0 T=T_1 ,C=C_1 on $x = -Lf(mz)$ (10)

w=0, w=0, T=T_2 +((T_1-T_2)Sin(mz+nt),C=C_2 on $x = -Lf(mz)$ (11)

Eliminating the pressure from equations(4)-(7) and introducing the Stokes Stream function ψ

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

the governing equations are (12)

$$\frac{\partial(\nabla^2\psi)}{\partial t}-\frac{\partial\psi}{\partial z}\frac{\partial(\nabla^2\psi)}{\partial x}+\frac{\partial\psi}{\partial x}\frac{\partial(\nabla^2\psi)}{\partial z}=\mu\nabla^4\psi+\beta g\frac{\partial(T-T_o)}{\partial x}$$
$$+\beta^{\bullet}g\frac{\partial(C-C_o)}{\partial x}-\left(\frac{\sigma\mu_e^2H_0^2Sin^2(\alpha_1)}{1+m^2H_0^2\,Sin^2(\alpha_1)}\right)\nabla^2\psi \qquad (13)$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+\frac{\partial\psi}{\partial x}\frac{\partial T}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial T}{\partial x}\right)=k_f\left(\frac{\partial^2T}{\partial x^2}+\frac{\partial^2T}{\partial z^2}\right)+Q+Q_1'(C-C_o) \qquad (2.14)$$

$$\left(\frac{\partial C}{\partial t}+\frac{\partial\psi}{\partial x}\frac{\partial c}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial C}{\partial x}\right)=D_1\left(\frac{\partial^2C}{\partial x^2}+\frac{\partial^2C}{\partial z^2}\right)-k_1(C-C_0) \qquad (15)$$

On introducing the following non-dimensional variables

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

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

$$\nabla^4\psi-M_1^2\nabla^2\psi+\frac{G}{R}\left(\frac{\partial\theta}{\partial z}+N\frac{\partial C}{\partial z}\right)=\delta R\left(\delta\frac{\partial}{\partial t}(\nabla^2\psi)+\left(\frac{\partial\psi}{\partial z}\frac{\partial(\nabla^2\psi)}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial(\nabla^2\psi)}{\partial z}\right)\right. \qquad (16)$$

$$\delta P\left(\delta\frac{\partial\theta}{\partial t}+\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial\theta}{\partial x}\right)=\left(\frac{\partial^2\theta}{\partial x^2}+\delta^2\frac{\partial^2\theta}{\partial z^2}\right)+\alpha+Q_1C \qquad (17)$$

$$\delta Sc\left(\delta\frac{\partial C}{\partial t}+\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial C}{\partial x}\right)=\left(\frac{\partial^2C}{\partial x^2}+\delta^2\frac{\partial^2C}{\partial z^2}\right)-KC \qquad (18)$$

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

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

$M^2=\frac{\sigma\mu_e^2H_o^2L^2}{\nu^2}$ (Hartman Number), $M_1^2=\frac{M^2Sin^2(\alpha_1)}{1+m^2}$

$R=\frac{qL}{\nu}$ (Reynolds Number), $P=\frac{\mu C_p}{k_f}$ (Prandtl Number)

$\alpha=\frac{QL^2}{k_fC_p(T_1-T_2)}$ (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)

$Q_1=\frac{Q_1'L^2(C_1-C_2)}{k_f(T_1-T_2)}$ (Radiation absorption parameter)

The corresponding boundary conditions are

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

$$\frac{\partial\psi}{\partial z}=0,\frac{\partial\psi}{\partial x}=0,\theta=1,C=1\quad at\ \ x=-f(z)$$
$$\frac{\partial\psi}{\partial z}=0,\frac{\partial\psi}{\partial x}=0,\theta=Sin(z+\gamma t),\ C=0\ \ at\ \ x=+f(z) \qquad (19)$$

III. METHOD OF SOLUTION

On introducing the transformation

$$\eta = \frac{x}{f(z)} \tag{20}$$

the equations(16)-(18) reduce to

$$F^4\psi - (M_1^2 f^2)F^2\psi + (\frac{Gf^3}{R})(\frac{\partial\theta}{\partial z} + N\frac{\partial C}{\partial z}) = (\delta Rf)(\delta\frac{\partial}{\partial t}(F^2\psi) + (\frac{\partial\psi}{\partial z}\frac{\partial(F^2\psi)}{\partial\eta} - \frac{\partial\psi}{\partial\eta}\frac{\partial(F^2\psi)}{\partial z}) \tag{21}$$

$$(\delta Pf)(\delta\frac{\partial\theta}{\partial t} + \frac{\partial\psi}{\partial\eta}\frac{\partial\theta}{\partial z} - \frac{\partial\psi}{\partial z}\frac{\partial\theta}{\partial\eta}) = (\frac{\partial^2\theta}{\partial\eta^2} + \delta^2 f^2\frac{\partial^2\theta}{\partial z^2}) + (\alpha f^2) + (Q_1 f^2)C \tag{22}$$

$$(\delta Scf)(\delta f^2\frac{\partial C}{\partial t} + \frac{\partial\psi}{\partial\eta}\frac{\partial C}{\partial z} - \frac{\partial\psi}{\partial z}\frac{\partial C}{\partial\eta}) = (\frac{\partial^2 C}{\partial\eta^2} + \delta^2 f^2\frac{\partial^2 C}{\partial z^2}) - (kf^2)C \tag{23}$$

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

$$\left.\begin{aligned}
&\psi(x,z,t) = \psi_0(x,z,t) + \delta\psi_1(x,z.,t) + \delta^2\psi_2(x,z,t) + \ldots\ldots\ldots\ldots\ldots\\
&\theta(x,z,t) = \theta_o(x,z,t) + \delta\theta_1(x,z,t) + \delta^2\theta_2(x,z,t) + \ldots\ldots\ldots\ldots\ldots\ldots\\
&C(x,z,t) = C_o(x,z,t) + \delta C_1(x,z,t) + \delta^2 C_2(x,z,t) + \ldots\ldots\ldots
\end{aligned}\right| \tag{24}$$

Substituting (24) in equations (21)-(23) and equating the like powers of δ the equations and the respective boundary conditions to the zeroth order are

$$\frac{\partial^2\theta_0}{\partial\eta^2} = -(\alpha f^2) = -(Q_1 f^2)C_o \tag{25}$$

$$\frac{\partial^2 C_0}{\partial\eta^2} - (kf^2)C_0 = 0 \tag{26}$$

$$\frac{\partial^4\psi_0}{\partial\eta^4} - (M_1^2 f^2)\frac{\partial^2\psi_0}{\partial\eta^2} = -(\frac{Gf^3}{R})(\frac{\partial\theta_0}{\partial z} + N\frac{\partial C_0}{\partial z}) \tag{27}$$

with

$$\begin{aligned}
&\psi_0(+1) - \psi_0(-1) = 1\\
&\frac{\partial\psi_0}{\partial\eta} = 0,\ \frac{\partial\psi_0}{\partial z} = 0,\quad \theta_0 = 1,\ C_0 = 1\ \ at\ \ \eta = -1\\
&\frac{\partial\psi_0}{\partial\eta} = 0,\ \frac{\partial\psi_0}{\partial z} = 0,\quad \theta_0 = Sin(z+\gamma t),\ C_0 = 0\ \ at\ \ \eta = +1
\end{aligned} \tag{28}$$

and to the first order are

$$\frac{\partial^2\theta_1}{\partial\eta^2} = (PRf)(\frac{\partial\psi_0}{\partial\eta}\frac{\partial\theta_0}{\partial z} - \frac{\partial\psi_0}{\partial z}\frac{\partial\theta_0}{\partial\eta}) \tag{29}$$

$$\frac{\partial^2 C_1}{\partial\eta^2} - (kf^2)C_1 = (ScRf)\left(\frac{\partial\psi_0}{\partial\eta}\frac{\partial C_0}{\partial z} - \frac{\partial\psi_0}{\partial z}\frac{\partial C_0}{\partial\eta}\right) \tag{30}$$

$$\frac{\partial^4\psi_1}{\partial\eta^4} - (M_1^2 f^2)\frac{\partial^2\psi_1}{\partial\eta^2} = -(\frac{Gf^3}{R})(\frac{\partial\theta_1}{\partial z} + N\frac{\partial C_1}{\partial z}) + \\ +(Rf)(\frac{\partial\psi_0}{\partial\eta}\frac{\partial^3\psi_0}{\partial z^3} - \frac{\partial\psi_0}{\partial\bar{z}}\frac{\partial^3\psi_0}{\partial\eta\partial z^2}) \qquad (31)$$

with

$$\psi_1(+1) - \psi_1(-1) = 0 \\ \frac{\partial\psi_1}{\partial\eta} = 0,\ \frac{\partial\psi_1}{\partial\bar{z}} = 0,\quad \theta_1 = 0,\ C_1 = 0\ \ at\ \ \eta = -1 \\ \frac{\partial\psi_1}{\partial\eta} = 0,\ \frac{\partial\psi_1}{\partial\bar{z}} = 0,\quad \theta_1 = 0,\ C_1 = 0\ \ at\ \ \eta = +1 \qquad (32)$$

IV. SOLUTIONS OF THE PROBLEM

Solving the equations(25)- (27) and (29) – (31) subject to the boundary conditions (26) & (32) we obtain

$$\theta_{0_0} = 0.5\alpha(x^2-1) + 0.5Sin(z+\gamma t)(1+x) + 0.5(1-x)$$
$$C_0 = 0.5(\frac{Ch(\beta_1 x)}{Ch(\beta_1)} - \frac{Sh(\beta_1 x)}{Sh(\beta_1)}) + a_3(\frac{Ch(\beta_1 x)}{Ch(\beta_1)} - 1)$$
$$\psi_0 = a_9 Cosh(M_1 x) + a_{10}Sinh(M_1 x) + a_{11}x + a_{12} + \phi_1(x)$$
$$\phi_1(x) = -a_6 x + a_7 x^2 - a_8 x^3$$

Similarly the solutions to the first order are

$$\theta_1 = a_{36}(x^2-1) + a_{37}(x^3-x) + a_{38}(x^4-1) + a_{39}(x^5-x) + a_{40}(x^6-1) + \\ +(a_{41}+xa_{43})(Ch(M\ \ x) - Ch(M_1) + a_{42}(Sh(M_1 x) - xSh(M_1)) + \\ +a_{44}(xSh(M_1 x) - Sh(M_1))$$

$$C_1 = a_{47}(1 - \frac{Ch(\beta_1 x)}{Ch(\beta_1)}) + a_{48}(x - \frac{Sh(\beta_1 x)}{Sh(\beta_1)}) + a_{49}(x^2 - \frac{Ch(\beta_1 x)}{Ch(\beta_1)}) + \\ +a_{50}(x^3 - \frac{Sh(\beta_1 x)}{Sh(\beta_1)}) + a_{51}(x^4 - \frac{Ch(\beta_1 x)}{Ch(\beta_1)}) + a_{52}(Ch(M_1 x) - Ch(M_1)\frac{Ch(\beta_1 x)}{Ch(\beta_1)}) + \\ +a_{53}(Sh(M_1 x) - Sh(M_1)\frac{Sh(\beta_1 x)}{Sh(\beta_1)}) + a_{54}(xCh(M_1 x) - Ch(M_1)\frac{Sh(\beta_1 x)}{Sh(\beta_1)}) + \\ +a_{55}(xSh(M_1 x) - Sh(M_1)\frac{Ch(\beta_1 x)}{Ch(\beta_1)}) + b_3(Sh(\beta_2 x) - Sh(\beta_2)\frac{Sh(\beta_1 x)}{Sh(\beta_1)}) + \\ +b_4(Sh(\beta_3 x) - Sh(\beta_3)\frac{Sh(\beta_1 x)}{Sh(\beta_1)}) + b_5(Ch(\beta_2 x) - Ch(\beta_2)\frac{Ch(\beta_1 x)}{Ch(\beta_1)}) +$$

$$+b_6(Ch(\beta_3 x)-Ch(\beta_2)\frac{Ch(\beta_1 x)}{Ch(\beta_1)})+b_7(xSh(\beta_1 x)-Sh(\beta_1)\frac{Ch(\beta_1 x)}{Ch(\beta_1)})+$$

$$+b_8(x^2 Sh(\beta_1 x)-Sh(\beta_1)\frac{Ch(\beta_1 x)}{Ch(\beta_1)})+b_9(x^3 Sh(\beta_1 x)-Sh(\beta_1)\frac{Ch(\beta_1 x)}{Ch(\beta_1)})+$$

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

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

$$\psi_1 = d_2 Cosh(M_1 x)+d_3 Sinh(M_1 x)+d_4 x+d_5+\phi_4(x)$$

$$\phi_4(x)=b_{65}x+b_{66}x^2+b_{67}x^3+b_{68}x^4+b_{69}x^5+b_{70}x^6+b_{71}x^7+(b_{72}x+$$
$$+b_{74}x^2+b_{77}x^3)Cosh(M_1 x)+(b_{73}x+b_{75}x^2+b_{76}x^3)Sinh(M_1 x)+$$
$$+b_{78}Cosh(\beta_1 x)+b_{79}Sinh(\beta_{1x} x)$$

V. NUSSELT NUMBER and SHERWOOD NUMBER

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

$$Nu=\frac{1}{(\theta_m-\theta_w)}(\frac{\partial\theta}{\partial x})_{x=\pm 1} \quad \text{where} \quad \theta_m = 0.5\int_{-1}^{1}\theta\,dx$$

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

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

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

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

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

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

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

VI. RESULTS AND DISCUSSION OF THE NUMERICAL RESULTS

We investigate the effect of Hall currents on the unsteady convective heat and mass transfer flow in a vertical wavy channel in the presence of heat generating sources under the influence of an inclined magnetic field. The equations governing the flow, heat and mass transfer are solved by employing a perturbation technique with the aspect ratio δ as a perturbation parameter. The unsteadiness in the flow is due to the traveling thermal waves imposed on the walls.

Figs.1-4 represent the axial velocity (w)for different variations of, M, m, β,λ. The actual axial flow is in the vertically downward direction and hence w>0 represents the reversal flow. Fig-1 represents w with Hartman number M and Hall parameters m. It is found that at M = 5, w exhibits a reversal flow in the region -0.8 ≤ η ≤ 0.4 and as M increases, the region of reversal flow reduces in its size. |w| reduces with M≤5 and for higher M = 7, |w| depreciates in the region -0.8 ≤ η ≤ 0 .2 and enhances in the remaining region and for still higher M = 9, |w| enhances in the regions adjacent to η = ±1 and reduces in the central region

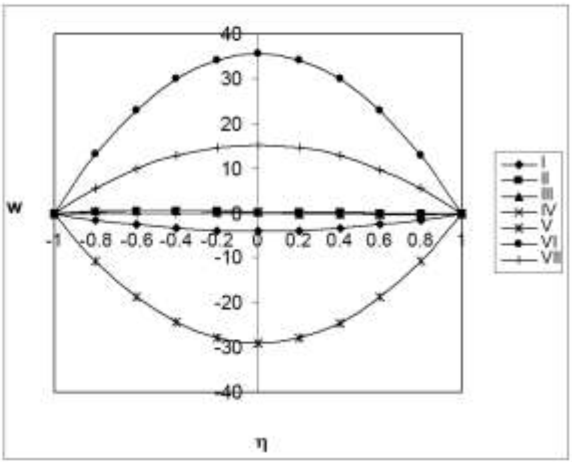


Fig. 1 : Variation of w with M, m

	I	II	III	IV	V	VI	VII
M	2	5	7	9	2	2	2
m	0.50	0.50	0.50	0.50	1.50	2.50	3.50

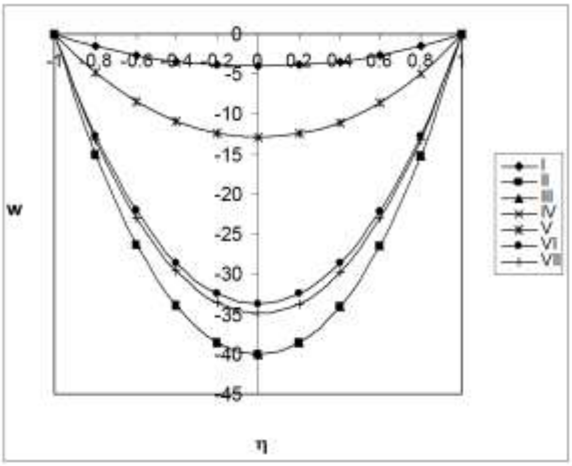


Fig. 2 : Variation of w with Q_1, K

	I	II	III	IV	V	VI	VII
Q_1	0.50	1.50	2.50	3.50	0.50	0.50	0.50
K	0.50	0.50	0.50	0.50	1.50	2.50	3.50

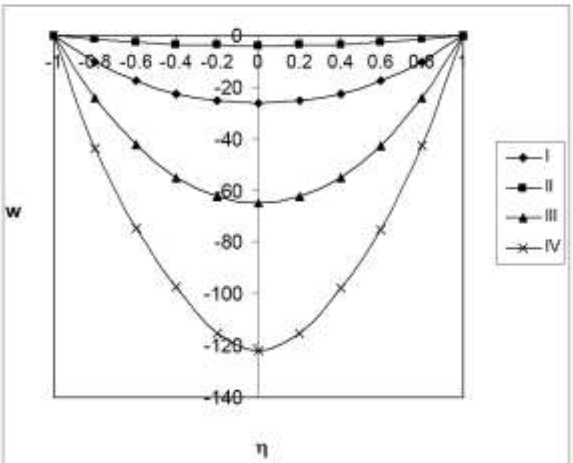


Fig. 3 : Variation of w with β

	I	II	III	IV
β	-0.3	-0.5	-0.7	-0.9

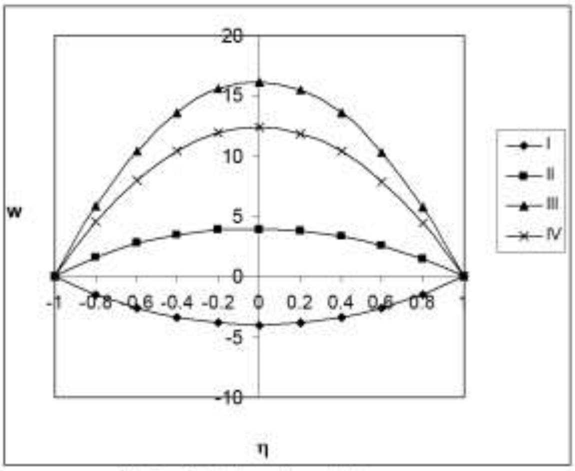


Fig. 4 : Variation of w with λ

	I	II	III	IV
λ	π/4	π/2	π	2π

The variation of w in m shows that w exhibits a reversal flow for $m \geq 2.5$ and region of reversal flow reduces with increase in m. |w| enhances with increase in $m \leq 2.5$ and reduces with $m > 2.5$. Fig-3 represents the effect of wall waviness on w. It is found that the higher the constriction of the channel walls lesser |w| in the flow region and for further higher constriction larger |w|. Fig-2 represents w with chemical reaction parameter k and radiation absorption parameter Q_1. Higher the chemical reaction parameter k larger |w|. An increase in Q_1 results in an enhancement in |w|. Fig-4 represents the variation of w with inclination λ of the magnetic field. It is found that |w| depreciates with increase in $\lambda \leq \pi/2$ and enhances with higher $\lambda = \pi$ and again depreciates with still higher $\lambda = 2\pi$.

The secondary velocity (u) which arises due to the non-uniform boundary temperature is exhibited in figures 5-8. Fig.5 represents |w| with M and m. It is found that higher the Lorentz force smaller |u| in the flow region. |u| enhances with $m \leq 1.5$ and for higher m = 2.5, |u| enhances in the left half and reduces in the right half and for still higher m = 3.5,we notice a depreciation in |u| in the entire flow region. Fig-6 represents u with k and Q_1. It is found that higher chemical reaction parameter k larger |u|. An increase in $Q_1 \leq 1.5$ enhances |u| and for higher $Q_1 \geq 2.5$, we notice a depreciation in |u|. The variation of u with inclination of λ is shown in fig-14. It is found that |u| enhances with increase in $\lambda \leq \pi/2$and for higher $\lambda \geq \pi$ we notice a depreciation in |u| in entire flow region(Fig-7). Fig-8 represents u with β. It is found that higher the constriction of channel walls smaller |u| in the flow region and for further higher constriction larger |u| in the flow region.

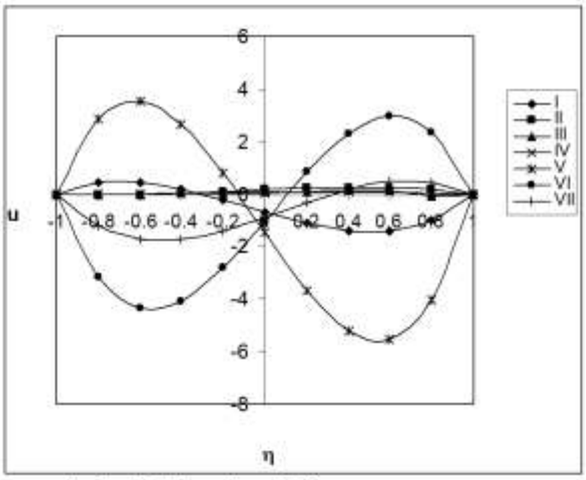


Fig. 5 : Variation of u with M, m

	I	II	III	IV	V	VI	VII
M	2	5	7	9	2	2	2
m	0.50	0.50	0.50	0.50	1.50	2.50	3.50

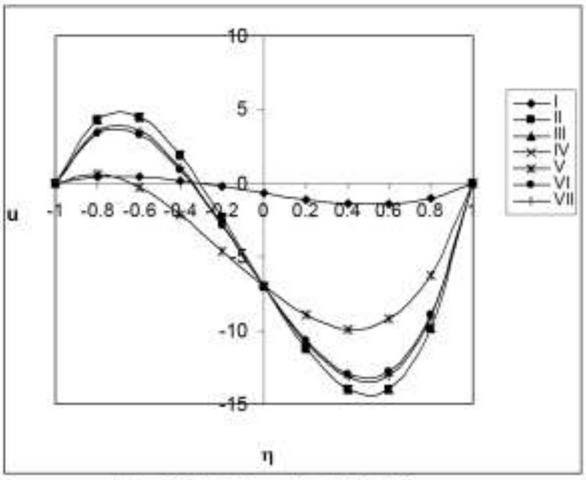


Fig. 6 : Variation of u with Q_1, K

	I	II	III	IV	V	VI	VII
Q_1	0.50	1.50	2.50	3.50	0.50	0.50	0.50
K	0.50	0.50	0.50	0.50	1.50	2.50	3.50

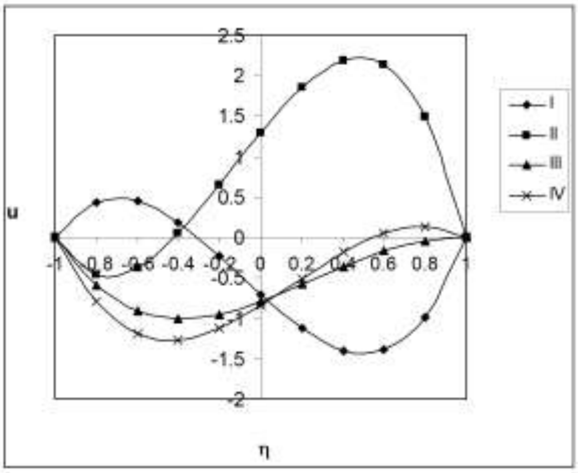


Fig. 7 : Variation of u with λ

	I	II	III	IV
λ	π/4	π/2	π	2π

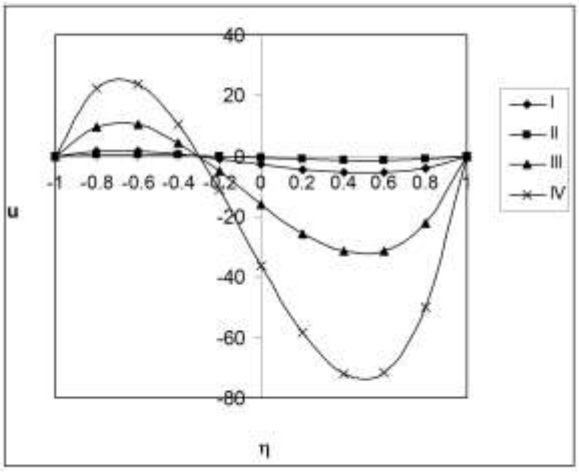


Fig. 8 : Variation of u with β

	I	II	III	IV
β	-0.3	-0.5	-0.7	-0.9

The non-dimensional temperature(θ) is shown in figs. 9-12 for different parametric values. We follow the convention that the non-dimensional temperature is positive or negative according as the actual temperature is greater or lesser than T_2. Fig.9 represents θ with M and m. It is found that higher the Lorentz force smaller the actual temperature. The variation of θ with m shows that the actual temperature enhances with $m \le 1.5$ and reduces with $m \ge 2.5$ and for still higher $m = 3.5$ we notice an enhancement in the actual temperature.. Fig-10 represents θ with k and Q_1. It is found that the actual temperature enhances in the left half and reduces in the right half with smaller and higher values of the chemical reaction parameter k and for intermediate values of k(=2.5) the actual temperature reduces in the left half and enhances in the right half. An increase in the radiation absorption parameter Q_1 enhances the actual temperature. Fig-11 represents θ with inclination λ of the magnetic field. It is found that the actual temperature reduces with $\lambda \le \pi/2$and enhances with $\lambda = \pi$ and again depreciates with higher $\lambda = 2\pi$. Fig.12 represents θ with β. It is found that higher the constriction of the channel walls larger the actual temperature and for higher $|\beta| \ge 0.7$ the actual temperature reduces in left half and enhances in the right half.

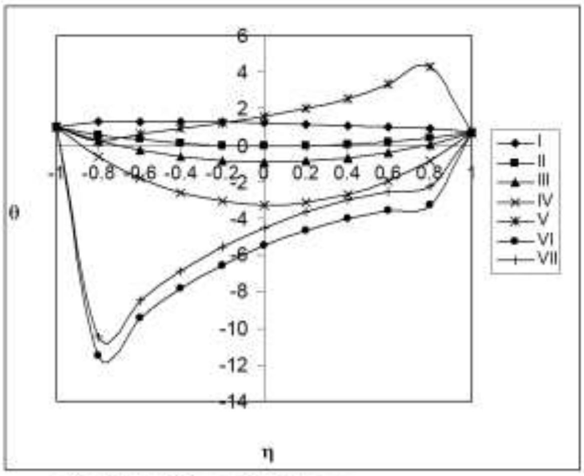


Fig. 9 : Variation of θ with M, m

	I	II	III	IV	V	VI	VII
M	2	5	7	9	2	2	2
m	0.50	0.50	0.50	0.50	1.50	2.50	3.50

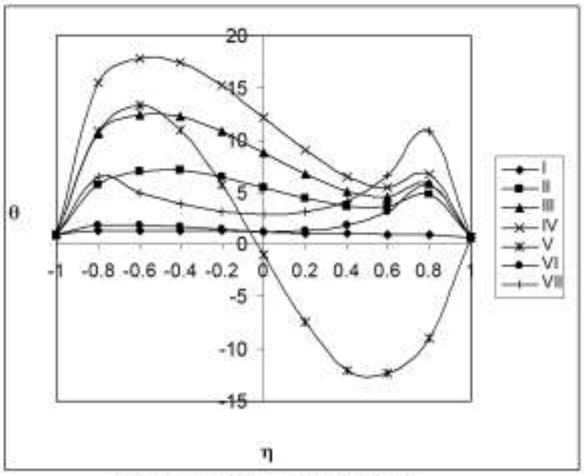


Fig. 10 : Variation of θ with Q_1, K

	I	II	III	IV	V	VI	VII
Q_1	0.50	1.50	2.50	3.50	0.50	0.50	0.50
K	0.50	0.50	0.50	0.50	1.50	2.50	3.5

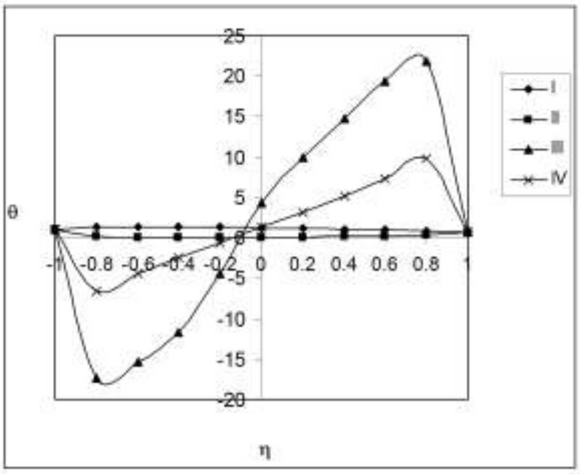


Fig. 11 : Variation of θ with λ

	I	II	III	IV
λ	π/4	π/2	π	2π

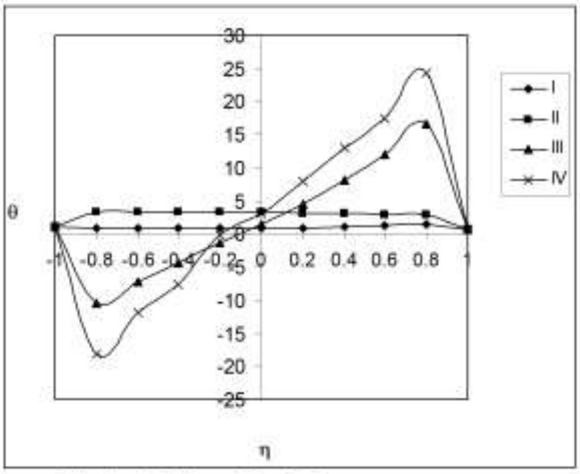


Fig. 12 : Variation of θ with β

	I	II	III	IV
β	-0.3	-0.5	-0.7	-0.9

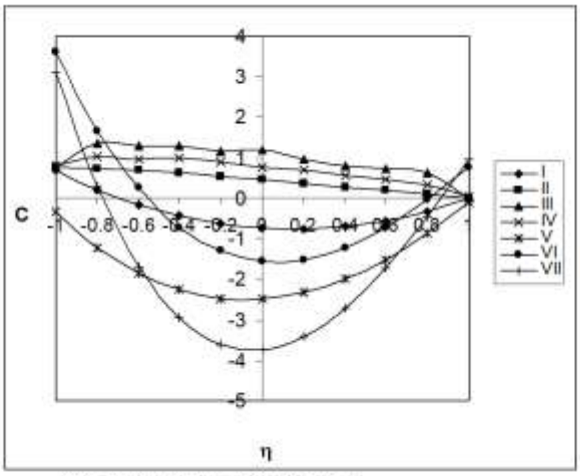


Fig. 13 : Variation of C with M, m

	I	II	III	IV	V	VI	VII
M	2	5	7	9	2	2	2
m	0.50	0.50	0.50	0.50	1.50	2.50	3.50

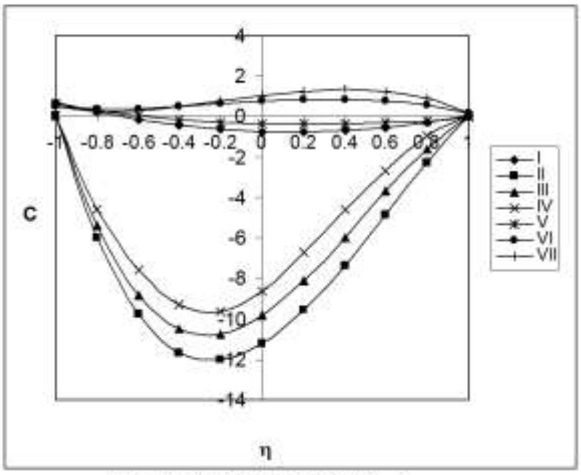


Fig. 14 : Variation of C with Q_1, K

	I	II	III	IV	V	VI	VII
Q_1	0.50	1.50	2.50	3.50	0.50	0.50	0.50
K	0.50	0.50	0.50	0.50	1.50	2.50	3.50

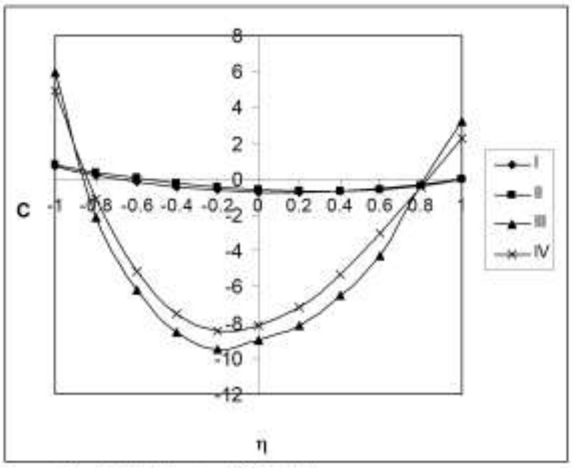


Fig. 15 : Variation of C with λ

	I	II	II	III
λ	π/4	π/2	π	2π

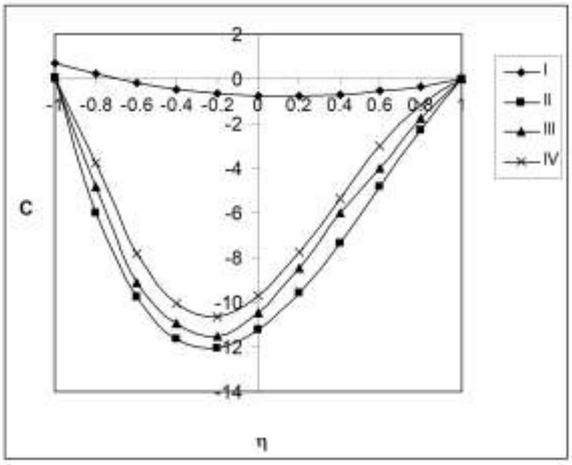


Fig. 16 : Variation of C with β

	I	II	III	IV
β	-0.3	-0.5	-0.7	-0.9

The non-dimensional concentration (C) is shown in figures 13-16 for different parametric values. We follow the convention that the non-dimensional concentration is positive or negative according as the actual concentration is greater or lesser than C_2. Fig.13 represents C with M and m. It is found that the actual concentration enhances with $M \leq 5$ and depreciates with $M \geq 10$. The actual concentration depreciates with smaller and higher values of m and for moderate values of m = 2.5, the concentration enhances in the flow region. Fig-14 represent C wit k and Q_1. It is found that the actual concentration enhances with $Q_1 \geq 2.5$. Fig.15 represents C with inclination λ of the magnetic field. It is found that the actual concentration enhances with $\lambda \leq \pi/2$and depreciates with $\lambda \geq \pi$. Fig.16 represents C with β. It is found that higher the constriction of the channel walls larger the actual concentration and for further higher constriction $|\beta| \geq 0.7$,we notice a depreciation in it.

The average Nusselt number (Nu) is exhibited in tables. 1-6 for different values of G, ,M, m, β, k, Q_1 . The variation of Nu with Hartmann number M shows that higher the Lorentz force smaller |Nu| and for further higher Lorentz force ($M \geq 10$) larger |Nu| at both the walls. An increase in m<1.5 reduces |Nu| and enhances with higher $m \geq 2.5$ at $\eta = \pm 1$. The variation of θ with β shows that higher the constriction of the channel walls larger |Nu| for G>0 and for higher $|\beta| \geq 0.7$ larger |Nu| in the heating case and smaller |Nu| in the cooling case at $\eta = 1$ and at $\eta = -1$, larger |Nu| for all G (tables. 1&3). An increase in the chemical reaction parameter $k \leq 1.5$ enhances |Nu| at $\eta = -1$ and reduces at $\eta = -1$ and for higher $k \geq 2.5$ it reduces at $\eta = +1$ and enhances at $\eta = -1$. An increase in the radiation absorption parameter Q_1 enhances |Nu| at $\eta = 1$ and at $\eta = -1$, |Nu| enhances with $Q_1 \leq 1.5$ and reduces with $Q_1 \geq 2.5$ (tables. 2&4).

Table 1

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

G	I	II	III	IV	V	VI	VII	VIII
10^2	-48.85744	-16.18368	-193.36560	-14.56674	-87.77473	8.40258	4.43797	-64.30024
$3x10^2$	-193.35780	-13.00918	-192.46040	-108.32930	-655.65470	-182.78910	3.96728	-361.03100
-10^2	84.18954	-19.35514	-195.27080	-1.09368	-39.13083	-74.08566	7.60493	5.89893
$-3x10^2$	205.78320	-22.52357	-196.67590	-68.41004	-509.72290	-430.25380	13.46812	-150.43350
M	2	5	10	2	2	2	2	2
m	0.5	0.5	0.5	1.5	2.5	3.5	0.5	0.5
β	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.7

Table 2
Average Nusselt number (Nu) at η = +1

G	I	II	III	IV	V	VI
10^2	-82.04272	-783.65770	-163.79100	-252.44410	-422.84540	-593.2468
$3x10^2$	-227.87220	-951.02950	-508.06370	-685.92480	-	-
-10^2	55.68642	-627.00200	129.89140	172.93620	290.18600	407.43580
$-3x10^2$	55.68642	-627.00200	129.89140	172.93620	290.18600	407.43580
k	0.5	1.5	2.5	0.5	0.5	0.5
Q_1	0.5	0.5	0.5	1.5	2.5	3.5

Table 3
Average Nusselt number (Nu) at η = -1

G	I	II	III	IV	V	VI	VII	VIII
10^2	-82.04272	15.20658	138.72830	-20.12613	54.97598	40.17641	-53.46166	-20.90696
$3x10^2$	-227.87220	17.80350	138.28590	-102.70590	-111.12320	-25.38758	-9.87950	-186.54640
-10^2	55.68642	12.61182	139.17070	5.31532	-146.15430	-87.81957	0.86312	-15.48188
$-3x10^2$	185.31520	10.01921	139.61320	-26.38150	-714.51390	-409.37550	9.09483	-170.27110
M	2	5	10	2	2	2	2	2
m	0.5	0.5	0.5	1.5	2.5	3.5	0.5	0.5
β	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.7

Table 4
Average Nusselt number (Nu) at η = -1

G	I	II	III	IV	V	VI
10^2	-82.04272	-25.93782	-43.85055	-130.81710	-5.46166	-20.90696
$3x10^2$	-227.87220	-63.36485	-109.76490	-385.76730	-9.87950	-186.54640
-10^2	55.68642	8.97174	19.17013	107.688890	0.86312	-15.48188
$-3x10^2$	185.31520	41.51382	79.29713	329.75060	9.09483	-170.27110
K	0.5	1.5	2.5	0.5	0.5	0.5
Q_1	0.5	0.5	0.5	1.5	2.5	3.5

The rate of mass transfer (Sherwood number)(Sh) at η = ±1 is shown in tables.5-8 for different variations. With respect to M,we find that the rate of mass transfer at η = 1 reduces with M≤5 and enhances with M≥10 and at η = -1, it enhances with M for all G. An increase in m≤1.5 reduces |Sh| at η = ±1 and enhances with higher m≥2.5. The variation of Sh with Sc shows that lesser the molecular diffusivity larger |Sh| at η = 1 and at η = -1 larger |Sh| and for further lowering of the diffusivity smaller |Sh|. Higher the of constriction of the channel walls larger |Sh| at η = 1. At η = -1, for |β| ≤ 0.5, larger |Sh| for G>0 and smaller |Sh| for G<0 and for still higher |β| ≥ 0.7, larger |Sh| for all G (tables.5&7). The variation of |Sh| with chemical reaction parameter k shows that |Sh| at η = 1 reduces with k≤1.5 and enhances with higher k≥2.5 while at η = -1, |Sh| depreciates for all G (tables. 6&8).

Table 5
Sherwood number (Sh) at η = +1

G	I	II	III	IV	V	VI	VII	VIII
10^2	-40.53192	-0.15278	-0.61242	-25.96120	26.85554	18.73391	-20.74987	-836.77510
$3x10^2$	-111.45770	-0.14498	-0.81747	-71.84126	93.75404	67.95721	-49.74468	-
-10^2	29.66318	-0.12312	48.24527	17.89869	-33.35181	-29.03828	8.38515	642.55190
$-3x10^2$	99.05874	-0.13675	-1.44310	59.59518	-88.01270	-75.64496	37.16119	1776.96600
M	2	5	10	2	2	2	2	2
m	0.5	0.5	0.5	1.5	2.5	3.5	0.5	0.5
β	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.7

Table 6
Sherwood number (Sh) at η = +1

G	I	II	III	IV	V	VI
10^2	-40.53192	0.00365	-35.42921	-40.53192	-40.53192	-40.53192
$3x10^2$	-111.45770	0.01185	-92.38190	-111.45770	-111.45770	-111.45770
-10^2	29.66318	-0.00394	23.82767	29.66318	29.66318	29.66318
$-3x10^2$	99.05874	-0.01213	94.04135	99.05874	99.05874	99.05874
k	0.5	1.5	2.5	0.5	0.5	0.5
Q_1	0.5	0.5	0.5	1.5	2.5	3.5

Table 7
Sherwood number (Sh) at η = -1

G	I	II	III	IV	V	VI	VII	VIII
10^2	-27.13410	23.62002	23.76799	-3.53385	21.05400	16.08531	-21.66488	-831.3570
$3x10^2$	-97.99581	23.35629	22.48002	-48.87457	87.56889	65.22829	-50.7448	-
-10^2	42.95737	22.85341	20.43503	39.71637	-38.97121	-31.76408	7.22442	646.14940
$-3x10^2$	112.29040	23.10046	21.38219	80.92419	-93.31511	-78.29342	36.08311	1779.893
M	2	5	10	2	2	2	2	2
m	0.5	0.5	0.5	1.5	2.5	3.5	0.5	0.5
β	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.7

Table 8
Sherwood number (Sh) at η = -1

G	I	II	III	IV	V	VI
10^2	-27.13410	0.96344	-473.2986	-27.13410	-27.13410	-27.13410
$3x10^2$	-97.99581	-69.94053	0.97137	-97.99581	-97.99581	-97.99581
-10^2	42.95737	35.70866	0.95477	42.95737	42.95737	42.95737
$-3x10^2$	112.29040	0.94684	-329.2973	112.29040	112.29040	112.29040
k	0.5	1.5	2.5	0.5	0.5	0.5
Q_1	0.5	0.5	0.5	1.5	2.5	3.5

VII. CONCLUSION

The effect of chemical reaction, radiation absorption and wall wavyness on mixed convective heat and mass transfer flow is analysed by employing perturbation technique. The velocity temperature and concentration and rate of heat and mass transfer are discussed for different variations k, Q_1, and β. The important conclusions of this analysis are

1. The axial velocity (w) exhibits the reversal flow for m≥2.5 and region of reversal flow reduces with increase in m. |w| enhances with increase in m≤2.5 and reduces with m>2.5. Higher the constriction of the channel walls lesser |w| in the flow region and for further higher constriction larger |w|. Higher the chemical reaction parameter k larger |w|. An increase in Q_1 results in an enhancement in |w|.
2) The secondary velocity (u) which arises due to the non-uniform boundary temperature enhances with m≤1.5 and for higher m = 2.5, |u| enhances in the left half and reduces in the right half and for still higher m = 3.5,we notice a depreciation in |u| in the entire flow region. Higher chemical reaction parameter k larger |u|. An increase in $Q_1 \leq 1.5$ enhances |u| and for higher $Q_1 \geq 2.5$, we notice a depreciation in |u|. Higher the constriction of channel walls smaller |u| in the flow region and for further higher constriction larger |u| in the flow region.
3) The actual temperature enhances with m≤1.5 and reduces with m≥2.5 and for still higher m = 3.5 we notice an enhancement in the actual temperature. The actual temperature enhances in the left half and reduces in the right half with smaller and higher values of the chemical reaction parameter k and for intermediate values of k(=2.5) the actual temperature reduces in the left half and enhances in the right half. An increase in the radiation absorption parameter Q_1 enhances the actual temperature. Higher the constriction of the channel walls larger the actual temperature and for higher |β| ≥ 0.7 the actual temperature reduces in left half and enhances in the right half.
4) The actual concentration depreciates with smaller and higher values of m and for moderate values of m=2.5, the concentration enhances in the flow region. The actual concentration enhances with Q_1≥2.5. Higher the

constriction of the channel walls larger the actual concentration and for further higher constriction $|\beta|\geq 0.7$,we notice a depreciation in it.

5) An increase in m<1.5 reduces |Nu| and enhances with higher $m\geq 2.5$ at $\eta = \pm 1$. Higher the constriction of the channel walls larger |Nu| for G>0 and for higher $|\beta| \geq 0.7$ larger |Nu| in the heating case and smaller |Nu| in the cooling case at $\eta = 1$ and at $\eta = -1$, larger |Nu| for all G. An increase in the chemical reaction parameter $k\leq 1.5$ enhances |Nu| at $\eta = -1$ and reduces at $\eta = -1$ and for higher $k\geq 2.5$ it reduces at $\eta = +1$ and enhances at $\eta = -1$. An increase in the radiation absorption parameter Q_1 enhances |Nu| at $\eta = 1$ and at $\eta = -1$, |Nu| enhances with $Q_1\leq 1.5$ and reduces with $Q_1\geq 2.5$.
6) An increase in $m\leq 1.5$ reduces |Sh| at $\eta = \pm 1$ and enhances with higher $m\geq 2.5$. The variation of Sh with Sc shows that lesser the molecular diffusivity larger |Sh| at $\eta = 1$ and at $\eta = -1$ larger |Sh| and for further lowering of the diffusivity smaller |Sh|. Higher the of constriction of the channel walls larger |Sh| at $\eta = 1$. At $\eta = -1$, for $|\beta| \leq 0.5$, larger |Sh| for G>0 and smaller |Sh| for G<0 and for still higher $|\beta| \geq 0.7$, larger |Sh| for all G. The variation of |Sh| with chemical reaction parameter k shows that |Sh| at $\eta = 1$ reduces with $k\leq 1.5$ and enhances with higher $k\geq 2.5$ while at $\eta = -1$, |Sh| depreciates for all G.

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