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Effect of Hall Currents and Thermo-Diffusion on Unsteady Convective Heat and Mass Transfer Flow in a Vertical Wavy Channel under an Inclined Magnetic Field

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ABSTRACT
In this chapter we investigate the convective study of heat and mass transfer flow of a viscous electrically conducting fluid in a vertical wavy channel under the influence of an inclined magnetic fluid with heat generating sources. The walls of the channels are maintained at constant temperature and concentration. The equations governing the flow heat and concentration are solved by employing perturbation technique with a slope δ of the wavy wall. The velocity, temperature and concentration distributions are investigated for different values of G, R, D^{-1}, M, m, Sc, So, N, β, λ and x. The rate of heat and mass transfer are numerically evaluated for a different variations of the governing parameters
Keywords: Heat and mass Transfer, Hall Currents, Wavy Channel, Thermo-diffusion, Magnetic Field

I. INTRODUCTION

The flow of heat and mass from a wall embedded in a porous media is a subject of great interest in the research activity due to its practical applications; the geothermal processes, the petroleum industry, the spreading of pollutants, cavity wall insulations systems, flat-plate solar collectors, flat-plate condensers in refrigerators, grain storage containers, nuclear waste management.

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 [13] 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 Moleam [1] has studied the effect of temperature dependent heat source θ = 1/ a + bT such as occurring in the electrical heating on the steady state transfer within a porous medium. Chandrasekhar [2], Palm [3] 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 re-circulation pattern.

In recent years, energy and material saving considerations have prompted an expansion of the efforts at producing efficient heat exchanger equipment through augmentation of heat transfer. It has been established [4] that channels with diverging – converging geometries augment the transportation of heat transfer and momentum. As the fluid flows through a tortuous path viz., the dilated – constricted geometry, there will be more intimate contact between them. The flow takes place both axially (primary) and transversely (secondary) with the secondary velocity being towards the axis in the fluid bulk rather than confining within a thin layer as in straight channels. Hence it is advantageous to go for converging-diverging geometries for improving the design of heat transfer equipment. Vajravelu and Nayfeh [5] have investigated the influence of the wall waviness on friction and pressure drop of the generated coquette flow. Vajravelu and Sastry [6] have analyzed the free convection heat transfer in a viscous, incompressible fluid confined between long vertical wavy walls is the presence of constant heat source. Later Vajravelu and Debnath [7] have extended this study to convective flow is a vertical wavy channel in four different geometrical configurations. This problem has been extended to the case of wavy walls by McMicheal and Deutsch [8], Deshikachar et al [9] Rao *et. al.,* [10] and Sree Ramachandra Murthy [11]. Hyan Gook Won *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. Mahdy *et.*

al., [13] 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.,*[14] have analyzed the convective heat and mass transfer in wavy finned-tube exchangers. Jer-Huan Jang *et. al.,*[15] have analyzed that the mixed convection heat and mass transfer along a vertical wavy surface.

The study of heat and mass transfer from a vertical wavy wall embedded into a porous media became a subject of great interest in the research activity of the last two decades: Rees and Pop [16, 17] studied the free convection process along a vertical wavy channel embedded in a Darcy porous media, a wall that has a constant surface temperature [16] or a constant surface heat flux [17]. Kumar and Gupta [18] for a thermal and mass stratified porous medium and Cheng [19] for a power law fluid saturated porous medium with thermal and mass stratification. The influence of a variable heat flux on natural convection along a corrugated wall in a non-Darcy porous medium was established by Shalini and Kumar [20].Rajesh et al [21] have discussed the time dependent thermal convection of a viscous, electrically conducting fluid through a porous medium in horizontal channel bounded by wavy walls. Kumar [18] has discussed the two-dimensional heat transfer of a free convective MHD (Magneto Hydro Dynamics) flow with radiation and temperature dependent heat source of a viscous incompressible fluid, in a vertical wavy channel. Recently Mahdy et al [13] have presented the Non-similarity solutions have been presented for the natural convection from a vertical wavy plate embedded in a saturated porous medium in the presence of surface mass transfer.

In all these investigations, the effects of Hall currents are not considered. However, in a partially ionized gas, there occurs a Hall current [22] when the strength of the impressed magnetic field is very strong. These Hall effects play a significant role in determining the flow features. Sato [23], Yamanishi [24], Sherman and Sutton [25] have discussed the Hall effects on the steady hydro magnetic flow between two parallel plates. These effects in the unsteady cases were discussed by Pop [26]. Debnath [27] has studied the effects of Hall currents on unsteady hydro magnetic flow past a porous plate in a rotating fluid system and the structure of the steady and unsteady flow is investigated. Alam *et. al.,* [28] 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 Krishna *et. al.,*[29] have investigated Hall effects on the unsteady hydro magnetic boundary layer flow. Rao *et. al.,* [10] have analyzed Hall effects on unsteady Hydrpomagnetic flow. Siva Prasad *et. al.,* [30] have studied Hall effects on unsteady MHD free and forced convection flow in a porous rotating channel. Recently Seth *et. al.,* [31] have investigated the effects of Hall currents on heat transfer in a rotating MHD channel flow in arbitrary conducting walls. Sarkar *et. al.,* [32] 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. Anwar Beg et al. [33] have discussed unsteady magneto hydrodynamics Hartmann- Couette flow and heat transfer in a Darcian channel with Hall current ,ionslip, Viscous and Joule heating effects .Ahmed [34] has discussed the Hall effects on transient flow pas an impulsively started infinite horizontal porous plate in a rotating system. Shanti [35] has investigated effect of Hall current on mixed convective heat and mass transfer flow in a vertical wavy channel with heat sources. Leela [36] has studied the effect of Hall currents on the convective heat and mass transfer flow in a horizontal wavy channel under inclined magnetic field.

In this chapter we investigate the convective study of heat and mass transfer flow of a viscous electrically conducting fluid in a vertical wavy channel under the influence of an inclined magnetic fluid with heat generating sources. The walls of the channels are maintained at constant temperature and concentration. The equations governing the flow heat and concentration are solved by employing perturbation technique with a slope δ of the wavy wall. The velocity, temperature and concentration distributions are investigated for different values of G, R, D^{-1}, M, m, Sc, So, N, β, λ and x. The rate of heat and mass transfer are numerically evaluated for different variations of the governing parameters.

II. FORMULATION AND SOLUTION OF THE PROBLEM

We consider the steady flow of an incompressible, viscous ,electrically conducting fluid through a porous medium 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 (y-z).The magnetic field is inclined at an angle $\alpha 1$ to the axial direction k and hence its components are $(0, H_0 Sin(\alpha_1), H_0 Cos(\alpha_1))$ .In view of the waviness of the wall 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 $x = \pm Lf(\frac{\delta z}{L})$.

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

$$\overline{J} + \omega_e \tau_e \overline{J} x \overline{H} = \sigma(\overline{E} + \mu_e \overline{q} x \overline{H}) \tag{2.1}$$

where q is the velocity vector. H is the magnetic field intensity vector. 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 (2.6) reduces

$$j_x - mH_0J_zSin(\alpha_1) = -\sigma\mu_eH_0wSin(\alpha_1) \quad (2.2)$$

$$J_z + mH_0J_xSin(\alpha_1) = \sigma\mu_eH_0u\,Sin(\alpha_1) \quad (2.3)$$

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

On solving equations (2.2)&(2.3) we obtain

$$j_x = \frac{\sigma\mu_eH_0Sin(\alpha_1)}{1+m^2H_0^2Sin^2(\alpha_1)}(mH_0Sin(\alpha_1) - w) \quad (2.4)$$

$$j_z = \frac{\sigma\mu_eH_0Sin(\alpha_1)}{1+m^2H_0^2Sin^2(\alpha_1)}(u + mH_0w\,Sin(\alpha_1)) \quad (2.5)$$

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

The Momentum equations are

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}) + \mu_e(-H_0J_zSin(\alpha)) - (\frac{\mu}{k})u \quad (2.6)$$

$$u\frac{\partial W}{\partial x} + w\frac{\partial W}{\partial z} = -\frac{\partial p}{\partial z} + \mu(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial z^2}) + \mu_e(H_0J_xSin(\alpha_1)) - (\frac{\mu}{k})W \quad (2.7)$$

Substituting J_x and J_z from equations (2.4)&(2.5)in equations (2.6)&(2.7) we obtain

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}) + -\frac{\sigma\mu_eH_{00}^2Sin^2(\alpha_1)}{1+m^2H_0^2Sin^2(\alpha_1)}(u + mH_0wSin(\alpha_1)) - (\frac{\mu}{k})u \quad (2.8)$$

$$u\frac{\partial W}{\partial x} + w\frac{\partial W}{\partial z} = -\frac{\partial p}{\partial z} + \mu(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial z^2}) - -\frac{\sigma\mu_eH_0^2Sin^2(\alpha_1)}{1+m^2H_0^2Sin^2(\alpha_1)}(w - mH_0uSin(\alpha_1)) - (\frac{\mu}{k})W - \rho g \quad (2.9)$$

The energy equation is

$$\rho C_p(u\frac{\partial T}{\partial x} + w\frac{\partial T}{\partial z} = k_f(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}) + Q(T_e - T) \quad (2.10)$$

The diffusion equation is

$$(u\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} = D_1(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}) + k_{11}(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}) \quad (2.11)$$

The equation of state is

$$\rho - \rho_0 = -\beta_T(T - T_o) - \beta_C(C - C_o) \quad (2.12)$$

Where T, C are the temperature and concentration in the fluid. k_f is the thermal conductivity, Cp is the specific heat constant pressure,D_1 is molecular diffusivity,k_{11} is the cross diffusivity, β_T is the coefficient of thermal expansion, β_C is the coefficient of volume expansion and Q is the strength of the heat source.

The flow is maintained by a constant volume flux for which a characteristic velocity is defined as

$$q = \frac{1}{L}\int_{-Lf}^{Lf} wdx \quad (2.13)$$

The boundary conditions are

u= 0 , w=0 T=T1 ,C=C_1 on $x = -Lf(\frac{\delta z}{L})$ (2.14a)

w=0, w=0, T=T_2 ,C=C_2 on $x = Lf(\frac{\delta z}{L})$ (2.14b)

Eliminating the pressure from equations(2.8)&(2.9) and introducing the Stokes Stream function ψ as

$$u = -\frac{\partial\psi}{\partial z} \quad , \quad w = \frac{\partial\psi}{\partial x} \quad (2.15)$$

the equations (2.8)&(2.9) ,(2.15)&(2.11) in terms of ψ is

$$\frac{\partial\psi}{\partial z}\frac{\partial(\nabla^2\psi)}{\partial x} - \frac{\partial\psi}{\partial x}\frac{\partial(\nabla^2\psi)}{\partial z} = \mu\nabla^4\psi + \beta_T g\frac{\partial(T - T_e)}{\partial x}\beta_C g\frac{\partial(C - C_e)}{\partial x} - -(\frac{\sigma\mu_e^2H_0^2Sin^2(\alpha_1)}{1+m^2H_0^2\,Sin^2(\alpha_1)} + \frac{\mu}{k})\nabla^2\psi \quad (2.16)$$

$$\rho C_p(\frac{\partial\psi}{\partial x}\frac{\partial T}{\partial z} - \frac{\partial\psi}{\partial z}\frac{\partial T}{\partial x} = k_f(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}) + Q(T_e - T) \quad (2.17)$$

$$(\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial z} - \frac{\partial\psi}{\partial z}\frac{\partial C}{\partial x} = D_1(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}) + k_{11}(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}) \quad (2.18)$$

On introducing the following non-dimensional variables

$$(x', z') = (x, z)/L,$$

$$\psi' = \frac{\psi}{qL},\ \theta = \frac{T - T_2}{T_1 - T_2},\ C' = \frac{C - C_2}{C_1 - C_2}$$

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

$$\nabla^4\psi - M_1^2\nabla^2\psi + \frac{G}{R}(\frac{\partial\theta}{\partial x} + N\frac{\partial C}{\partial x}) = R(\frac{\partial\psi}{\partial z}\frac{\partial(\nabla^2\psi)}{\partial x} - \frac{\partial\psi}{\partial x}\frac{\partial(\nabla^2\psi)}{\partial z}) \quad (2.19)$$

$$PR(\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial\theta}{\partial x})=\nabla^2\theta-\alpha\,\theta \qquad (2.20)$$

$$ScR(\frac{\partial\psi}{\partial x}\frac{\partial C}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial C}{\partial x})=\nabla^2 C+\frac{ScSo}{N}\nabla^2\theta \qquad (2.21)$$

where

$G=\frac{\beta_T g\,\Delta T_e L^3}{\nu^2}$ (Grashof Number)

$M^2=\frac{\sigma\mu_e^2 H_o^2 L^2}{\nu^2}$ (Hartman 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)

$\alpha=\frac{QL^2}{\Delta TK_f}$ (Heat Source Parameter)

$Sc=\frac{\nu}{D_1}$ (Schmidt Number) $S_o=\frac{k_{11}\beta_C}{\nu\beta_T}$ (Soret parameter)

$N=\frac{\beta_C(C_1-C_2)}{\beta_T(T_1-T_2)}$ (Buoyancy ratio)

The corresponding boundary conditions are

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

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

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

III. ANALYSIS OF THE FLOW

Introduce the transformation such that

$$\bar{z}=\delta z,\frac{\partial}{\partial z}=\delta\frac{\partial}{\partial\bar{z}}$$

Then

$$\frac{\partial}{\partial z}\approx O(\delta)\rightarrow\frac{\partial}{\partial\bar{z}}\approx O(1)$$

For small values of δ <<1,the flow develops slowly with axial gradient of order δ and hence we take $\frac{\partial}{\partial\bar{z}}\approx O(1)$.

Using the above transformation the equations (2.23)-(2.25) reduce to

$$F^4\psi-M_1^2F^2\psi+\frac{G}{R}(\frac{\partial\theta}{\partial x}+N\frac{\partial C}{\partial x})=\delta R(\frac{\partial\psi}{\partial\bar{z}}\frac{\partial(F^2\psi)}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial(F^2\psi)}{\partial\bar{z}}) \qquad (3.1)$$

$$\delta PR(\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial\theta}{\partial x})=F^2\theta-\alpha_1\theta \qquad (3.2)$$

$$\delta ScR(\frac{\partial\psi}{\partial x}\frac{\partial c}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial C}{\partial x})=F^2C+\frac{ScSo}{N}F^2\theta \qquad (3.3)$$

where

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

Assuming the slope δ of the wavy boundary to be small we take

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

$$\theta(x,z)=\theta_o(x,z)+\delta\theta_1(x,z)+\delta^2\theta_2(x,z)+..........$$

$$C(x,z)=C_o(x,z)+\delta c_1(x,z)+\delta^2 c_2(x,z)+......... \qquad (3.4)$$

Let $\eta=\frac{x}{f(\bar{z})}$ (3.5)

Substituting (3.3) in equations (3.1)&(3.2) and using (3.4) and equating the like powers of δ the equations and the respective boundary conditions to the zeroth order are

$$\frac{\partial^2\theta_0}{\partial\eta^2}-(\alpha_1 f^2)\theta_0=0 \qquad (3.6)$$

$$\frac{\partial^2 C_0}{\partial\eta^2}=-\frac{\text{Sc So}}{\text{N}}\frac{\partial^2\theta_0}{\partial\eta^2} \qquad (3.7)$$

$$\frac{\partial^4\psi_0}{\partial\eta^4}-(M_1^2 f^2)\frac{\partial^2\psi_0}{\partial\eta^2}=-\frac{Gf^3}{R}(\frac{\partial\theta_0}{\partial\eta}+N\frac{\partial C_0}{\partial\eta}) \qquad (3.8)$$

with

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

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

$$\frac{\partial\psi_0}{\partial\eta}=0,\ \frac{\partial\psi_0}{\partial\bar{z}}=0,\quad \theta_0=0\ ,\ C_0=0 \quad at\quad \eta=+1 \qquad (3.9)$$

and to the first order are

$$\frac{\partial^2\theta_1}{\partial\eta^2}-(\alpha_1 f^2)\theta_1 = P_1 Rf\,(\frac{\partial\psi_0}{\partial\eta}\frac{\partial\theta_0}{\partial\overline{z}}-\frac{\partial\psi_0}{\partial\overline{z}}\frac{\partial\theta_0}{\partial\eta}) \tag{3.10}$$

$$\frac{\partial^2 C_1}{\partial\eta^2}=ScRf\,(\frac{\partial\psi_0}{\partial\eta}\frac{\partial C_0}{\partial\overline{z}}-\frac{\partial\psi_0}{\partial\overline{z}}\frac{\partial C_0}{\partial\eta})-\frac{Sc\,So}{N}\frac{\partial^2\theta_1}{\partial\eta^2} \tag{3.11}$$

$$\frac{\partial^4\psi_1}{\partial\eta^4}-(M_1^2 f^2)\frac{\partial^2\psi_1}{\partial\eta^2}=-\frac{Gf^3}{R}(\frac{\partial\theta_1}{\partial\eta}+N\frac{\partial C_1}{\partial\eta})+ Rf\,(\frac{\partial\psi_0}{\partial\eta}\frac{\partial^3\psi_0}{\partial z^3}-\frac{\partial\psi_0}{\partial\overline{z}}\frac{\partial^3\psi_0}{\partial x\partial z^2}) \tag{3.12}$$

with

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

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

$$\frac{\partial\psi_1}{\partial\eta}=0,\ \frac{\partial\psi_1}{\partial\overline{z}}=0,\quad \theta_1=0\,.C_1=0\quad at\quad \eta=+1 \tag{3.13}$$

IV. SOLUTIONS OF THE PROBLEM

Solving the equations (3.5) & (3.6) subject to the boundary conditions (3.7).we obtain

$$\theta_{0_0}=0.5(\frac{Ch(h\eta)}{Ch(h)}-\frac{Sh(h\eta)}{Sh(h)})$$

$$C_0=0.5(1-\eta)+\frac{a_1}{h^2}(Sh(h\eta)-\eta Sh(h))-\frac{a_2}{h^2}(Ch(h\eta)-Ch(h))$$

$$\psi_0=a_{11}Cosh(\beta_1\eta)+a_{12}Sinh(\beta_1\eta)+a_{15}\eta+a_{14}+\phi_1(\eta)$$

$$\phi_1(\eta)=a_8\eta^2-a_9Sh(h\eta)-a_{10}Ch(h\eta)+2a_8\eta-a_9hCh(h\eta)-a_{10}hSh(h\eta)$$

Similarly the solutions to the first order are

$$\theta_1=a_{34}Ch(h\eta)+a_{35}Sh(h\eta)+\phi_2(\eta)$$

$$\begin{aligned}\phi_2(\eta)=&\,a_{14}+a_{15}\eta+(a_{16}+a_{18}\eta+a_{25}\eta^2)Ch(h\eta)+(a_{17}+a_{19}\eta+\\&+a_{24}\eta^2)Sh(h\eta)+(a_{20}+a_{22}\eta)Ch(2h\eta)+(a_{21}+a_{23}\eta)Sh(2h\eta)\\&+a_{26}\eta Sh(\beta_2\eta)+a_{27}\eta Sh(\beta_3\eta)+a_{28}\eta Ch(\beta_2\eta)+a_{29}\eta Ch(\beta_3\eta)\\&+a_{30}Ch(\beta_2\eta)+a_{31}Ch(\beta_3\eta)+a_{32}Sh(\beta_2\eta)+a_{33}Sh(\beta_3\eta)\end{aligned}$$

$$\begin{aligned}C_1=&\,a_{36}(\eta^2-1)+a_{37}(\eta^3Sh(\beta_1\eta)-Sh(\beta_1))+a_{38}\eta(Ch(\beta_1\eta)-Ch(\beta_1))+\\&+(a_{39}+a_{53})(\eta Sh(\beta_1\eta)-Sh(\beta_1))+(a_{40}+a_{52}+a_{50})\eta(Ch(\beta_1\eta)-Ch(\beta_1))\\&+(a_{41}+a_{60}+\eta(a_{64}-a_{47}))\eta(Ch(\beta_1\eta)-Ch(\beta_1))+(a_{62}-a_{41}+\eta(a_{66}+a_{47}))x\\&x(Ch(\beta_3\eta)-Ch(\beta_3))+(a_{49}+a_{61})(Sh(\beta_2\eta)-\eta Sh(\beta_2))+(a_{63}+a_{49})(Sh(\beta_3\eta)\\&-\eta Sh(\beta_3))+(a_{42}+a_{56}+\eta(a_{45}+a_{58}))(Ch(2h\eta)-Ch(2h))+(a_{57}+\eta a_{59})(Sh(2h\eta)\\&-\eta Sh(2h))+a_{51}(Sh(h\eta)-\eta Sh(h))+a_{54}(\eta^2Ch(h\eta)-Ch(h))+a_{55}\eta(\eta sh(h\eta)-\\&-Sh(h))+(a_{65}+a_{46})(\eta Sh(\beta_2\eta)-Sh(\beta_2))+(a_{67}+a_{40})((\eta Sh(\beta_3\eta)-Sh(\beta_3))+\\&+a_{48}((\eta Sh(2\beta_1\eta)-Sh(2\beta_1))\end{aligned}$$

$$\psi_1 = b_{49}Cosh(\beta_1\eta) + b_{50}Sinh(\beta_1\eta) + b_{51}\eta + b_{52} + \phi_2(\eta)$$

$$\phi_2(\eta) = b_{21} + b_{22}\eta + b_{23}\eta^2 + b_{24}\eta^3 + b_{25}\eta^4 + b_{26}\eta^5 + b_{27}\eta^6 + b_{28}\eta^7 + (b_{29} + b_{30}\eta + b_{31}\eta^2 + b_{32}\eta^3 + b_{33}\eta^4 + b_{34}\eta^5 + b_{35}\eta^6)Cosh(\beta_1\eta) + (b_{36} + b_{37}\eta + b_{38}\eta^2 + b_{39}\eta^3 + b_{40}\eta^4 + b_{41}\eta^5 + b_{42}\eta^6)Sinh(\beta_1\eta) + b_{43}Cosh(2\beta_1\eta) + b_{44}Sinh(2\beta_1\eta)$$

where $a_1, a_2, \ldots\ldots\ldots\ldots, a_{90}, b_1, b_2, \ldots\ldots\ldots\ldots, b_{51}$ are constants .

V. NUSSELT NUMBER AND SHERWOOD NUMBER

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

$$Nu = \frac{1}{f(\theta_m - \theta_w)}\left(\frac{\partial\theta}{\partial\eta}\right)_{\eta=\pm1}$$

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

$$(Nu)_{\eta=+1} = \frac{1}{f\theta_m}(a_{78} + \delta(a_{76} + a_{77}))), (Nu)_{\eta=-1} = \frac{1}{f(\theta_m - 1)}(a_{79} + \delta(a_{77} - a_{76})))$$

Where $\theta_m = a_{80} + \delta a_{81}$

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

$$Sh = \frac{1}{f(C_m - C_w)}\left(\frac{\partial C}{\partial\eta}\right)_{\eta=\pm1} \text{ where } C_m = 0.5\int_{-1}^{1} C\, d\eta$$

$$(Sh)_{\eta=+1} = \frac{1}{fC_m}(a_{74} + \delta a_{70}), (Sh)_{\eta=-1} = \frac{1}{f(C_m - 1)}(a_{75} + \delta a_{71})$$

where $C_m = a_{73} + \delta a_{72}$

VI. RESULTS AND DISCUSSION OF THE NUMERICAL RESULTS

In this analysis we investigate the effect of Hall currents on the free convective heat and mass transfer flow of a viscous electrically conducting fluid in a vertical wavy channel under the influence of an inclined magnetic field. The governing equations are solved by employing a regular perturbation technique with slope δ of the wave walls as a parameter. The analysis has been carried out with Prandtl number $P = 0.71$.

The axial velocity (w) is shown in figs.1-6 for different values of G, R, D^{-1}, M, m, Sc, So, N, β, λ and x. The variation of w with Darcy parameter D^{-1} shows that lesser the permeability of the porous medium larger $|w|$ in the flow region. Also higher the Lorentz force smaller $|w|$ in the flow region. An increase in Hall parameter $m \le 1.5$ enhances $|w|$ and for further higher values of $m \ge 2.5$ we notice a depreciation in the axial velocity (fig.1). Fig.2 represents the variation of w with Schmidt Number (Sc) and Soret parameter (So). It is found that lesser the molecular diffusivity larger $|w|$ and for further lowering of diffusivity smaller $|w|$ in the flow region. An increase in $|S_O|$ enhances w in the entire flow region. The variation of w with buoyancy ratio N shows that when the molecular buoyancy force dominates over the thermal buoyancy force the axial velocity enhances when the buoyancy forces are in the same direction and for the forces acting in opposite directions it depreciates in the flow region. The variation of w with β shows that higher the dilation of the channel walls lesser w in the flow region (fig.3). The effect of inclination of the magnetic field is shown in fig.4. It is found that higher the inclination of the magnetic field larger the velocity w in the flow region. Moving along the axial direction of the channel the velocity depreciates with $x \le \pi$ and enhances with higher $x \ge 2\pi$.

The secondary velocity (u) is shown in figs5-8 for different parametric values. The variation of u with Darcy parameter D^{-1} and Hartman number M shows that lesser the permeability of porous medium / higher the Lorentz force lesser $|u|$ in the flow region. An increase in Hall parameter m leads to an enhancement in $|u|$ everywhere in the flow region (fig.5). The variation of u with Schmidt Number (Sc) shows that lesser the molecular diffusivity larger $|u|$ and for still lowering of the diffusivity larger $|u|$. Also the magnitude of u enhances with increase in $S_O > 0$ and reduces with increase in $|S_O|$ (fig.6). When the molecular buoyancy force dominates over the thermal buoyancy force $|u|$ enhances when the buoyancy forces act in the same direction and for the forces acting in opposite directions it experiences a depreciation. The variation of u with β shows that higher the dilation of the channel walls lesser $|u|$ in the flow region (fig.7). The variation of u with λ shows that higher the inclination of the magnetic field smaller $|u|$ in the flow region. Moving along axial direction of the channel walls $|u|$ enhances with $x \le \pi$ and reduces with $x \ge 2\pi$ (fig.8).

The non dimensional temperature (θ) is shown in figs.9-13 for different parametric values. The variation of θ with D^{-1} shows that lesser the permeability of porous medium smaller the actual temperature and for further lowering of the permeability larger the temperature. Also higher the Lorentz force lesser the actual temperature and for higher Lorentz forces larger the actual temperature(fig.9). Also it depreciates with increase in Hall parameter $m \le 1.5$ and enhances with higher $m \ge 2.5$ (fig.10). The variation of θ with Schmidt Number (Sc) shows that lesser the molecular diffusivity smaller the actual temperature and for further lowering of diffusivity larger the temperature and for still lowering of the diffusivity larger θ in the flow region(fig.17). Also it reduces with increase in Sorret parameter $|S_O|$ (<0 >0) (fig.11). The variation of θ with β shows that higher the dilation of the channel walls larger the actual temperature in the flow region (fig.12). An increase in the inclination $\lambda \le 0.5$ we notice a depreciation in the actual temperature and for higher $\lambda \ge 1$ the actual temperature enhances in the flow region(fig.13).

The non-dimensional concentration (C) is shown in figs.14-17 for different parametric values. The variation of C with D^{-1} and M shows that lesser the permeability of porous medium / higher the Lorentz force results in an enhancement in the left half and depreciation in the actual concentration in the right half. The variation of C with Hall parameter m shows that an increase in $m \le 1.5$ reduces the actual concentration and for higher $m \ge 2.5$ the actual concentration depreciates in the left half and enhances in the right half (fig.14). Also the actual concentration enhances in the left half and reduces in the right half of the channel with increase in S_O (fig.15). When the molecular buoyancy force dominates over the thermal buoyancy force the actual concentration enhances in the left half and reduces in the right half when buoyancy forces act in the same direction and for the forces acting in opposite directions it reduces in the left half and enhances in the right half of the channel. Higher the dilation of the channel walls we notice an enhancement in the left half and depreciation in the right half (fig.16). An increase in the inclination of the magnetic field reduces the actual concentration in the right half and enhances in the left half. Moving along the axial direction the actual concentration enhances in the left half and depreciates in the right half (fig.17).

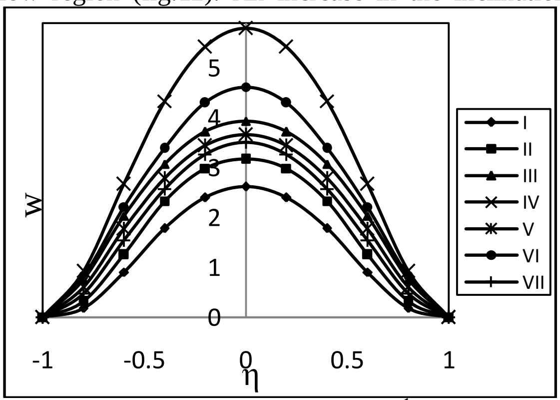

Fig.1. Variation of w with D^{-1},M and m

	I	II	III	IV	V	VI	VII
D	10^2	$2x10^2$	$3x10^2$	10^2	10^2	10^2	10^2
M	2	2	2	4	6	2	2
m	0.5	0.5	0.5	0.5	0.5	1.5	2.5

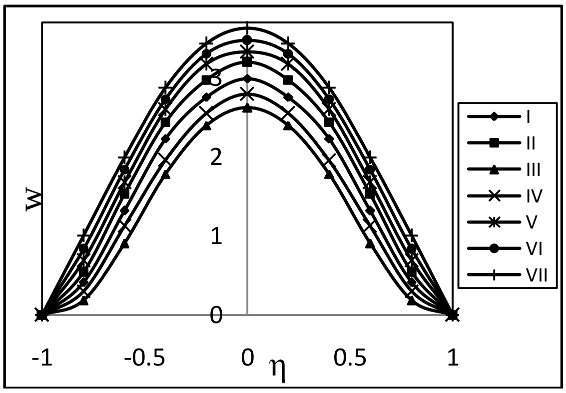

Fig.2. Variation of w with Sc and So

	I	II	III	IV	V	VI	VII
Sc	0.24	0.6	1.3	2.01	1.3	1.3	1.3
So	0.5	0.5	0.5	0.5	1	-0.5	-1

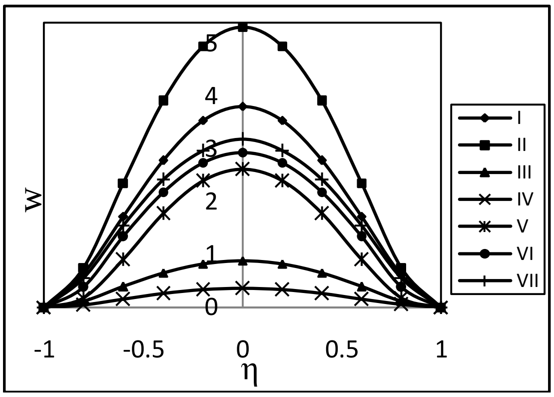

Fig.3. Variation of w with N and β

	I	II	III	IV	V	VI	VII
N	1	2	-0.5	-0.8	1	1	1
β	0.3	0.3	0.3	0.3	0.5	0.7	0.9

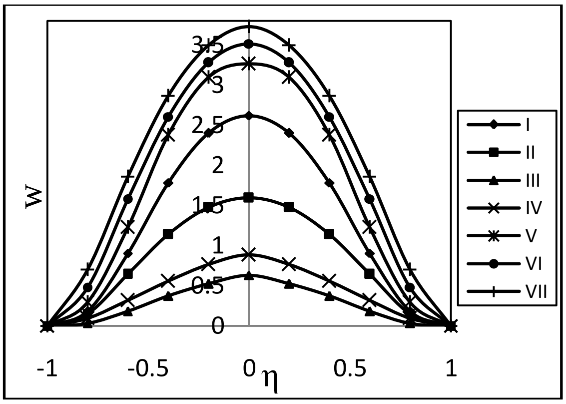

Fig.4. Variation of w with x and λ

	I	II	III	IV	V	VI	VII
x	$\frac{\pi}{4}$	$\frac{\pi}{2}$	π	2π	$\frac{\pi}{4}$	$\frac{\pi}{4}$	$\frac{\pi}{4}$
λ	0.5	0.5	0.5	0.5	0.25	0.75	1

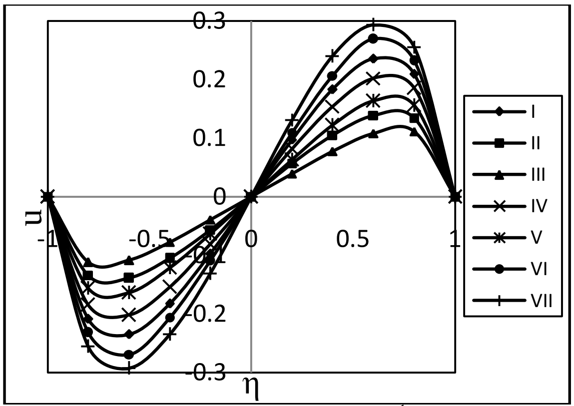

Fig.5. Variation of u with D^{-1}, M and m

	I	II	III	IV	V	VI	VII
D	10^2	$2x10^2$	$3x10^2$	10^2	10^2	10^2	10^2
M	2	2	2	4	6	2	2
m	0.5	0.5	0.5	0.5	0.5	1.5	2.5

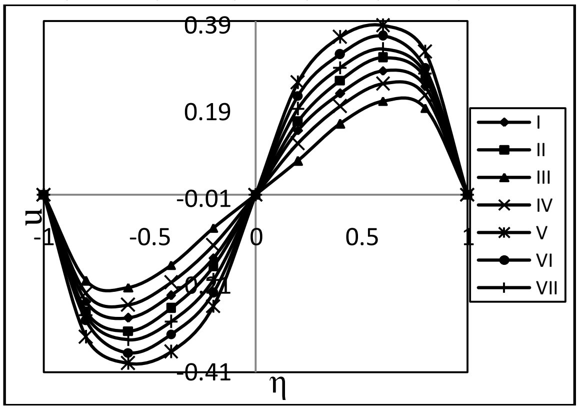

Fig.6. Variation of u with Sc and So

	I	II	III	IV	V	VI	VII
Sc	0.24	0.6	1.3	2.01	1.3	1.3	1.3
So	0.5	0.5	0.5	0.5	1	-0.5	-1

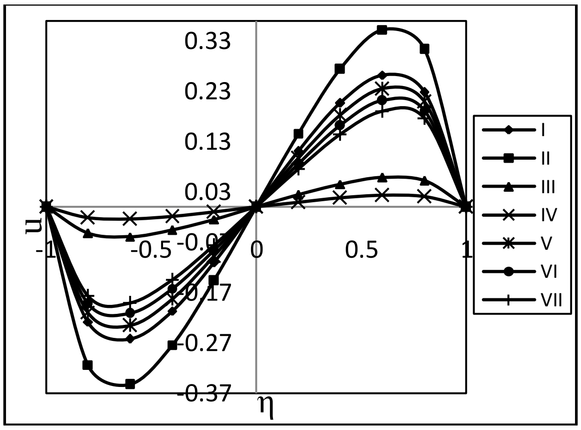

Fig.7. Variation of u with N and β

	I	II	III	IV	V	VI	VII
N	1	2	-0.5	-0.8	1	1	1
β	0.3	0.3	0.3	0.3	0.5	0.7	0.9

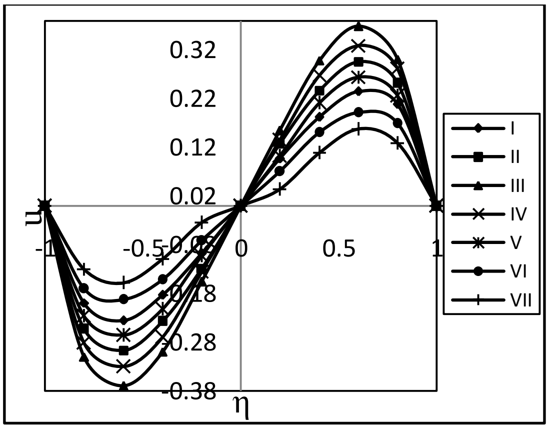

Fig.8. Variation of u with x and λ

	I	II	III	IV	V	VI	VII
x	$\frac{\pi}{4}$	$\frac{\pi}{2}$	π	2π	$\frac{\pi}{4}$	$\frac{\pi}{4}$	$\frac{\pi}{4}$
λ	0.5	0.5	0.5	0.5	0.25	0.75	1

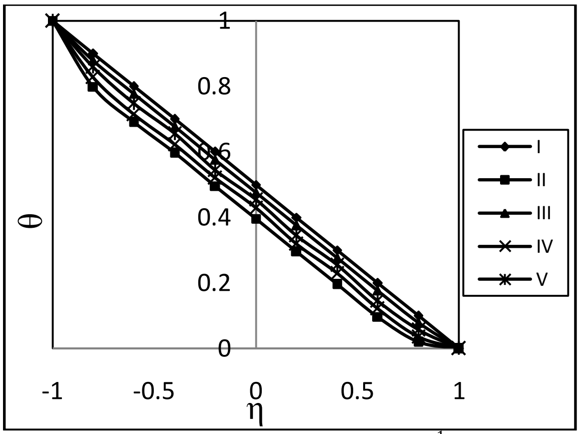

Fig.9. Variation of θ with D^{-1} and M

	I	II	III	IV	V
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2
M	2	2	2	4	6

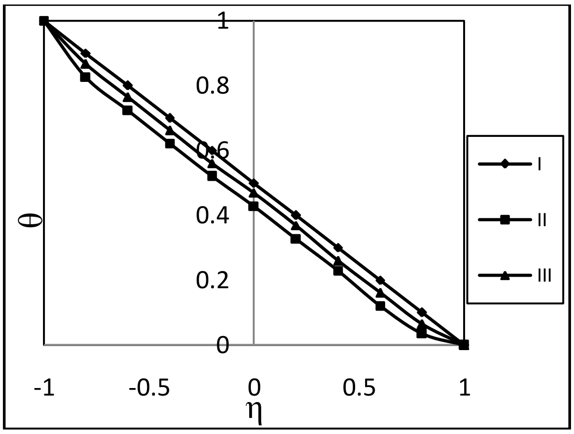

Fig.10. Variation of θ with m

	I	II	III
m	0.5	1.5	2.5

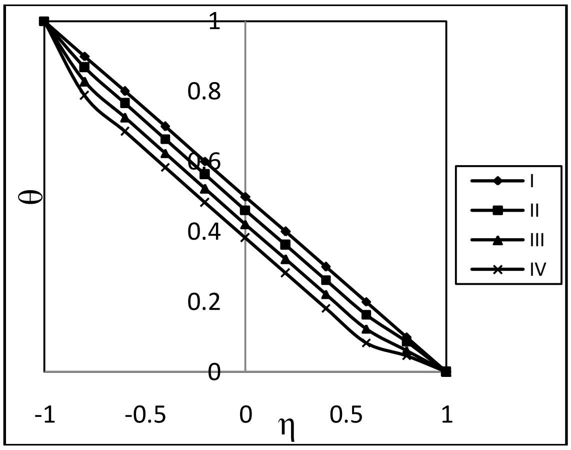

Fig.11. Variation of θ with So

	I	II	III	IV
So	0.5	1	-0.5	-1

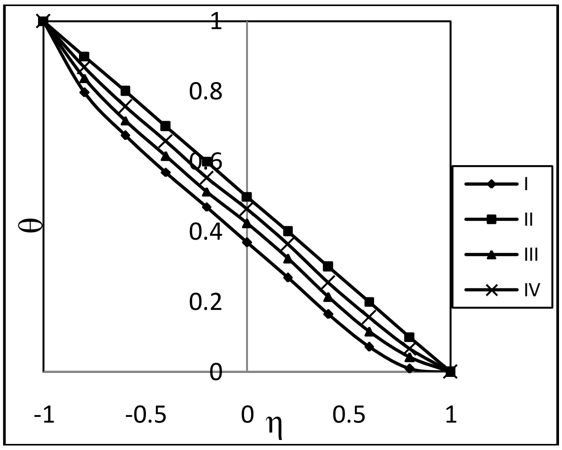

Fig.12. Variation of θ with β

	I	II	III	IV
β	0.3	0.5	0.7	0.9

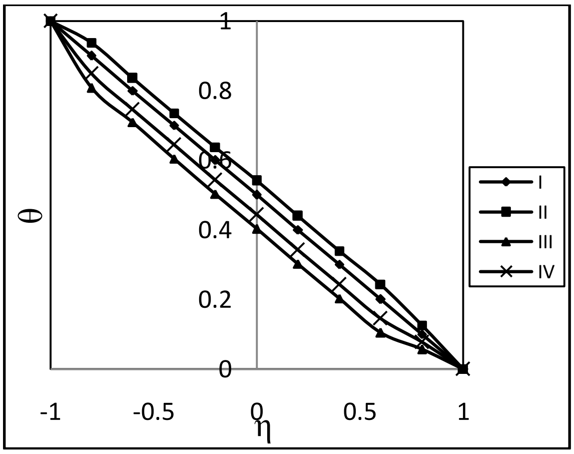

Fig.13. Variation of θ with λ

	I	II	III	IV
λ	0.5	0.25	0.75	1

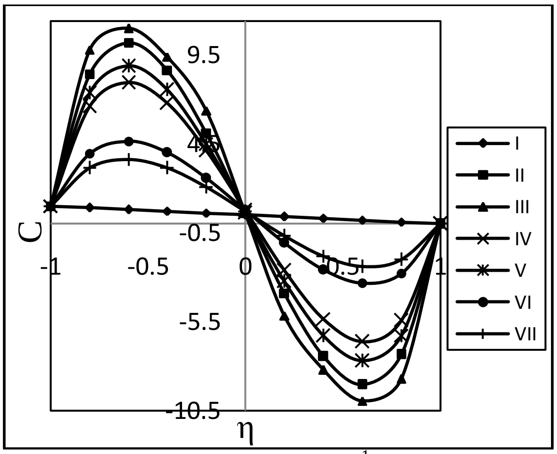

Fig.14. Variation of C with D^{-1}, M and m

	I	II	III	IV	V	VI	VII
D	10^2	$2x10^2$	$3x10^2$	10^2	10^2	10^2	10^2
M	2	2	2	4	6	2	2
m	0.5	0.5	0.5	0.5	0.5	1.5	2.5

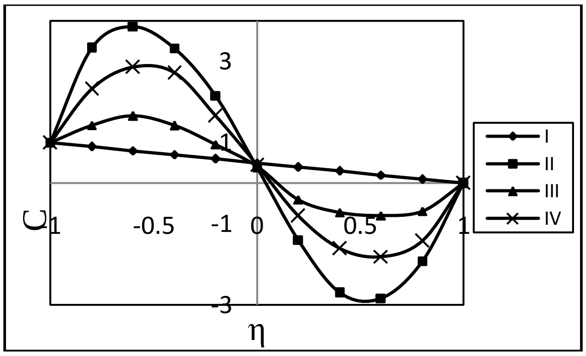

Fig.15. Variation of C with So

	I	II	III	IV
So	0.5	1	-0.5	-1

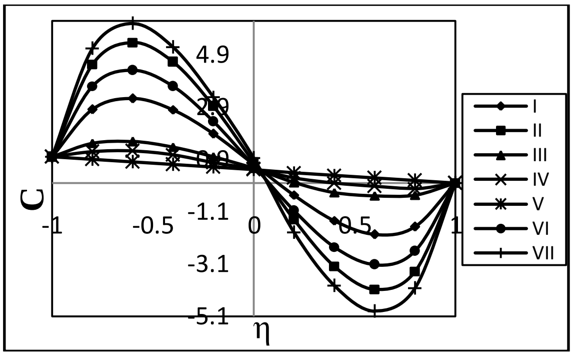

Fig.16.Variation of C with N and β

	I	II	III	IV	V	VI	VII
N	1	2	-0.5	-0.8	1	1	1
β	0.3	0.3	0.3	0.3	0.5	0.7	0.9

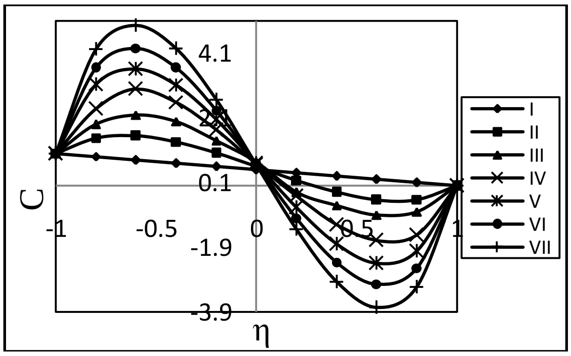

Fig.17. Variation of C with x and λ

	I	II	III	IV	V	VI	VII
x	$\frac{\pi}{4}$	$\frac{\pi}{2}$	π	2π	$\frac{\pi}{4}$	$\frac{\pi}{4}$	$\frac{\pi}{4}$
λ	0.5	0.5	0.5	0.5	0.25	0.75	1

Table: 1
Nusselt Number (Nu) at η = 1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	0.4196	0.4186	0.4176	0.4199	0.4190	0.4188	0.4180	0.4199	0.4207
$3x10^3$	0.4459	0.4441	0.4420	0.4479	0.4452	0.4445	0.4429	0.4460	0.4466
-10^3	0.3685	0.3695	0.3705	0.3675	0.3688	0.3693	0.3701	0.3675	0.3624
$-3x10^3$	0.3438	0.3457	0.3477	0.3428	0.3440	0.3453	0.3469	0.3437	0.3436
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2	10^2	10^2	10^2	10^2
R	35	35	35	70	140	35	35	35	35
M	2	2	2	2	2	4	6	2	2
m	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.5	2.5

Table: 2
Nusselt Number (Nu) at η = 1

G	I	II	III	IV	V	VI	VII	VIII	IX	X
10^3	0.4496	0.4191	0.3932	0.3696	0.4189	0.4082	0.3976	0.4919	0.4662	0.4287
$3x10^3$	0.4659	0.4480	0.4244	0.4039	0.3336	0.3143	0.3021	0.5042	0.4900	0.4780
-10^3	0.4185	0.3619	0.3335	0.3047	0.3592	0.3200	0.3105	0.4676	0.4206	0.4080
$-3x10^3$	0.3938	0.3436	0.3049	0.2738	0.3352	0.3067	0.2977	0.4555	0.4106	0.3886
β	0.3	0.5	0.7	0.9	0.5	0.5	0.5	0.5	0.5	0.5
λ	0.25	0.25	0.25	0.25	0.50	0.75	1	0.25	0.25	0.25
So	0.5	0.5	0.5	0.5	1	-0.5	-1	0.5	0.5	0.5

Table: 3
Nusselt Number (Nu) at η = -1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	-40.860	-40.590	-49.160	-40.860	-40.860	-40.100	-43.890	-41.000	-41.250
$3x10^3$	-22.090	-23.350	-32.150	-22.090	-22.090	-22.690	-26.870	-22.140	-22.220
-10^3	34.1900	28.3700	18.8800	34.1900	34.1900	29.5300	24.1800	34.4600	34.8700
$-3x10^3$	15.4300	11.1300	1.8710	15.4300	15.4300	12.1300	7.1640	15.5900	15.8400
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2	10^2	10^2	10^2	10^2
R	35	35	35	70	140	35	35	35	35
M	2	2	2	2	2	4	6	2	2
m	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.5	2.5

Table: 4
Nusselt Number (Nu) at η = -1

G	I	II	III	IV	V	VI	VII	VIII	IX	X
10^3	-42.8600	-43.1500	-49.3800	-54.0100	-44.0400	-46.9000	-40.8900	-41.5000	-42.9500	-43.5000
$3x10^3$	-38.0900	-22.0100	-16.6700	-14.3800	-42.5900	-45.8600	-31.8800	-36.0600	-37.5100	-39.1345
-10^3	67.1900	34.4300	21.4500	14.5200	29.7400	25.2700	19.1500	70.0100	68.1300	57.6543
$-3x10^3$	32.4300	15.2800	8.7410	4.8910	12.2900	8.2290	2.1380	33.7500	30.9700	27.8976
β	0.3	0.5	0.7	0.9	0.5	0.5	0.5	0.5	0.5	0.5
λ	0.25	0.25	0.25	0.25	0.50	0.75	1	0.25	0.25	0.25
So	0.5	0.5	0.5	0.5	1	-0.5	-1	0.5	0.5	0.5

Table: 5
Sherwood Number (Sh) at η = 1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	-0.6711	-0.6517	-0.5935	-0.7920	-0.8573	-0.6577	-0.6255	-0.6715	-0.6720
$3x10^3$	-0.7854	-0.7923	-0.7563	-0.8601	-0.8963	-0.7927	-0.7808	-0.7869	-0.7871
-10^3	-0.1483	-1.9800	-3.2490	-1.1290	-1.0260	-1.8420	-2.5440	-1.4710	-1.4530
$-3x10^3$	-0.1153	-1.3340	-1.5720	-1.0260	-0.9800	-1.2900	-1.4700	-1.1470	-1.1390
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2	10^2	10^2	10^2	10^2
R	35	35	35	70	140	35	35	35	35
M	2	2	2	2	2	4	6	2	2
m	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.5	2.5

Table: 6
Sherwood Number (Sh) at η = 1

G	I	II	III	IV	V	VI	VII	VIII	IX	X
10^3	-0.6311	-0.6715	-0.6720	-0.6584	-0.6587	-0.6325	-0.5950	-0.6584	-0.0009	-0.0006
$3x10^3$	-0.7754	-0.7851	-0.7987	-0.7430	-0.7627	-0.7750	-0.7576	-0.7865	-0.0018	-0.0012
-10^3	-0.0783	-0.1490	-1.2760	-1.1530	-1.8200	-2.3950	-3.2150	-6.0550	-0.0008	-0.0004
$-3x10^3$	-0.1053	-0.1190	-1.0520	-0.9783	-1.2830	-1.4400	-1.5680	-1.8260	-0.0017	-0.0011
β	0.3	0.5	0.7	0.9	0.5	0.5	0.5	0.5	0.5	0.5
λ	0.25	0.25	0.25	0.25	0.50	0.75	1	0.25	0.25	0.25
So	0.5	0.5	0.5	0.5	1	-0.5	-1	0.5	0.5	0.5

Table: 7
Sherwood Number (Sh) at η = -1

G	I	II	III	IV	V	VI	VII	VIII	IX
10^3	1.1400	1.2940	1.5450	1.1602	1.1206	1.2560	1.4220	1.1350	1.1280
$3x10^3$	1.1370	1.2920	1.5420	1.1380	1.1286	1.2540	1.4200	1.1320	1.1260
-10^3	1.1320	1.2870	1.5400	1.1346	1.1266	1.2490	1.4160	1.1270	1.1200
$-3x10^3$	1.1340	1.2900	1.5420	1.1385	1.1236	1.2510	1.4190	1.1290	1.1230
D^{-1}	10^2	$2x10^2$	$3x10^2$	10^2	10^2	10^2	10^2	10^2	10^2
R	35	35	35	70	140	35	35	35	35
M	2	2	2	2	2	4	6	2	2
m	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.5	2.5

Table: 8
Sherwood Number (Sh) at η = -1

G	I	II	III	IV	V	VI	VII	VIII	IX	X
10^3	1.1700	1.1460	1.1100	1.0850	1.2500	1.3920	1.5390	1.1290	1.1900	3.0400
$3x10^3$	1.1770	1.1330	1.0800	1.0730	1.2470	1.389	1.5370	1.1560	1.2190	3.1453
-10^3	1.1620	1.1370	1.0300	1.0190	1.1642	1.3850	1.5340	1.1400	1.3010	3.3454
$-3x10^3$	1.1740	1.1300	1.1050	1.0810	1.2450	1.3880	1.5370	1.1620	1.2750	3.2176
β	0.3	0.5	0.7	0.9	0.5	0.5	0.5	0.5	0.5	0.5
λ	0.25	0.25	0.25	0.25	0.50	0.75	1	0.25	0.25	0.25
So	0.5	0.5	0.5	0.5	1	-0.5	-1	0.5	0.5	0.5

The rate of heat transfer $\eta = \pm 1$ is shown in tables.1-4 for different variations of G, R, D^{-1}, M, m, Sc, So, N, β, λ and x. It is found that the rate of heat transfer enhances at $\eta = +1$ and reduces at $\eta = -1$ with $G > 0$,while it reduces at both the walls with $G < 0$.An increase in $R \le 70$ enhances $|Nu|$ in the heating case and reduces in the cooling case while for higher $R \ge 140$ it reduces in the heating case and enhances in the cooling case at $\eta = +1$. At $\eta = -1$, $|Nu|$ enhance with $R \le 70$ and depreciates with higher $R \ge 140$. The variation of Nu with D^{-1} shows that lesser the permeability of the porous medium smaller $|Nu|$ for $G > 0$ and for $G < 0$ and at $\eta = -1$ smaller $|Nu|$ for $D^{-1} \le 2\times10^2$ and it enhances with higher $D^{-1} \ge 3\times10^2$. The variation of Nu with Hartmann number M shows that higher the Lorentz force smaller $|Nu|$ and lager for $M \ge 6$. An increase in the Hall parameter m enhances $|Nu|$ for $G > 0$ and for $G < 0$ we notice a reduction in $|Nu|$ at $\eta = +1$ and an enhancement at $\eta = -1$ (tables.1&3). The variation of Nu with β shows that higher the dilation of channel walls lesser $|Nu|$ at both the walls. With respect to λ, we find that higher the inclination of magnetic field smaller $|Nu|$ at $\eta = +1$ and at $\eta = -1$ smaller $|Nu|$ with $\lambda \le 0.75$ and for higher $\lambda = 1$ it enhances in the heating case and reduces in the cooling case. The rate heat transfer enhances with $So > 0$ and reduces with $|So|$ at $\eta = \pm 1$ (tables2&4).

The rate of mass transfer is shown in tables 5-8 for different parametric values. It is found that the rate of mass transfer enhances at $\eta = +1$ and reduces at $\eta = -1$ with increase in $G > 0$ while for $G < 0$ it reduces at $\eta = +1$ and enhances at $\eta = -1$. The variation of Sh with D^{-1} shows that lesser the permeability of the porous medium smaller $|Sh|$ at $\eta = +1$ and larger at $\eta = -1$ for $G > 0$ and for $G < 0$ larger $|Sh|$ at $\eta = \pm 1$. The variation of Sh with R shows that $|Sh|$ at $\eta = +1$ enhances with R in heating case and reduces in cooling case. At $\eta = -1$ $|Sh|$ enhances with $R \le 70$ and depreciates with $R \ge 140$. Higher the Lorentz force smaller $|Sh|$ for $G > 0$ and larger for $G < 0$ and at $\eta = -1$ larger $|Sh|$ for all G. The variation of Sh with Hall parameter m shows that an increase in $m \le 1.5$ enhances $|Sh|$ and for higher $m \ge 2.5$ it enhances in the heating case and reduces in the cooling case. At $\eta = -1$ the rate of mass transfer depreciates with increase in m for all G (tables.5&7).The variation of Sh with β shows that higher the dilation of the channel walls larger $|Sh|$ and for further higher dilation smaller $|Sh|$ in the heating case and larger $|Sh|$ in cooling case. At $\eta = -1$ smaller the rate of mass transfer. With respect to λ we find the rate of mass transfer enhances with increase in the inclination of magnetic field. An increase in the Soret parameter $So > 0$ enhances $|Sh|$ at $\eta = \pm 1$ while for an increase in $|So|$ we notice a depreciation at $\eta = +1$ and enhancement at $\eta = -1$ for all G (tables.6&8).

VII. CONCLUSIONS

An attempt has been made to investigate the effect of hall currents and thermo-diffusion on the unsteady convective heat and mass transfer flow in vertical wavy channel. Using perturbation technique the governing equations have been solved and flow characteristics are discussed for different variations.

(i). The variation of w with Darcy parameter D^{-1} shows that lesser the permeability of the porous medium larger $|w|$ in the flow region. The variation of u with Darcy parameter D^{-1} shows that lesser the permeability of porous medium lesser $|u|$ in the flow region. The variation of θ with D^{-1} shows that lesser the permeability of porous medium smaller the actual temperature and for further lowering of the permeability larger the temperature. The variation of C with D^{-1} shows that lesser the permeability of porous medium.

(ii). The variation of w with Hartman number M higher the Lorentz force smaller $|w|$ in the flow region. The variation of u with Hartman number M, higher the Lorentz force lesser $|u|$ in the flow region. Also higher the Lorentz force lesser the actual temperature and for higher Lorentz forces larger the actual temperature. The variation of C with M shows that higher the Lorentz force results in an enhancement in the left half and depreciation in the actual concentration in the right half

(iii). An increase in Hall parameter $m \le 1.5$ enhances $|w|$ and for further higher values of $m \ge 2.5$ we notice a depreciation in the axial velocity. An increase in Hall parameter m leads to an enhancement in $|u|$ everywhere in the flow region. Also it depreciates with increase in Hall parameter $m \le 1.5$ and enhances with higher $m \ge 2.5$. The variation of C with Hall parameter m shows that an increase in $m \le 1.5$ reduces the actual concentration and for higher $m \ge 2.5$ the actual concentration depreciates in the left half and enhances in the right half

(iv). An increase in $|S_O|$ enhances w in the entire flow region. Also the magnitude of u enhances with increase in $S_O > 0$ and reduces with increase in $|S_O|$. The variation of θ with So reduces with increase in Sorret parameter $|S_O|$ (<0 >0). Also the actual concentration enhances in the left half and reduces in the right half of the channel with increase in S_O

(v). The variation of w with β shows that higher the dilation of the channel walls lesser w in the flow region. The variation of u with β shows that higher the dilation of the channel walls lesser $|u|$ in the flow region. The variation of θ with β shows that higher the dilation of the channel walls larger the actual temperature in the flow region. Higher the dilation of the channel walls we notice an enhancement in the left half and depreciation in the right half.

(vi). Higher the inclination of the magnetic field larger the velocity w in the flow region. The variation of u with λ shows that higher the inclination of the magnetic field smaller $|u|$ in the flow region. An increase in the inclination $\lambda \le 0.5$ we notice a depreciation in the actual temperature and for higher $\lambda \ge 1$ the actual temperature enhances in the flow region. An increase in the inclination of the magnetic field reduces the actual concentration in the right half and enhances in the left half

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