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

P.Vijayalakshmi[#1], Prof.U. Rajeswara Rao[#1], and Prof. D.R.V.Prasada Rao[#1]
[#1]*Department of Mathematics, Sri Krishnadevaraya University, Ananthapuramu-515003, Andhra Pradesh, India*

ABSTRACT
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 M, m, N, β, So, and λ . The rate of heat and mass transfer are numerically evaluated for different variations of the governing parameters.

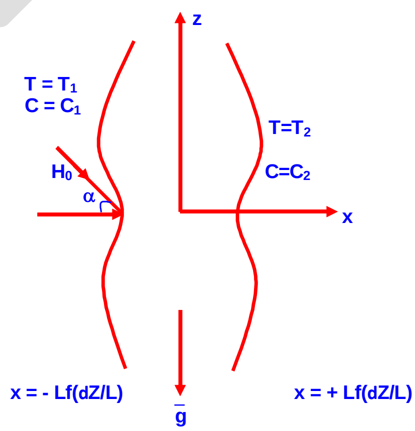
Keywords : Thermo-Diffusion, Hall Currents, Heat and Mass Transfer, Wavy Channel, Inclined Magnetic Field.

Corresponding Author : Vijayalakshmi

INTRODUCTION

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 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. They have determined an increased heat transfer due to wall roughness and provided the mean flow for stability anayalsis. In all these studies the authors have taken the wavy wall to be oriented in a horizontal direction and studied the effect of the waviness on the flow field. Vajravelu and Nayfeh [29] have investigated the influence of the wall waviness on friction and pressure drop of the generated coquette flow. Vajravelu and Sastry [28] 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 [27] 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 [13], Deshikachar et al [7] Rao *et. al.*, [15] and Sree Ramachandra Murthy [25]. Hyan Gook Won *et. al.,* [8] 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.,* [11] 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.*,[9] have analyzed that the mixed convection heat and mass transfer along a vertical wavy surface. Rees and Pop [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 or a constant surface heat flux [18].Kumar and Gupta [16] for a thermal and mass stratified porous medium and Cheng [4] 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 [21]. Manjulata et.al., [12] have analyzed Heat and mass Transfer effects in a viscous in compressible fluid through a porous medium confined between a long vertical wavy wall and a parallel flat wall in an aligned magnetic field.

In all these investigations, the effects of Hall currents are not considered. However, in a partially ionized gas, there occurs a Hall current [10] when the strength of the impressed magnetic field is very strong. These Hall effects play a significant role in determining the flow features. Sato [19], Yamanishi [30], Sherman and Sutton [23] have discussed the Hall effects on the steady hydromagnetic flow between two parallel plates. Alam *et. al.*,[2] 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.*,[10] have investigated Hall effects on the unsteady hydromagnetic boundary layer flow. Rao *et. al.*, [15] have analyzed Hall effects on unsteady Hydromagnetic flow. Siva Prasad *et. al.*, [24] have studied Hall effects on unsteady MHD free and forced convection flow in a porous rotating channel. Recently Seth *et. al.*, [20] have investigated the effects of Hall currents on heat transfer in a rotating MHD channel flow in arbitrary conducting walls.Anwar Beg et.al., [3] 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 [1] has discussed the Hall effects on transient flow pas an impulsively started infinite horizontal porous plate in a rotating system. Shanti [22] has investigated effect of Hall current on mixed convective heat and mass transfer flow in a vertical wavy channel with heat sources. Leela [14] has studied the effect of Hall currents on the convective heat and mass transfer flow in a horizontal wavy channel under inclined magnetic field. Recently Sreerangavani [26] has studied hall effects and radiation on mixed convective heat and mass transfer in a vertical wavy channel.



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 (x-z).The magnetic field is inclined at an angle α_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 $x = \pm f(\frac{\delta z}{L})$.

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

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

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 (1) reduces

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

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

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

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

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

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

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

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

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

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

$$\begin{aligned} u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} &= -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}) + \\ &- \frac{\sigma\mu_e H_{0\,0}^2 Sin^2(\alpha_1)}{1 + m^2 H_0^2 Sin^2(\alpha_1)}(u + mH_0 w Sin(\alpha_1)) - (\frac{\mu}{k})u \end{aligned} \tag{8}$$

$$\left.\begin{aligned} u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} &= -\frac{\partial p}{\partial z} + \mu(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial z^2}) - \\ &- \frac{\sigma\mu_e H_0^2 Sin^2(\alpha_1)}{1 + m^2 H_0^2 Sin^2(\alpha_1)}(w - mH_0 u Sin(\alpha_1)) - (\frac{\mu}{k})w - \rho g \end{aligned}\right| \tag{9}$$

The energy equation is

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

The diffusion equation is

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

The equation of state is

$$\rho - \rho_0 = -\beta(T - T_o) - \beta^\bullet(C - C_o) \tag{12}$$

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 is the coefficient of thermal expansion, $\beta^{\bullet}$ is the coefficient of volume expansion ,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

$$q = \frac{1}{L}\int_{-Lf}^{Lf} w dx \tag{13}$$

The boundary conditions are

$$\text{u= 0 ,w=0 T=T1 ,C=}C_1 \text{ on } x = -f(\frac{\delta z}{L}) \tag{14}$$

$$\text{w=0, w=0, T=}T_2\text{ ,C=}C_2 \text{ on } x = f(\frac{\delta z}{L}) \tag{15}$$

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

$$u = -\frac{\partial \psi}{\partial z} \quad , \; w = \frac{\partial \psi}{\partial x} \tag{16}$$

the equations (2.8)&(2.9) ,(2.10)&(2.11) in terms of ψ is

$$\begin{aligned}\frac{\partial \psi}{\partial z}\frac{\partial(\nabla^2\psi)}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial(\nabla^2\psi)}{\partial z} = \mu\nabla^4\psi + \beta g\frac{\partial(T-T_e)}{\partial x}\beta^{\bullet} g\frac{\partial(C-C_e)}{\partial x} - \\ -(\frac{\sigma\mu_e^2 H_0^2 Sin^2(\alpha_1)}{1+m^2 H_0^2\, Sin^2(\alpha_1)} + \frac{\mu}{k})\nabla^2\psi\end{aligned} \tag{17}$$

$$\rho C_p(\frac{\partial \psi}{\partial x}\frac{\partial T}{\partial z} - \frac{\partial \psi}{\partial z}\frac{\partial T}{\partial x} = k_f(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}) + Q(T_e - T) \tag{18}$$

$$(\frac{\partial \psi}{\partial x}\frac{\partial C}{\partial z} - \frac{\partial \psi}{\partial z}\frac{\partial C}{\partial x} = D_1(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}) + k_{11}(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}) \tag{19}$$

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

$$\nabla^4\psi - M_1^2\nabla^2\psi + \frac{G}{R}(\frac{\partial\theta}{\partial x} + N\frac{\partial C}{\partial x}) = R(\frac{\partial \psi}{\partial z}\frac{\partial(\nabla^2\psi)}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial(\nabla^2\psi)}{\partial z}) \tag{20}$$

$$PR(\frac{\partial \psi}{\partial x}\frac{\partial \theta}{\partial z} - \frac{\partial \psi}{\partial z}\frac{\partial \theta}{\partial x}) = \nabla^2\theta - \alpha\,\theta \tag{21}$$

$$ScR(\frac{\partial \psi}{\partial x}\frac{\partial C}{\partial z} - \frac{\partial \psi}{\partial z}\frac{\partial C}{\partial x}) = \nabla^2 C + \frac{ScSo}{N}\nabla^2\theta \tag{22}$$

where

$G = \frac{\beta g\, \Delta T_e L^3}{\nu^2}$ (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) $S_o=\frac{k_{11}\beta^{\bullet}}{\nu\beta}$ (Soret parameter)

$N=\frac{\beta^*(C_1-C_2)}{\beta(T_1-T_2)}$ (Buoyancy ratio)

The corresponding boundary conditions are

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

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

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

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 (20)-(22) reduce to

$$F^4\psi-M_1^2F^2\psi+\frac{G}{R}(\frac{\partial\theta}{\partial x}+N\frac{\partial C}{\partial x})=\delta R(\frac{\partial\psi}{\partial\bar{z}}\frac{\partial(F^2\psi)}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial(F^2\psi)}{\partial\bar{z}}) \quad (23)$$

$$\delta PR(\frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial\theta}{\partial x})=F^2\theta-\alpha\theta \quad (24)$$

$$\delta ScR(\frac{\partial\psi}{\partial x}\frac{\partial c}{\partial z}-\frac{\partial\psi}{\partial z}\frac{\partial C}{\partial x})=F^2C+\frac{ScSo}{N}F^2\theta \quad (25)$$

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

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

$$\theta(x,z)=\theta_o(x,z)+\delta\theta_1(x,z)+\delta^2\theta_2(x,z)+\dots\dots\dots \quad (26)$$

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

Let $\eta=\frac{x}{f(\bar{z})}$ (27)

Substituting (26) in equations (23)-(25) and using (27) and equating the like powers of δ the equations and the respective boundary conditions to the zeroth order are

$$\frac{\partial^2\theta_0}{\partial\eta^2}-(\alpha f^2)\theta_0=0 \quad (28)$$

$$\frac{\partial^2 C_0}{\partial \eta^2} = -\frac{\mathrm{Sc\,So}}{\mathrm{N}}\frac{\partial^2 \theta_0}{\partial \eta^2} \tag{29}$$

$$\frac{\partial^4 \psi_0}{\partial \eta^4} - (M_1^2 f^2)\frac{\partial^2 \psi_0}{\partial \eta^2} = -\frac{Gf^3}{R}\left(\frac{\partial \theta_0}{\partial \eta} + N\frac{\partial C_0}{\partial \eta}\right) \tag{30}$$

with

$$\begin{aligned}
&\psi_0(+1) - \psi_0(-1) = 1 \\
&\frac{\partial \psi_0}{\partial \eta} = 0, \quad \frac{\partial \psi_0}{\partial \bar{z}} = 0, \quad \theta_0 = 1\ ,\ C_0 = 1 \quad at \quad \eta = -1 \\
&\frac{\partial \psi_0}{\partial \eta} = 0, \quad \frac{\partial \psi_0}{\partial \bar{z}} = 0, \quad \theta_0 = 0\ ,\ C_0 = 0 \quad at \quad \eta = +1
\end{aligned} \tag{31}$$

and to the first order are

$$\frac{\partial^2 \theta_1}{\partial \eta^2} - (\alpha f^2)\theta_1 = P_1 Rf\left(\frac{\partial \psi_0}{\partial \eta}\frac{\partial \theta_0}{\partial \bar{z}} - \frac{\partial \psi_0}{\partial \bar{z}}\frac{\partial \theta_0}{\partial \eta}\right) \tag{32}$$

$$\frac{\partial^2 C_1}{\partial \eta^2} = ScRf\left(\frac{\partial \psi_0}{\partial \eta}\frac{\partial C_0}{\partial \bar{z}} - \frac{\partial \psi_0}{\partial \bar{z}}\frac{\partial C_0}{\partial \eta}\right) - \frac{Sc\,So}{N}\frac{\partial^2 \theta_1}{\partial \eta^2} \tag{33}$$

$$\begin{aligned}
\frac{\partial^4 \psi_1}{\partial \eta^4} - (M_1^2 f^2)\frac{\partial^2 \psi_1}{\partial \eta^2} = -\frac{Gf^3}{R}\left(\frac{\partial \theta_1}{\partial \eta} + N\frac{\partial C_1}{\partial \eta}\right) + \\
Rf\left(\frac{\partial \psi_0}{\partial \eta}\frac{\partial^3 \psi_0}{\partial z^3} - \frac{\partial \psi_0}{\partial \bar{z}}\frac{\partial^3 \psi_0}{\partial x \partial z^2}\right)
\end{aligned} \tag{34}$$

with

$$\begin{aligned}
&\psi_1(+1) - \psi_1(-1) = 0 \\
&\frac{\partial \psi_1}{\partial \eta} = 0, \quad \frac{\partial \psi_1}{\partial \bar{z}} = 0, \quad \theta_1 = 0, C_1 = 0 \quad at \quad \eta = -1 \\
&\frac{\partial \psi_1}{\partial \eta} = 0, \quad \frac{\partial \psi_1}{\partial \bar{z}} = 0, \quad \theta_1 = 0\ .C_1 = 0 \quad at \quad \eta = +1
\end{aligned} \tag{35}$$

The equations 28 – 30 & 32-34 are solved algebraically subject to the Boundary conditions 31 & 35.

NUSSELT NUMBER and SHERWOOD NUMBER

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

$$Nu = \frac{1}{f(\theta_m - \theta_w)}\left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=\pm 1} \quad \text{where} \quad \theta_m = 0.5\int_{-1}^{1} \theta\, d\eta$$

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

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

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

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

$$(Sh)_{\eta=+1} = \frac{1}{fC_m}(a_{74} + \delta a_{70})$$

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

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

RESULTS AND DISCUSSION OF THE NUMERICAL RESULTS

In this analysis we investigate the effect of hall currents, thermo diffusion on the 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 a inclined magnetic field. The non-linear coupled differential equations governing the flow heat & mass are solved by using a regular perturbation technique with a slope δ of the wavy wall as a perturbation parameter .The axial velocity (w) for different values of M, m, Sc, N, β, S_0,& λ It is found that the axial flow is in the vertically downward direction and hence u>0 represents the reversal flow. Fig. 1 represents w with M and m, it can be seen that |w| depreciates with increase in M and enhances with increase in the hall parameter m. The effect of hall waviness on w is shown in (fig 2), it is observed that higher constriction of channel walls larger the magnitude of w. With respect to the buoyancy ratio N, it can be seen from the profiles that when the molecular buoyancy force dominates over the thermal buoyancy force |w| enhances when the buoyancy forces act in same direction and for the forces acting in opposite direction |w| depreciates in the flow region (fig 3). The effect of Soret parameter S_0 on w is shown in (fig 4). |w| enhances with increase in S_0>0 and depreciates with increase $|S_0|$<0. The effect of inclination magnetic field on w is shown in (fig 5) higher the inclination of the magnetic field smaller |w| in the flow region.

The secondary velocity (u) which is due to the waviness of the boundary (6-10) for different parametric values . Fig.6 represents u with M & m. It is found that higher the Lorentz force smaller |u| in the flow region also |u| depreciates with increase in m. Fig 7 represents u with β, it is found that higher the constriction of channel walls smaller |u| in the flow region. |u| enhances with increase in N>0 and reduces with increase in |N| (fig. 8). With respect to S_0 it is observed that the magnitude of u enhances with increase in S_0>0 and reduces with $|S_0|$<0 (fig 9). Fig 10 represents u with λ. Higher the inclination of the magnetic field larger |u| in the flow region.

The non - dimensional temperature (θ) is shown in figures (11-14) for different parametric values. It is found that the non - dimensional temperature is always positive for different variations. That is the actual temperature is greater than the temperature on the left wall η=-1.From fig.11 we find that the actual temperature enhances with increase in M and m. The effect of wall waviness of θ is shown in fig.12. Higher the constriction of the channel walls smaller the actual temperature. When the molecular buoyancy force dominates over the thermal buoyancy force the actual temperature experiences an enhancement irrespective the directions of buoyancy forces (fig.13). fig.14 we notice that the higher the inclination of the magnetic field (λ≤0.75) larger the actual temperature and for further higher inclination the actual temperature enhances in the left half and reduces in the right half.

The concentration distribution (C) is shown in figures (15-19) for different parametric values we follow the convention that the non - dimensional concentration is positive or negative according as the actual concentration is greater- lesser than C_1. The variation of C with M and m shows that an increase in M≤4 reduces the actual concentration in the entire flow region and for higher M≥6 it depreciates in the left half and enhances in the right half of the channel. An increase in the hall parameter m reduces the actual concentration in the left half and enhances in the right half (fig 15).

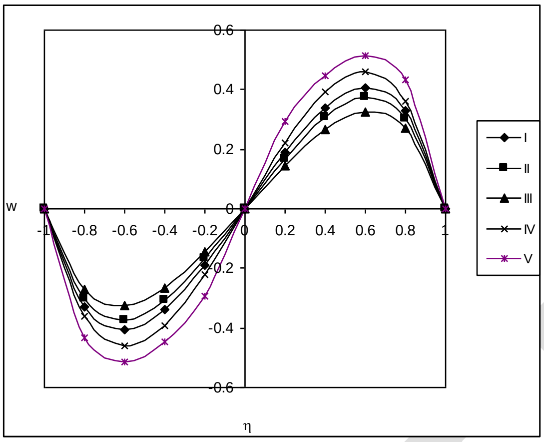


Fig. 1 : Variation of w with M, m

	I	II	III	IV	V
M	2	4	6	2	2
m	0.5	0.5	0.5	1.5	2.5

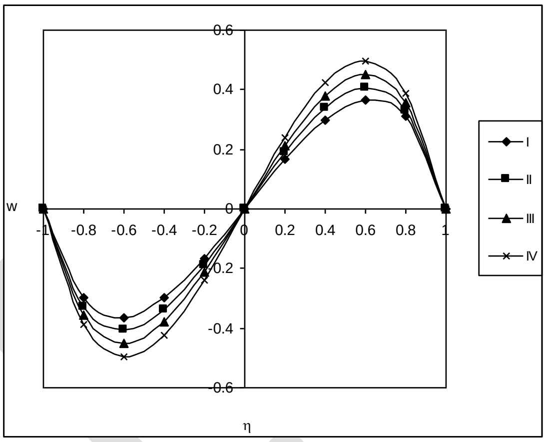


Fig. 2 : Variation of w with β

	I	II	III	IV
β	-0.3	-0.5	-0.7	-0.9

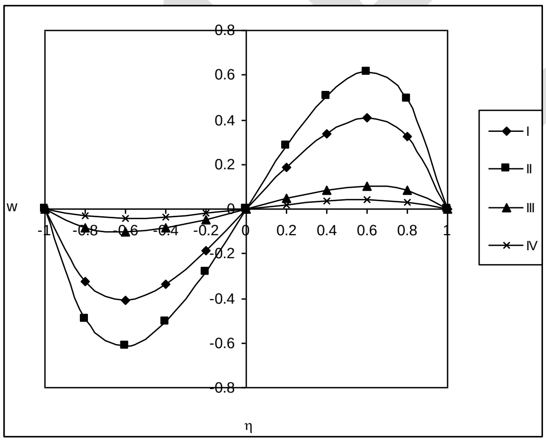


Fig. 3 : Variation of w with N

	I	II	III	IV
N	1	2	-0.5	-0.8

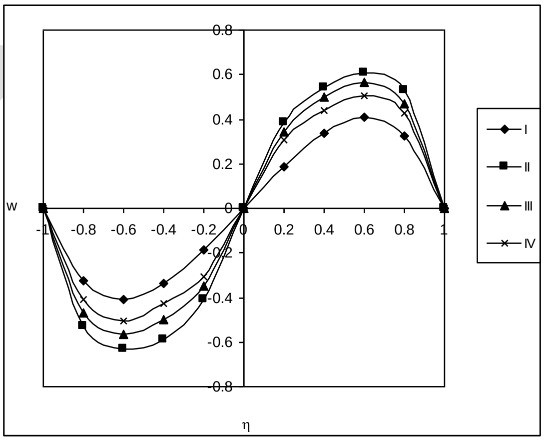


Fig. 4 : Variation of w with S_0

	I	II	III	IV
S_0	0.5	1	-0.5	-1

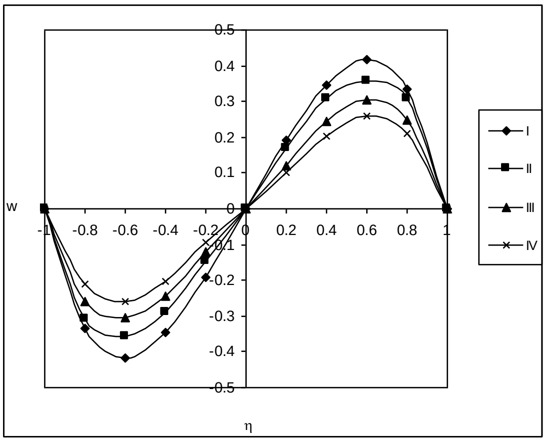


Fig.5 : Variation of w with λ

	I	II	III	IV
λ	0.25	0.5	0.75	1

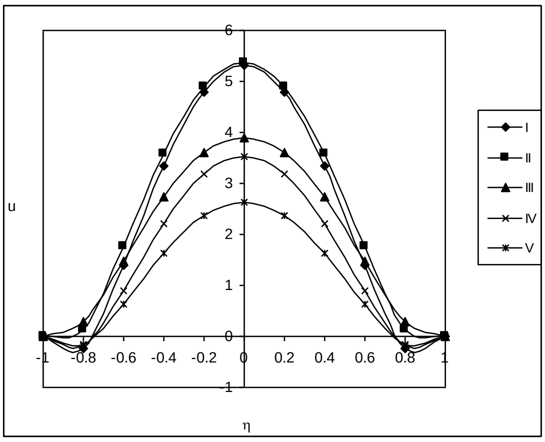


Fig.6 : Variation of u with M, m

	I	II	III	IV	V
M	2	4	6	2	2
m	0.5	0.5	0.5	1.5	2.5

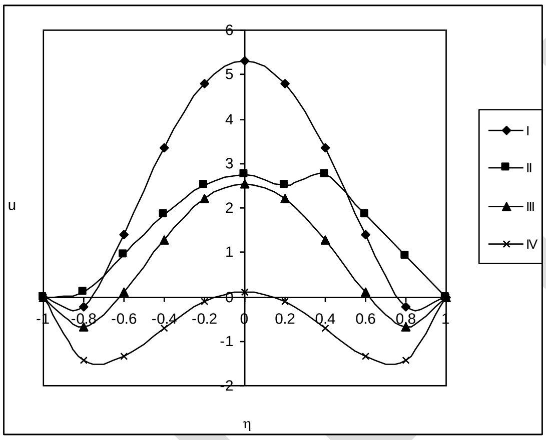


Fig. 7 : Variation of u with β

	I	II	III	IV
β	-0.3	-0.5	-0.7	-0.9

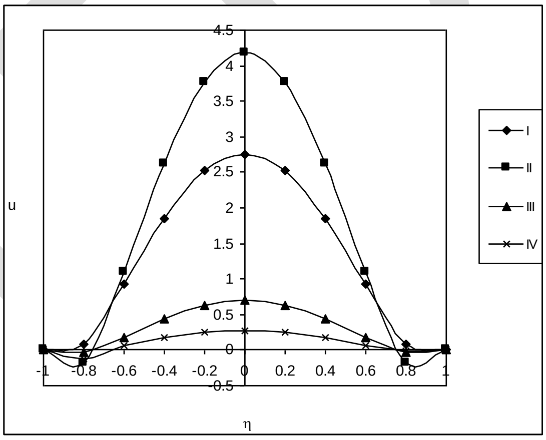


Fig. 8 : Variation of u with N

	I	II	III	IV
N	1	2	-0.5	-0.8

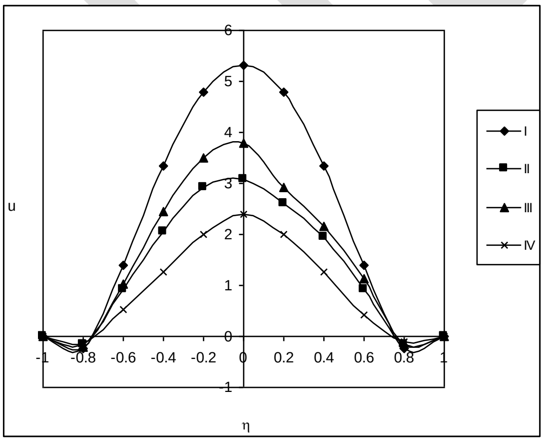


Fig. 9 : Variation of u with S_0

	I	II	III	IV
S_0	0.5	1	-0.5	-1

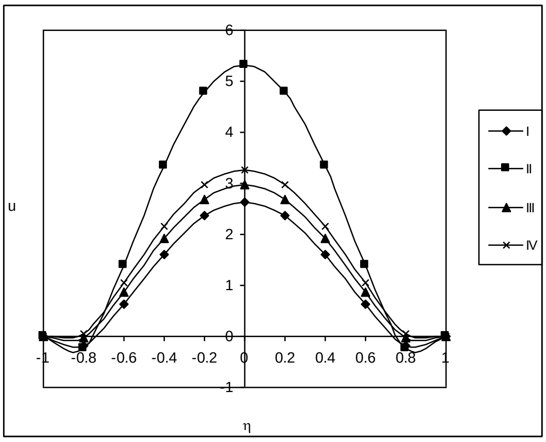


Fig.10 : Variation of u with λ

	I	II	III	IV
λ	0.25	0.5	0.75	1

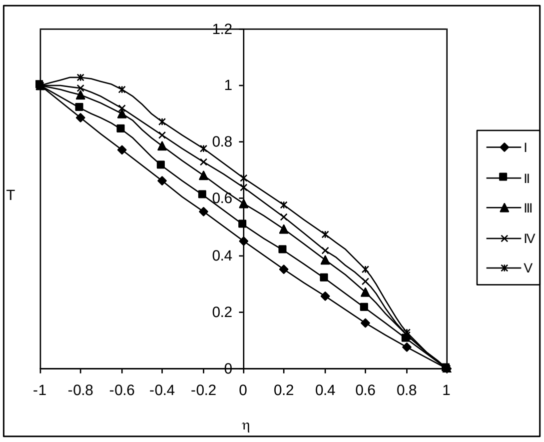


Fig.11 : Variation of T with M, m

	I	II	III	IV	V
M	2	4	6	2	2
m	0.5	0.5	0.5	1.5	2.5

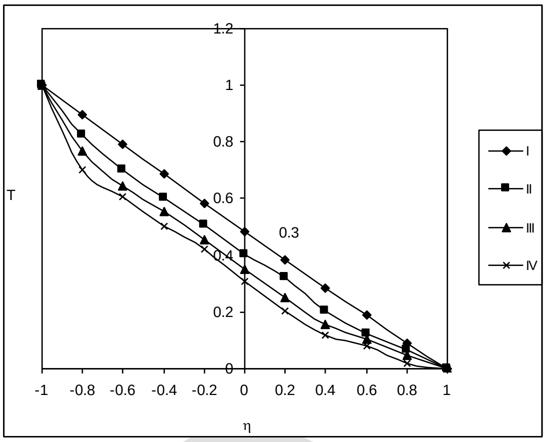


Fig. 12 : Variation of T with β

	I	II	III	IV
β	-0.3	-0.5	-0.7	-0.9

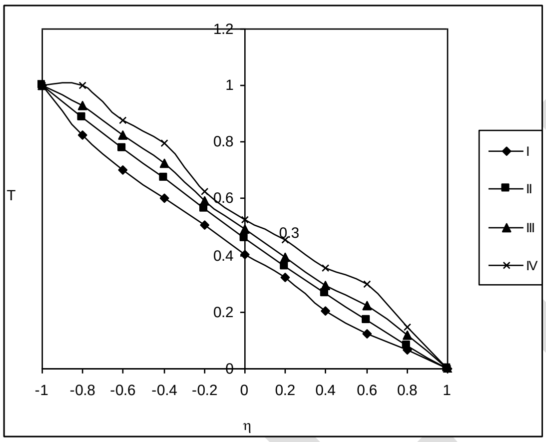


Fig.13 : Variation of T with N

	I	II	III	IV
N	1	2	-0.5	-0.8

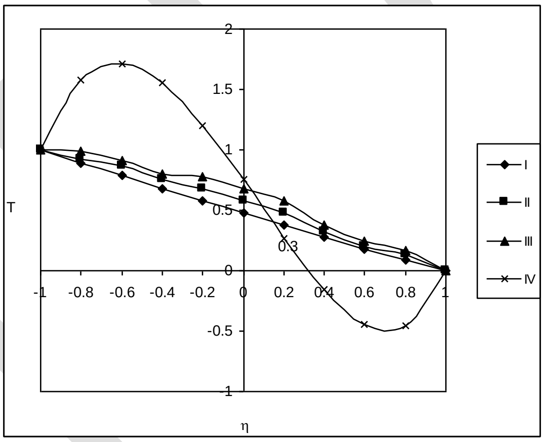


Fig. 14 : Variation of T with λ

	I	II	III	IV
λ	0.25	0.5	0.75	1

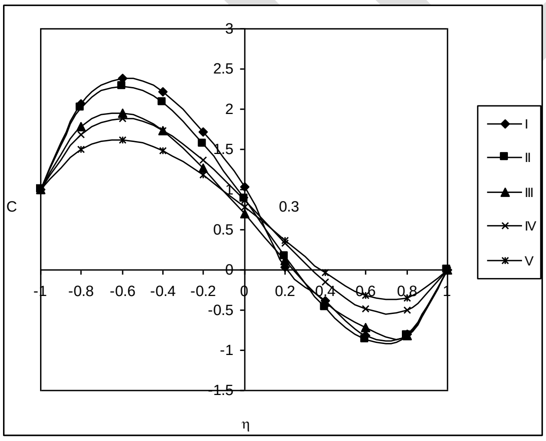


Fig.15 : Variation of C with M, m

	I	II	III	IV	V
M	2	4	6	2	2
m	0.5	0.5	0.5	1.5	2.5

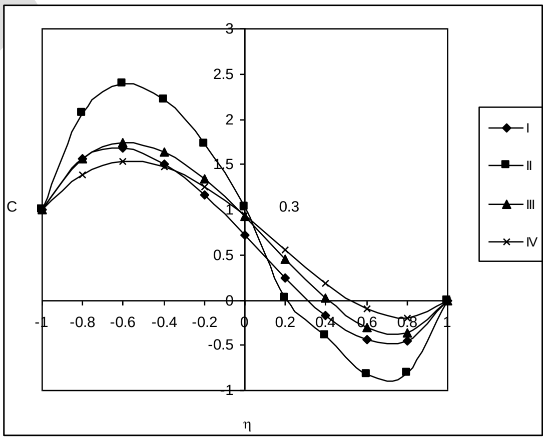


Fig.16 : Variation of C with β

	I	II	III	IV
β	-0.3	-0.5	-0.7	-0.9

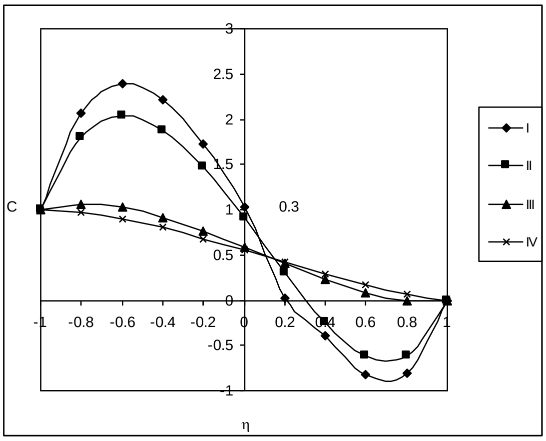


Fig.17 : Variation of C with N

	I	II	III	IV
N	1	2	-0.5	-0.8

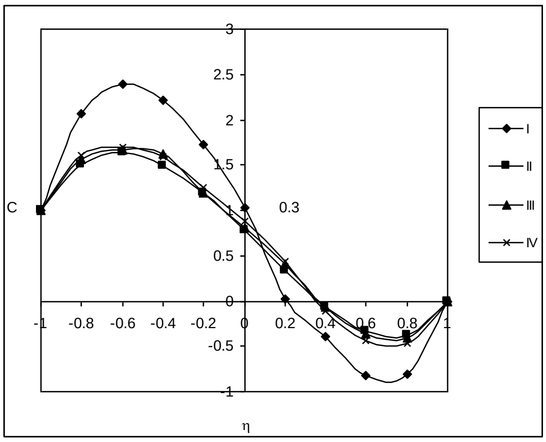


Fig. 18 : Variation of C with S_0

	I	II	III	IV
S_0	0.5	1	-0.5	-1

From fig.16 we find that higher the constriction of the channel walls larger the concentration in the left half and smaller in the right half and for higher constriction of the channel walls smaller the actual concentration in the left half and larger in the right half. When the molecular buoyancy force dominates over the thermal buoyancy force the actual concentration reduces in the left half and enhances in the right half irrespective of the directions of the buoyancy forces (fig 17). From fig 18 we notice that the actual concentration reduces in the left half and enhances in the right half with increase in S_0 >0,while a reversed effect is observed in the behavior of C with increase in $|S_0|$. From fig 19 we notice that an increase in smaller and higher values of λ, larger the actual concentration in the left half and smaller in the right half. While for an intermediate value λ=0.75 the actual concentration reduces in the left half and enhances in the right half.

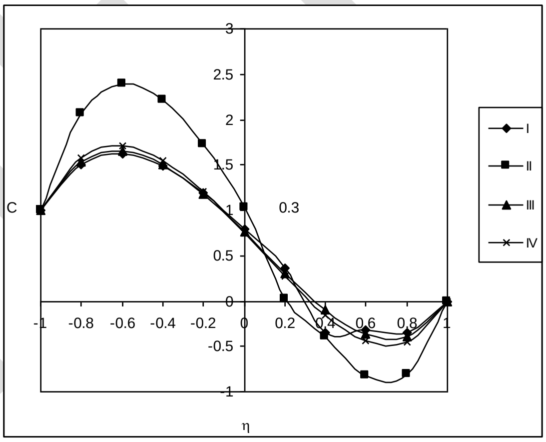


Fig. 19 : Variation of C with λ

	I	II	III	IV
λ	0.25	0.5	0.75	1

The rate of heat transfer at η=±1 is evaluated numerically for different parametric equations and are executed in tables 1&2. The variation of Nu with D^{-1} and M shows that lesser the molecular diffusivity higher the Lorentz force smaller |Nu| at η=+1.At η=-1 |Nu| enhances with increase in M≤4 and depreciates with higher M≥6.An increase in the hall parameter m enhances at η=+1 and depreciates at η=-1. The variation of |Nu| with β shows that higher the constriction of the channel walls larger |Nu| at η=+1 and smaller at η=-1 and for higher constriction (β≥0.7) smaller |Nu| at both the walls.With respect to the buoyancy ratio N. It is found that when the molecular buoyancy force dominates over the thermal buoyancy force the rate of heat transfer enhances at η=+1 and smaller at η=-1 for G>0and for G<0 |Nu| enhances at both the walls. The variation of |Nu| with the inclination λ of the magnetic field shows that higher the inclination of the magnetic field smaller |Nu| at η=+1 and larger at η=-1 in the heating case while in the cooling case larger |Nu| at η=-1.

The rate of mass transfer (Sherwood number (sh)) at the boundaries η=±1 are executed in tables 3-4 for different parametric variations.With respect to M it can be seen that lesser the permeability of the porous medium higher the Lorentz force larger |Sh| for G>0 and for G<0 smaller |Sh| at both the walls. The variation of Sh with hall parameter m the rate of mass transfer at η=+1 enhances with m≤1.5 and depreciates with m≥2.5 while at η=-1 it enhances with m. The variation of Sh with β shows that higher the constriction of the channel walls smaller |Sh| at η=+1 and larger at η=-1 and for higher |β|≥0.7 larger |Sh| at both the walls. With respect to the buoyancy ratio |N| it is observed that the rate of mass transfer enhances at η=+1 and depreciates at η=-1 for G>0 and for G<0 |Sh| enhances at η=±1 when the buoyancy forces act in the same direction and for the forces act in opposite direction |Sh| depreciates at η=+1 and enhances at η=-1 in the heating case and reduces in the cooling case at both the walls. An increase in the inclination of magnetic field enhances |Sh| moving along the axial direction of the channel walls.

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

G	I	II	III	IV	V	VI	VII	VII	IX	X	XI
103	0.6426	0.613	0.6064	0.6449	0.6487	0.5644	0.1101	-0.2222	0.6426	0.6066	0.5869
$3x10^3$	0.5921	0.5386	0.5294	0.5968	0.6045	0.5316	0.4399	0.02662	0.5921	0.5294	0.5014
-10	0.7203	0.7537	0.7643	0.718	0.7145	0.628	0.6966	0.3902	0.7203	0.7636	0.7648
$-3x10^3$	0.7509	0.8201	0.8452	0.7464	0.7395	0.6588	0.6416	0.3047	0.7509	0.8435	0.8472
M	2	4	6	2	2	2	2	2	2	2	2
m	0.5	0.5	0.5	1.5	2.5	0.5	0.5	0.5	0.5	0.5	0.5
Β	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.7	-0.9	-0.5	-0.5	-0.5
Λ	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.25	0.75	1

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

G	I	II	III	IV	V	VI	VII	VII	IX	X	XI
103	-0.8464	-0.9573	0.7771	-0.8055	-0.7491	-1.5642	-0.6849	-0.393	-0.8464	1.1172	0.7246
$3x10^3$	-0.4334	-0.6772	0.3661	-0.413	-0.3849	-1.2815	-0.2982	-0.1254	-0.4334	0.858	0.5909
-10	0.8054	0.9632	-0.867	0.7643	0.7079	1.5667	0.1555	0.1274	0.8054	-1.1285	-0.5103
$-3x10^3$	0.3924	0.683	-0.456	0.3719	0.3437	1.284	0.2042	0.1098	0.3924	-0.8703	-0.5766
M	2	4	6	1.5	2.5	2	2	2	2	2	2
m	0.5	0.5	0.5	1.5	2.5	0.5	0.5	0.5	0.5	0.5	0.5
Β	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.7	-0.9	-0.5	-0.5	-0.5
Λ	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.25	0.75	1

Table 3 : Average Sherwood number (Sh) at η=-1

G	I	II	III	IV	V	VI	VII	VII	IX	X	XI
103	-0.1694	-0.1764	-0.2008	-0.1699	-0.1685	-0.182	-0.2054	-0.4098	-0.1694	-0.3758	-0.4247
$3x10^3$	-0.1598	-0.1675	-0.1706	-0.1556	-0.1546	-0.1471	-0.1954	-0.3916	-0.1552	-0.2572	-0.3827
-10	-0.1256	-0.1211	-0.1201	-0.1259	-0.1244	-0.9605	-0.1716	-0.3474	-0.1256	-0.3213	-0.42
$-3x10^3$	-0.1335	-0.1306	-0.1224	-0.1338	-0.1332	-0.1679	-0.1782	-0.3596	-0.1335	-0.3306	-0.4646
M	2	4	6	1.5	2.5	2	2	2	2	2	2
m	0.5	0.5	0.5	1.5	2.5	0.5	0.5	0.5	0.5	0.5	0.5
β	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.7	-0.9	-0.5	-0.5	-0.5
λ	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.25	0.75	1

Table 4 : Average Sherwood number at η=-1

G	I	II	III	IV	V	VI	VII	VII	IX	X	XI
103	0.1581	0.16	0.1715	0.1583	0.1585	0.1393	0.2022	0.408	0.1581	0.169	0.1819
$3x10^3$	0.1578	0.1597	0.1711	0.158	0.1582	0.139	0.2018	0.3991	0.1578	0.1686	0.1815
-10	0.1573	0.159	0.1704	0.1575	0.1577	0.1384	0.2015	0.4002	0.1573	0.1679	0.1807
$-3x10^3$	0.1576	0.1593	0.1707	0.1577	0.158	0.1387	0.2019	0.401	0.1576	0.1682	0.1811
M	2	4	6	1.5	2.5	2	2	2	2	2	2
m	0.5	0.5	0.5	1.5	2.5	0.5	0.5	0.5	0.5	0.5	0.5
β	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.7	-0.9	-0.5	-0.5	-0.5
λ	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.25	0.75	1

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