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EFFECT OF CHEMICAL REACTION AND THERMO-DIFFUSION ON CONVECTIVE HEAT AND MASS TRANSFER FLOW OF A ROTATING FLUID THROUGH A POROUS MEDIUM IN A VERTICAL CHANNEL WITH STRETCHING WALLS

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ABSTRACT

In this paper, we investigate the combined effect of Heat sources, Chemical reaction and thermo-diffusion on convective and mass transfer flow of an electrically conducting, viscous,incompressible rotating fluid through a porous medium in a vertical channel bounded by a stretching sheet and a stationary wall. The nonlinear governing equations have been solved by using Runge-Kutta shooting technique. The velocity, temperature and conconcentration have been analysed for different variations of G, M, D^{-1}, N, Sc, γ, Q, R, Sr and Pr The Skin friction,rate of heat and mass transfer are evaluated numerically for different variations.

Keywords: *Chemical Reaction, Heat and Mass Transfer, Rotating Fluid, Vertical Channel, Porous Medium, Stretching Walls.*

1. INTRODUCTION

Laminar flows through channels have applications in the fields of gas diffusion, ablation cooling, filtration, microfluidic devices, surface sublimation, grain regression (as in the case of combustion in rocket motors) and the modelling of air circulation in the respiratory system. Laminar air –flow systems have been used by the aerospace industry to control particular contamination. Futhermore, the laminar flow cabinet have been used in the maintainance of negative pressure and in the adjustment of the fans to exhaust more air. Therefore, the Navier-Stokes equations which are the governing equations for these problems. have attracted the interest of the researchers. Sutton and Barto [38] described an exact solution of Navier-Stokes equations for motion of an incompressible viscous fluid in a channel with different pressure gradients. Their solutions are helpful in verifying and validating computational models of complex on unsteady motions, to guide the design of fuel injectors and controlled experiments. Simulation of flow through microchannels with design roughness was presented numerically by Rawool *et al.* [31]. A numerical investigations is made by Robinson [4] for the problem of steady laminar incompressible flow in a porous channel with uniform suction at both walls. Taylor *et al.* [41] studied three dimensional flow buy uniform suction through parallel porous walls. The investigations of Taylor [50] were further extended to a more general three dimensional stagnation point which can capture the phenomena in a single class of state by Hewitt *et al.* [18]. Two dimensional viscous incompressible fluid flow between two porous walls with uniform suction was analysed by Cox [9]. Berman [5] proposed the two dimensional laminar steady flow through a porous channel which was driven by suction or injection. Similarity one/two dimensional laminar flow in a porous channel with wall suction or injection was examined analytically by Laurent *et al.* [9]. The problem of fluid flow in a channel with porous walls was solved by Karode [19]. Zheng *et al.* [48] investigated asymptotic solutions for steady laminar flow of an incompressible viscous fluid along a channel with accelerating rigid porous walls.The exact solution solution for two dimensional steady laminar flow through a porous channel was generalized by Terril [13], Shrestril and Terril [39,40], Brady [7], Waston *et al.* [46] and Cox [10] under varied conditions. Deng and Marinez [11] worked on two dimensional flow of a viscous fluid in a channel partially filled with porous medium with wall suction. Wang [45] worked on viscous flow due to stretching sheet with slip and suction and proved a closed form unique solution for two dimensional flows.For axisymmetric stretching both existence and uniqueness were shown. Muhammad Asraf *et al.* [3] investigated micropolar fluid flow in

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a channel with Shrinking walls. Hajipour and Dehkordi [15] studied the transient behavioue of fluid flow and heat transfer in vertical channel partially filled with a porous medium including the effects of inertial term and viscous dissipation. Kasif Ali *et al.* [20] have discussed numerical study of micropolar fluid flow and heat transfer in a channel eith shrinking and stationary wall. Xinuui *et al.* [47] have considered flow and heat transfer in porous channel with expanding or contracting walls. Misra *et al.* [25] have investigated the blood flow and heat transfer in a parallel plate channel with stretching walls modelling blood as a viscoelastic fluid. Raftari and Vajravelu [29] have discussed the flow and heat transfer characteristics of a magnetohydrodynamic viscoelastic fluid in a parallel plate channel with a stretching wall. Asia *et al.* [2] have investigated MHD unsteady flow and heat transfer of micropolar fluid through porous channel with expanding or contracting walls. Sami Ullah Khan *et al.* [32] have discussed hydromagnetic flow and heat transfer over a porous oscillating stretching surface in a viscoelastic fluid with porous medium. Sarojamma *et al.* [34] have discussed MHD Casson fluid flow, heat and mass transfer in a vertical channel with stretching walls. Vijayalakshmi *et al.* [44] have investigated unsteady flow of a casson fluid through a vertical channel with walls of expansion and contraction. Recently, Sreenivasa rao [37] has discussed the combined influence of chemical reaction and Soret effect on MHD convective heat and mass transfer in a vertical channel with stretching walls.

The motion of rotation fluids enclosed with in a body or vice versa, was given by Green span, discussed these problems relating to the boundary layers and their interaction in rotating flows and gave so many examples relating to such interaction. The rotating viscous flow equation yields a layer known as Eckman boundary layer after the Swedish oceanographer Eckman who discovered it. Attempts to observe the structure of the Eckman layer in the surface layers of the sea have been successful. Eckman layers are easy to produce and observe in the laboratory. Such boundary layers or similar ones are required to connect principally geotropic flow in the interior of the fluid to the horizontal boundaries where conditions like a prescribed horizontal stress or no slip on a solid bottom are given. In a similar way other kinds of various boundaries have been studies so as to connect geotropic flow to vertical boundaries (for example a vertical well along which the depth varies) on which boundary conditions consistent with geotropic flow are given. Mahendra Mohan [23] has discussed the free and forced convections in rotating Hydromagnetic viscous fluid between two finitely conduction parallel plates maintained at constant temperature gradients. In view of many scientific and engineering applications of fluids flow through porous media, Mahendra Mohan and Srivastava [24] have studied the combined free and forced convection flow of an incompressible viscous fluid in a parallel plates channel bounded below by a permeable bed and rotating with a constant angular velocity about an axis perpendicular to the length of the plates. Rao *et al.* [28] made an investigation of the combined free and forced convective effects on an unsteady Hydro magnetic viscous incompressible flow in a rotating porous channel. This analysis has been extended to porous boundaries by Sarojamma and Krishna [33]. An initial value investigation of the hydro magnetic and convective flow of a viscous electrically conducting fluid through a porous medium in a rotating channel has been made by Krishna *et al.* [21]. In all these papers the viscous dissipative effect has not been considered. But the viscous dissipation has its importance when the natural convection flow fixed is of extreme size or the temperature is low or in higher gravity field. Seth and Ghosh [35] has investigated the unsteady hydromagnetic flow of viscous incompressible electrically conducting fluid in rotating channel under the influence of periodic pressure gradient and of uniform magnetic field, which is inclined with the axes of rotation. The problem of steady laminar micro polar fluid flow through porous walls of different permeability had been discussed by Agarwal and Dhanpal [1]. Steady and unsteady hydro magnetic flow of viscous incompressible electrically conducting fluid under the influence of constant and periodic pressure gradient in the presence of include magnetic field had been investigated by Ghouse [14] to study the effect of slowly rotating systems with low frequency of oscillation when the conductivity of the fluid is low and the applied magnetic field is weak. El-Mistikawy *et al.* [12] were discussed the rotating disk flow in the presence of strong magnetic field and weak magnetic field. Hazim Ali Attia [17] was developed the MHD flow of incompressible, viscous and electrically conducting fluid above an infinite rotating porous disk was extended to flow starting impulsively from rest. The fluid was subjected to an external uniform magnetic field perpendicular to the plane of the disk. The effects of uniform suction or injection through the disk on the unsteady MHD flow were also considered. Circar and Mukherjee [8] have analyzed the effect of mass transfer and rotation on flow past a porous plate in a porous medium with variable suction in a slip flow regime. Balasubramanyam [4] have investigated convective heat and mass transfer flow in horizontal rotating fluid under different conditions. Singh and Mathew [36] have studied on oscillatory free convective MHD flow in a rotating vertical porous channel with heat sources. Jayasudha *et al.* [15] have discussed the effect of chemical reaction, Non-Uniform Heat source on convective heat and mass transfer flow past a stretching sheet in a rotating fluid. Garg *et al.* [13] have investigated rotating MHD convective flow of Oldroyd B fluid through a porous medium in a vertical porous channel with thermal radiation. Venkatarami Reddy [43] has analysed radiation absorption on convective heat and mass transfer flow past a vertical porous plate in a rotating fluid with chemical reaction and dissipation. Bhuvana vijaya *et al.* [6] have analysed double diffusive convection of a rotating fluid over a vertical plate embedded in Darcy-Forchheimer porous medium with non-uniform heat source.

2. FORMULATION OF THE PROBLEM

We consider the steady two dimensional hydromagnetic laminar convective heat and mass transfer flow of a viscous electrically conducting rotating fluid in a vertical channel bounded by a stretching sheet on the left a stationary plate on the right.we choose a rectangular coordinate system O(x, y.z) with the walls at $y=\pm L$. The flow is subjected to a strong

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magnetic field with a constant intensity Bo along the positive y-direction. Assuming magnetic Reynolds number Rm to be small we neglect the induced magnetic field in comparison to the applied magnetic field.It is used to compare the transport of magnetic lines of the force in a conducting fluid with the leakage of such lines from the fluid. Taking the viscous dissipation and joule heating effects into consideration, the governing equations of the flow, heat and mass transfer for the problem are

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\sigma\mu_e^2H_o^2u-\rho g+2\Omega w \tag{2}$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}\right)=\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)-\sigma\mu_e^2H_o^2w-2\Omega u \tag{4}$$

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k_f\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+Q_H(T-T_0)+\lim_{x\to\infty}+2\mu\left(\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right)+\sigma\mu_e^2H_o^2(u^2+w^2) \tag{5}$$

$$\left(u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}\right)=D_b\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)-k_c^{'}(C-C_o)+\frac{D_TK_T}{T_m}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{6}$$

$$\rho-\rho_o=-\beta(T-T_o)-\beta^*(C-C_o) \tag{7}$$

Where (u, v. 0) are the velocity components along x, y directions respectively, T, C are the dimensional temperature and concentration respectively, ρ is the density, p is the pressure, σ is the electrical conductivity, μ_e is the magnetic permeability of the medium, μ is the dynamic viscosity, g is the gravity, is the strength of the heat source, Db is the molecular diffusivity, D_T is the mass diffusivity, K_T is the thermal diffusion ratio, β is the coefficient of thermal expansion, β^* is the coefficient of volume expansion,Tm is the mean fluid temperature,

The boundary conditions for the velocity, temperature and concentration are

$$\begin{aligned}&u(x,-L)=us=bx, u(x,+L)=0, v(x,\pm L)=0,\\&T(x,-L)=T_1, T(x,+L)=T_2\\&C(x,-L)=C_1, C(x,+L)=C_2\end{aligned} \tag{8}$$

Where b > 0 is the stretching rate of the channel wall, T_1, T_2 (with ($T_1 > T_2$) are the fixed temperature of the left and right walls respectively, C_1, C_2 (with $C_1 > C_2$) or the fixed concentrations of the channel walls respectively. We introduce the following Similarity variables as:

$$\begin{aligned}&\eta=\frac{y}{L}; u=bxf'(\eta); v=-bLf(\eta), w=bxg_0(\eta)\\&\theta(\eta)=\frac{T-T_2}{T_1-T_2}, \phi(\eta)=\frac{C-C_2}{C_1-C_2}\end{aligned} \tag{9}$$

Eliminating the pressure between the equations (2) and (3) and using (6) & (8) the momentum equation reduces to

$$f^{iv}+\mathrm{Re}_x(f'''f-ff'')-M^2f''+Gr(\theta'+N\phi')+Rg_0{}'=0 \tag{10}$$

$$g_0+\mathrm{Re}_x(f_0g'-f'g_0)-M^2g_0-Rf'=0 \tag{11}$$

where as the equations (6) & (7) in view of equation (9) are

$$\theta''+\Pr\mathrm{Re}\,x(f\theta')-Q\theta+\Pr Ec((f'')^2+(g_o^{'})^2)+M^2Ec((f')^2+g_0{}^2)=0 \tag{12}$$

$$\phi''+Sc\,\mathrm{Re}\,x(f\phi')-\gamma\phi+ScSo\theta''=0 \tag{13}$$

Where $Gr = \dfrac{\beta g(T_1 - T_2)L}{bx}$, is the Grashof number, $N = \dfrac{\beta^*(C_1 - C_2)}{\beta(T_1 - T_2)}$, is the buoyancy ratio, $M^2 = \dfrac{\sigma\mu_e^2 H_o^2 L^2}{\nu x}$, magnetic parameter, $R = \dfrac{2\Omega}{xL}$, Rotation parameter, $\Pr = \dfrac{\mu C_p}{k_f}$ is Prandtl number, $\operatorname{Re} x = \dfrac{bL^2}{\mu}$, is the local Reynolds number, $Sc = \dfrac{\nu}{D_m}$, is the Schmidt number, $So = \dfrac{D_T K_T (T_1 - T_2)}{T_m (C_1 - C_2)}$, is the Soret parameter $\gamma = \dfrac{k_c L^2}{D_m}$ is the chemical reaction parameter, $Ec = \dfrac{b^2 x^2}{C_p \Delta T}$ is the Eckert number

Boundary conditions (8), in view of equation (10) in dimensional form reduces to

$$f(\pm 1) = 0,\ f'(-1) = 1,\ f'(+1) = 0,\ g_0(-1) = 0,\ g_0(+1) = 0$$
$$\theta(-1) = 1, \theta(+1) = 0, \phi(-1) = 1, \phi(+1) = 0, \tag{14}$$

3. MTHOD OF SOLUTION

A usual approach is to write the nonlinear ODE in form of a first order initial value problem as follows:

$$f = f_1, f' = f_2 f'' = f_3, f''' = f_4, g = f_5, g' = f_6, \theta = f_7, \theta' = f_8, \phi = f_9, \phi' = f_1 \tag{15}$$

$$f^{iv} = f_4' = -\operatorname{Re} x(f_4 f_1 - f_2 f_3) - M^2 f_3 + Gr(f_6 + N f_8) - R f_6 \tag{16}$$

$$g_o{}^{ii} = f_6' = -\operatorname{Re} x(f_6 f_1 - f_2 f_5) - M^2 f_5 + R f_2 \tag{17}$$

$$\theta'' = f_6' = [-\Pr \operatorname{Re} x(f_1 f_6) - Q f_7 - \Pr Ec(f_3^2 + f_6^2) - M^2 Ec(f_2^2 + f_5^2) \tag{18}$$

$$\begin{aligned}\phi'' = f_8' = [&-Sc \operatorname{Re} x(f_1 f_{10}) + \gamma f_9 - ScSo(-\Pr \operatorname{Re}_x(f_1 f_8)) - Q f_7 - \\ &- M^2 Ec(f_2^2 + f_5^2) - \Pr Ec(f_3^2 + f_5^2)] / (1 + ScSo)\end{aligned} \tag{19}$$

The corresponding boundary conditions are

$$\begin{aligned}&f_1(\pm 1) = 0,\ f_2(-1) = 1,\ f_2(+1) = 0,\ f_5(-1) = 1,\ f_5(+1) = 0, \\ &f_6(-1) = 1,\ f_6(+1) = 0,\ f_7(-1) = 1, \\ &f_7(+1) = 0,\ f_8(-1) = 1,\ f_8(+1) = 0,\end{aligned} \tag{20}$$

Here $f_3(-1), f_4(-1), f_6(-1), f_8(-1), f_{10}(-1)$ are the unknown initial condition, Therefore, a shooting methodology is incorporated to solve the above system,which may be a combination of the Runge-Kutta method(to solve first order ODE) and a five dimensional zero finding algorithm(to find the missing coordinates). It is note that the missing initial conditions are coupled so that the solution satisfies the boundary conditions f(+1) = 0, f'(+1) = 0, g(+1) = 0, θ(+1) = 0, $\phi(+1) = 0$ of the original boundary value problem.

4. DISCUSSION OF THE NUMERICAL RESULTS

In this analysis we investigate the influence of rotation, thermo-diffusion and temperature dependent heat sorce, chemical reaction on convective heat and mass transfer flow of a viscous, dissipative fluid in a vertical channel bounded by a stretching plate and stationary plate. The non-linear governing equations have been solved by employing Fourth order Runge-Kutta –Shooting technique.

The primary velocity, secondary velocity, temperature and concentration have been analysed for different variations of G, M, D-1, R, N, Q, Ec, So, γ and Pr.

The variation of the primary velocity (f'(η), Secondary velocity, temperature (θ) and concentration (C) with Grashof number G is exhibited in figs.2a-2d respectively. It can be found from the profiles that increasing the values of thermal buoyancy parameter (G) has an enhancing effect on primary and secondary velocity components. This is due the fact that the thermal buoyancy increases the thickness of the momentum boundary layer. From the figure. 2c & 2d we find that the temperature reduces and concentration enhances with increasing values of G. This may be attributed to the fact the thickness of the thermal reduces and solutal boundary layers increases with increasing G.

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The variation of f', g, θ and C with magnetic field M is depicted in figs. 3a-3d.From the profiles we find the magnitude of the primary and secondary velocity components reduces with increasing M. This reduction can be attributed to the fact that the magnetic field provides a resisting type of force known as the Lorentz force.This force tends to lessen the motion of the fluid and as a consequence the velocity reduces. The temperature enhances and the concentration reduces with increasing values of M. Thus the thickness of the thermal boundary increases and the solutal boundary layer decreases with increasing M.

Figs.4a-4d demonstrate f', g, θ and C with inverse Darcy paramneter D^{-1}. The primary and secondary velocity components reduces and consequently the boundary layer becomes thinner. An increase in D^{-1} enhances the temperature and reduces concentration .

Figs.5a-5d represent the variation of the velocity, temperature and Concentrate with buoyancy ratio (N). It can be seen from the profiles that when the molecular buoyancy force dominates over the thermal buoyancy force the primary velocity, secondary velocity components are vertically upwards and increases irrespective of the directions of the buoyancy forces. Fig.6c and fig.6d shows the variation of θ and the concentration ϕ with buoyancy ratio (N). We observe from the figure that when the molecular buoyancy force dominates over the thermal buoyancy force the temperature and concentration reduces when the buoyancy forces are in the same direction and for the forces acting in opposite directions, they enhances in the flow region.

The effect of Schmidt number (Sc) on f', g, θ and C is exhibited in figs.6a-6d. It can be seen from the profiles that the primary & secondary velocities and concentration enhance and temperature decreases with increase in Sc. Thus lesser the molecular diffusivity larger the thickness of the momentum and solutal boundary layer and smaller the thermal boundary layer

Figs.7a-7d, 8a-8d show the variation of primary velocity ,secondary velocity, temperatrure and concentration with chemical reaction parameter (γ). It can be noticed from the graphs that the primary velocity increases in both the degenerating and generating chemical reaction cases (figs.7a & 8a). The secondary velocity, the concentration reduces in the degenerating chemical reaction case and enhances in the generating case (figs.7b-7d, 8b-8d). The temperature increases in the degenerating chemical reaction case and reduces in the generating chemical reaction case.

The effect of rotation parameter (R) on f', g, θ, ϕ is demonstrated in figs. 9a-9d. We observe from the profiles that the primary velocity and the concentration reduces and the secondary velocity and the temperature increases with increase in R in the entire flow region. Thus higher the coriolis force larger the thickness of the momentum and thermal boundary layer and smaller the solutal boundary layers.

Figs.10a-10d, illustrates f', g, θ, ϕ with variation in temperature dependent Heat source parameter ($Q > 0$). The presence of the heat generating sources generates energy in the momentum, thermal boundary layers and as a consequence the velocity components, temperature increase in the boundary layers. In the case of heat absorption ($Q<0$) the velocity components, temperature and the concentration reduces with decreasing values of $Q<0$, owing to the absorption of energy in the boundary layer.

Figs.11a-11d represent f', g, θ and C with Soret parameter So, It can be noticed from the profiles that higher the thermo-diffusion effects larger the magnitude of primary and secondary velocity components, temperature and concentration in the flow region. This can be attributed to the fact that increasing values of So increases the thickness of the momentum, thermal and solutal boundary layers.

The effect of dissipation (Ec) on f', g, θ and C is shown in figs.12a-12d. It can be found that higher the dissipative energy larger the magnitude of the primary, secondary velocity components, temperature and the concentration in the flow region. This is due to the fact that heat energy is reserved due to frictional heating (figs.12a-12d).

The variation of f', g, θ and C with Prandtl number (Pr) is depicted in figs.13a-13d respectively. It can be observed from the profiles that an increase in Pr reduces the primary & secondary velocities, temperature and enhances the concentration in the flow region. This can be attributed to the fact the lesser the thermal diffusivity smaller the thickness of the momentum and thermal boundary layer and larger the solutal boundary layers..

The skin friction component (τx) reduces at η=-1 with increase in G and enhances at η=+1 while (τz) enhances at η=-1 and reduces at η=+1 with increase in G. An increase in magnetic parameter M increases (τx) at η=-1 and reduces at η=+1 while (τz) decreases at η=-1&+1.With reference to inverse darcy parameter D^{-1} , we find that the skin friction(τx) enhances while (τz) reduces at η=-1. At η=+1, (τx) reduces & (τz) increases with increase in D^{-1}. When the molecular buoyancy force dominates over the thermal buoyancy force (τx) decreases at η=-1 and increases at η=+1 when the buoyancy forces are in the same directions and for the buoyancy forces acting in opposite directions,(τx) enhances at

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both the walls. (τz) enhances with N>0 and reduces at η=-1 and enhances at η=+1 with N<0.An increase in rotation parameter R increases (τx) at η=-1 and reduces at η=+1 while (τz) enhances at both the walls. The variation of Stress components with chemical reaction parameter(γ) shows that (τx) increases at η=-1 and enhances at η=+1 in the degenerating and in the case of generating chemical reaction case,it reduces at both the walls while (τz) increases with γ in both the degenerating and generating case at η=+1 and at η=-1, it reduces in the degenerating chemical reaction case and enhances in the generating case.With reference to heat source parameter Q we find that (τx) reduces at η=-1 and enhances at η=+1 with increasing heat generating source and in the case of heat absorbing source,it enhances at η=-1 and reduces at η=+1while, (τz) enhances at η=± 1 with increase in the heat generating source (Q>0) while in the heat absorbing heat source. (τz) reduces at η=± 1. An increase in Sc reduces (τx) and (τz) at η=-1 and enhances at η=+1. With increase in Ec, we notice that (τx) reduces at η=-1 and enhances at η=+1 while (τz) increases at both the walls.The variation of Skin friction component with Soret parameter (So) shows that (τx) reduces at η=-1 and enhances at η=+1 while (τz) increases at both the walls with increasing So. An increase in the Prandtl number (Pr) increases (τx) at η=-1 and reduces at η=+1 while (τz) reduce at the wall $\eta = \pm 1$.

The rate of heat transfer (Nusselt number) at $\eta = \pm 1$ is exhibited in tables. 1&2 for different parametric variations It is found that the rate of heat transfer enhances at η=-1 and reduces at η=+1 with increasing G.Higher the Lorentz force smaller the rate of heat transfer at η=-1 and larger at η=+1. An increase in D^{-1} reduces Nu at η=-1 and enhances at η=+1. When the molecular buoyancy force dominates over the thermal buoyancy force the rate of heat transfer increases at η=± 1 when the buoyancy forces are in the same directions and for the forces acting in opposite directions, it reduces at η=-1 and enhances at η=+1.The rate of heat transfer reduces at η=-1 and enhances at η=+1 with increase in Sc.

The rate of heat transfer reduces at η= -1 and enhances at η=+1 in the degenerating chemical reaction case and in the generating chemical reaction case, it enhances at η=-1 and reduces at η=+1.An increase in rotation parameter R reduces Nu at η=-1 and increases it at η=+1. The rate of heat transfer reduces at η=-1 and enhances at η=+1 in heat generating source (Q>0) while in the heat absorbing source, Nu enhances at η=-1 and reduces at η=+1. The variation of Nu with So shows that higher the thermo-diffusion effects larger Nu at η=-1 and smaller Nu at η=+1.

With respect to Eckert number (Ec) we find that higher the dissipation smaller Nu at η=-1 and larger at η=+1. The variation of Nu with Pr shows that lesser the thermal diffusivity, larger Nu at η=-1 and smaller Nu at η=+1.

The rate of mass transfer (Sherwood number) at $\eta = \pm 1$ is exhibited in tables.1 & 2 for different parametric variations. It is found that the rate of mass transfer enhances at η=-1 and reduces at η=+1 with increase in G.Higher the Lorentz force smaller the rate of mass transfer at η=± 1. An increase in D^{-1} decreases Sh at η=± 1.When the molecular buoyancy force dominates over the thermal buoyancy force the rate of mass transfer increases at $\eta = -1$ and reduces at η=+1 when the buoyancy forces are in the same direction and for the forces acting in opposite direction ,it reduces at η=± 1.An increase in Q>0 reduces Sh at $\eta = -1$ and enhances it at η=+1 while an increase in Q<0 enhances at η=-1 and reduces at η=+1. With respect to R we find that the rate of mass transfer reduces at η=± 1 fixing the other parameters. The rate of mass transfer enhances at $\eta = -1$ and reduces at $\eta = +1$ both in degenerating /generating chemical reaction cases.An increase in Sc increases Sh at η=-1 and reduces at η=+1. Higher the dissipation lesser Sh at $\eta = -1$ and enhances at η=+1.With reference to So we notice an enhancement in Sh at both the walls. The rate of mass transfer enhances with Pr at η=-1 and reduces at η=+1. Thus lesser the thermal diffusivity larger Sh at the left wall η=-1 and smaller Sh at η=+1.

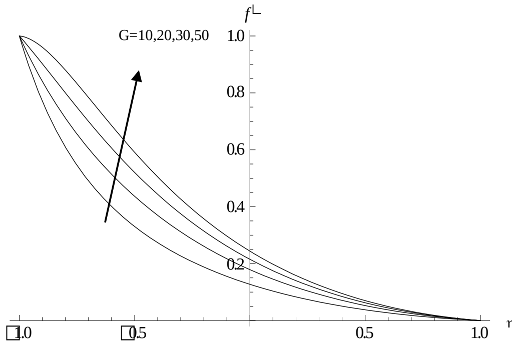

Fig.2a : Variation of f' with G
M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.1,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

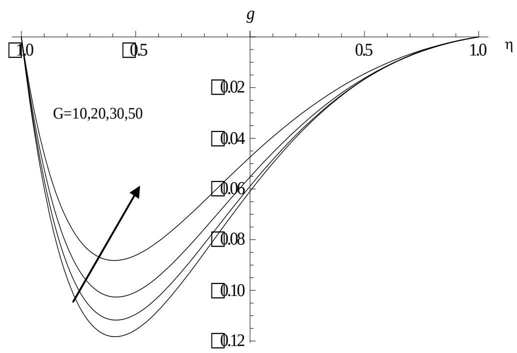

Fig.2b : Variation of g_0 with G
M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.1,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

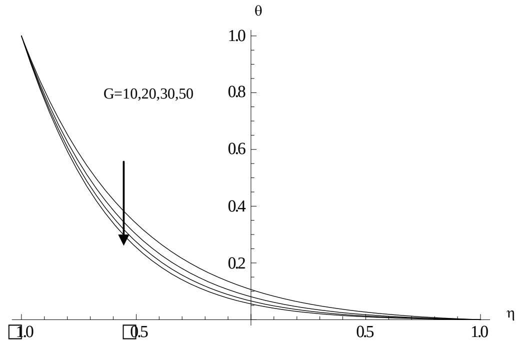

Fig.2c : Variation of θ with G
M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.1,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

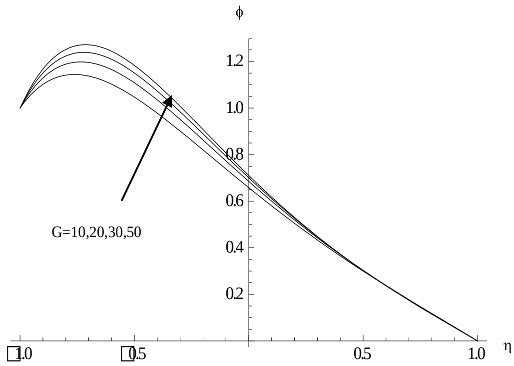

Fig.2d : Variation of ϕ with G
M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

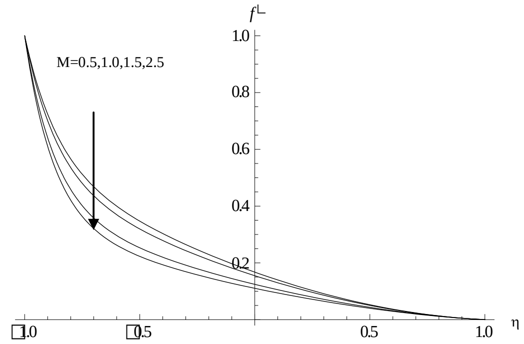

Fig.3a : Variation of f' with M
G=10, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

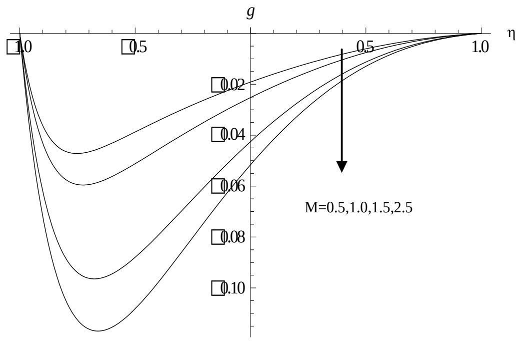

Fig.3b : Variation of g_0 with M
G=10, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

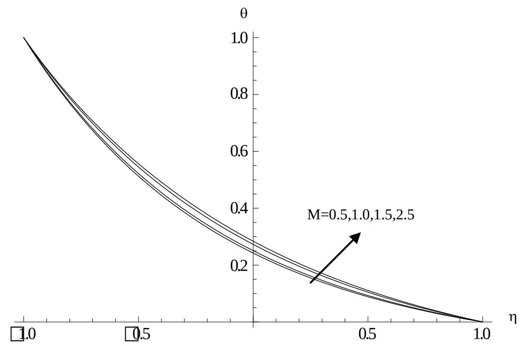

Fig.3c : Variation of θ with M
G=10, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

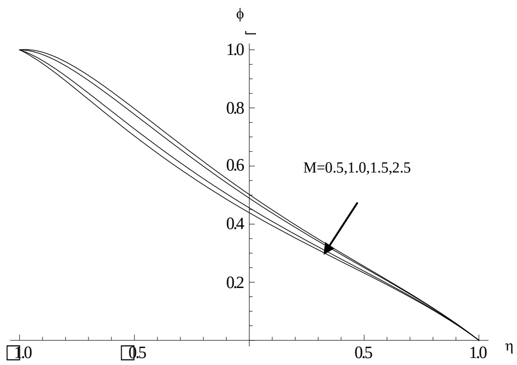

Fig.3d : Variation of ϕ with M
G=10, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

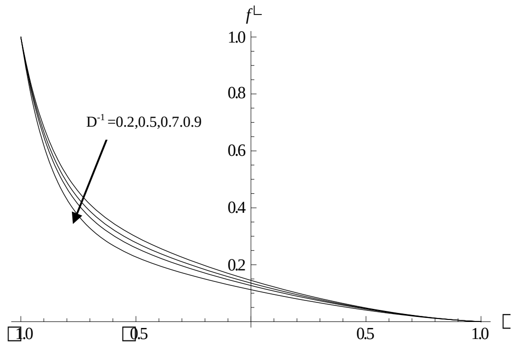

Fig.4a : Variation of f' with D^{-1}
G=10, M=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

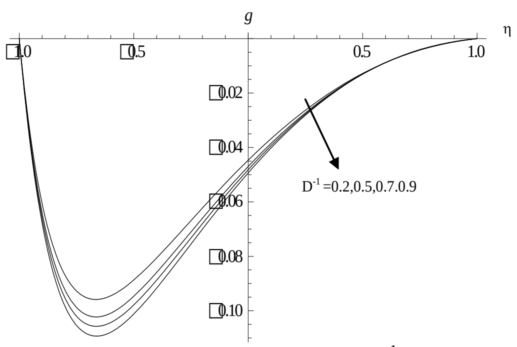

Fig.4b : Variation of $g_0$with D^{-1}
G=10, M=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

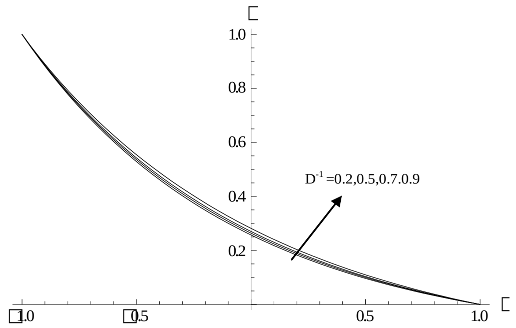

Fig.4c : Variation of θ with D^{-1}
G=10, M=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

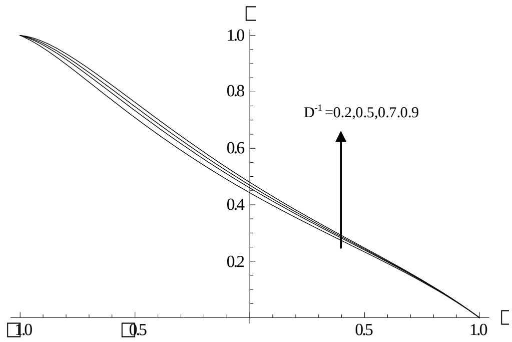

Fig.4d : Variation of ϕ with D^{-1}
G=10, M=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

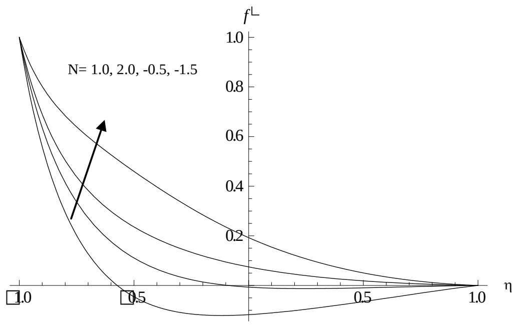

Fig.5a : Variation of f' with N
G=10, M=0.5, D^{-1}=0.5, Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

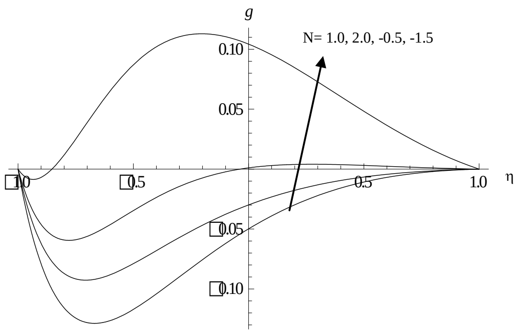

Fig.5b : Variation of g_0 with N
G=10, M=0.5, D^{-1}=0.5, Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

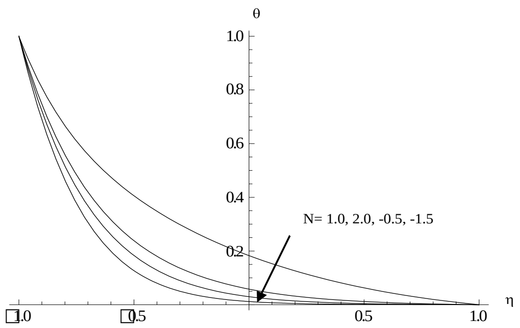

Fig.5c : Variation of θ with N
G=10, M=0.5, D^{-1}=0.5, Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

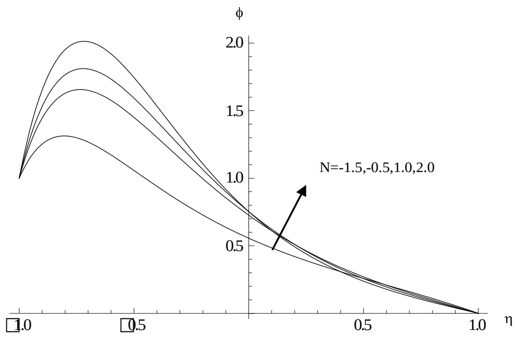

Fig.5d : Variation of ϕ with N
G=10, M=0.5, D^{-1}=0.5, Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

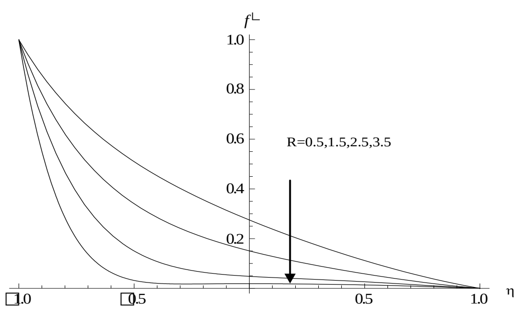

Fig.6a : Variation of f' with R
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

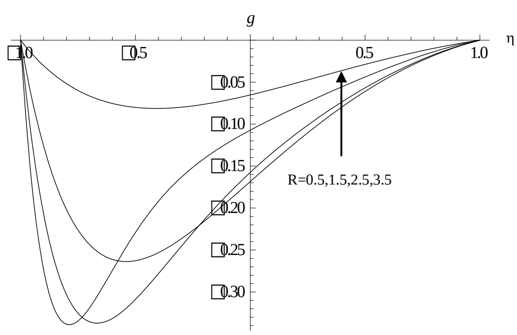

Fig.6b : Variation of g_0 with R
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

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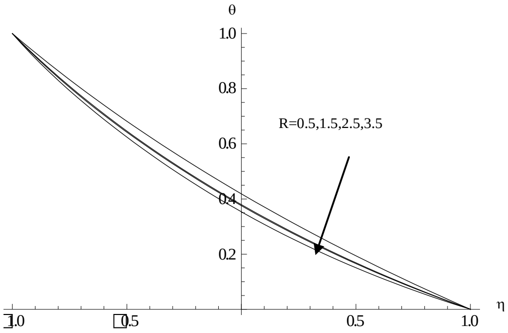

Fig.6c : Variation of θ with R
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

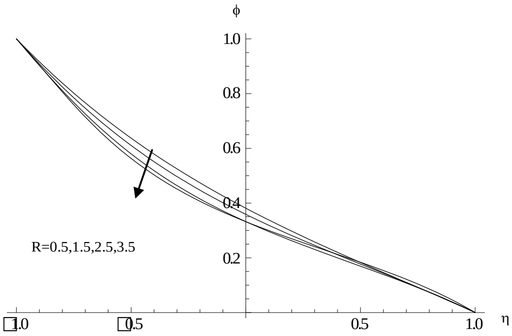

Fig.6d : Variation of ϕ with R
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

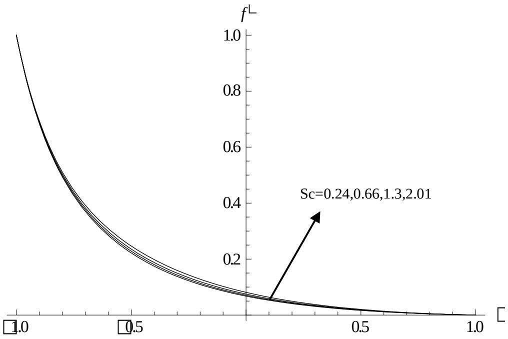

Fig.7a : Variation of *f ′* with Sc
G=10, M=0.5, D^{-1}=0.5, N=1, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

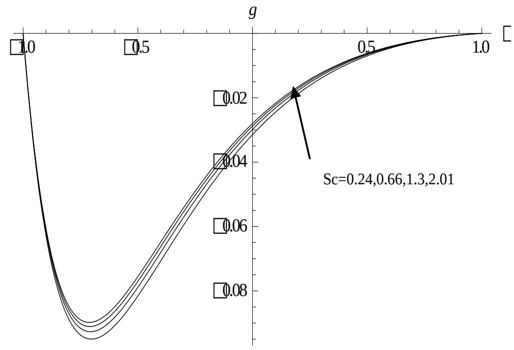

Fig.7b : Variation of *g* with Sc
G=10, M=0.5, D^{-1}=0.5, N=1, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

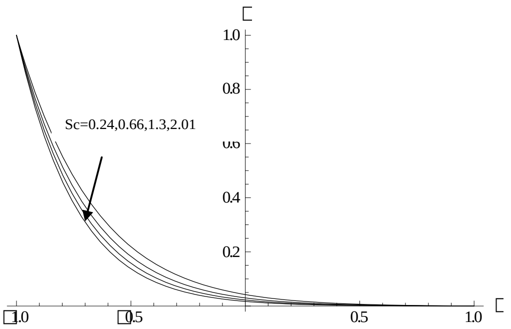

Fig.7c : Variation of θ with Sc
G=10, M=0.5, D^{-1}=0.5, N=1, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

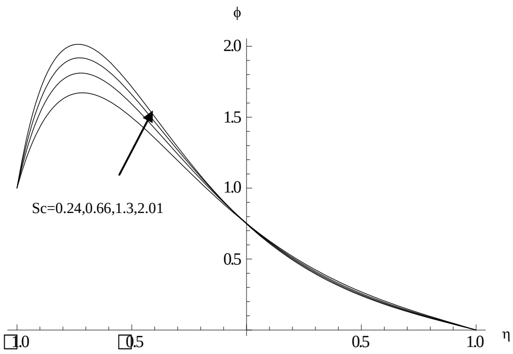

Fig.7d : Variation of ϕ with Sc
G=10, M=0.5, D^{-1}=0.5, N=1, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

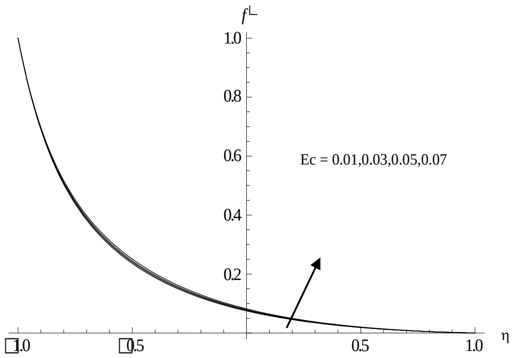

Fig.8a : Variation of *f ′* with Ec
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5, Sr=0.5, Pr=0.71

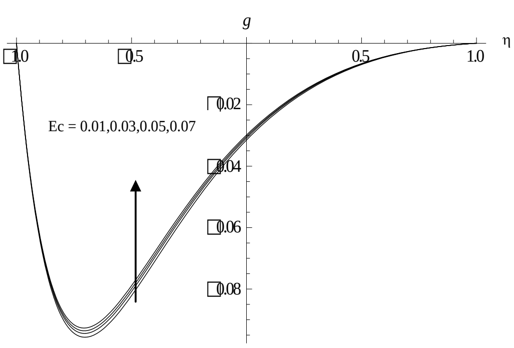

Fig.8b : Variation of g_0 with Ec
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5, Sr=0.5, Pr=0.71

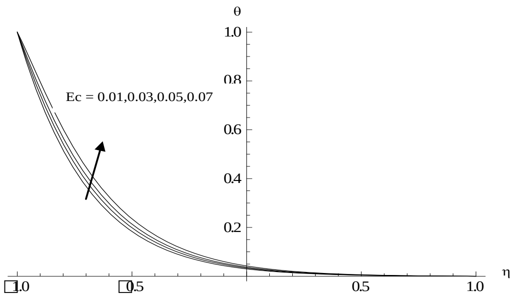

Fig.8c : Variation of θ with Ec
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5, Sr=0.5, Pr=0.71

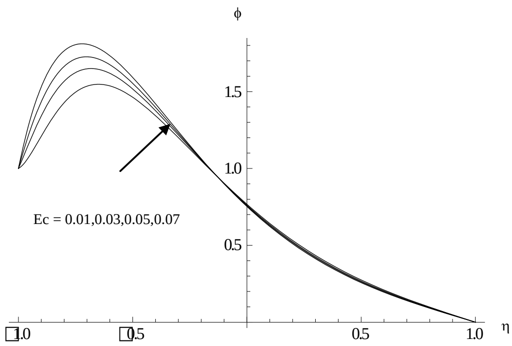

Fig.8d : Variation of ϕ with Ec
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5, Sr=0.5, Pr=0.71

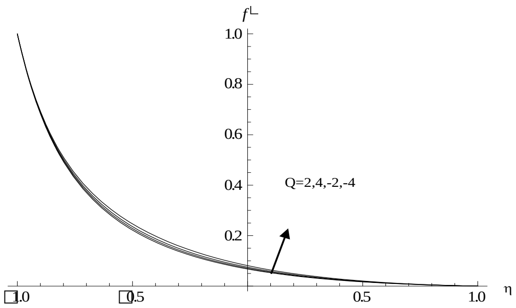

Fig.9a : Variation of *f′* with Q
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

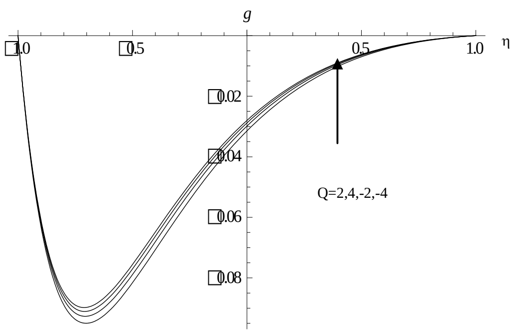

Fig.9b : Variation of g_0 with Q
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

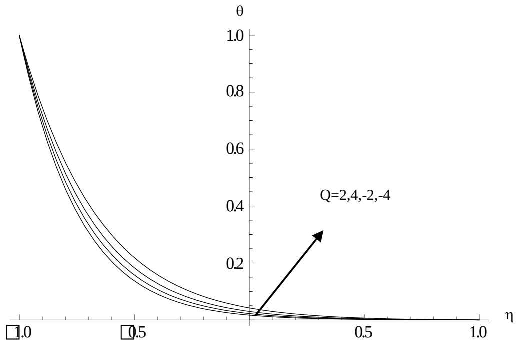

Fig.9c : Variation of θ with Q
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

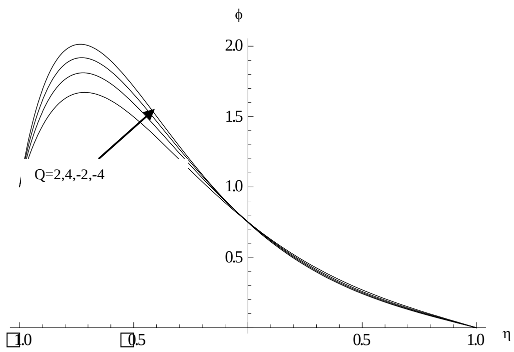

Fig.9d : Variation of ϕ with Q
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3,
γ=0.5,Ec=0.01,Sr=0.5, Pr=0.71

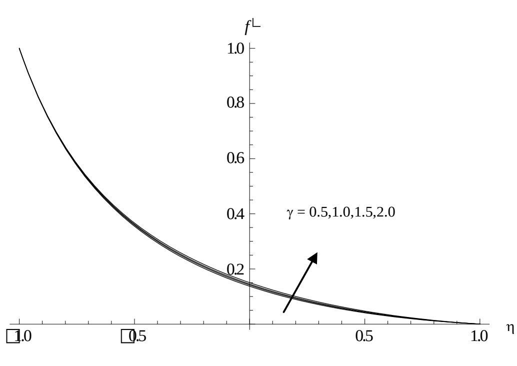

Fig.10a : Variation of *f′* with γ
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
Ec=0.01,Sr=0.5, Pr=0.71

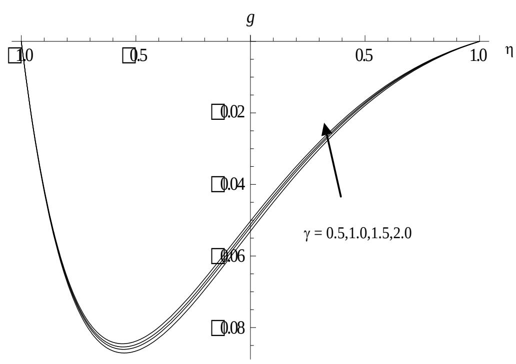

Fig.10b : Variation of g_0 with γ
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
Ec=0.01,Sr=0.5, Pr=0.71

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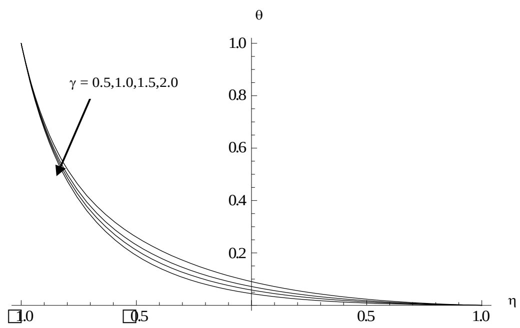

Fig.10c : Variation of θ with γ
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
Ec=0.01,Sr=0.5, Pr=0.71

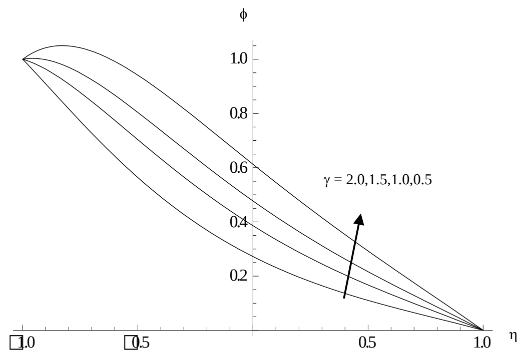

Fig.10d : Variation of ϕ with γ
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
Ec=0.01,Sr=0.5, Pr=0.71

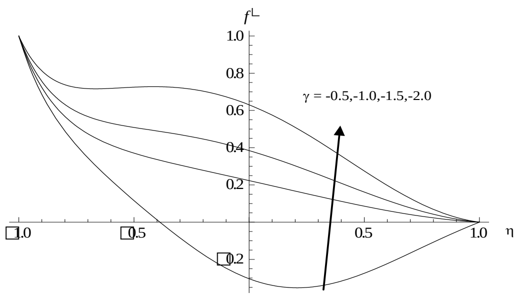

Fig.11a : Variation of f' with γ<0
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
Ec=0.01,Sr=0.5, Pr=0.71

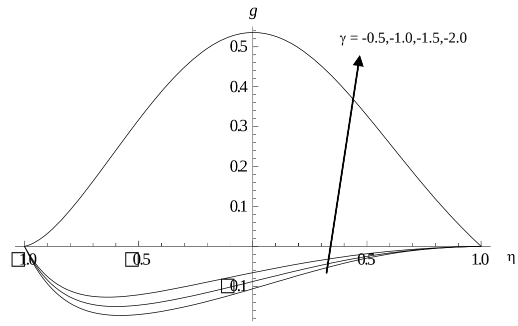

Fig.11b : Variation of g_0 with γ<0
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
Ec=0.01,Sr=0.5, Pr=0.71

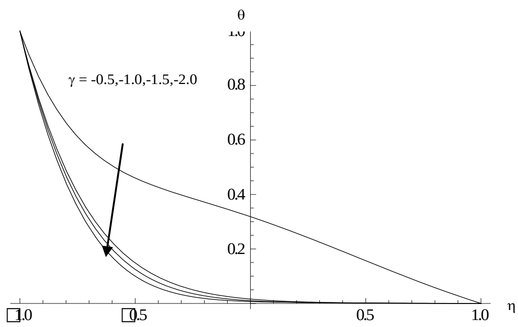

Fig.11c : Variation of θ with γ<0
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
Ec=0.01,Sr=0.5, Pr=0.71

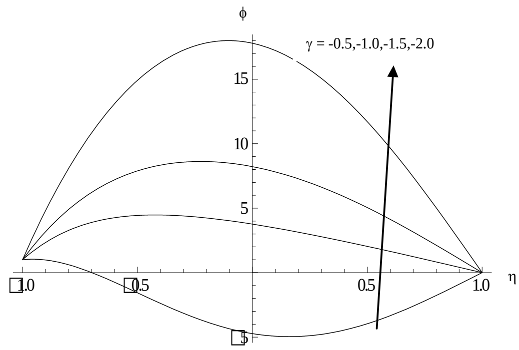

Fig.11d : Variation of ϕ with γ<0
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
Ec=0.01,Sr=0.5, Pr=0.71

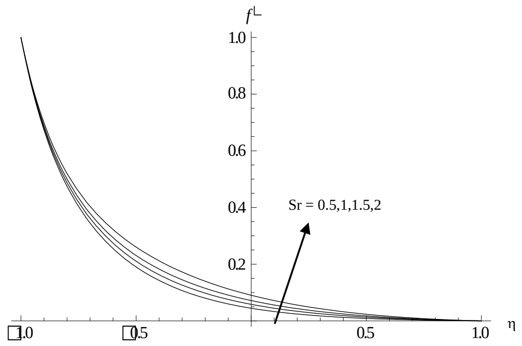

Fig.12a : Variation of f' with Sr
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01, Pr=0.71

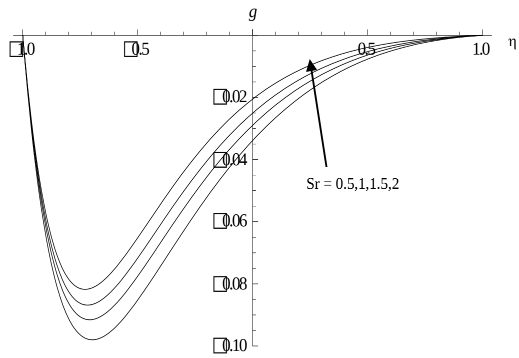

Fig.12b : Variation of g_0 with Sr
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01, Pr=0.71

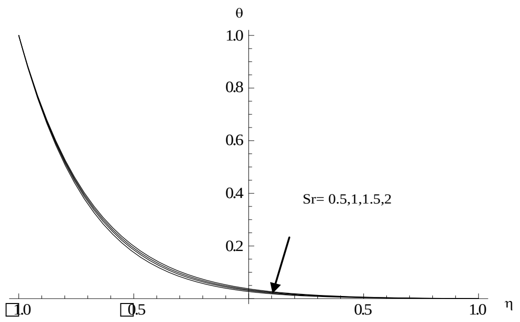

Fig.12c : Variation of θ with Sr
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01, Pr=0.71

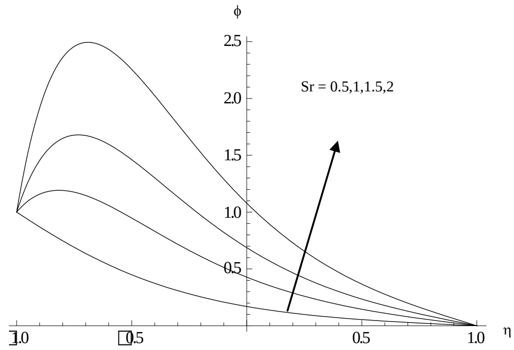

Fig.12d : Variation of ϕ with Sr
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01, Pr=0.71

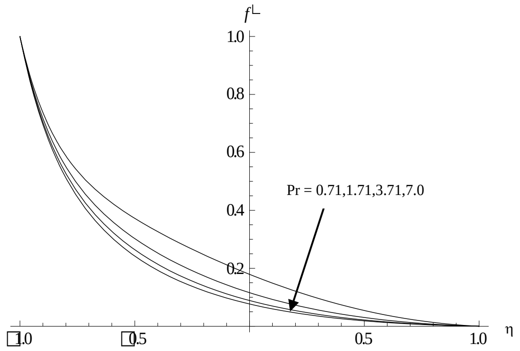

Fig.13a : Variation of *f ′* with Pr
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5

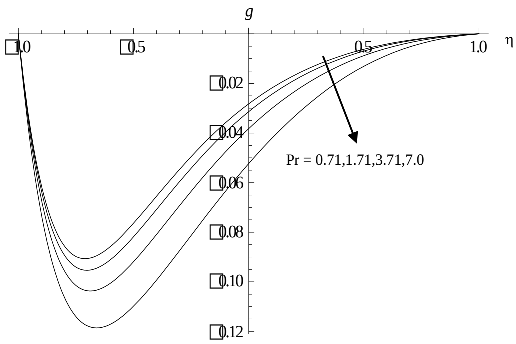

Fig.13b : Variation of g_0 with Pr
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5

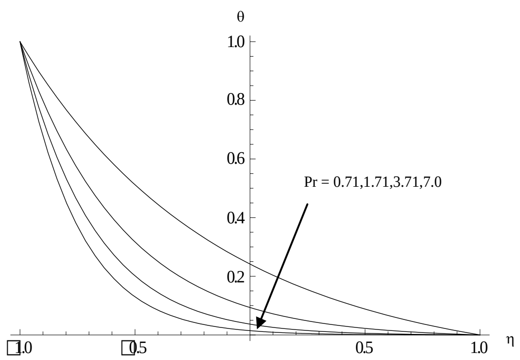

Fig.13c : Variation of θ with Pr
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5

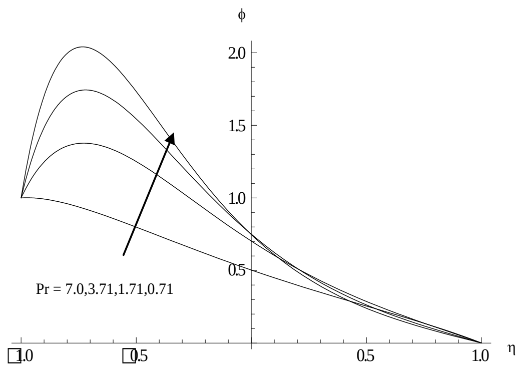

Fig.13d : Variation of ϕ with Pr
G=10, M=0.5, D^{-1}=0.5, N=1,Sc=1.3, Q=0.5,
γ=0.5,Ec=0.01,Sr=0.5

Skin friction, Nusselt number ans Sherwood number at η=-1

Parameters		**τx(-1)**	**τz(-1)**	**Nu(-1)**	**Sh(-1)**
G	**10**	-2.03703	-0.587974	1.77486	-0.692889
	20	-1.08064	-0.642366	1.94204	-0.995348
	30	-0.19567	-0.681915	2.06226	-1.220039
	50	-0.06459	-0.714219	2.15125	-1.389780
M	**0.5**	-2.03703	-0.587974	1.77486	-0.692889
	1.0	-2.40974	-0.508044	1.70043	-0.559817
	1.5	-3.51572	-0.358304	1.48393	-0.175049
	2.0	-4.37294	-0.289916	1.29837	-0.100155
D^{-1}	**0.2**	-2.45194	-0.561335	1.69234	-0.547193
	0.5	-2.64511	-0.549156	1.65426	-0.480112
	0.7	-3.17866	-0.516519	1.55115	-0.298853
	0.9	-3.80642	-0.480335	1.43532	-0.095385

Ec	**0.01**	-2.03703	-0.587974	1.77486	-0.692889
	0.03	-2.02043	-0.590332	1.61652	-0.347543
	0.05	-2.01267	-0.59143	1.54279	-0.186875
	0.07	-2.00215	-0.592924	1.44265	0.0311430
N	**1.0**	-2.03703	-0.587974	1.77486	-0.692889
	2.0	-0.67024	-0.697892	2.08936	-1.250290
	-0.5	-2.29998	-0.558676	1.69334	-0.556843
	-1.5	-3.44245	-0.404941	1.24797	-0.166996
Sc	**0.24**	-2.03703	-0.587974	1.77486	-0.692889
	0.66	-2.03653	-0.586574	1.72486	-0.642889
	1.3	-2.03553	-0.585674	1.68487	-0.602889
	2.01	-2.03453	-0.584513	1.59428	-0.569935
γ	**0.5**	-2.03703	-0.58797	1.77486	-0.692889
	1.5	-2.07074	-0.58135	1.75777	1.0581368
	-0.5	-2.48072	0.302694	0.84633	1.2654456
	-1.5	-2.00147	-0.55226	1.72106	-5.668678
Q	**2**	-2.03703	-0.587974	1.7748	-0.692889
	4	-1.91656	-0.608403	1.09333	-0.618692
	-2	-2.06888	-0.582541	1.98019	-1.107257
	-4	-2.12954	-0.572484	2.42046	-2.024470
Sr	**0.5**	-2.03703	-0.587974	1.7748	-0.692889
	1.0	-1.95101	-0.603112	1.81478	-5.448449
	1.5	-1.86069	-0.617444	1.85339	-10.45980
	2.0	-1.76681	-0.630955	1.89041	-15.71685
R	**0.5**	-2.03703	-0.58797	1.7748	-0.692889
	1.5	-2.34647	-1.61519	1.62672	-0.446092
	2.5	-2.75908	-2.35785	1.42162	-0.110303
	3.5	-3.15578	-2.91083	1.24069	-0.088475
Pr	**0.71**	-2.03703	-0.587974	1.7748	-0.692889
	1.71	-2.19956	-0.560658	2.91163	-3.045695
	3.71	-2.28479	-0.549473	3.76788	-4.949066
	7.00	-2.33541	-0.544151	4.42733	-6.463197

Skin friction, Nusselt number ans Sherwood number at η=+1

Parameters		**τx(+1)**	**τz(+1)**	**Nu(+1)**	**Sh(+1)**
G	**10**	-0.0655451	0.0275487	0.0521966	0.606915
	20	-0.0779018	0.0253816	0.0299008	0.604275
	30	-0.0827877	0.0227305	0.0195802	0.59695
	50	-0.0855782	0.0204517	0.0141228	0.590085
M	**0.5**	-0.0655451	0.0275487	0.0521966	0.606915
	1.0	-0.061142	0.0201814	0.0646841	0.604617
	1.5	-0.0495033	0.0086822	0.1097083	0.584358
	2.0	-0.0427335	0.0049826	0.1494846	0.558138
D^{-1}	**0.2**	-0.059364	0.0279413	0.0670003	0.603638
	0.5	-0.0567857	0.0280445	0.0745017	0.601086
	0.7	-0.0506492	0.0281107	0.0967824	0.590913
	0.9	-0.0449594	0.0278358	0.1249585	0.573951
Ec	**0.01**	-0.0655451	0.0275487	0.0521966	0.606915
	0.03	-0.0673177	0.0277391	0.0568069	0.612315
	0.05	-0.0681508	0.0278258	0.0590208	0.614833
	0.07	-0.0692906	0.0279414	0.0620996	0.618253
N	**1.0**	-0.0655451	0.0275487	0.052196	0.606915
	2.0	-0.145661	0.0277458	0.012603	0.592467
	-0.5	-0.0361235	0.0231468	0.071699	0.599659
	-1.5	0.0978579	-0.0269586	0.239909	0.458458
Sc	**0.24**	-0.0655451	0.0275487	0.0521966	0.606915
	0.66	-0.0675450	0.0287485	0.0531964	0.596910
	1.3	-0.0655451	0.0295487	0.0540969	0.546909
	2.01	-0.0645623	0.0305615	0.0555971	0.457273
γ	**0.5**	-0.0655451	0.0275487	0.052196	0.606915
	1.5	-0.0559177	0.0260933	0.056654	0.228457
	-0.5	0.809027	-1.41319	0.960033	-20.6673
	-1.5	0.13677	-0.0165963	0.084417	-6.39483

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Q	**2**	-0.0655451	0.0275487	0.052196	0.606915
	4	-0.0859544	0.0297902	0.111184	0.645987
	-2	-0.0604617	0.0268497	0.039589	0.59681
	-4	-0.051954	0.0255656	0.020641	0.576283
Sr	**0.5**	-0.065545	0.0275487	0.0521966	0.606915
	1.0	-0.086329	0.0300762	0.0430097	1.55876
	1.5	-0.104468	0.0316217	0.0354804	2.51013
	2.0	-0.120039	0.0324001	0.0293755	3.45357
R	**0.5**	-0.065545	0.0275487	0.0521966	0.606915
	1.5	-0.034318	0.0659673	0.0893252	0.591217
	2.5	-0.012706	0.0669055	0.155246	0.545665
	3.5	-0.011085	0.0726603	0.219296	0.491788
Pr	**0.71**	-0.0655451	0.0275487	0.0521966	0.606915
	1.71	-0.0429498	0.0239878	0.0030104	0.551841
	3.71	-0.0391188	0.0234294	0.0002614	0.515451
	7.00	-0.0383326	0.0234424	0.0001336	0.500745

Comparison: In the absence of rotation (R=0) the results are in good agreement with hat of **Sreenivasa rao [37].**

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