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EFFECT OF NON-LINEAR THERMAL RADIATION ON CONVECTIVE HEAT AND MASS TRANSFER FLOW OF A MICROPOLAR FLUID IN A VERTICAL CHANNEL WITH SORET AND DUFOUR EFFECT

Authored by:

Dr. P. Gayathri

From

Govt. Degree College, Rayachoti, Kadapa District, A.P., India.

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EFFECT OF NON-LINEAR THERMAL RADIATION ON CONVECTIVE HEAT AND MASS TRANSFER FLOW OF A MICROPOLAR FLUID IN A VERTICAL CHANNEL WITH SORET AND DUFOUR EFFECT

Dr. P. Gayathri
Lecturer in Mathematics, Govt. Degree College, Rayachoti, Kadapa District, A.P., India
Email : pgayathri.p@gmail.com

Abstract : *The purpose of the present paper is to analyze the combined influence of non-linear thermal radiation and radiation absorption on mixed convective heat and mass transfer flow of a micropolar fluid between two vertical parallel plates with varying temperature in the presence of heat sources. Such type of study may be applicable in nuclear reactors, heat exchangers and various electronic devices.*

Keywords : Thermal radiation, Heat and Mass transfer, micropolar fluid, vertical channel, Soret and Dufour effect

1. INTRODUCTION

The analysis of mixed convection boundary layer flow along a vertical plate embedded in a fluid saturated porous media has received considerable theoretical and practical interest. The phenomenon of mixed convection occurs in many technical and industrial problems such as electronic devices cooled by fans, nuclear reactors cooled during an emergency shutdown, a heat exchanger placed in a low-velocity environment, solar collectors and so on. A detailed review of convective heat transfer in Darcy and non-Darcy porous medium can be found in the book by Nield and Bejan [24].

Combined heat and mass transfer problems with chemical reaction are of importance in many processes and have, therefore, received a considerable amount of attention in recent years. In processes such as drying evaporation at the surface of a water body, energy transfer in a wet cooling tower and the flow in a desert cooler, heat and the mass transfer occur simultaneously. Many practical diffusive operations involve the molecular diffusion of a species in the presence of chemical reaction within or at the boundary. The study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. Several authors have discussed [Muthucumaraswamy and Ganesan [21, 22, 23], Deka *et al.* [9], Chamkah [7], Raptis and Peridikis [26], Seddeek *et al.* [28], Ibrahim *et al.* [16] the effect of chemical reaction on fluid flow past semi infinite plate.

The study of heat generation or absorption effects in moving fluids is important in view of several physical problems such as fluids undergoing exothermic or endothermic chemical reactions. The volumetric heat generation has been assumed to be constant or a function of space variable. For example, a hypothetical core – disruptive accident in a liquid metal fast breeder reactor (LMFBR) could result in the setting of fragmented fuel debris on horizontal surfaces below the core. The porous debris could be saturated sodium coolant and heat generation will result from the radioactive decay of the fuel particulate. Several authors [Vajravelu and Hadjinicolaou [33], Hossain *et al.* [14], Alam *et al.* [2], Chamkha [7], Hady *et al.* [13]] have studying heat and mass transfer flow past semi infinite plate under varied conditions.

The study of non-Newtonian fluid flows has gained much attention from researchers because of its applications in biology, physiology, technology and industry. In addition, the effects of heat and mass transfer in non-Newtonian fluid also have great importance in engineering applications such as thermal design of industrial equipment dealing with molten plastics, polymeric liquids, foodstuffs, or slurries. The micropolar fluid model introduced by Eringen [10] exhibits some microscopic effects arising from the local structure and micro motion of the fluid elements. The mathematical theory of equations of micropolar fluids and applications of these fluids in the theory of lubrication and porous media is presented by Lukaszewicz. Eringen [11] developed a subclass of these micro fluids, called micropolar fluids, where the micro-rotational effects and micro-rotational inertia exist but they do not support stretch. They can support couple stresses and body couples only. Physically some polymeric fluids, fluids containing small amounts of polymeric additives, blood, paints, lubricating oils, liquid crystals,

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colloidal fluids and suspension fluid may be represented by the mathematical model, underlying micropolar fluids. An excellent review of micropolar fluids and their applications were provided by Ariman *et al.* [4]. Hoyt and Fabula [15] have shown experimentally that the fluids containing minute polymeric additives indicate considerable reduction of the skin friction (about 25–30%); a concept, which is well explained by the theory of micropolar fluids. As an application, these fluids with microstructure are also capable of representing the body fluids.

The problems of micropolar fluid flow between two vertical plates (channel) are of great technical interest. Several researchers [Sastry and Rao [27], Agarwal and Dhanapal [1], Bhargava and Rani [5], Chamkha *et al.* [6] Srinivasacharya *et al.* [30], Gorla *et al.* [12], Lukaszewicz [18], Tulasi *et al.* [32], Kumar *et al.* [17]] have analyzed micropolar fluids flow in channels under different conditions. Venkatalakshmi et al [34] have studied the influence thermal radiation on convective heat and mass transfer flow micropolar fluid in vertical channels with between two vertical parallel plates with varying temperature in the presence of heat sources. Such type of study may be applicable in nuclear reactors, heat exchangers and various electronic devices. Several authors have been [Mahanthesh et al [19], Mustafa et al[20], Anuradha et al[3], Sher Muhammad et al[29]. Suguna et al[31]] discussed the influence of non-linear thermal radiation on three dimensional steady flow of a nanofluid past a non-linear stretching sheet in the presence of Soret and Dufour effects.

2. FORMULATION OF THE PROBLEM

We consider a fully developed laminar convective heat and mass transfer flow of a viscous, electrically conducting fluid through a porous medium confined in a vertical channel bounded by flat walls. We choose a Cartesian co-ordinate system O (x, y, z) with x- axis in the vertical direction and y-axis normal to the walls. 'u' is the velocity component along the x-axis the component of micro rotation, T-the temperature and C –the concentration. Temperature is varying linearly along the x-axis with cx and mcx being the temperature of the left (y=-L) and the right hand plate (y=+L) respectively while the walls are maintained at constant concentration. The porous medium is assumed to be isotropic and homogeneous with constant porosity and effective thermal diffusivity. The thermo physical properties of porous matrix are also assumed to be constant and Boussinesq approximation is invoked by confining the density variation to the buoyancy term. In the absence of any extraneous force flow is unidirectional along the x-axis which is assumed to be infinite.

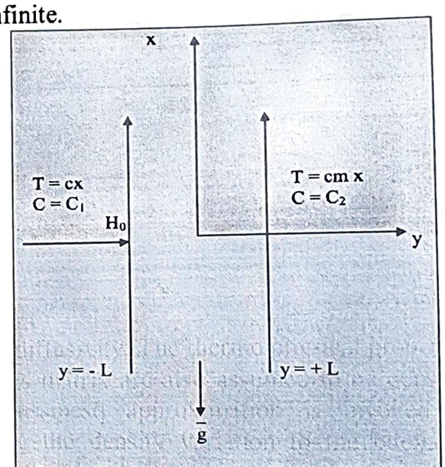

Fig. 1 : Configuration of the Problem

Thus, the governing equations of this type of flow can be written as:

Momentum:

$$(\mu+k)\frac{d^2u}{dy^2}+k\frac{dN}{dy}-\frac{dP}{dx}+\rho_e g(\beta T+\beta^* C)-(\frac{\mu}{k})u-(\frac{\sigma\mu_e^2H_o^2}{\rho_e})u=0 \quad (1)$$

Angular Momentum:

$$\gamma\frac{d^2N}{dy^2}-k\frac{du}{dy}-2kN=0 \quad (2)$$

Energy equation:

$$k\frac{d^2T}{dy^2}+(\mu+\frac{k}{2})(\frac{du}{dy})^2+\frac{k}{2}(\frac{du}{dy}+2N)^2+\gamma(\frac{dN}{dy})^2-Q_HT+Q_1C-\frac{\partial(q_R)}{\partial y}+\frac{D_TK_T}{C_sC_p}\frac{d^2C}{dy^2}=0 \quad (3)$$

Diffusion equation:

$$D_b\frac{d^2C}{dy^2}-k_cC+\frac{D_TK_T}{T_m}\frac{d^2T}{dy^2}=0 \quad (4)$$

The appropriate physical boundary conditions are given by

$$u=0,\ N=N_o,\ T=cx,\ C=C1, on\ y=-L$$
$$u=0,\ N=N_o,\ T=cmx,\ C=C2,\ on\ y=+L \quad (5)$$

where m is the wall temperature ratio parameter and c is the varying temperature.
The non-dimensional temperature

$\theta(\eta)=\dfrac{T-T_\infty}{T_w-T_\infty}$ can be simplified as

$T=T_\infty(1+(\theta_w-1)\theta)$

where $\theta_w=\dfrac{T_w}{T_\infty}$ is the temperature ratio and equation (3) under Rosseland approximation reduces to

$$k\frac{d^2T}{dy^2}+(\mu+\frac{k}{2})(\frac{du}{dy})^2+\frac{k}{2}(\frac{du}{dy}+2N)^2+\gamma(\frac{dN}{dy})^2 -Q_HT+Q_1C+\frac{16\sigma^*T_\infty^3}{3\beta_R}\frac{d^2T}{dy^2}+\frac{D_TK_T}{C_sC_p}\frac{d^2C}{dy^2}=0 \quad (6)$$

Introducing the dimensionless functions f, g,θ and ϕ.defined by

$$\eta=\frac{y}{L},u=\frac{U_0}{S}f,T=\frac{cL}{S}\theta,C=\frac{L}{S}\phi, \quad N=\frac{U_o}{LS}g,U_0=\frac{\rho\beta g_eL^3c}{\mu},S=\frac{\mu U_o^2}{k_fcl} \quad (7)$$

The set of differential equations (1)-(4) can be written in the following form:

$$(1+\Delta)\frac{d^2f}{d\eta^2}+\Delta\frac{dg}{d\eta}+(\theta+N\phi)- -(D^{-1}+M^2)f=\frac{\mu U_o^2}{k_f\rho g_e\beta(cL)^2}\frac{dP}{dx} \quad (8)$$

$$A\frac{d^2g}{d\eta^2}-\frac{df}{d\eta}-2g=0 \quad (9)$$

$$(1+4Rd)\frac{d^2\theta}{dy^2}+(1+\frac{\Delta}{2})(\frac{df}{dy})^2+\frac{\Delta}{2}(\frac{df}{dy}+2g)^2 +A\Delta(\frac{dg}{dy})^2-\alpha\theta+Q_1\phi+Du\frac{d^2\phi}{dy^2}+ +Rd(\theta_w-1)^3(3\theta^2\theta'^2+\theta^3\theta'')+3Rd(\theta_w-1)^2 (2\theta\theta'^2+\theta^2\theta'')+3Rd(\theta_w-1)(\theta'^2+\theta\theta'')=0 \quad (10)$$

$$\frac{d^2\varphi}{d\eta^2}-\gamma\varphi+ScSo\frac{d^2\theta}{d\eta^2}=0 \quad (11)$$

Where Δ=k/μ is the dimensionless micropolar parameter, $A=\dfrac{\gamma}{kL^2}$ is the dimensionless micro rotation parameter, $\Delta P=\dfrac{\mu U_o^2}{k_f\rho g_e\beta(cL)^2}\dfrac{dP}{dx}$ is the pressure gradient parameter, $D^{-1}=\dfrac{L^2}{k_1}$ Is the Darcy parameter, $Sc=\dfrac{\nu}{D_m}$ is the Schmidt number,

$N=\dfrac{\beta^*\Delta C}{\beta\Delta T}$ is the buoyancy ratio,

$Rd=\dfrac{4\sigma^*T_e^3}{\beta_Rk_f}$ is the radiation parameter, $So=\dfrac{D_mK_T(T_1-T_2)}{T_m(C_1-C_2)}$ is the Soret parameter, $Du=\dfrac{D_mK_T(C_1-C_2)}{C_sC_p(T_1-T_2)}$ is the Dufour parameter ,where $\overline{q}$=(u,0,0) is the velocity, T, C are the temperature and Concentration, p is the pressure ,ρ is the density of the fluid ,Cp is the specific heat at constant pressure, μ is the coefficient of viscosity, k is the permeability of the porous medium, δ is the porosity of the medium,β is the coefficient of thermal expansion, k_f is the coefficient of thermal conductivity , β^* is the volumetric coefficient of expansion with mass fraction concentration, kc is the chemical reaction coefficient and Dm is the chemical molecular diffusivity, q_r is the radiative heat flux, k_1 is the cross diffusivity and k_1' is the chemical reaction coefficient. Here, the thermo physical properties of the solid and fluid have been assumed to be constant except for the density variation in the body force term (Boussinesq approximation) and the solid particles and the fluids are considered to be in the thermal equilibrium).

The condition: $\Delta P=0\rightarrow\dfrac{dp}{dx}=0$ corresponds to a free convection flow, while non-zero values of the pressure gradient corresponds to a mixed convection flow.

The corresponding boundary conditions are

$$f=0,g=\frac{LS}{U_o}N_0=g_o,\theta=\frac{x}{L}S,C=1 \; on \; \eta=-1 \qquad f=0,g=\frac{LS}{U_o}N_0=g_o,\theta=m\frac{x}{L}S,C=0 \; on \; \eta=+1 \quad (12)$$

The differential equations (8)-(11) with the boundary conditions as those given in (12) have been solved numerically using the finite element technique for the different parameters, namely the pressure gradient parameter ΔP, micropolar parameter Δ, Surface condition parameter go, Magnetic parameter M, Darcy parameter D^{-1}, Schmidt number Sc, heat source parameter α, Radiation parameter Nr, Radiation absorption parameter Q1 and the variable x.

3 SHEAR STRESS, NUSSELT NUMBER AND SHERWOOD NUMBER

The shear stress on the boundaries $y = \pm 1$ in the non-dimensional form is $\tau_{y=\pm 1} = (\frac{df}{dy})_{y=\pm 1}$

The rate of micro rotation on the boundaries $y = \pm 1$ in the non-dimensional form is

$$m_{y=\pm 1} = (\frac{dg}{dy})_{y=\pm 1}$$

The rate of heat transfer (Nusselt Number) is given by $Nu_{y=\pm i} = (\frac{d\theta}{dy})_{y=\pm 1}$

The rate of mass transfer (Sherwood Number) is given by $Sh_{y=\pm 1} = (\frac{d\phi}{dy})_{y=\pm 1}$

4 COMPARISON

In the absence of temperature ratio (A1 = 1.0) the results are good agreement with *Venkatalakshmi et. al.*[34].

Table – 1

Shear Stress, Couple Stress, Nusselt Number and Sherwood Number at $\eta = 1$

Parameter		Venkatalakshmi et al[34]				Present Results			
		τ (1)	Cw(1)	Nu(1)	Sh(1)	τ (1)	Cw(1)	Nu(1)	Sh(1)
Rd	0.5	-1.5588	5.26308	5.46877	-1.918	-1.5589	5.26301	5.46880	-1.919
	1.5	-1.2022	5.46282	3.39508	-1.0221	-1.2024	5.46283	3.39509	-1.0222
	3.5	-0.9157	5.63022	1.93356	-0.3911	-0.9156	5.63023	1.93355	-0.3913
	5.0	-0.2976	5.9316	1.18083	-0.2459	-0.2974	5.9315	1.18084	-0.2462
γ	0.5	-1.5588	5.26308	5.46877	-1.918	-1.5586	5.26309	5.46879	-1.921
	1.5	-1.5803	5.27268	5.48521	-1.9051	-1.5800	5.27269	5.48522	-1.9053
	-0.5	-1.6258	5.30623	5.53745	-1.9688	-1.6255	5.30622	5.53746	-1.9687
	-1.5	-1.4056	6.13629	5.91793	-2.9463	-1.4058	6.13621	5.91794	-2.9462
Q1	0.5	-1.5588	5.26308	5.46877	-1.918	-1.5587	5.26307	5.46878	-1.919
	1.0	-1.578	5.27281	5.45947	-1.914	-1.575	5.27282	5.45949	-1.912
	1.5	-1.624	5.30613	5.48689	-1.9262	-1.622	5.30614	5.48688	-1.9263
	2.0	-0.0336	6.11506	5.7651	-2.7443	-0.0334	6.11505	5.7650	-2.7453
Sr/Du	0.6/0.1	-1.7965	5.1357	5.37882	-0.2374	-1.7968	5.1356	5.37883	-0.2375
	1.0/0.06	-1.7529	5.18316	5.42057	-0.7152	-1.7522	5.18317	5.42058	-0.7155
	1.5/0.04	-1.7161	5.26454	5.51149	-1.3599	-1.7160	5.26455	5.51151	-1.3601
	2.0/0.03	-0.0111	6.12948	5.90754	-2.833	-0.0112	6.12949	5.90756	-2.834
Δp	1	-1.5588	5.26308	5.46877	-1.918	-1.5587	5.26309	5.46873	-1.912
	2	-0.8844	5.59884	5.91299	-2.1151	-0.8846	5.59885	5.91301	-2.1153
	3	-0.1241	5.94955	6.44158	-2.3493	-0.1242	5.94956	6.44152	-2.3495
	4	-0.1158	6.91629	7.57095	-3.4539	-0.1159	6.91631	7.57097	-3.4542

5. RESULTS AND DISCUSSION

The velocity, micro rotation, temperature and concentration have been evaluated by employing the finite element method and the results as shown graphically in Fig. 2a – 9a. The values of material constants S, L and A are taken to be fixed at 1.0 each while m is kept to be fixed at 2.0 and the effect of other important parameters, namely pressure gradient parameter Δp, micropolar parameter Δ, buoyancy ratio N, temperature ratio(A1=θw), Schmidt number Sc, surface condition go, heat source parameter α, chemical reaction parameter γ, radiation absorption parameter Q_1 ,thermal radiation parameter Rd, Soret parameter So, Dufour parameter Du and axial distance x.

The velocity (f), microrotation (g), temperature (θ) and concentration (C) with Grashof number (G). Figs.2a-2d represent the variation of f,g,θ and C with magnetic parameter(M). Higher the Lorentz force smaller the velocity and actual concentration, larger the temperature. The microrotation reduces in the left half and enhances in the right half of the channel with increase in M(fig.2b).

The effect of micropolar parameter (Δ) and A on the flow variables can be observed from figs.3a-3d. From the profiles we find that the velocity and temperature grows with increase in Δ (figs.3a&c). An increase in Δ reduces the microrotation (g) and actual concentration in the left half and enhance in the right half of the channel (figs.3b&d).

Figs.4a-4d demonstrate the variation of the flow variables with temperature ratio (A1). For higher values of A1,we notice an enhancement in the velocity, temperature and depreciation in the actual concentration in (-1,1). The microrotation reduces in the left half and enhances in the right half of the channel (fig.4b).

Figs.5a-5d demonstrate f,g,θ and C with thermal radiation parameter(Rd).We find that an increase in Rd reduces f in (-1,-0.5) and microrotation in (-1.0,0) while in the remain in g region they enhance. The temperature enhances in the region (-1,-0.5),in the region (-0.5,-0.25) ,it reduces with increase in Rd≤3.5,enhances with higher values of Rd≥5 while in the region(-0.25,1.0),it enhances with Rd(fig.5c).Higher the thermal radiation larger the actual concentration in the flow region(-1,1)(fig.5d).

The effect of thermo-diffusion and diffusion-thermo on f,g,θ and C can be seen from figs.6a-6d. From the profiles we find that increasing Sr(or decreasing Du) leads to a reduction in the velocity and temperature in the entire flow region. An increase in Sr (or decrease in Du) enhances the microrotation in(-1,0),actual concentration in (-1.0,0.5) while g reduces in (0,1),C reducers in (0.5,1.0)

The effect of chemical reaction parameter (γ) on f,g,θ and C is exhibited in figs.7a-7d. The velocity, temperature enhances, The microrotation (g) reducers in both the degenerating/ generating chemical reaction cases. The actual concentration reduces in the degenerating chemical reaction case and enhances in the generating case in the left half while in the right half of the channel, the actual concentration reduces in both degenerating/ generating cases.

The effect of radiation absorption parameter (Q1) on the flow variables can be observed from figs.8a-8d.From the profiles we find that Higher the radiation absorption larger the velocity and temperature in the flow region (-1.0, 1.0) The microrotation reduces in the left half (-1.0, 0), actual concentration reduces in (-1.0, -0.25) while in region (-0.25, 1.0) they enhance with increase in Q1.

Figs.9a-9d represent the variation of velocity, micro rotation, temperature and concentration distributions with pressure gradient Δp, while other parameters x, R, g_0, Sc, Sr, Du, A, N, α, are assumed to be fixed as 1, 1, 3, 1.3, 2.0, 0.03, 1.01, 1, 2, respectively. From the profiles we find that an increase in the pressure gradient (Δp), reduces the velocity and increases the temperature. An increase in Δp, enhances the microrotation, reduces the actual concentration in the left half while in the right half of the channel, a reversed effect is noticed in g and C.

The skin friction(τ),couple stress (Cw), Nusseltr number(Nu) and Sherwood number (Sh) on the walls $\eta = \pm 1$ are exhibited in tables 2&3 for different parametric variations. The skin friction enhances with increase in G at both the walls. The couple stress (Cw), Nusselt number (Nu) and Sherwood number(Sh) enhance at the left wall η=-1 and reduces at the right wall η=+1.An increase in magnetic parameter(M) enhances τ at $\eta = \pm 1$.Cw, Nu and Sh enhancer at η=-1 an d reduce at η=+1 with increase in M.

Lesser the molecular diffusivity larger the skin friction and smaller Cw at η=-1 while at η=+1, smaller τ and larger Cw. Nu and Sh enhance at η=±1. Increasing Soret parameter Sr(or decreasing Du) leads to an enhancement in τ and Sh, depreciation in Nu at η=±1.Cw enhances at η=-1 and reduces at η=+1 with increasing Sr(or decreasing Du).

An increase in chemical reaction parameter (γ) reducers the skin friction at the left wall and enhances at the right wall in the degenerating chemical reaction case while in the generating case,,τ enhances at both the walls. Cw enhances at η=-1 and reduces at η=+1 in both degenerating/generating chemical reaction cases. Nu enhances at η=-1 and reduces at η=+1 with increasing |γ|. Sh enhances at η=-1 and reduces at η=+1 for γ>0 and for γ<0, it reduces at both the walls.

An increase in radiation absorption parameter (Q1) reduces τ at η=-1 and enhances at η=+1, Cw, Nu and Sh enhance at the left wall and depreciate at the right wall with increase in Q1.

With respect to thermal radiation parameter (Rd) we find that higher the radiative heat flux, larger τ, smaller Cw at η=-1 and at η=+1,smaller τ,larger Cw. The rate of heat and mass transfer depreciate with Rd at both the walls.

An increase in temperature ratio(A1≤1.15) decays τ and for higher A1≥1.20, it enhances at the left wall and reduces at the right wall. Cw, Nu and Sh enhances at η=-1 and reduces at η=+1 with increase in A1.Thus the non-linear thermal radiation (A1) leads to an enhancement in Nu and Sh at the left wall and reduction at the right wall.

An increase4 in micropolar parameter (Δ≤2) reduces τ and for higher Δ≥3, it enhances at η=-1.At η=+1,τ enhances with increase in Δ. The couple stress enhances at η=-1 and reduces at η=+1 with increase in Δ. The rate of heat and mass transfer experience an enhancement at η=±1 with increasing Δ.

With respect to pressure gradient (Δp), we find that τ enhances, Cw reduces at η=-1 while at η=+1, τ reduces, Cw enhances with Δp. The rate of heat and mass transfer reduce at both the walls with increase in Δp.

6. CONCLUSIONS

The non-linear equations governing the flow, heat and mass transfer flow of a micropolar fluid in a vertical channel in the presence of non-linear thermal radiation have been solved by Runge-Kutta –Shooting technique .The conclusions of this analysis are

i) An increase in magnetic field (M) reduces the axial velocity, actual concentration and enhances the temperature. The skin friction (τ), couple stress (Cw), Nusselt number (Nu) and Sherwood number (Sh) grow with increase in M.
ii) Higher the thermal radiation (Rd) smaller the velocity, larger the temperature and actual concentration in the region (-1,0) and they

5

enhance in (0,1),τ enhances, Cw, Nu and Sh reduce o0n the walls with Rd

iii) Increasing Sr (or decreasing Du) leads to aq reduction in f, enhancement in θ and actual concentration in (-1,0) and in(0,1) f, actual concentration reduce, temperature enhances. τ, Cw, Sh enhance, Nu reduces on the walls with increase in Sr(or decrease in Du)

iv) An increase in radiation absorption (Q1) enhances the axial velocity, temperature and reducers the microrotation, actual concentration. τ reduces, Cw, Nu and Sh enhance on the walls with increase in Q1.

v) An increase in micropolar parameters (Δ) enhances the axial velocity, temperature sand reduces the microrotation, actual concentration. τ reduces, Cw, nu and Sh enhance on the walls with increase in Δ. τ enhances, Cw, Nu.

vi) An increase in pressure drop (Δp) enhances microrotation, temperature and reduces the axial velocity, actual concentration.τ enhances, Cw, Nu and Sh reduce with in crease in Δp.

vii) An increase in temperature ratio (A1) enhances the axial velocity, temperature and reduces microrotation, actual concentration.τ reduces, Cw, Nu and Sh enhance on the walls with A1.

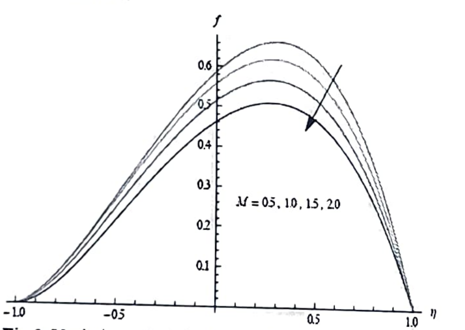

Fig.2aVariation of axial velocity(f) with M
A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

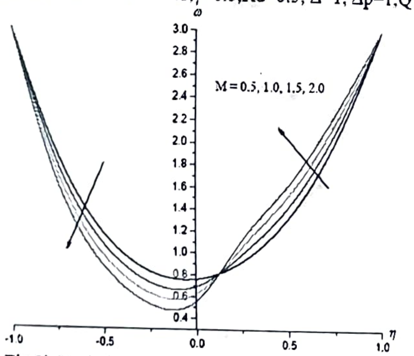

Fig.2b Variation of micro-rotation(ω) with M
A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

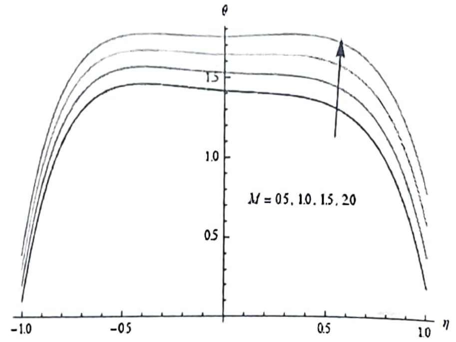

Fig.2c Variation of temperature(θ) with M
A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

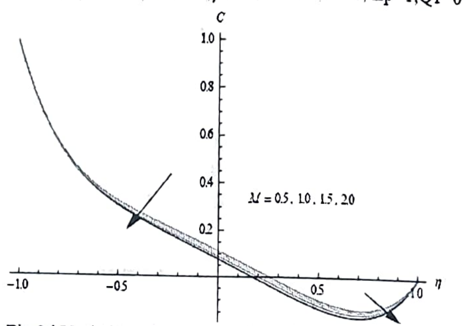

Fig.2d Variation of Concentration (C) with M
A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

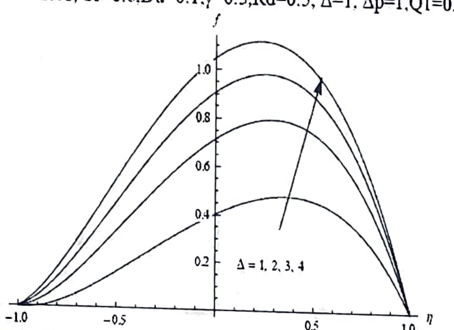

Fig.3aVariation of axial velocity(f) with Δ
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δp=1,Q1=0.5

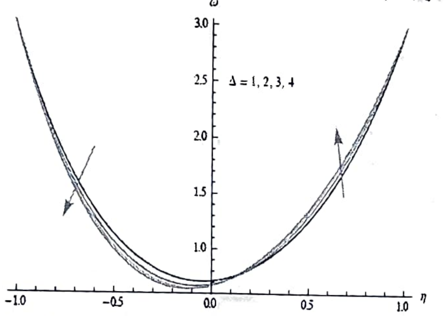

Fig.3b Variation of micro-rotation(ω) with Δ
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δp=1,Q1=0.5

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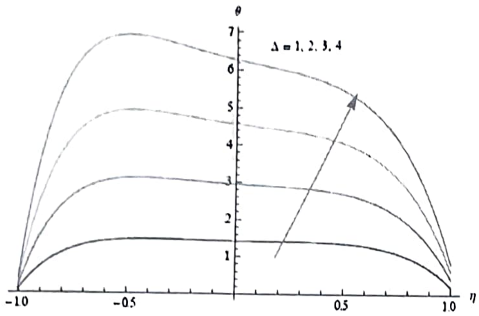

Fig.3c Variation of temperature(θ) with Δ
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δp=1,Q1=0.5

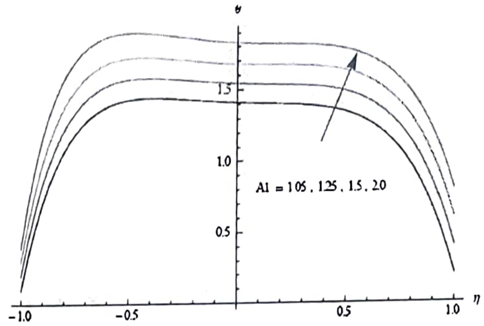

Fig. 4c Variation of temperature(θ) with A1
M=0.5, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

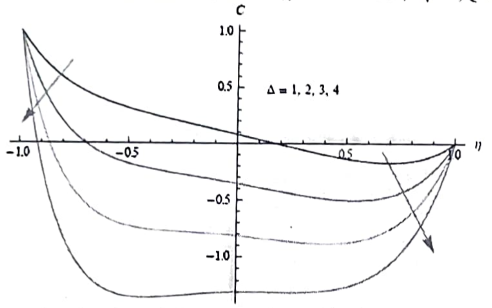

Fig.3d Variation of Concentration (C) with Δ
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δp=1,Q1=0.5

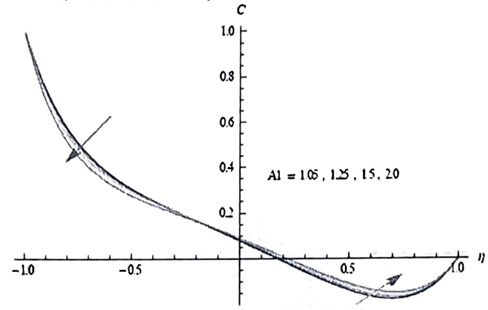

Fig. 4d Variation of Concentration (C) with A1
M=0.5, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

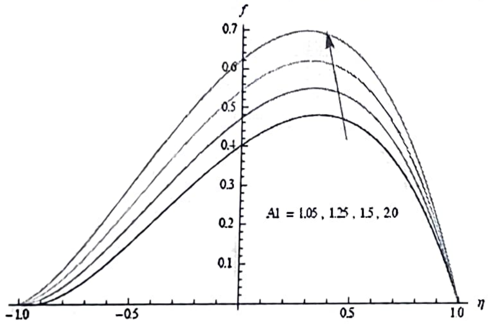

Fig. 4aVariation of axial velocity(f) with A1
M=0.5, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

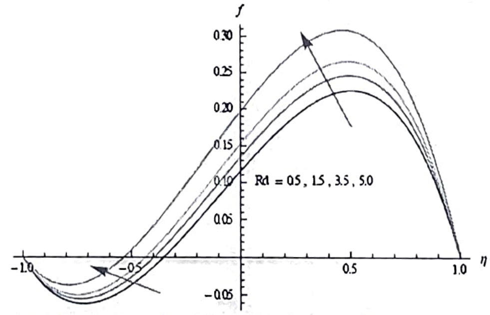

Fig.5aVariation of axial velocity(f) with Rd
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5, Δ=1, Δp=1,Q1=0.5

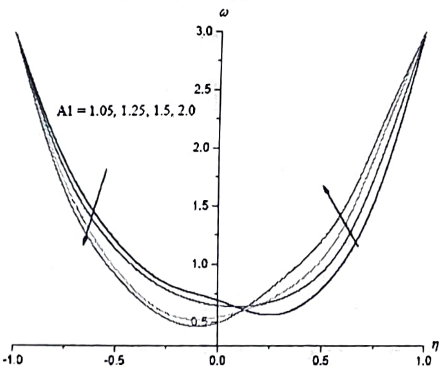

Fig. 4b Variation of micro-rotation(ω) with A1
M=0.5, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

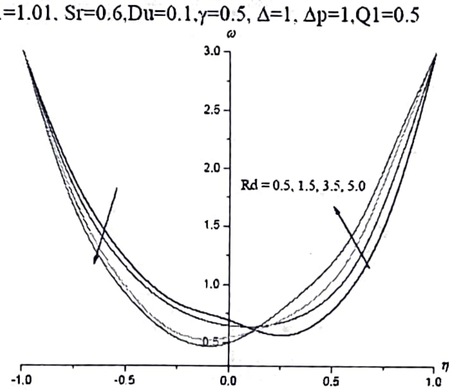

Fig.5b Variation of micro-rotation(ω) with Rd
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5, Δ=1, Δp=1,Q1=0.5

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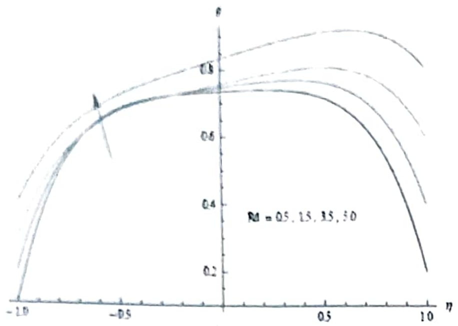

Fig.5c Variation of temperature(θ) with Rd
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5, Δ=1, Δp=1,Q1=0.5

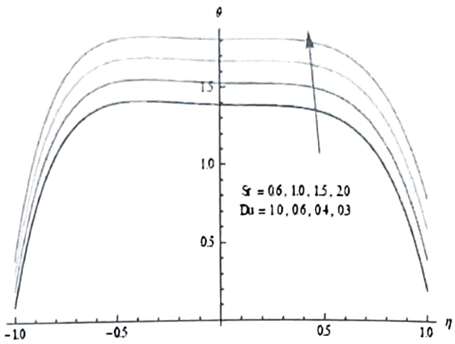

Fig.6c Variation of temperature(θ) with Sr&Du
M=0.5,A1=1.01, γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

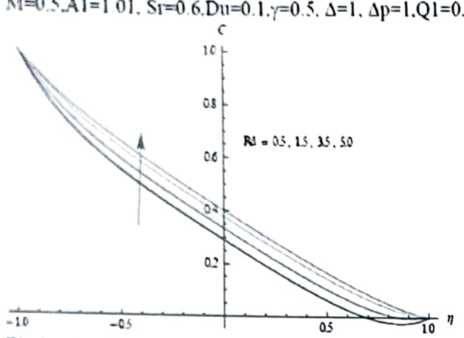

Fig.5d Variation of Concentration (C) with Rd
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5, Δ=1, Δp=1,Q1=0.5

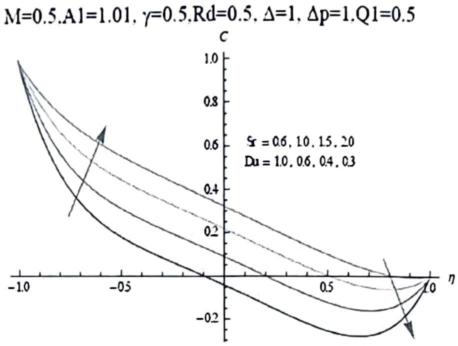

Fig.6d Variation of Concentration(C) with Sr&Du
M=0.5,A1=1.01, γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

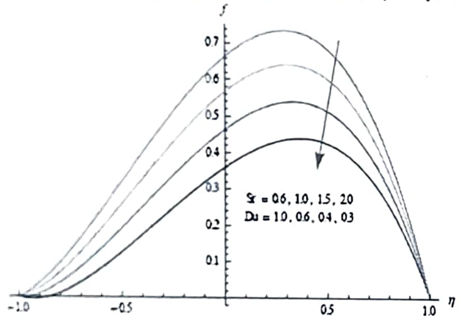

Fig.6aVariation of axial velocity(f) with Sr&Du
M=0.5,A1=1.01, γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

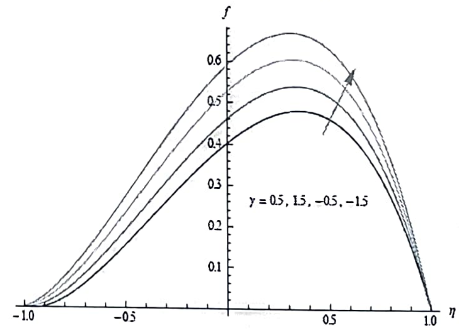

Fig.7aVariation of axial velocity(f) with γ
M=0.5,A1=1.01, Sr=0.6,Du=0.1,Rd=0.5, Δ=1, Δp=1,Q1=0.5

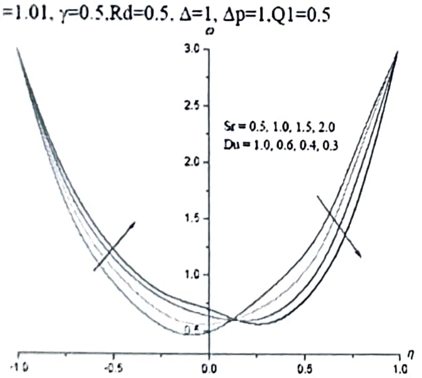

Fig.6b Variation of micro-rotation(ω) with Sr&Du
M=0.5,A1=1.01, γ=0.5,Rd=0.5, Δ=1, Δp=1,Q1=0.5

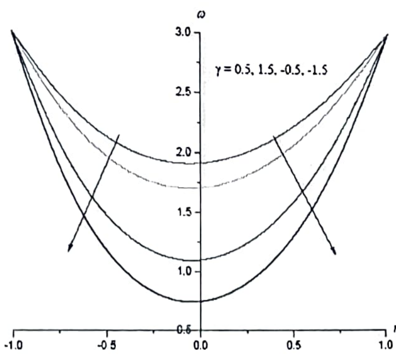

Fig.7b Variation of micro-rotation(ω) with γ
M=0.5,A1=1.01, Sr=0.6,Du=0.1,Rd=0.5, Δ=1, Δp=1,Q1=0.5

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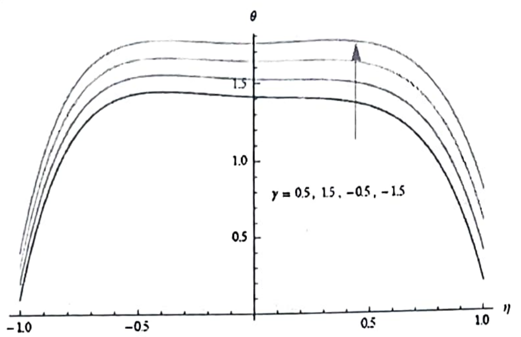

Fig.7c Variation of temperature(θ) with γ
M=0.5,A1=1.01, Sr=0.6,Du=0.1,Rd=0.5, Δ=1, Δp=1,Q1=0.5

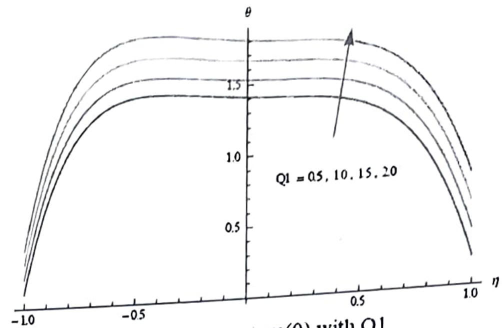

Fig.8c Variation of temperature(θ) with Q1
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1

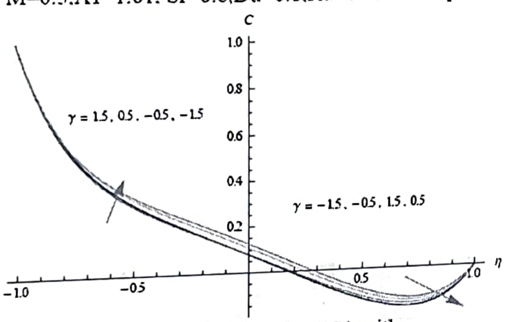

Fig.7d Variation of Concentration (C) with γ
M=0.5,A1=1.01, Sr=0.6,Du=0.1,Rd=0.5, Δ=1, Δp=1,Q1=0.5

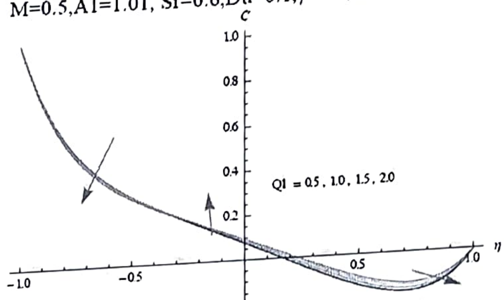

Fig.8d Variation of Concentration (C) with Q1
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1

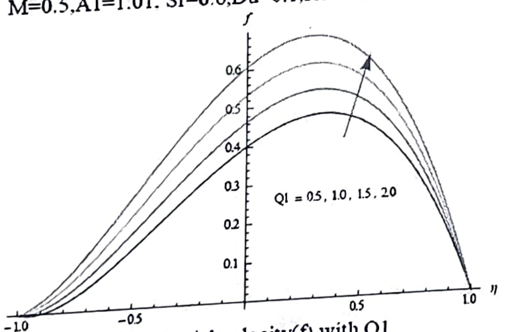

Fig.8aVariation of axial velocity(f) with Q1
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1

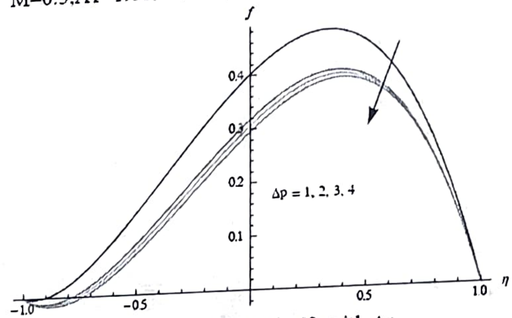

Fig.9aVariation of axial velocity(f) with Δp
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Q1=0.5

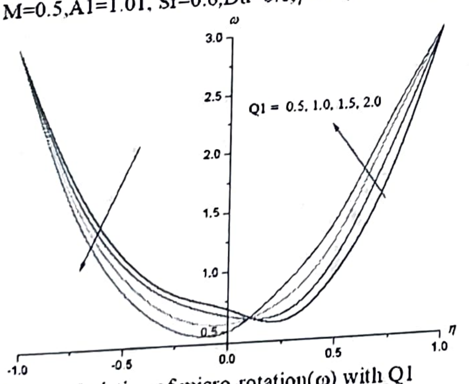

Fig.8b Variation of micro-rotation(ω) with Q1
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Δp=1

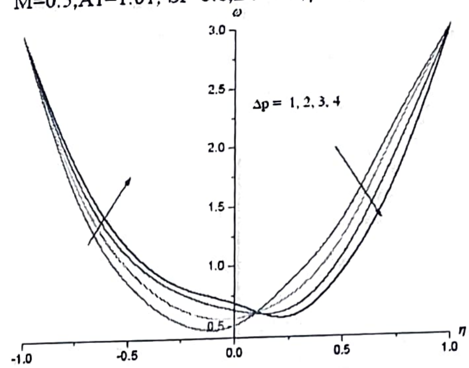

Fig.9b Variation of micro-rotation(ω) with Δp
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Q1=0.5

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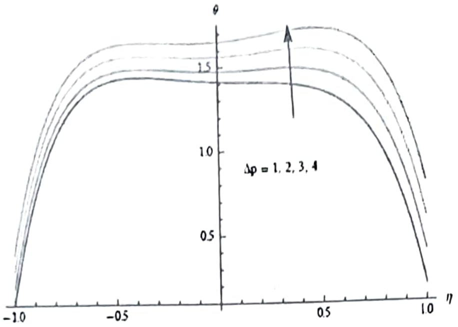

Fig.9c Variation of temperature(θ) with Δp
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Q1=0.5

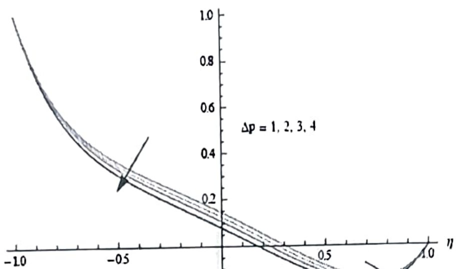

Fig.9d Variation of Concentration (C) with Δp
M=0.5,A1=1.01, Sr=0.6,Du=0.1,γ=0.5,Rd=0.5, Δ=1, Q1=0.5

Table – 1 : Stress (τ),Couple stress(g′(0),Nusselt and Sherwood number at y=-1

Parameter		τ(-1)	g'(-1)	Nu(-1)	Sh(-1)
M	0.5	-0.0164307	-6.11789	-7.91095	3.12666
	1.0	0.0336705	-6.1569	-7.9657	3.12901
	1.5	0.0539137	-6.18	-7.97867	3.11765
	2.0	0.0459873	-6.18463	-7.94054	3.08956
Sr/Du	0.6/0.1	-0.00864653	-6.14178	-8.06213	1.61286
	1.0/0.06	0.025853	-6.16308	-8.02571	2.28921
	1.5/0.04	0.0539137	-6.18	-7.97867	3.11765
	2.0/0.03	0.0867199	-6.20086	-7.94846	3.93302
γ	0.5	-0.115472	-6.06234	-7.76413	3.0785
	1.5	-0.0345397	-6.11851	-7.87098	3.16194
	-0.5	0.0583253	-6.18318	-7.97914	3.04819
	-1.5	0.149314	-6.24673	-8.09529	2.9924
Q1	0.5	-0.115472	-6.06234	-7.76413	3.0785
	1.0	-0.0240622	-6.1255	-7.96236	3.12773
	1.5	0.0696996	-6.19036	-8.18722	3.18562
	2.0	0.16274	-6.25491	-8.39773	3.23881
Δ	1.0	-0.115472	-6.06234	-7.76413	3.0785
	2.0	0.0151068	-6.23493	-12.5313	4.61418
	3.0	0.138381	-6.36975	-17.8931	6.34484
	4.0	0.303034	-6.53633	-30.3234	10.382
Δp	1	-0.115472	-6.06234	-7.76413	3.0785
	2	-0.244815	-5.97858	-7.4681	2.96656
	3	-0.267179	-5.9661	-7.37222	2.91989
	4	-0.289397	-5.95376	-7.27704	2.87344
Rd	1.01	-0.115472	-6.06234	-7.76413	3.0785
	1.15	-0.2922	-5.93225	-4.32367	1.94222
	1.20	-0.3751	-5.86749	-2.3575	1.28717
	1.25	-0.366915	-5.87054	-1.4986	0.992277
A1	0.5	-0.115472	-6.06234	-7.76413	3.0785
	1.5	-0.0170114	-6.12935	-8.25642	3.2244
	3.5	0.074279	-6.19198	-8.56009	3.30844
	5.0	0.16929	-6.25675	-8.97993	3.43062

Table – 2 : Stress (τ),Couple stress(g′(0),Nusselt and Sherwood number at y = +1

Parameter		τ(1)	g'(1)	Nu(1)	Sh(1)
M	0.5	-1.60078	5.17085	5.72918	-1.40605
	1.0	-1.80517	5.10305	5.43238	-1.3257
	1.5	-2.03842	5.04108	5.15405	-1.25141
	2.0	-2.2966	4.99013	4.90048	-1.1853
Sr/Du	0.6/0.1	-1.86351	5.09963	5.71171	-0.280567
	1.0/0.06	-1.95532	5.06799	5.42904	-0.727617
	1.5/0.04	-2.03842	5.04108	5.15405	-1.25141
	2.0/0.03	-2.13054	5.00936	4.87935	-1.72684
γ	0.5	-1.69465	5.19067	5.77417	-1.42083
	1.5	-1.8622	5.11853	5.46286	-1.33403
	-0.5	-2.0438	5.03782	5.15189	-1.24779
	-1.5	-2.22449	4.95792	4.84561	-1.15294
Q1	0.5	-1.69465	5.19067	5.77417	-1.42083
	1.0	-1.8721	5.11206	5.4496	-1.33118
	1.5	-2.05272	5.03163	5.13093	-1.24339
	2.0	-2.23377	4.9512	4.82307	-1.15915
Δ	1.0	-1.69465	5.19067	5.77417	-1.42083
	2.0	-2.23967	4.94341	8.09468	-2.18516
	3.0	-2.5929	4.76802	10.3544	-2.92903
	4.0	-2.95033	4.56974	15.2858	-4.53377
Δp	1	-1.69465	5.19067	5.77417	-1.42083
	2	-1.52359	5.28259	5.6739	-1.40613
	3	-1.52403	5.29115	5.46746	-1.35601
	4	-1.52484	5.29952	5.26267	-1.30641
A1	1.01	-1.69465	5.19067	5.77417	-1.42083
	1.15	-1.88075	5.1079	5.58328	-1.37501
	1.20	-2.05849	5.02961	5.30134	-1.29942
	1.25	-2.23956	4.94932	5.02986	-1.22718
Rd	0.5	-1.69465	5.19067	5.77417	-1.42083
	1.5	-1.45269	5.33308	3.32176	-0.642255
	3.5	-1.35239	5.40157	1.68754	-0.129193
	5.0	-1.40498	5.39041	0.86327	0.12145

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