Effect of Thermal Radiation and Viscous Dissipation on Steady MHD Free Convection and Mass Transfer Flow of a Micro Polar Fluid with Constant Heat and Mass Fluxes

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ABSTRACT:

We study, the effect of thermal radiation and viscous dissipation on steady MHD free convection and mass transfer flow of a micropolar fluid with constant heat and mass fluxes. The diffusion thermo, thermal diffusion, viscous dissipation and Joule heating have been considered for high speed fluid. The governing equations of the problem contain the partial differential equations which are transformed by similarity technique into dimensionless ordinary coupled non-linear differential equations. The dimensionless governing equations are solved numerically by using fourth order Runge–Kutta shooting iteration technique. We investigate in detail the distributions of velocity, microrotation, temperature and concentration across the boundary layer and also evaluated the skin friction, couple stress, the rate of heat and mass transfer at the plate.

Keywords: Micropolar fluids, Heat and Mass transfer, Soret effect, Dofur effect, Similarity

1. INTRODUCTION

Because of the increasing importance of materials flow in industrial processing and elsewhere and the fact shear behavior cannot be characterized by Newtonian relationships, a new stage in the evaluation of fluid dynamic theory is in the progress. Eringen [10] proposed a theory of micropolar fluids taking into account the inertial characteristics of the substructure particles, which are allowed to undergo rotation. Physically, the micropolar fluid can consist of a suspension of small, rigid, cylindrical elements such as large dumbell shaped molecules. The theory of micropolar fluids is generating a very much increased interest and many classical flows are being re-examined to determine the effects of the fluid microstructure.

The concept of micropolar fluid deals with a class of fluids that exhibit certain microscopic effects arising from the micro motions of the fluid elements. These fluids contain dilute suspension of rigid micro molecules with individual motions that support stress and body moments and are influenced by spin inertia. Micropolar fluids are those which contain micro constituents that can undergo rotation, the presence of which can affect the hydrodynamics of the flow so that it can be distinctly non-Newtonian. It has many practical applications, for example, analyzing the behavior of exotic lubricants Khonsari[23]. Lee and Eringen [25] additive suspensions, human and animal blood Ariman et al. [2], turbulent shear flow and so fourth. Earlier Sakiadis [33] introduced the concept of continuous surfaces such as polymer sheets of filaments continuously drawn from die. He studied the boundary layer behavior on continuum solid and flat surfaces. The boundary layer flow on continuous surfaces is an important type of flow occurring in a number of technical processes, for example, continuous casting, glass fiber production, metal extrusion, hot rolling, cooling and/or dying of paper and textiles, wire drawing, etc Tadmor and Klein [35] , Fisher, [12], Altan et al. [1]. Eringen [11] developed the theory of thermo micro polar fluids by extending the theory of micropolar fluids. Yucel [38] studied the mixed convection flow of micropolar fluid over a horizontal plate. Mohammed Ibrahim et al. [27] studied Radiation Effects on Unsteady MHD Free Convective Heat and Mass Transfer Flow of Past a Vertical Porous Plate Embedded in a Porous Medium with Viscous Dissipation. Ziaul Haque et al. [39] have studied Micropolar fluid behaviors on steady MHD free convection and mass transfer flow with constant heat and Mass fluxes, joule heating and viscous dissipation. Venkateswarlu et al. [37] have studied Effects of Thermal Radiation on Unsteady MHD Micropolar Fluid past a Vertical Porous Plate in the Presence of Radiation Absorption. Olajuwon and Oahimire [29] studied unsteady free convection heat and mass transfer in an mhd micropolar fluid in the presence of thermo diffusion and thermal radiation. Chandrakala et al. [4] has studied Radiation effects on MHD flow past an impulsively started infinite vertical plate with mass diffusion. GnaneswaraReddy and Machireddy [14] have investigated Thermal Radiation and Chemical Reaction Effects on Steady Convective Slip Flow with Uniform Heat and Mass Flux in the Presence of Ohmic heating and a Heat Source. Harish Babu et al. [16] studied Joule heating effects on MHD mixed convection of a Jeffrey fluid over a stretching sheet with power law heat flux. Hitesh Kumar [17] studied Mixed convective magneto hydrodynamic flow of a micropolar fluid with ohmic heating, radiation and viscous dissipation over a chemically reacting porous plate subjected to a constant heat flux and concentration gradient. Kesavaiah et al. [21] studied Radiation absorption, chemical reaction and magnetic filed effects on the free convection and mass transfer flow through porous medium with constant suction and constant heat flux. Usha et al. [36] studied Thermal diffusion and radiation effects on mhd mixed convection flow in a channel with porous medium.

El-Haikem et al. [9] have studied the Joule heating effects on magneto hydrodynamic free convection flow of a micropolar fluid. El-Amin [7] has studied the magneto hydrodynamic free convection and mass transfer flow in micropolar fluid with constant suction. Very recently Rahman and Sattar [31] have studied the magneto hydrodynamic convective flow of a micropolar fluid past a continuously moving vertical porous plate in the presence of heat generation/absorption. In the above mentioned work they have extended the work of El-Arabawy [8] to a MHD flow taking into account the effect of free convection and micro rotation. Kim [24] studied the unsteady MHD free convection flow of micropolar fluid past a vertical moving porous plate in a porous medium.

2. FORMULATION OF THE PROBLEM

We consider the steady two dimensional MHD free convective and mass transfer micropolar fluid flow past a semi-infinite vertical porous plate y=0. The x-axis is taken along the heated plate in the upward direction and the y-axis normal to it. The constant heat flux $(-k\dfrac{\partial T}{\partial y})$=Q and constant mass flux $(-D_m\dfrac{\partial C}{\partial y})$=m are considered. The plate is immersed in a micropolar fluid of temperature T, a magnetic field $\bar{B}$ of uniform strength is applied transversely to the direction of the flow. The magnetic Reynolds number of the flow is taken to be sufficiently small enough so that the induced magnetic field can be neglected in comparison with the applied magnetic field so that $\bar{B}=(0,B_o,0)$ where B_0 is the uniform magnetic field acting normal to the plate. The equation of conservation of charge $\nabla.\bar{J}=0$ gives j_y =constant where $\bar{J}=(j_x,j_y,j_z)$ is the current density. The direction of propagation is considered only along the y-axis and does not have any variation along the y-axis the derivative of J_y with respect to y namely $\dfrac{\partial j_y}{\partial y}=0$. Since the plate is electrically non-conducting this constant is zero and hence J_y =0 at the plate and hence zero elsewhere .The flow configuration and the co-ordinate system are shown in fig.1.

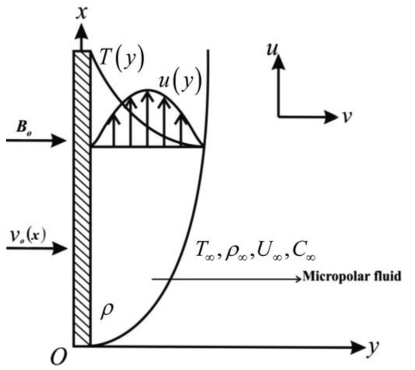

Fig.1: Physical configuration and co-ordinate system

Since the occupying the plate y=0 is of semi-infinite extent and the micropolar fluid motion is steady, all physical quantities will depend only upon x and y. Within the framework of the above noted assumptions, the flow of a steady viscous incompressible micropolar fluid flow subject to the Boussinesq's approximation can be written in the following form

The Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad [1]$$

The Momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=(\nu+\frac{\chi}{\rho})\frac{\partial^2 u}{\partial y^2}+\frac{\chi}{\rho}\frac{\partial \tau}{\partial y}+\beta g(T-T_\infty)$$
$$+\beta^{\bullet}g(C-C_\infty)-(\frac{\nu}{k})u-(\frac{\sigma B_o^2}{\rho})u \qquad [2]$$

The Angular momentum equation

$$u\frac{\partial \Gamma}{\partial x}+v\frac{\partial \Gamma}{\partial y}=\frac{\gamma}{\rho j}\frac{\partial^2 \Gamma}{\partial y^2}+\frac{\gamma}{\rho j}(2\Gamma+\frac{\partial u}{\partial y}) \quad [3]$$

The Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\frac{1}{C_p}(\nu+\frac{\chi}{\rho})(\frac{\partial u}{\partial y})^2+(\frac{\sigma B_o^2}{\rho C_p})u^2+\frac{D_m k_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2}-\frac{1}{\rho C_p}\frac{\partial q_R}{\partial y} \quad [4]$$

The Concentration equation

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}+\frac{D_m k_T}{C_s C_p}\frac{\partial^2 T}{\partial y^2} \quad [5]$$

The boundary conditions for the problem are

$$u=0, v=v_0, \Gamma=-s\frac{\partial u}{\partial y}, \frac{\partial T}{\partial y}=-\frac{Q}{k}, \frac{\partial C}{\partial y}=-\frac{m}{D_m} \quad at\ y=0$$
$$u=0, \Gamma=0, T\to T_\infty, C\to C_\infty \quad at\ y\to\infty \quad [6]$$

When s=0, we obtain $\Gamma=0$ which represents no-spin condition , the micro elements in a concentrated particle flow close to the wall are not able to rotate. The case s=1/2 represents vanishing of the anti-symmetric part of the stress tensor and stress tensor and represents weak concentration. In a fine particle suspension of the particle spin is equal to the fluid velocity at the wall. The case s=1, represents turbulent boundary layer flow.

Invoking Rosseland approximation the radiative flux q_r is

$q_r=\frac{-4\sigma_s}{3K_e}\frac{\partial T^{1^4}}{\partial y}$, and lineralized by expanding T^{1^4} into Taylor series about T_∞^1 which after neglecting higher order terms and takes the form $T^{1^4}\cong 4T_\infty^{1^3}T^1-3T_\infty^{1^4}$. With this the energy equation reduces to

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\frac{1}{C_p}(\nu+\frac{\chi}{\rho})(\frac{\partial u}{\partial y})^2+(\frac{\sigma B_o^2}{\rho C_p})u^2+\frac{D_m k_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2}+\frac{16\sigma^\bullet T_\infty^3}{3\beta_R C_p}\frac{\partial^2 T}{\partial y^2} \quad [7]$$

We introduce the usual similarity variables

$$\eta=y\sqrt{\frac{U_\infty}{2\nu x}}\ ,\quad f'(\eta)=\frac{u}{U_\infty}\ ,\quad \Gamma=\sqrt{\frac{U_\infty^3}{2\nu x}}g(\eta)$$
$$\theta(\eta)=\frac{T-T_\infty}{Q/k}\sqrt{\frac{U_\infty}{2\nu x}}\ ,\quad \varphi(\eta)=\frac{C-C_\infty}{m/D_m}\sqrt{\frac{U_\infty}{2\nu x}} \quad [8]$$

Introducing the relations Eq.(2.2.7) and Eq.(2.2.2) into the Eqs.(2.2.1) - (2.2.5),we obtain the following similarity equation

$$(1+\Delta)f'''(\eta)+f(\eta)f''(\eta)+\Delta g(\eta)+G_r(\theta(\eta)+N\phi(\eta))-(M^2+D^{-1})f'(\eta)=0 \quad [9]$$

$$g''(\eta)+f'(\eta)g(\eta)+f(\eta)g'(\eta)-2\lambda g(\eta)-\lambda f'(\eta)=0 \quad [10]$$

$$(1+\frac{4Rd}{3})\theta''(\eta)+P_r f(\eta)\theta(\eta)-f(\eta)\theta'(\eta))+(1+\Delta)P_r Ecf''^2(\eta)+$$
$$+MP_r Ecf'^2(\eta)+P_2 Df\varphi''(\eta)=0 \quad [11]$$

$$\varphi''(\eta)+S_c(f(\eta)\varphi'(\eta)-f'(\eta)\varphi(\eta)+S_r\theta''(\eta)=0 \quad [12]$$

The corresponding boundary conditions are

$$f(\eta)=f_w\ ,\ f'(\eta)=0\ ,\ g(\eta)=-sf'(\eta)\ ,\ \theta(\eta)=-1\ ,\ \phi(\eta)=-1 \quad at\ \ \eta=0$$
$$f(\eta)=0\ ,\ f'(\eta)=0\ ,\ g(\eta)=0\ ,\ \theta(\eta)=0\ ,\ \phi(\eta)=0 \quad as\ \eta\to\infty \quad [13]$$

where

$\Delta=\frac{\chi}{\rho}$ Micro Rotation Parameter, $Gr=\beta g\sqrt{\frac{2\nu x}{U_\infty^3}}\frac{Q}{k}$ Grashof Number

$N = \frac{\beta^{\bullet} mk}{\beta Q D_m}$ Buoyancy Ratio, $M = \frac{2\sigma B_o^2 x}{\rho U_\infty}$ Magnetic Parameter

$D^{-1} = \frac{K^2 U_\infty}{2\nu x}$ Inverse Darcy Parameter, $\Pr = \frac{\rho \nu C_p}{k}$ Prandtl Number

$\Lambda = \frac{\gamma}{\nu \rho j}$ Dimensionless Spin gradient viscosity parameter

$Ec = \frac{kU_\infty^3}{2xQC_p}\sqrt{\frac{2x}{\nu U_\infty}}$ Eckert Number, $Du = \frac{mk_T}{\nu CsCp}\frac{k}{Q}$ Dufour Parameter

$Sc = \frac{\nu}{D_m}$ Schmidt Number, $Sr = \frac{D_m k_T}{mCsCp}\frac{Q}{k}$ Soret Parameter

$\lambda = \frac{\gamma}{\rho \nu J}$ Dimension less vertex viscosity parameter Rd - Radiation parameter

3. SOLUTION OF THE PROBLEM

The coupled ordinary differential equations (9)-(12) are of third order in f, and second order in g, θ and ϕ which have been reduced to a system of nine simultaneous equations of first-order for nine unknowns. In order to solve this system of equations numerically we require nine initial conditions but two initial conditions on f and one initial condition each on g, θ and ϕ are known. However the values of f, g, θ and ϕ are known at $\eta \to \infty$. These four end conditions are utilized to produce four unknown initial conditions at η=0 by using shooting technique. The most crucial factor of this scheme is to choose the appropriate finite value of η_∞. In order to estimate the value of η_∞, we start with some initial guess value and solve the boundary value problem consisting of equations (9)-(12) to obtain f ″(0), g′(0) θ′ (0) and ϕ′ (0). The solution process is repeated with another large value of η_∞ until two successive values of $f'^{'}(0)$, g′(0), θ′(0) and ϕ′(0) differ only after desired significant digit. The last value of η_∞ is taken as the final value of η_∞ for a particular set of physical parameters for determining velocity components f(η), g(η), temperature θ(η) and concentration ϕ(η) in the boundary layer. After knowing all the nine initial conditions, we solve this system of simultaneous equations using fourth-order Runge-Kutta shooting iteration technique. The value of η_∞ greatly depends also on the set of the physical parameters such as Magnetic parameter, buoyancy ratio, Microrotation parameter , Prandtl number, Inverse Darcy parameter, Schmidt number, Soret number and dimensionless vertex viscosity parameter so that no numerical oscillations would occur. During the computation, the shooting error was controlled by keeping it to be less than 10^{-6}. Thus, the coupled non-linear boundary value problem of third order in f, second order in g, θ and ϕ has been reduced to a system of nine simultaneous equations of first-order for nine unknowns as follows :

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

$f_3 =[f_1 f_3 - \Delta f_4, g_8 (f_6 + N f_8) – (M + D^{-1}) f_2] / (1+\Delta)$

$g_5 = [f_2 f_4 – f_1 f_5 + 2 \times f_4 + \lambda f_2] / \Delta$

$f_7' = [P_r (f_1 f_7 + f_2 f_6) – (1+\Delta)P_r Ec f_2^2 – M P_r Ec f_1^2 + P_r Sc D_f (f_1 f_9 – f_2 f_8)] / (1+ \frac{4Rd}{3} +P_r Sr D_f)$

$f_9' = [-Sc(f_1 f_9 - f_2 f_8)+ Sc Sr (1+\Delta) Pr Ec f_2^2 + Sc Sr M P_r Ec f_1^2 + Sc Pr Sr (f_1 f_7 – f_2 f_6)] / (1+ \frac{3 \Pr D_f}{3+4Rd})$

where

$$\left.\begin{array}{l} f_1 = f, \ f_2 = f^1, \ f_3 = f^{11}, \ f_4 = \theta, \ f_5 = g^1, \\ f_6 = \theta, \ f_7 = \theta^1, \ f_8 = \phi, \ f_8^1 = \phi^1 = f_9 \end{array}\right\} \quad [14]$$

and a prime denotes differentiation with respect to η. The boundary conditions now become

$$f_1 = f_w, f_2 = 1, f_4 = 0, f_6 = 1, f_8 = 1 \quad \text{at} \quad \eta = 0$$
$$f_2 \to 0, f_4 \to 0, f_6 \to 0, f_8 \to 0 \quad \text{at} \quad \eta \to \infty \qquad [15]$$

Since $f_3(0)$, $f_5(0)$, $f_7(0)$ and $f_9(0)$ are not prescribed so we have to start with the initial approximations as $f_3(0)=s_{10}$, $f_5(0)=s_{20}$, $f_7(0)=s_{30}$ and $f_9(0)=s_{40}$. Let γ_1, γ_2, γ_3 and γ_4 be the correct values of $f_3(0)$, $f_5(0)$ and $f_7(0)$ respectively. The resultant system of nine ordinary differential equations is integrated using fourth order Runge-Kutta shooting iteration technique method and denote the values of f_3, f_5 ,f_7 and f_9 at $\eta = \eta_\infty$ by f_3 (s_{10}, s_{20}, s_{30}, s_{40}, η_∞), f_5(s_{10}, s_{20}, s_{30}, s_{40}, η_∞), f_7(s_{10}, s_{20}, s_{30}, s_{40}, η_∞) and f_9(s_{10}, s_{20}, s_{30}, s_{40}, η_∞) respectively. Since f_3, f_5, f_7 and f_9 at $\eta = \eta_\infty$ are clearly function of γ_1, γ_2, γ_3 and γ_4, they are expanded in Taylor series around $\gamma_1 - s_{10}$, $\gamma_2 - s_{20}$, $\gamma_3 - s_{30}$ and $\gamma_4 - s_{40}$ respectively by retaining only the linear terms. The use of difference quotients is made for the derivatives appeared in these Taylor series expansions.

Thus, after solving the system of Taylor series expansions for $\delta\gamma_1 = \gamma_1 - s_{10}$, $\delta\gamma_2 = \gamma_2 - s_{20}$, $\delta\gamma_3 = \gamma_3 - s_{30}$, and $\delta\gamma_4 = \gamma_4 - s_{40}$ we obtain the new estimates $s_{11}=s_{10}+\delta s_{10}$, $s_{21}= s_{20}+\delta s_{20}$, $s_{31}=s_{30}+\delta s_{30}$ and $s_{41}=s_{40}+\delta s_{40}$. Next the entire process is repeated starting with $f_1(0)$, $f_2(0)$, s_{11}, $f_4(0)$, s_{21} , s_{31} and s_{41} as initial conditions. Iteration of the whole outlined process is repeated with the latest estimates of γ_1, γ_2, γ_3 and γ_4 until prescribed boundary conditions are satisfied.

Finally, $s_{1n}=s_{1(n-1)}+ \delta\, s_{1(n-1)}$, $s_{2n}=s_{2(n-1)}+ \delta\, s_{2(n-1)}$,$s_{3n}=s_{3(n-1)}+\delta\, s_{3(n-1)}$ and $s_{4n}=s_{4(n-1)}+\delta\, s_{4(n-1)}$ for n=1,2,3,... are obtained which seemed to be the most desired approximate initial values of $f_3(0)$, $f_5(0)$, $f_7(0)$ and $f_9(0)$. In this way all the six initial conditions are determined. Now it is possible to solve the resultant system of seven simultaneous equations by fourth-order Runge-Kutta shooting iteration technique so that velocity, micro rotation, temperature and concentration fields for a particular set of physical parameters can easily be obtained. The results are provided in several tables and graphs.

4. RESULTS AND DISCUSSION

In this analysis, we investigate the combined influence of thermal radiation, Soret and Dufour effects on steady MHD free convective heat and mass transfer flow of a micro polar fluid past a vertical plate with constant heat and mass fluxes. The non linear governing equations have been solved by employing fourth order Runge-Kutta shooting iteration technique to study the physical significance of this problem. We have collected the numerical values of velocity, micro rotation, temperature and concentration within the boundary layer and also evaluated the skin friction, couple stress, the rate of heat and mass transfer at the plate. It can be seen that the solution effected by the parameters namely suction parameter (f_w), grashof number (G), buoyancy ratio (N), magnetic parameter (M), micro rotation parameter (Δ), dimension less spin gradient viscosity parameter ($\wedge$), dimension less vertex viscosity parameter (λ), prandtl number (Pr), Eckert number (Ec), Schmidt number (Sc), Soret parameter (Sr), Dufour parameter (Du), radiation parameter (Rd) . The values of M, G are taken to be large for cooling Newtonian fluid, since these large values correspond to a strong magnetic problem and cooling problem. That is generally occurs nuclear engineering in connection with cooling of reactions. The values of 0.2, 0.5, 0.71, 1, 2, 5 are considered for Pr (0.2, 0.5, 0.71 for air and 1, 2, 3 for water). The values 0.1, 0.5, 0.6, 0.95, 5, 10 are also considered for S_c, which represents a specific condition of the flow, (0.95 for $C0_2$ 0.6,5,10 for water). The values of other parameters choose arbitrarily.

Figs (2-5) shows the velocity, micro rotation, temperature and concentration profiles for different values of grashof number (G). It is found that an increase in G, enhances the velocity and micro rotation and reduces the temperature and concentration.

Figs (6-9) represent the effect of magnetic parameter (M) on velocity, micro rotation, temperature and concentration. Fig.6 shows that the velocity fields decreases with increase of magnetic parameter (M) these effects are more stronger near the surface of the plate. Fig.7 shows that the micro rotation field increasing negatively and decreases with increase of M. Figs (8 & 9) respectively shows that the variation of temperature and concentration with M. It can be seen from profile that the temperature and concentration gradually enhance with increase in M within boundary layer.

Figs (10-13) represent the variation of inverse Darcy parameter (D^{-1}) on velocity, micro rotation, temperature and concentration. It is found that the velocity reduces with increase in D^{-1}. From Fig 11 the micro rotation field remains negative and increases with increase of permeability parameter D^{-1} with in the domain. From Figs (12 and13) the temperature and concentration enhances with increase in D^{-1}.

Figs (14-17) represent the effect of thermal radiation (Rd) on velocity, micro rotation, temperature and concentration. It is found that the higher the radiative heat flux larger the velocity and smaller the micro rotation. The temperature enhances and concentration reduces with increase in the radiation parameter R_d Figs (15 and 17).

The variation of velocity, micro rotation, temperature and concentration with Eckert number (Ec) are represented in Figs (18-21). Fig 18 shows that higher the dissipation larger the velocity in the boundary layer. From Fig 19 the micro rotation remains negative and reduces with increase in Ec. From figs (20 & 21), we find that the higher the dissipation larger the temperature and smaller the concentration within the domain.

Figs (22-25) represent the velocity, micro rotation, temperature and concentration for different values of suction parameter fw. Here fw>0 correspond to suction fw<0 correspond to injection or cooling at the plate. From figs 22 and 26 it can be seen that the velocity field decreases with increase in suction parameter fw , for fw>0 and for fw<0 the velocity decreases for fw< -1.0,enhances with higher fw=-1.5 and again reduces with still higher fw=-2.5 indicate the usual fact that suction stabilizer the boundary layer growth. Figs. (23 and 27) represent the micro rotation field with fw. It can be seen from profile that the micro rotation field or angular velocity (g) remains negative and decreases with fw>0 and for fw<0.It enhances fw<-1.0 reduces with higher fw=-1.5 and again enhances with higher fw=-2.5. Figs 24, 25, 28 and 29 represents the temperature and concentration with suction parameter fw an increase in(fw>0) reduces the temperature and concentration in the boundary layer while for fw<0 the temperature reduces for fw<-1.0 enhances for fw=-1.5 and again reduces with still higher fw=-2.5 also the concentration increases for lower and higher values of fw<0 and reduces for intermediate value fw=-1.5.

Figs (30-33) represent the effect of dimension less vertex viscosity parameter (λ), Fig. 30 shows that the velocity field increases with increasing values of vertex viscosity parameter λ. Fig. 31 shows that micro rotation remains negative and increases with increasing of λ<0.6 and for higher λ=0.8 it reduces in the boundary layer. Fig. 32 shows that the temperature reduces with increase in vertex viscosity parameter λ. Fig. 33 shows that the concentration reduces with increasing of λ < 0.6 and enhance with higher λ=0.8.

Figs (34-37) represent the velocity and micro rotation with spin gradient viscosity parameter (Λ). Fig. 34 shows that the velocity reduces with increase in viscosity parameter (Λ). Fig 35 shows that the micro rotation remains negative and increases with increase in Λ . From Figs (36 & 37) we observe that an increase in Λ reduces temperature and concentration within the boundary layer.

Figs (38–41) represent Soret and Dufour parameter on velocity, micro rotation, temperature and concentration. It is found that increase Sr (or decrease in Du), enhances the velocity. Fig. 39 shows that micro rotation remains negative and decreases with increase in Sr (or decrease in Du). The temperature decreases while concentration enhances with increase in Sr (or decrease in Du) (Figs 40 & 41).

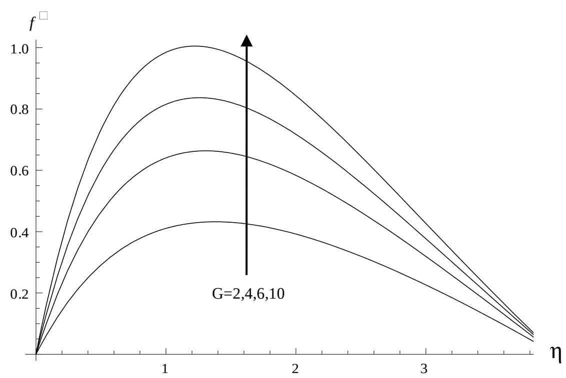

Fig.2: Variation of f^I with G
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01, Pr=0.71
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, Rd=0.5, fw=0.5

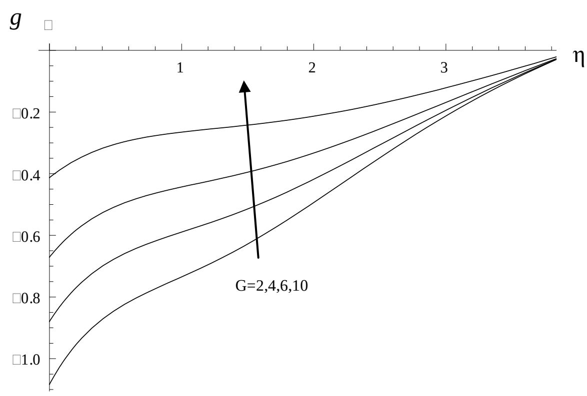

Fig.3: Variation of g with G
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01, Pr=0.71
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, Rd=0.5, fw=0.5

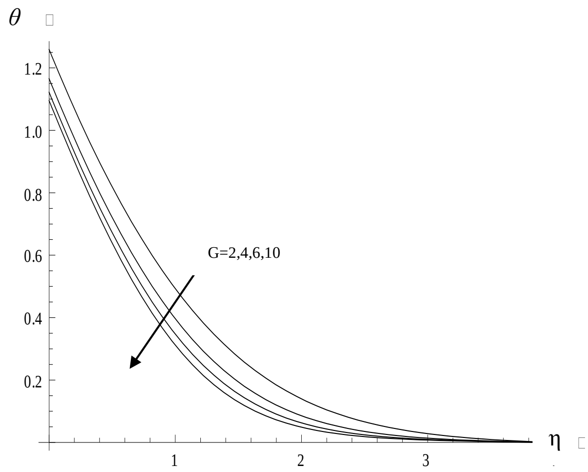

Fig.4: Variation of θ with G
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01, Pr=0.71, Rd=0.5
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

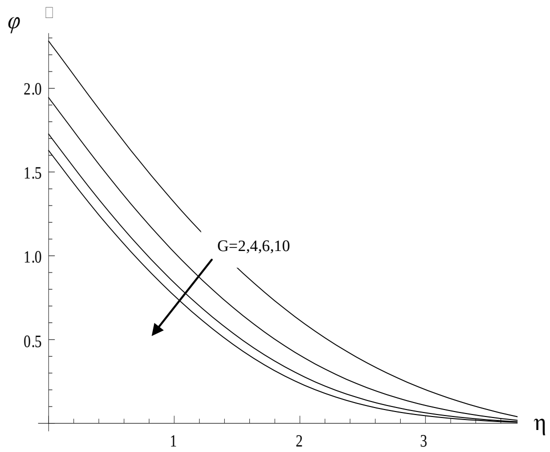

Fig.5: Variation of φ with G
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01, Pr=0.71
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, Rd=0.5, fw=0.5

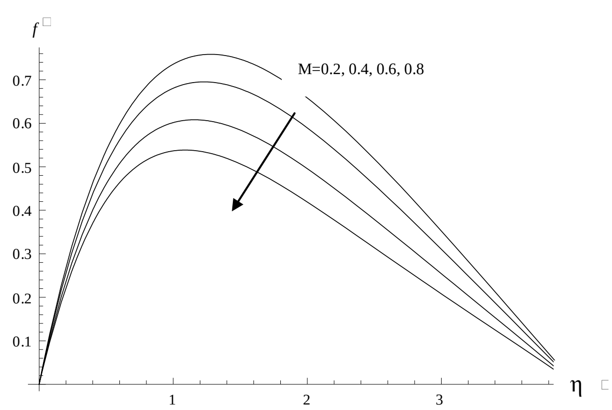

Fig.6: Variation of f^{I} with M
G=2, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01, Pr=0.71
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

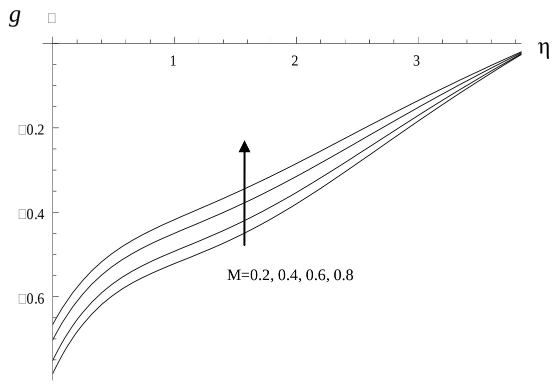

Fig.7: Variation of g with M
G=2, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01, Pr=0.71
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

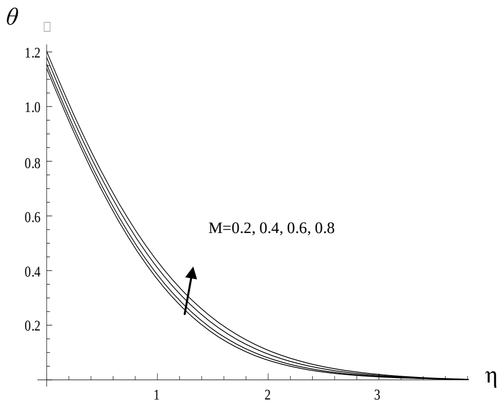

Fig.8: Variation of θ with M
G=2, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01, Pr=0.71
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

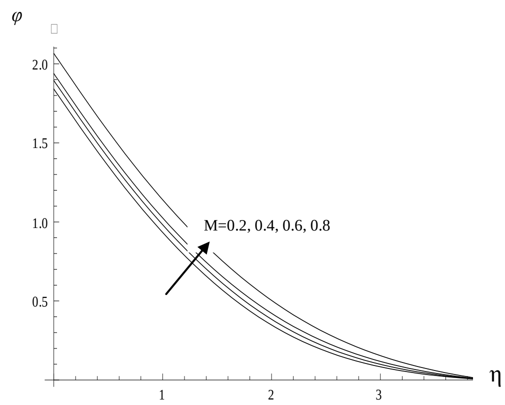

Fig.9: Variation of φ with M
G=2, D^{-1}=0.5, Pr=0.71, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

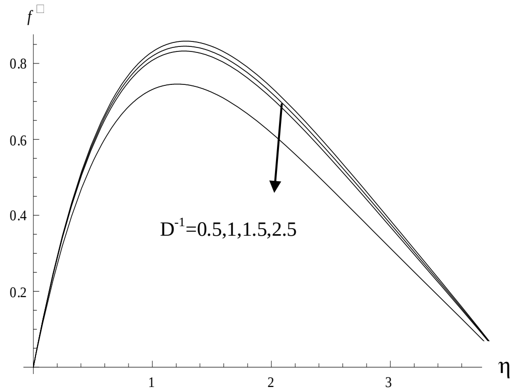

Fig.10: Variation of f^{I} with D^{-1}
G=2, M=0.5, Pr=0.71, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5.

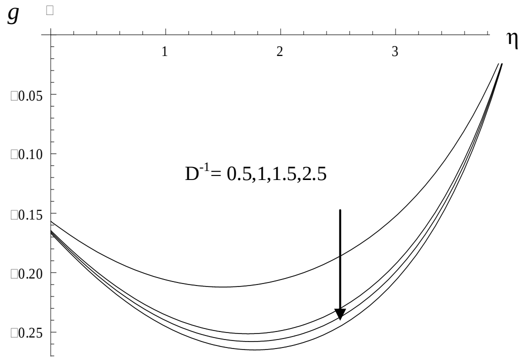

Fig.11: Variation of g with D^{-1}
G=2, M=0.5, N=1, Sc=1.3, Ec=0.01, Pr=0.71
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

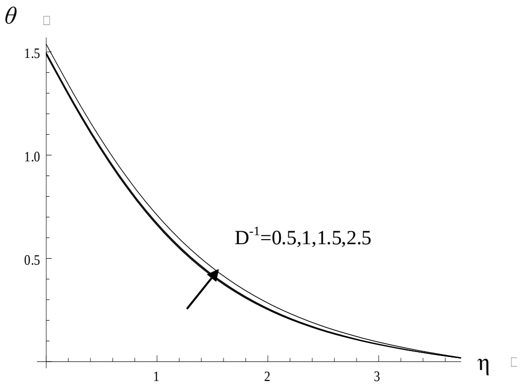

Fig.12: Variation of θ with D^{-1}
G=2, M=0.5, N=1, Sc=1.3, Ec=0.01, Pr=0.71
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

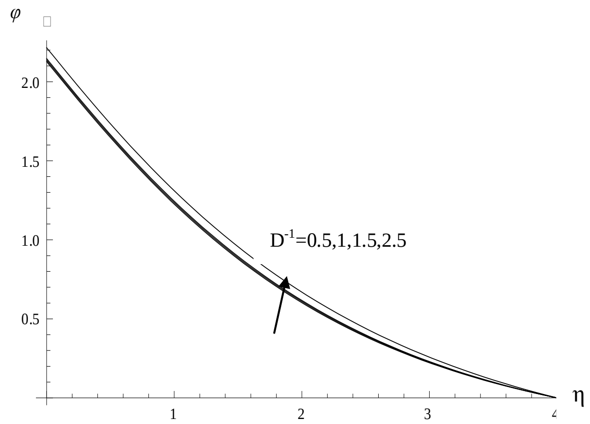

Fig.13: Variation of φ with D^{-1}
M=0.5, G=2, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5

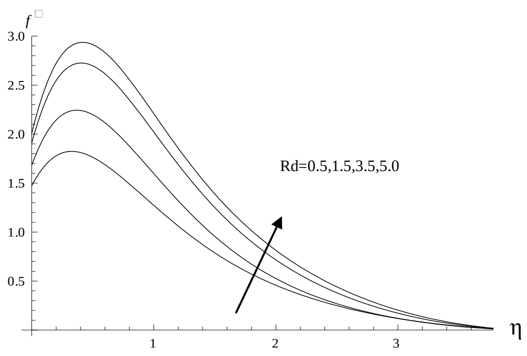

Fig.14: Variation of f^{I} with Rd
G=2, M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

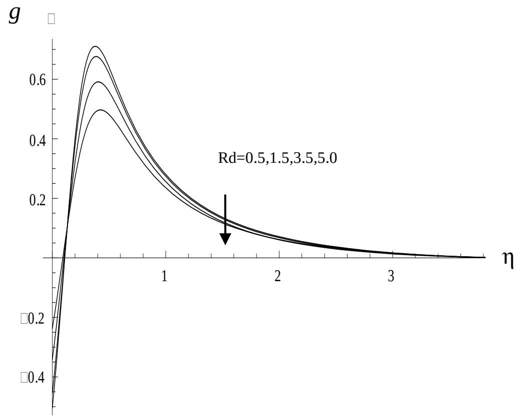

Fig.15: Variation of g with Rd
G=2, M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

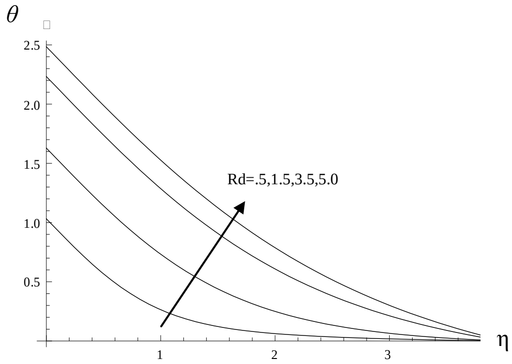

Fig.16: Variation of θ with Rd
G=2, M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

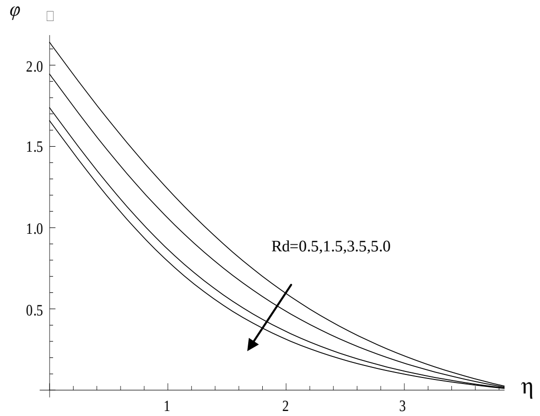

Fig.17: Variation φ with Rd
G=2, M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, fw=0.5

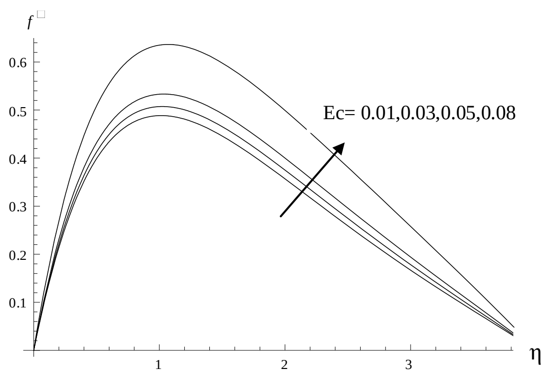

Fig.18: Variation of f^{I} with Ec
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, fw=0.5,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, G=2

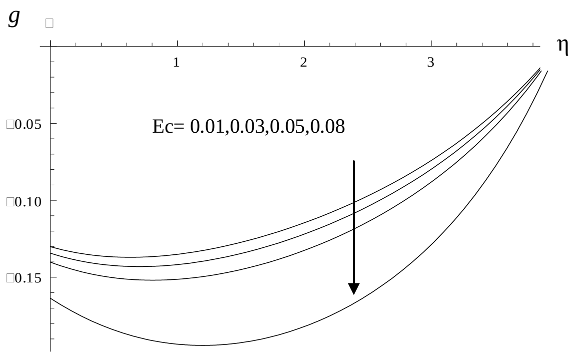

Fig.19: Variation of g with Ec
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, fw=0.5, G=2
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5

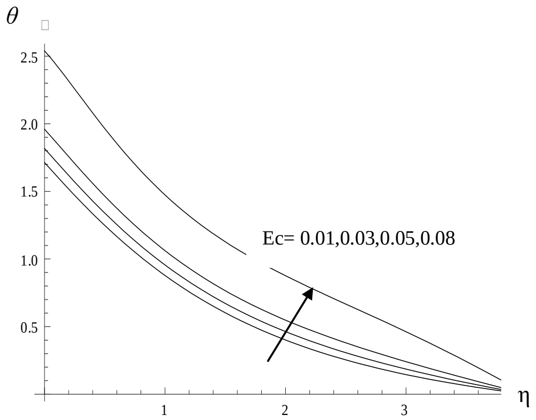

Fig.20: Variation of θ with Ec
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, fw=05,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, G=2

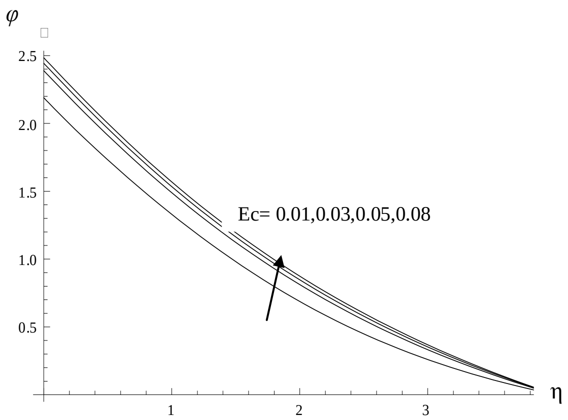

Fig.21: Variation of φ with Ec
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, fw=0.5,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, G=2

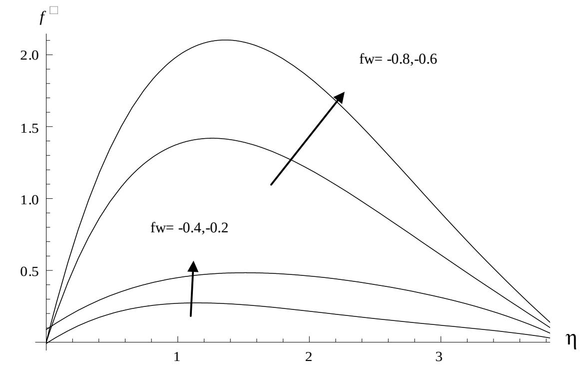

Fig.22: Variation of f^1 with fw<0
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, G=2

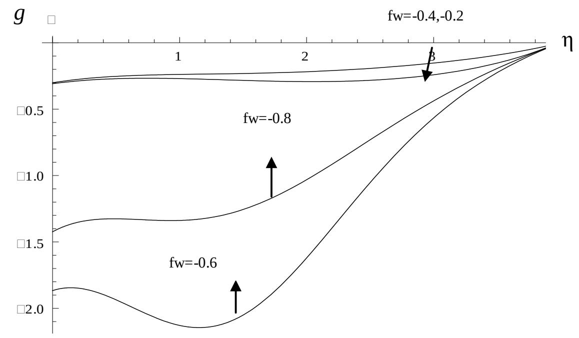

Fig.23: Variation of g with fw<0
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, G=2

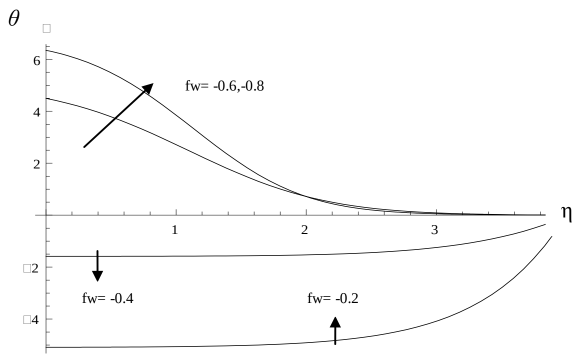

Fig.24: Variation of θ with fw<0
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, G=2

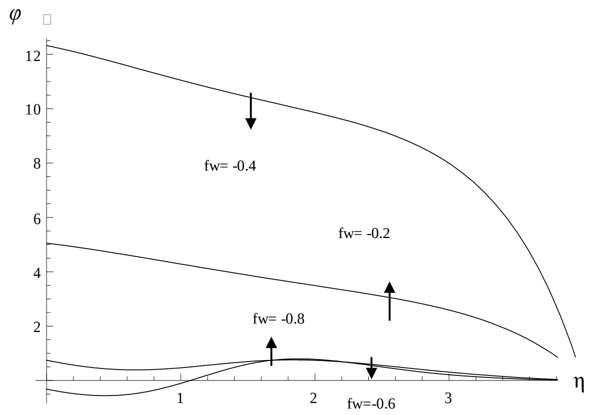

Fig.25: Variation of φ with fw<0
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, G=2, G=2

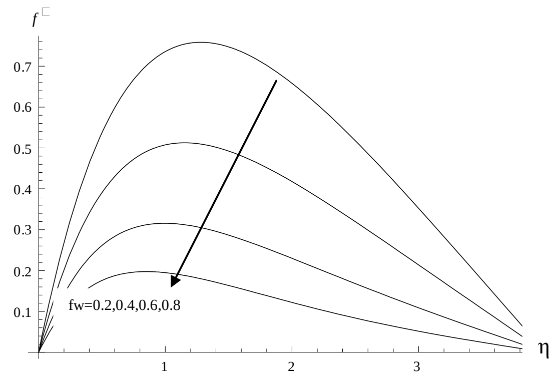

Fig.26: Variation of f^1 with fw>0
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, G=2

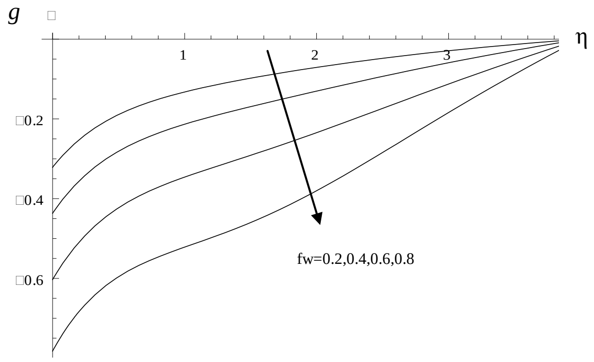

Fig.27: Variation of g with fw>0
M=0.5,D^{-1}=0.5,N=1,Sc=1.3,Ec=0.01,
Sr=1.0,Du=0.03,Λ=0.5,G=2,s=0.2

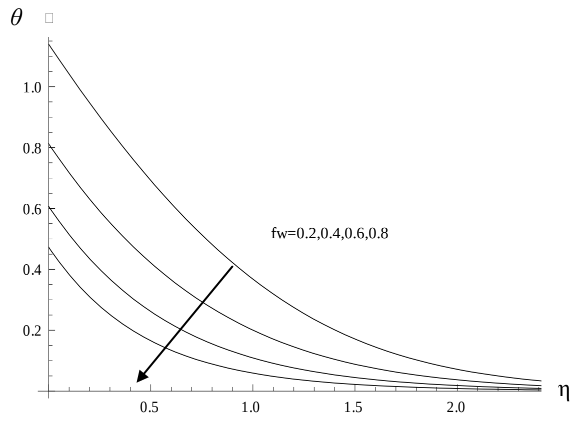

Fig.28: Variation of θ with fw>0
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, G=2

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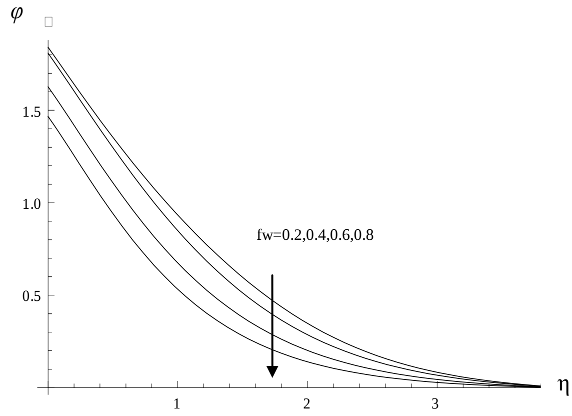

Fig.29: Variation of φ with fw>0
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, G=2

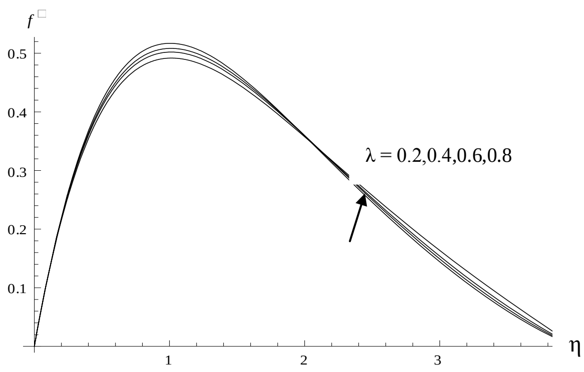

Fig.30: Variation of f^I with λ
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, G=2

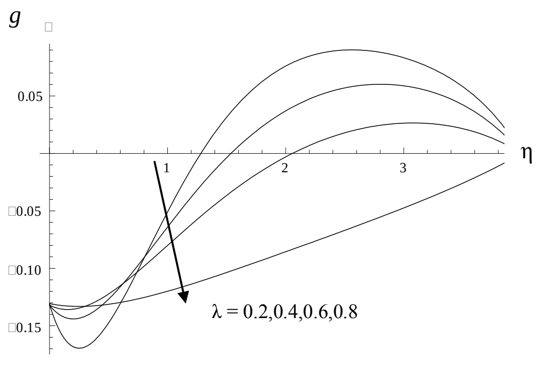

Fig.31: Variation of g with λ
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, Λ=0.5, Δ=0.5, G=2

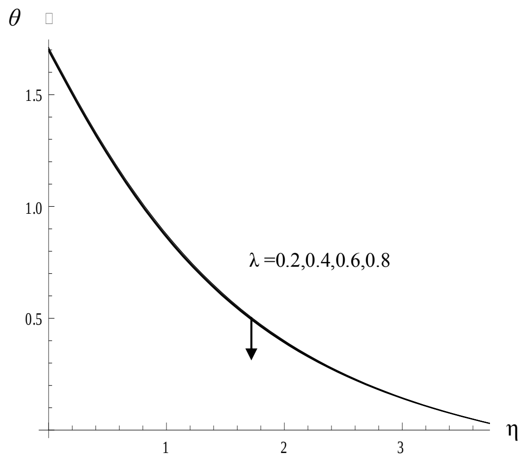

Fig.32: Variation of θ with λ
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, G=2, Δ=0.5

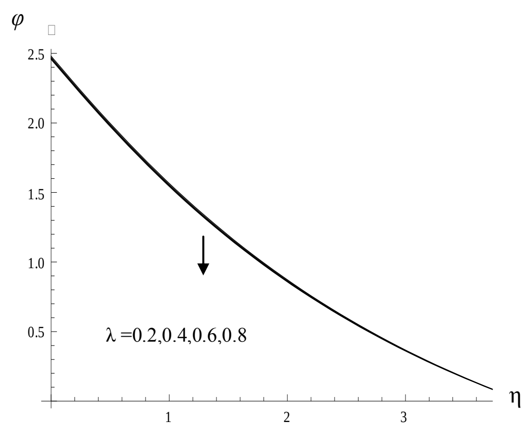

Fig.33: Variation of φ with λ
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, G=2, Δ=0.5

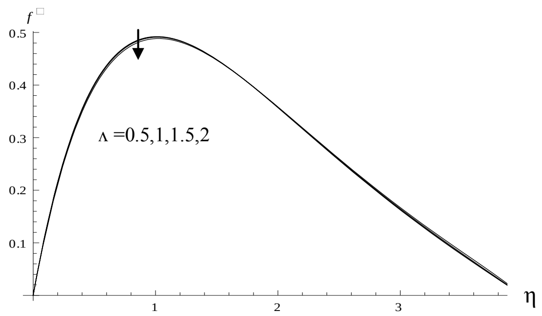

Fig.34: Variation of f^I with Λ
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, G=2, Δ=0.5

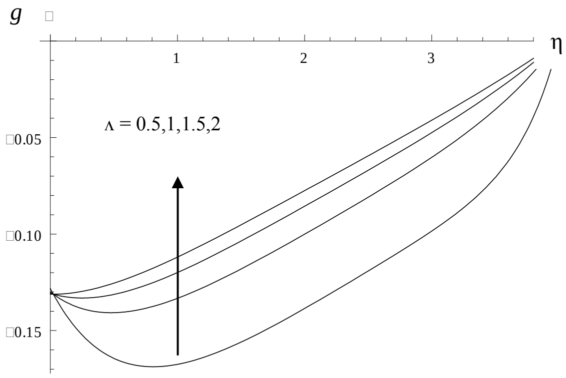

Fig.35: Variation of g with Λ
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, G=2, Δ=0.5

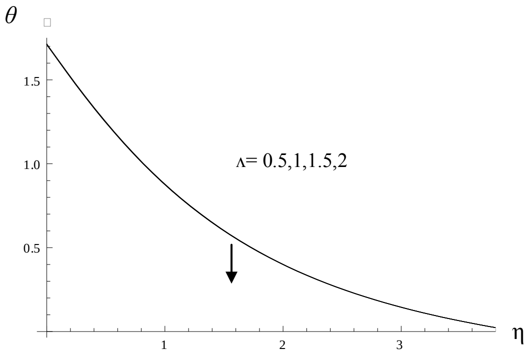

Fig.36: Variation of θ with Λ
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, G=2, Δ=0.5

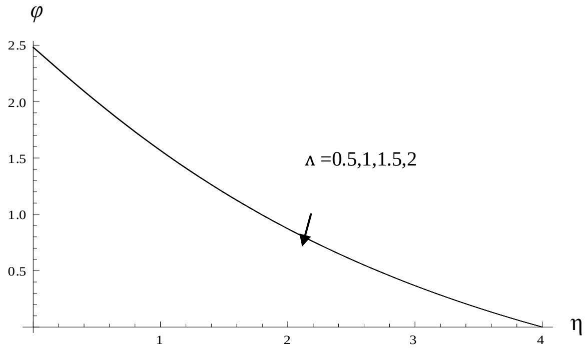

Fig.37: Variation of φ with Λ
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
Sr=1.0, Du=0.03, G=2, Δ=0.5

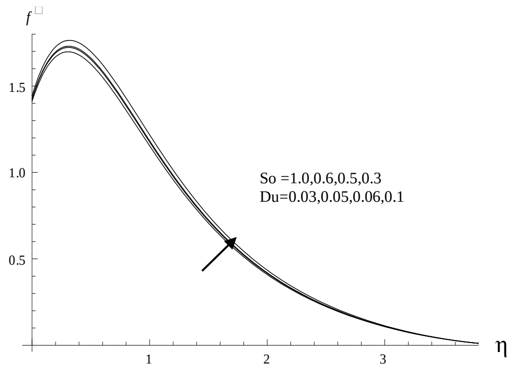

Fig.38: Variation of f^I with Sr & Du
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
G=2.0, Du=0.03, Λ=0.5, Δ=0.5

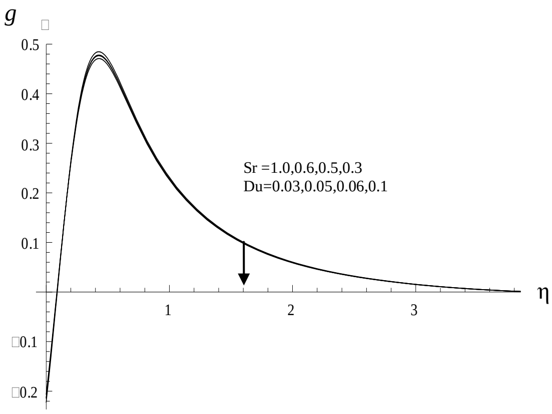

Fig.39: Variation of g with Sr&Du
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01,
G=2.0, Λ=0.5, Δ=0.5

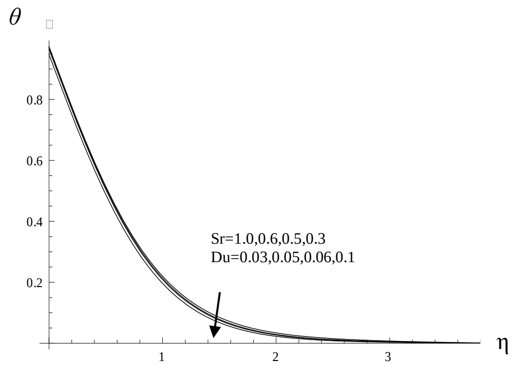

Fig.40: Variation of θ with Sr&Du
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01, G=2.0, Λ=0.5, Δ=0.5

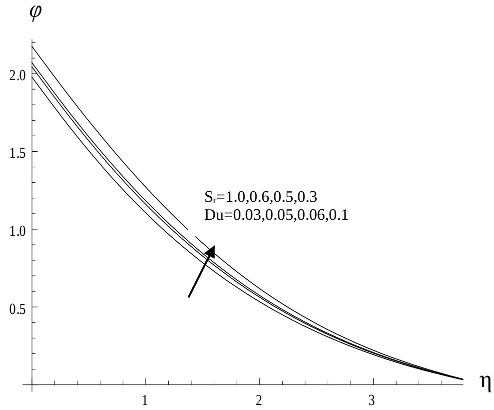

Fig.41: Variation of with Sr&Du
M=0.5, D^{-1}=0.5, N=1, Sc=1.3, Ec=0.01, G=2.0, Λ=0.5, Δ=0.5

The effect various parameters on skin friction (Cf), couple stress (Cw). Nusslet number (Nu) and Sherwood number (Sh) are tabulated in table1.from the tabler values we find that the skin friction coefficient increases with increasing in G and decreases with increase in M and D^{-1}.When the molecular buoyancy force dominates over the thermal buoyancy force. We find that lesser molecular diffusivity/ thermal diffusivity smaller the skin friction coefficient. Increase in the Soret parameter (Sr) or decrease in dufour parameter Du. Increases the cf on the wall. W.r.t to Eeckert number Ec or thermal radiation parameter Rd, we find that higher the dissipative effect / radiation heat flux, larger the skin friction coefficient on the wall.

Table 1 : The local Skin-friction (Cf), couple stress (Cw), Nusselt number (Nu), Sherwood number (Sh) for different values of important parameters

G	M	D^{-1}	Sc	fw	Pr	Cf	Cw	Nu	Sh
2	0.2	0.2	0.24	0.2	0.71	0.825991	0.349755	0.794002	0.43834
4	0.2	0.2	0.24	0.2	0.71	1.34155	0.535858	0.857889	0.51438
6	0.2	0.2	0.24	0.2	0.71	1.75863	0.673888	0.891086	0.579101
10	0.2	0.2	0.24	0.2	0.71	2.16559	0.799068	0.912806	0.613696
2	0.4	0.2	0.24	0.2	0.71	0.785394	0.334469	0.782008	0.426076
2	0.6	0.2	0.24	0.2	0.71	0.72489	0.310866	0.764338	0.417915
2	0.8	0.2	0.24	0.2	0.71	0.67784	0.291945	0.749327	0.392602
2	0.2	0.4	0.24	0.2	0.71	0.811639	0.344404	0.790112	0.43402
2	0.2	0.6	0.24	0.2	0.71	0.792061	0.336977	0.785096	0.43841
2	0.2	0.8	0.24	0.2	0.71	0.773012	0.329715	0.779284	0.42224
2	0.2	0.2	0.24	0.4	0.71	0.631531	0.311916	1.17834	0.477983
2	0.2	0.2	0.24	0.6	0.71	0.479999	0.274005	1.62328	0.555336
2	0.2	0.2	0.24	0.8	0.71	0.277224	0.207416	2.60084	0.784205

An increase in spin gradient parameter (ʌ) enhances C_f on the wall. A growth in viscosity vertex parameter (λ), reduces the skin friction coefficient (C_f), fixing the other parameters. The tabular values of couple stress shows that an increase in G, N, Sr, Ec, Rd leads to an enhancement in the couple stress on the wall. While it decreases with increase in M, D^{-1}.

From the tabular values of rate of heat transfer (Nusselt number) we find that an increase in G or ʌ, enhances the rate of heat transfer on the wall, while it reduces with increase in M or D^{-1}.

The variation of rate of Mass transfer (Sherwood number) with various parameters shows that the rate of mass transfer experiences an enhancement on the wall with increase in G, Ec, ʌ. It decreases with M or D^{-1}. Increase in Soret parameter Sr (or decrease in Du) reduces the Sherwood number on the wall. An increase in radiation parameter Rd and vortex viscosity parameter λ, leads to an enhancement in the Sherwood number.

Table 2 : The local Skin-friction (Cf) ,couple stress (Cw), Nusselt number(Nu), Sherwood number(Sh) for different values of important parameters

Sr/Du	Ec	ʌ	Rd	Cf	Cw	Nu	Sh
1.0/0.03	0.01	0.5	0.5	0.825991	0.349755	0.794002	0.43834
0.6/0.05	0.01	0.5	0.5	0.77177	0.329091	0.77322	0.50465
0.5/0.06	0.01	0.5	0.5	0.75980	0.324477	0.76579	0.52571
0.3/0.1	0.01	0.5	0.5	0.74016	0.316866	0.74202	0.57558
1.0/0.03	0.5	0.5	0.5	0.845645	0.357184	0.750185	0.448257
1.0/0.03	0.07	0.5	0.5	0.867977	0.365566	0.707394	0.459757
1.0/0.03	0.09	0.5	0.5	0.904884	0.379304	0.644788	0.479947
1.0/0.03	0.01	1.0	0.5	0.830194	0.299887	0.793884	0.438349
1.0/0.03	0.01	1.5	0.5	0.834079	0.320941	0.794119	0.438548
1.0/0.03	0.01	2.0	0.5	0.840611	0.349984	0.794169	0.438525
1.0/0.03	0.01	0.5	1.5	1.16421	0.468944	0.457931	0.585042
1.0/0.03	0.01	0.5	3.5	1.46243	0.559144	0.350278	0.715524
1.0/0.03	0.01	0.5	5.0	1.57584	0.589853	0.323264	0.764877

5. CONCLUSIONS

To analyze the combined influence of thermal radiation, dissipation, Soret effect (Sr), Dufour effect (Du) on convective heat and mass transfer flow of a micropolar fluid past vertical plate. The governing equations have been solved by employing fourth order Runge-kutta shooting iteration technique. The conclusions of the analysis are a components velocity (f^I), microrotation (g), temperature (θ), concentration(C).

- An increasing grashof number (G) enhances the velocity (f^I) microrotation(g), and reduces the temperature and concentration while Cf, Cw. The rate of heat and mass transfer enhances with G.
- Higher the Lorenz force smaller the velocity larger microrotation (g), temperature and concentration while Cf, Cw, Nu, Sh reduces with M.
- With respect to D^{-I} we find that the velocity reduces microrotation (g), temperature and concentration enhances with D^{-1} also Cf, Cw, Nu, Sh reduces with D^{-I}.
- Higher the radiative heat flux larger the velocity (f^I), temperature (θ) and smaller microrotation (g) and concentration increasing Rd enhances Cf, Cw, Sh and reduces Nu.
- Higher the dissipation larger the velocity and concentration, microrotation (g) larger the temperature flow field an increasing Ec enhances Cf, Cw, Nu and Sh.
- Increasing Soret parameter (Sr) (or decreasing Dufour parameter (Du)) enhances velocity and concentration and reduces microrotation (g) and temperature increase Sr (or decrease in Du) reduces to enhancement Cf, Cw ,Nu , and depreciation Sh .
- An increase the suction parameter fw reduces velocity, microrotation and concentration. An increasing Cf, Cw, reduces Nu, Sh increases on the plate η=0 with increase in fw.
- An increasing vertex viscosity parameter (λ) enhances velocity, microrotation and reduces temperature while the concentration reduces with λ<0.6 and enhance with higher λ=0.8, Cf, Cw reduces on the wall while Nu and Sh enhances in the wall with increase in λ.

6. REFERENCES

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