THERMAL RADIATION AND CHEMICAL REACTION EFFECTS ON MHD MIXED CONVECTION FLOW OF A MICROPOLAR FLUID PAST A CONTINUOUS SURFACE IN A PARALLEL MOVING STEAM WITH VISCOUS DISSIPATION

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Abstract: In this paper, the effects of thermal radiation and chemical reaction MHD mixed convection flow of a micropolar fluid past a continuously moving flat plate placed in a parallel moving stream with viscous dissipation has been investigated. The Rosseland approximation has been used to describe the radiative heat flux in energy equation. The governing systems of partial severalial equations are converted to ordinary severalial equations by using the similarity transformations, which are then solved numerically by using fourth order Runge–Kutta scheme together with shooting method. The Velocity, micro-rotation, temperature and concentration prifiles have been obtained for several parameters, namely the Grashof numbers *Gr* & *Gc*, Magnetic field parameter *M*, the Prandtl number *Pr*, the radiation parameter *R*, the Eckert number *Ec*, the Schmidt number *Sc* and the chemical reaction parameter *Kr*. Discussion has been given for both the cases i.e. the plate moving with more or less velocity as compared to that of free the stream velocity. All the results are shown graphically. The Skin friction coefficient, couple stress coefficient, Nusselt number and Sherwood number giving the rate of the surface, are also computed.

Keywords: **Thermal radiation; Chemical reaction; MHD; Micropolar fluid; Viscous dissipation**

List of Symbols:

Roman letters

C	concentration of the fluid (Kmol m^{-3})
C_∞	concentration at infinity of the fluid (Kmol m^{-3})
C_w	surface concentration of the fluid (Kmol m^{-3})
C_f	coefficient of skin friction
C_p	specific heat at constant pressure, J/kg K
Ec	Eckert number
f	dimensionless stream function
g	dimensionless angular momentum
Gc	local solutal Grashof number
Gr	local modified Grashof number
K	dimensionless coupling parameter
K_1	coupling constant
K_f	thermal diffusivity of the fluid, W/mK
Kr	Chemical reaction parameter
M	magnetic parameter
N	micro-rotation component
Nu	Nusselt number
Pr	Prandtl number

q_r	rate of heat transfer
R	radiation parameter
Re	Reynolds number
s	constant characteristic of the fluid
T	temperature of the fluid, K
T_w	surface temperature, K
T_∞	temperature at infinity, K
u, v	component velocities, m/s
U_r	reference velocity, m/s
U_w	velocity at the wall, m/s
U_∞	velocity at infinity, m/s
x, y	Cartesian co-ordinates, m

Greek letters

α	dimensionless micro-rotation parameter
α_1	micro-rotation constant
η	dimensionless similarity variable
θ	dimensionless temperature
μ	coefficient of dynamic viscosity. kg/ms
ν	coefficient of apparent kinematic viscosity, m2/s
Ψ	dimensionless stream function

1. Introduction:

The theory of micropolar fluids has drawn much attention during recent years due to its importance in many technological applications such as cooling of nuclear reactors during emergency shutdown, cooling electronic devices, enhancing oil recovery etc. Eringen [1]. Later he developed the theory of thermomicropolar fluids [2]. An excellent review of the study of micropolar fluid and its applications were provided by Ariman et al. [3]. These micropolar fluids are suitable in modeling the body fluids and the cerebro-spinal fluid (CSF). Power [4] has shown that the fluid flowing in the brain can be modeled by the micropolar fluids. The concept of continuous surfaces was introduced by Sakiadis [5] who defined them as polymer sheets or filaments continuously drawn from a die. Some of the practical applications of continuous flat surfaces are the extrusion of plastic sheets, cooling of a metallic plate in a bath, and boundary layer along material handling conveyors. This type of flow is important in the manufacture of fibers. In glass and polymer industries, fibers are manufactured by extruding hot material through a circular nozzle to form a continuous filament. A knowledge of heat transfer is of special interest in such flows because of the cooling of the fibers in the formation process [6]. Takhar and Soundalgekar [7] studied the flow and heat transfer past a continuous moving plate in a stream of a micropolar fluid. However in all these above flows, the moving surface was placed in a stream of flow which was at rest. An interesting extension to the above problem was made by Gorla and Reddy [8] who studied the problem of flow and heat transfer of a continuous plane sheet in a stream moving with speed U_∞.

The applied magnetic field may play an important role in controlling momentum and heat transfers in the boundary layer flow of a micropolar fluid over a vertical plate. Kim [9] has analysed the unsteady MHD convection flow of polar fluids past a vertical moving porous plate in a porous medium. Ibrahim et al. [10] have examined the effects of unsteady MHD micropolar fluid flow over a vertical porous plate through a porous medium in the presence of thermal and mass diffusion with a constant heat source. The effect of heat and mass transfer on MHD micropolar flow over a vertical moving porous plate in a porous medium has studied by Kim [11]. In all the previous investigations, the effect of thermal radiation on MHD flow and heat transfer has not been provided.

The effect of radiation on MHD flow and heat transfer problem has become more important industrially. At high operating temperatures, radiation effect can be quite significant, many processes in engineering areas occur at high temperatures and knowledge of radiation heat transfer become very important for design of reliable equipment, nuclear plants, gas turbines and various propulsion devices or aircrafts, missiles, satellites, and space vehicles. The effect of variable viscosity on hydromagnetic flow and heat transfer past a continuously moving porous boundary with radiation has been studied by Seddeek [12]. The same author investigated [13] thermal radiation and buoyancy effects on MHD free convective heat generating flow over an accelerating permeable surface with temperature-dependent viscosity. Ghaly and Elbarbary [14] have investigated the radiation effect on MHD free convection flow of a gas at a stretching surface with a uniform free stream. Pal and Chatterjee [15] performed analysis for heat and mass in MHD non-Darcian flow of a micropolar fluid over a stretching sheet embedded in a porous media with non-uniform heat source and thermal radiation. In all the above investigations only steady state flows over a semi-infinite vertical plate have been studied. The unsteady free convection flows over vertical plate were studied by Raptis [16]. The radiation effects on MHD free-convection flow of a gas past a semi-infinite vertical plate is studied by Takhar et al. [17]. Sankar Reddy et al. [18] presented unsteady MHD convective heat and mass transfer flow of a micropolar fluid past a semi-infinite vertical moving porous plate in the presence radiation. The study of the MHD Oscillatory flow of a micropolar fluid over a semi-infinite vertical moving porous plate through a porous medium with thermal radiation is considered by Sankar Reddy et al. [18]. Mahmoud [19] has analyzed thermal radiation effects on MHD flow of a micropolar fluid over a stretching surface with variable thermal conductivity.

The 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 the tower, and the flow in a desert cooler, the heat and mass transfer occurs simultaneously. Das *et al.* [20] considered the effects of first order chemical reaction on the flow past an impulsively started infinite vertical plate with constant heat flux and mass transfer. Muthucumarswamy and Ganesan [21] and Muthucumarswamy [22] studied first order homogeneous chemical reaction on flow past infinite vertical plate. Seddeek et al. [23] analyzed the effects of chemical reaction, radiation and variable viscosity on hydromagnetic mixed convection heat and mass transfer for Hiemenz flow through porous media. Ibrahim et al. [24] analyzed the effects of the chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate with heat source and suction. Demesh et al. [25] investigated combined effect of heat generation or absorption and first-order chemical reaction on micropolar fluid flow over a uniformly stretched permeable surface. Pal et al. [26] used perturbation analysis to study unsteady magnetohydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction. The buoyancy and chemical reaction effects on MHD mixed convection heat and mass transfer in a porous medium with thermal radiation and Ohmic heating was investigated by Pal and Talukdar [27] Ghaly and Seddeek [28] have investigated the effect of chemical reaction, heat and mass transfer on laminar flow among a semi-infinite horizontal plate with temperature dependent viscosity. Recently, Kandasamy et al. [29] discussed heat and mass transfer effect along a wedge with heat source and concentration in the presence of suction/injection taking into account the chemical reaction of first order.

The present study mainly focused on exploring the effects of thermal radiation and chemical reaction on MHD mixed convection flow of a micropolar fluid continuously moving plate in the presence of viscous dissipation placed in a parallel moving stream, both in the same direction but with different velocities. The governing non-linear PDEs are transformed into a system of coupled non-linear ODEs using similarity transformation and then inspected numerically using a Runge–Kutta fourth order with shooting method. The radiative heat transfer and first order homogeneous chemical reaction in the mass transfer on the flow field are of particular concern here.

2. Mathematical analysis:

We consider steady, two dimensional, incompressible, laminar mixed convective flow heat and mass transfer of a micropolar, electrically conducting fluid past a continuous flat plate moving with a constant velocity U_w and free stream velocity U_∞ and subjected to a uniform transverse magnetic field in the presence of viscous dissipation. The continuous moving flat surface sucks the ambient fluid and pumps it again in the downstream direction. It is assumed that the plate and the fluid move in the same direction. An interesting case can be obtained when the plate is moving in a direction opposite to that of fluid. A uniform magnetic field of strength is assumed to be applied in the positive *y*-direction normal to the plate. The model of first order chemical reaction has been considered following Das et.al. [20]. Neglecting external body forces and moments, the field equations of the micropolar fluid flow with the boundary layer approximations can be expressed as follows:

(i) Continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0 \quad (1)$$

(ii) Momentum:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+k_1\frac{\partial N}{\partial y}-\frac{\sigma B_0^2}{\rho}u \qquad (2)$$

(iii) Angular momentum:

$$G_1\frac{\partial^2 N}{\partial y^2}-2N-\frac{\partial u}{\partial y}=0 \qquad (3)$$

(vi) Energy:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y}+\frac{\nu}{C_p}\left(\frac{\partial u}{\partial y}\right)^2 \qquad (4)$$

(v) Concentration:

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-k_r(C-C_\infty) \qquad (5)$$

The surface is maintained at a fixed temperature T_w. If $T_w > T_\infty$, the buoyancy force created will assist the forced flow. On the other hand for, $T_w < T_\infty$, the buoyancy force will oppose the forced flow. The boundary conditions are given by;

$$\begin{aligned} &y=0: u=U_w,\ v=0,\ N=-\frac{1}{2}\frac{\partial u}{\partial y},\ T=T_w,\ C=C_w \\ &y\to\infty: u\to U_\infty,\ N\to 0,\ T\to T_\infty,\ C\to C_\infty \end{aligned} \qquad (6)$$

Here u, v are the velocity components along x and y directions, respectively, $\nu=(\mu+S)/\rho$ is the apparent kinematic viscosity, μ the coefficient of viscosity, S a constant characteristic of the fluid, N the microrotation component, $K_1=S/\rho\,(K_1>0)$ the coupling constant, G_1 the microrotation constant, ρ the density, U_0 the uniform velocity of the plate in the x-direction, T the temperature of the fluid in the boundary layer, T_w the wall temperature of the plate, T_∞ the temperature of the fluid for away from the plate, α the thermal diffusivity, c_p the specific heat at constant pressure, q_r the radiative heat flux, C concentration of the fluid in the boundary layer, C_w the wall concentration of the plate and C_∞ the concentration of the fluid for away from the plate, respectively. The second and third terms on the right hand side of Eq. (4) denote the radiative heat flux and viscous dissipation effects respectively. The last term on the right hand side of Eq. (5) represents the chemical reaction effect.

By using the Rosseland approximation (Brewster [30]), the radiative heat flux in the y' direction is given by

$$q_r=-\frac{4\sigma_1}{3k_1}\frac{\partial T^4}{\partial Y} \qquad (7)$$

where σ_1 is the Stefan-Boltzmann constant and k_1 is the mean absorption coefficient.

Assuming that the temperature differences within the flow are sufficiently small so that T^4 can be expanded in Taylor series about the free stream temperature T_∞ to yield

$$T^4 \cong 4T_\infty^3 T-3T_\infty^4 \qquad (8)$$

where the higher-order terms of the expansion are neglected.

By using (6) and (7), Eq. (4) gives

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k_e}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{16\sigma T_\infty^3}{3\rho c_p k_1}\frac{\partial^2 u}{\partial y^2}+\frac{\nu}{c_p}\left(\frac{\partial u}{\partial y}\right)^2 \qquad (9)$$

If the dimensional stream function $\psi(x,y)$ then

$u=\dfrac{\partial \psi}{\partial y}$ and $u=-\dfrac{\partial \psi}{\partial x}$.

The following non-dimensional variables (Takhar and Soundalgekar [6]):

$$\begin{aligned} &\eta=\left(\frac{U_0}{2\nu x}\right)^{1/2} y,\ \psi=(2\nu U_0 x)^{1/2} f(\eta),\ \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\ \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}, \\ &u=U_0 f'(\eta),\ v=-\sqrt{\frac{2\nu U_0}{x}}\left[f(\eta)-\eta f'(\eta)\right],\ N=\left(\frac{U_0}{2\nu x}\right)^{1/2} U_0 g(n) \end{aligned} \qquad (10)$$

the continuity equation is automatically satisfied and the system of Eqs. (2), (3), (5) and (9) becomes:

$$f''' + ff'' - Mf' + Gr\theta + Gc\phi + Kg' = 0 \quad (11)$$

$$Gg'' - 2(2g + f'') = 0 \quad (12)$$

$$\left(3R+4\right)\theta'' + 3R\Pr f\theta' + 3R\Pr\phi\theta + R\Pr Ecf''^2 = 0 \quad (13)$$

$$\phi'' + Sc\phi' - KrSc\phi = 0 \quad (14)$$

The primes mean severaliation with respect to η, $M = \left(\frac{\sigma U_\infty}{\rho}\right)^{1/2} B_0$ is the is the magnetic field parameter, $G = \frac{G_1 U_0}{2\nu x}$ is the micro-rotation parameter, $G_r = g\beta\rho\frac{\nu x}{U_o^2}$, is the Grashof number, $G_c = g\beta^*\rho\frac{\nu x}{U_o^2}$ is the modified Grashof number, $K = \frac{K_1}{\nu}$ is the coupling parameter, $\Pr = \frac{\nu}{K}$ is the Prandtl number, $R = \frac{kk_e}{4\sigma_s T_\infty^3}$ is the thermal radiation parameter, $Ec = \frac{U_0^2}{c_p\left(T_w - T_\infty\right)}$ is the Eckert number, $Sc = \frac{\nu}{D}$ is the Schmidt number, $Kr = \frac{K_r'}{a}$ is the non-dimensional chemical reaction parameter.

The transformed boundary conditions (6) are given by

$$\begin{aligned} &f(0) = 0,\ f'(0) = U_w / U_r,\ g(0) = -\frac{1}{2} f''(0),\ \theta(0) = 1,\ \phi(0) = 1, \\ &f(\infty) = U_\infty / U_r,\ g(\infty) = 0,\ \theta(\infty) = 0,\ \phi(\infty) = 0 \end{aligned} \quad (15)$$

Where U_r is the reference velocity defined as

$$U_r = \begin{cases} U_w & \text{if } U_w > U_\infty \\ U_\infty & \text{if } U_w < U_\infty \end{cases}$$

Boundary conditions are given by (15), then can be re-written as

(i) For $U_w > U_\infty$:

$$\begin{aligned} &f(0) = 0,\ f'(0) = 1,\ g(0) = -\frac{1}{2} f''(0),\ \theta(0) = 1,\ \phi(0) = 1 \\ &f'(\infty) = \frac{U_\infty}{U_w},\ g(\infty) = 0,\ \theta(\infty) = 0,\ \phi(\infty) = 0 \end{aligned} \quad (16)$$

(ii) For $U_w < U_\infty$:

$$\begin{aligned} &f(0) = 0,\ f'(0) = \frac{U_w}{U_\infty},,\ g(0) = -\frac{1}{2} f''(0),\ \theta(0) = 1,\ \phi(0) = 1 \\ &f'(\infty) = 1,\ g(\infty) = 0,\ \theta(\infty) = 0,\ \phi(\infty) = 0 \end{aligned} \quad (17)$$

The physical quantities of interest are the local skin friction coefficient, the wall heat transfer coefficient (or the local Nusselt number) and the wall deposition flux (or the local Stanton number) which are defined as

$$C_f = \frac{\tau_w}{\rho U_o^2/2},\quad Nu_x = \frac{q_w x}{\lambda(T_w - T_\infty)},\ St_x = \frac{J_s}{U_0 C_\infty} \quad (18)$$

Respectively, where the skin friction τ_w, the heat transfer from the wall q_w and the deposition flux from wall J_s are given by

$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0},\ q_w = -\lambda\left(\frac{\partial T}{\partial y}\right)_{y=0} - \frac{4\sigma}{k}\left(\frac{\partial T^4}{\partial y}\right)_{y=0},\ J_s = -D\left(\frac{\partial C}{\partial y}\right)_{y=0} \quad (19)$$

Hence the expressions for the skin friction, the rate of heat transfer and the deposition flux for general flow over a radiative isothermal surface are written as

$$C_f \operatorname{Re}_x^{(1/2)} = 2f''(0),\ Nu_x \operatorname{Re}_x^{-(1/2)} = \frac{-1}{2}\theta'(0),\ St_x Sc \operatorname{Re}_x^{(1/2)} = -\phi'(0) \quad (20)$$

where $\operatorname{Re}_x = U_0 x/\nu$ the local Reynolds number.

3. Numerical solution:

The set of coupled non-linear differential Eqs. (11)–(14) subject to the boundary conditions Eqs. (15) constitute a two-point boundary value problem. In order to solve these equations numerically we follow most efficient numerical method by using Runge-Kutta fourth order along with shooting method. The computations were done by a program which uses a symbolic and computational computer language (Mathematica 11.0) on a Pentium 1 PC machine. The above procedure is repeated until we get the results up to the desired degree of accuracy, 10^{-6}. From the process of numerical computation, the skin-friction coefficient, the Nusselt number and the Sherwood number, which are respectively proportional to $f''(0), -\theta'(0)$ and $-\phi'(0)$ are also sorted out and their numerical values are presented in a tabular form.

4. Results and discussion:

The transformed non linear differential Eqs. (11)–(14) subjected to the boundary conditions (16) and (17) was solved numerically using Runge-Kutta fourth order technique along with shooting method. The velocity, microrotattion, temperature and concentration profiles were obtained and utilized to compute the skin friction coefficient, the local Nusselt number and Sherwood number. The results of the velocity, microrotation, temperature and concentration profiles for several values of the governing parameters viz., magnetic parameter *M*, Grashof number *Gr*, solutal Grashof number *Gc*, Prandtl number *Pr*, radiation parameter *R*, viscous dissipation parameter i.e., Eckert number *Ec*, Schimdt number *Sc*, and Chemical reaction parameter *Kr* are presented in graphs, while the values of the skin friction coefficient, Nusselt number and local Sherwood number for some values of the parameters are presented in tables.

The velocity, microrotation, temperature and concentration distributions have been computed for several parameter values and these are displayed in graphs. Figures 1, 2, 3, 4, 5, 6, 7 and 8 depict the velocity, microrotation, temperature and concentration profiles for several values of *M, Gr, Gc, Pr,Rr, Ec Sc* and *Kr*, respectively for the case $U_w > U_\infty$. Figures 9, 10, 11, 12, 13, 14, and 15 show the velocity profiles for several values of *M, Gr, Gc, Pr, Rr, Ec, Sc* and *Kr* respectively for the case $U_w < U_\infty$.

Fig. 1 shows the velocity and microrotation profiles for several values of magnetic parameter *M*. It is seen that the velocity and microrotation increase with increasing values of M.

In Fig. 2, the velocity and microrotation profiles are plotted for various values of Grashof number *Gr*. As seen in this figure, the velocity is increases with the increasing of *Gr* whereas microrotation deceases.

The velocity and microrotation profiles for several values of solutal Grashof number *Gc* are described in Fig. 3. It is seen that the velocity increases, as *Gc* increases. Also, it is observed that the microrotation decreases, as *Gc* increases.

The effect of Prandtl number *Pr* on the velocity, microrotation and temperature Profiles are shown in Fig. 4. It is noticed that both the velocity and temperature decrease as *Pr* increases, whereas the microrotation increases.

For various values of the thermal radiation parameter *R*, the velocity, microrotation and temperature Profiles are shown in Fig. 5. It is observed that as *R* increases, both the velocity and temperature decreases whereas the microrotation increases.

In Fig. 6, the effect of various values of the Eckert number *Ec* on the velocity, mocrorotation and temperature Profiles. It is clear that as *Ec* increases, both the velocity and temperature increases whereas the microrotation decreases.

For several values of Schmidt number *Sc* on the velocity, microrotation and concentration profiles are shown in Fig.7. It is noticed that as *Sc* increases, both the velocity and concentration decreases whereas the microrotation increases.

Fig. 8 displays the profiles of the velocity, microrotation and concentration with the chemical reaction parameter *Kr*. It is observed that as *Kr* increases, both the velocity and concentration decreases whereas the microrotation increases.

The influence of the magnetic parameter *M* on the velocity profile is plotted in Fig. 9. It is seen that as *M* increases, the velocity decreases.

The velocity profiles for several values of the Grashof number *Gr* and solutal Grashof number *Gc* is shown in Figs. 10 and 11, respectively. It is observed that the velocity increases as *Gr* or *Gc* increases.

Figs. 12 and 13 display the results for the velocity profiles for several values of the Prandtl number and radiation parameter. From these figures, we observe that as *Pr* or *R* increases the velocity decreases.

The effect of the viscous dissipation parameter i.e., Eckert number *Ec* on the velocity is plotted in Fig.14. It is noticed that, the velocity increases as *Ec* increases.

The influence of the Schmidt number *Sc* on the velocity profile is shown in Fig.15. It is seen that as *Sc* increases, the velocity decreases.

Tables 1 and 2 show the variation of the skin friction, Nusselt number and Sherwood number with M, *Gr*, *Gc*, *Sc* and *Kr* for the case $U_w > U_\infty$ and *Pr*, *R* and *Ec* for the case $U_w < U_\infty$. The behaviors of different physical parameters are clear from these tables.

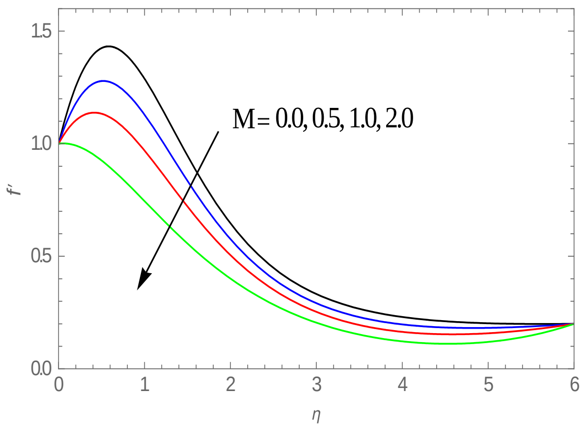

Fig. 1(a) Velocity profiles for several values of *M*

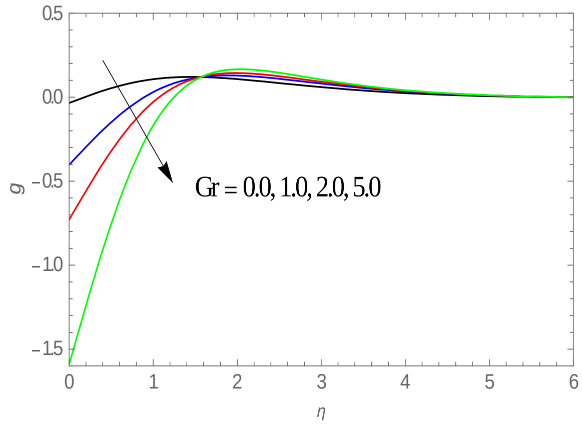

Fig.2(b)Microrotation profiles for several values of *Gr*

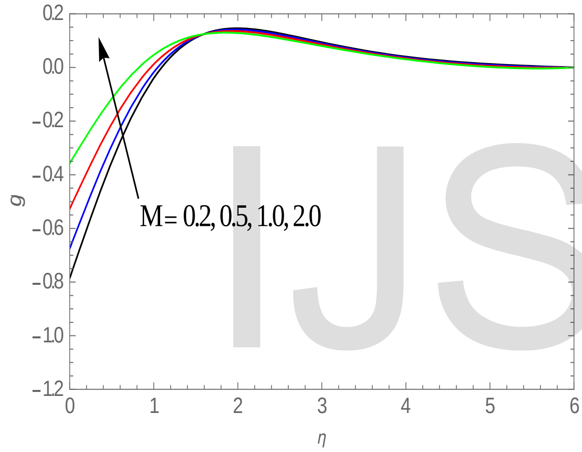

Fig.1(b) Microrotation profiles for several values of *M*

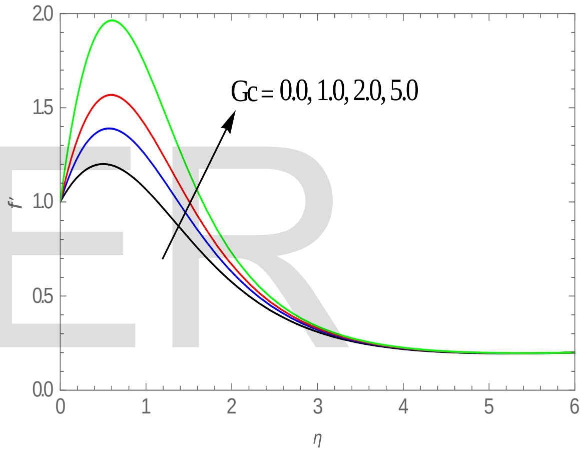

Fig. 3(a) Velocity profiles for several values of *Gc*

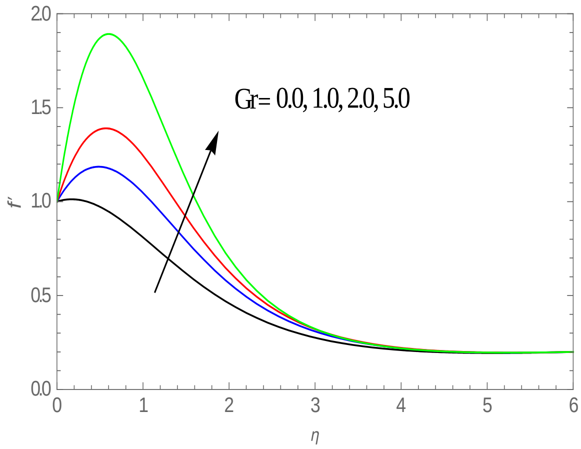

Fig. 2(a) Velocity profiles for several values of *Gr*

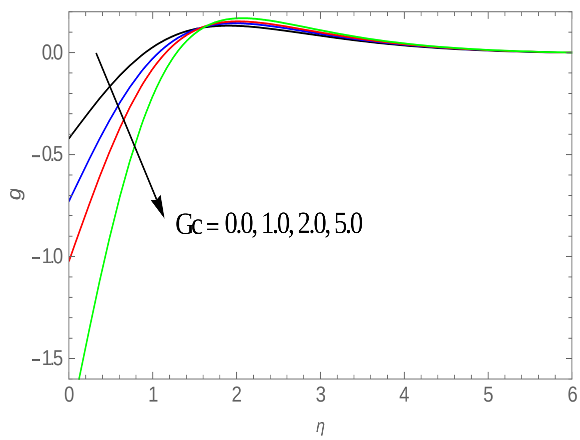

Fig.3(b) Microrotation profiles for several values of *Gc*

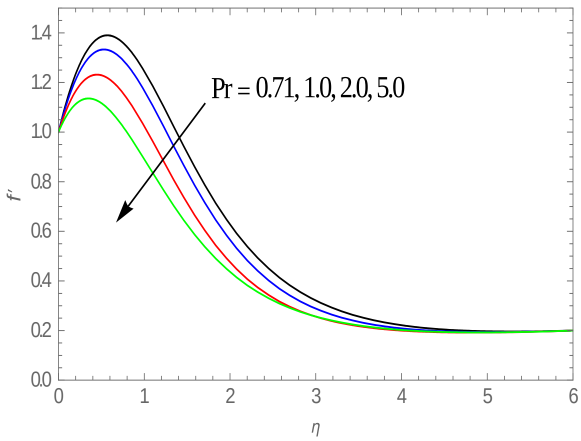

Fig. 4(a) Velocity profiles for several values of *Pr*

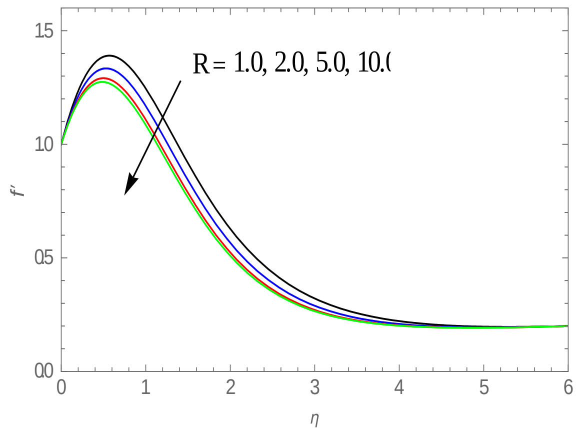

Fig. 5(a) Velocity profiles for several values of *R*

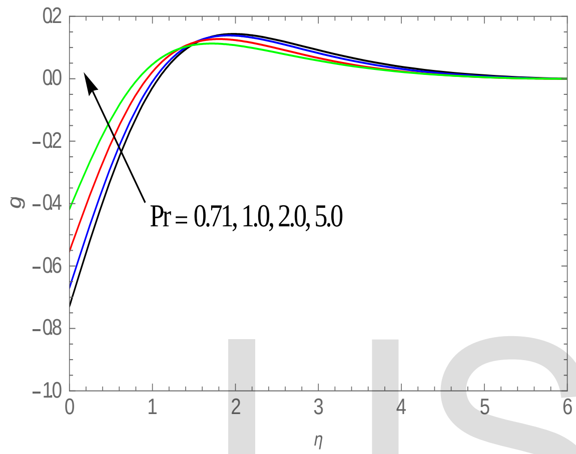

Fig.4(b)Microrotation profiles for several values of *Pr*

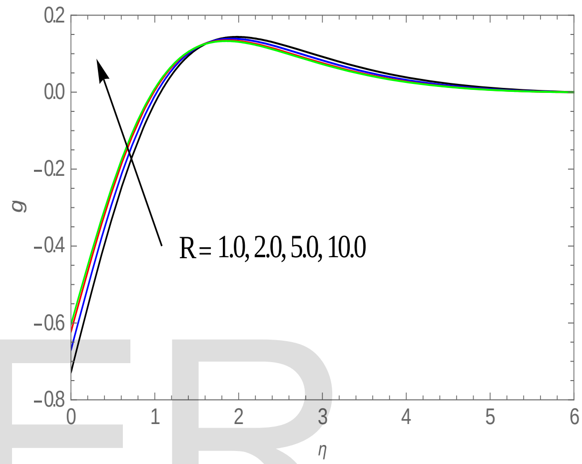

Fig.5(b) Microrotation profiles for several values of *R*

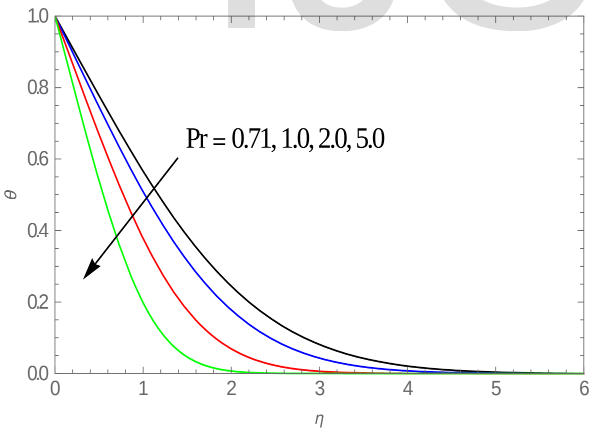

Fig.4(c) Temperature profiles for several values of *Pr*

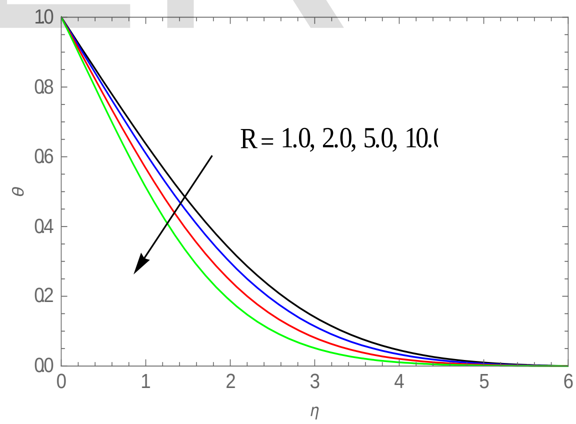

Fig.5(c) Temperature profiles for several values of *R*

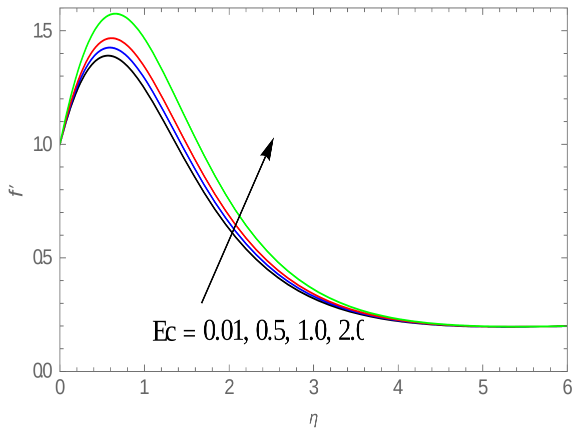

Fig. 6(a) Velocity profiles for several values of *Ec*

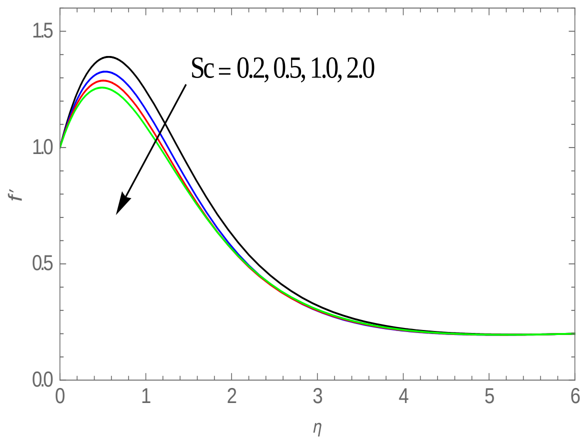

Fig. 7(a) Velocity profiles for several values of *Sc*

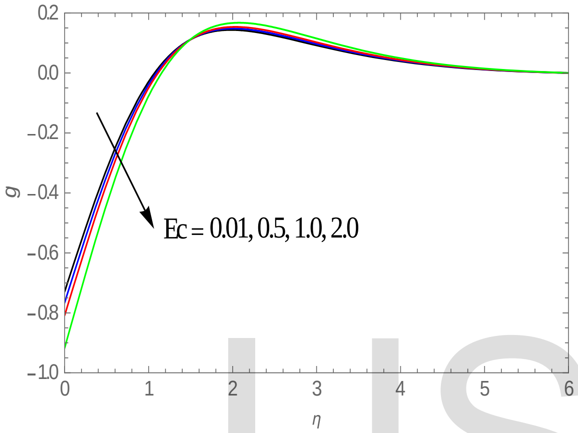

Fig.6(b) Microrotation profiles for several values of *Ec*

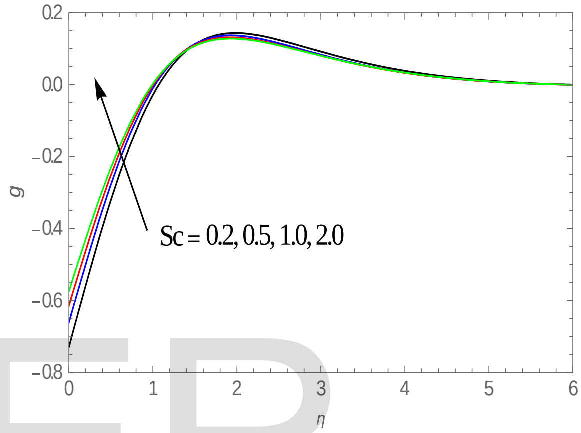

Fig. 7(b) Microrotation profiles for several values of *Sc*

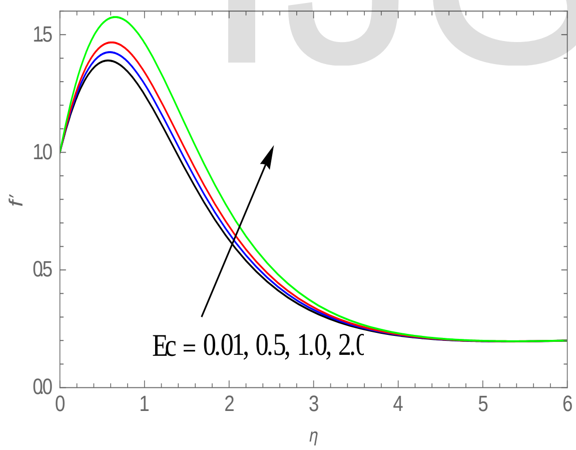

Fig.6(c) Temperature profiles for several values of *Ec*

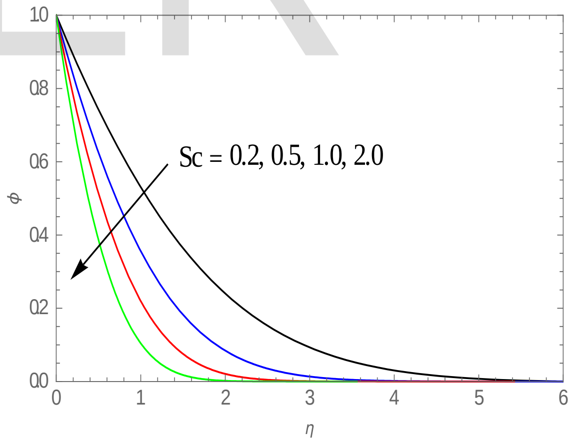

Fig. 7(c) Concentration profiles for several values of *Sc*

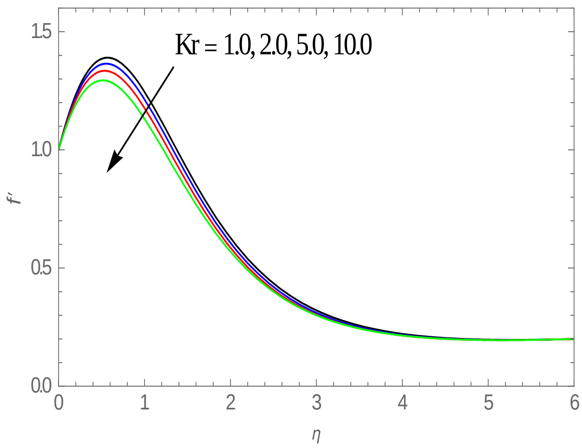

Fig. 8(a) Velocity profiles for several values of *Kr*

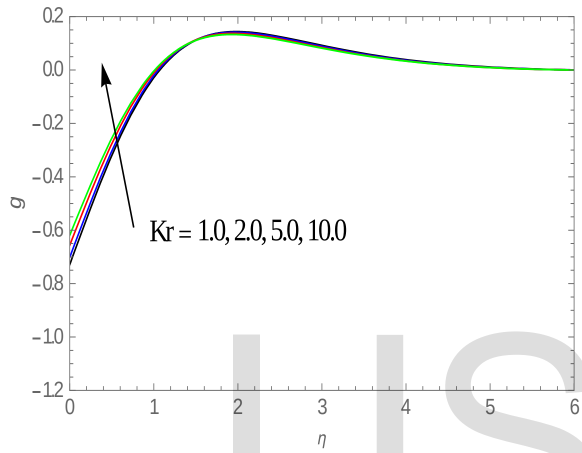

Fig.8(b) Microrotation profiles for several values of Kr

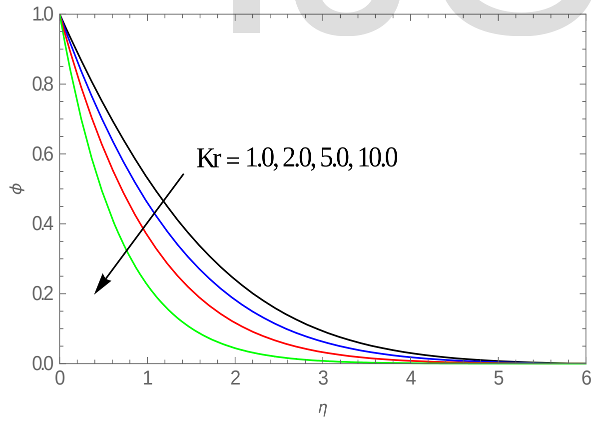

Fig. 8(c) Concentration profiles for several values of *Kr*

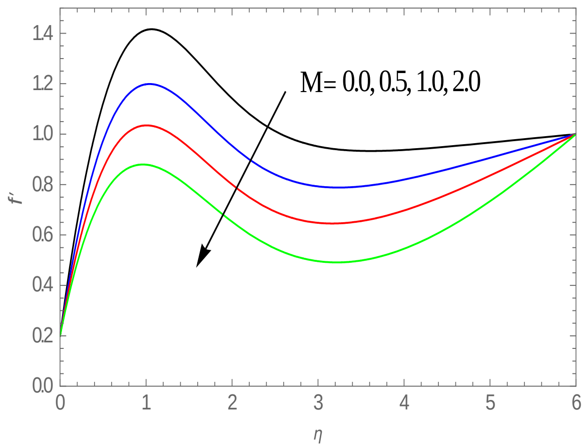

Fig. 9 Velocity profiles for several values of *M*

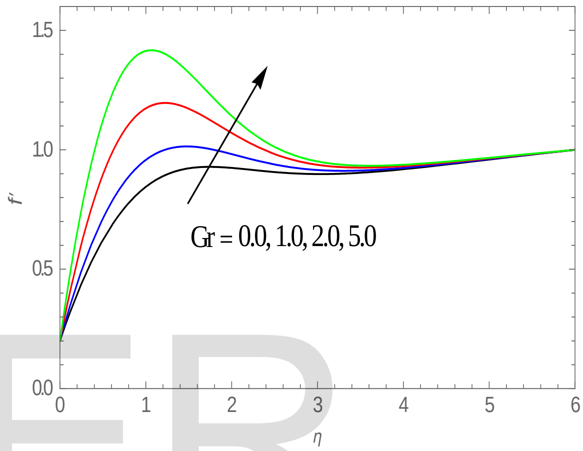

Fig. 10 Velocity profiles for several values of *Gr*

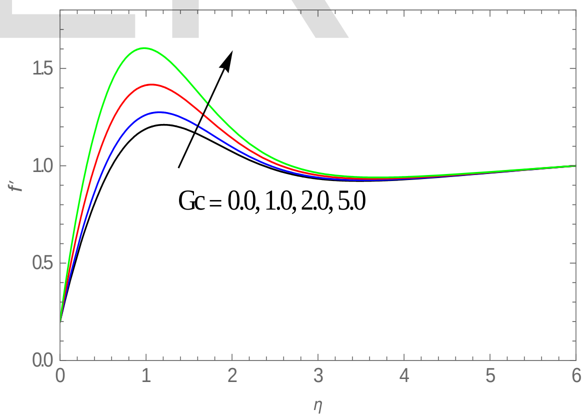

Fig. 11 Velocity profiles for several values of *Gc*

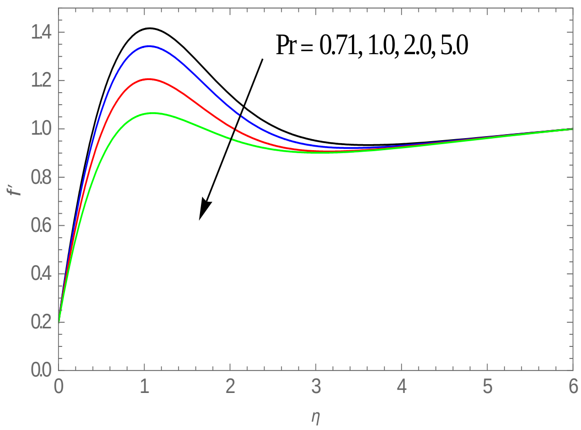

Fig. 12 Velocity profiles for several values of *Pr*

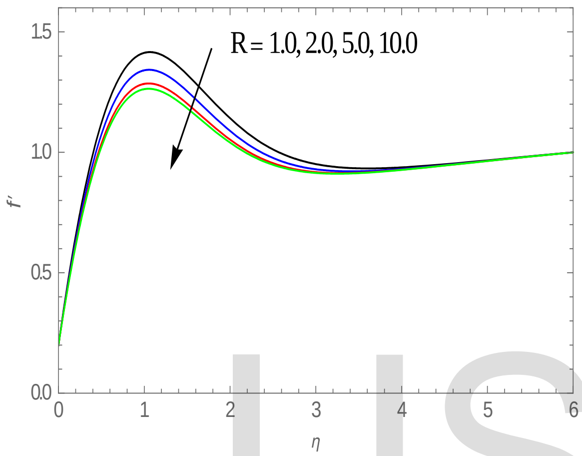

Fig. 13 Velocity profiles for several values of *R*

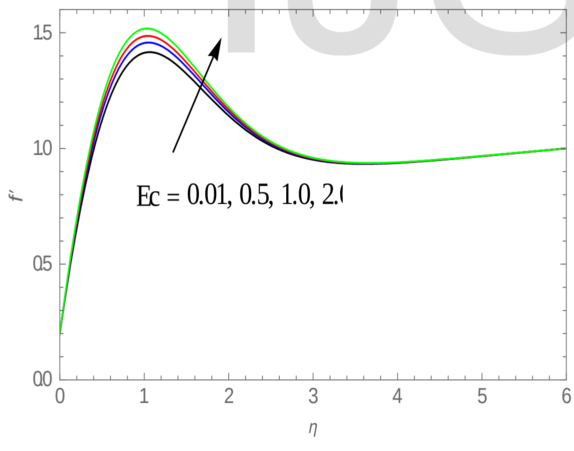

Fig. 14 Velocity profiles for several values of *Ec*

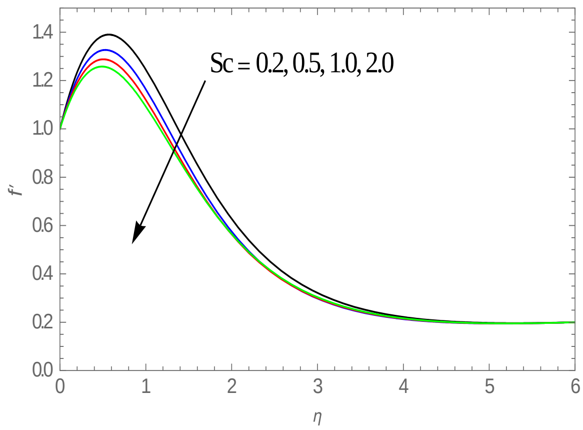

Fig. 15 Velocity profiles for several values of *Sc*

Table 1: Values of $f''(0)$, $-\theta'(0)$ and $-\phi'(0)$ for various values of *M*, *Gr*, *Gc* and *Sc* with *G*=2.0, *K* = 0.1, *Pr* = 0:71, *R* =1.0 and *Ec*=0.01 for the case $U_w > U_\infty$.

M	Gr	Gc	Sc	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0.0	2.0	1.0	0.2	1.67075	0.467006	0.370908
0.2	2.0	1.0	0.2	1.46276	0.456662	0.362668
0.5	2.0	1.0	0.2	1.17682	0.441652	0.351477
0.2	1.0	1.0	0.2	0.84414	0.427590	0.341008
0.2	2.0	1.0	0.2	1.46276	0.456662	0.362668
0.2	3.0	1.0	0.2	2.04072	0.479374	0.380806
0.2	2.0	1.0	0.2	1.46276	0.456662	0.362668
0.2	2.0	2.0	0.2	2.10002	0.485672	0.385926
0.2	2.0	3.0	0.2	2.70332	0.509129	0.403529
0.2	2.0	1.0	0.2	1.46276	0.456662	0.362668
0.2	2.0	1.0	0.4	1.35649	0.442883	0.523532
0.2	2.0	1.0	0.6	1.29203	0.437727	0.652243

Table 2: Values of $f''(0)$, $-\theta'(0)$ and $-\phi'(0)$ for various *Pr*, *R* and *Ec* with *G*=2.0, *M*=0.2, *K*=0.1, *G=2.0*, *Gr*=2.0, *Gc*=1.0 and *Sc*=0.2 for the case $U_w < U_\infty$.

Pr	R	Ec	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0.71	1.0	0.01	1.46276	0.456662	0.362668
1.0	1.0	0.01	1.25287	0.542606	0.365184
2.0	1.0	0.01	1.13504	0.770712	0.368894
0.71	1.0	0.01	1.46276	0.456662	0.362668
0.71	2.0	0.01	1.26652	0.540954	0.353663
0.71	5.0	0.01	1.23135	0.621741	0.346694
0.71	1.0	0.01	1.46276	0.456662	0.344092
0.71	1.0	0.5	1.49399	0.413273	0.365142
0.71	1.0	1.0	1.54636	0.337402	0.368999

6. Conclusion:

In this paper, the effects of thermal radition and chemical reaction on MHD mixed convection flow heat and mass transfer flow over a continuously moving flat plate placed in a parallel moving stream in the presence of viscous dissipation was investigated. The following conclusions are drawn:

1. The fluid velocity distribution higher for the case $U_w > U_\infty$ as compared to the case $U_w < U_\infty$. However the velocity in the boundary layer increases with an increasing of *Gr, Gc* and *Ec* while decreases with increasing of values of *M, Pr, R, Sc* and *Kr*.
2. The micro-rotation in the boundary layer increases with an increasing of *M, Pr, R, Sc* and *Kr* while decreases with increasing of values of *Gr, Gc* and *Ec*.
3. The fluid temperature decreases with increasing of *Pr* and *R* while increases with increasing of *Ec.*
4. The fluid concentration decreases with increasing of *Sc* and *Kr.*
5. The skin friction continuously decreases with increasing of *M* and *Sc* while increases with increasing values of *Gr* and *Gc* for the case $U_w > U_\infty$ where as increases with increasing of *Ec* and decreases with increasing of *Pr* and *R* for the case $U_w < U_\infty$
6. The rate of heat transfer increases with increasing of *Gr* and *Gc* while decreases with increasing values of *M* and *Sc* for the case $U_w > U_\infty$ where as increases with increasing of *Pr, R* and decreases with increasing of *Ec* for the case $U_w < U_\infty$
7. The rate of mass transfer decreases with increasing of *M* while increases with increasing values of *Gr, Gc* and *Sc* for the case $U_w > U_\infty$ where as increases with increasing of *Pr, R* and *Ec* for the case $U_w < U_\infty$

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