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HEAT AND MASS TRANSFER EFFECTS ON CONVECTIVE MHD SLIP FLOW WITH VARIABLE VISCOSITY OVER INCLINED POROUS MEDIUM

S. A. Amoo[1], Akeem B. Disu[2], & A. S. Idowu[3]

[1]Department of Mathematics and Statistics, Federal University Wukari, Wukari, Nigeria
[2]Department of Mathematics, National Open University of Nigeria
[3]Department of Mathematics, University of Ilorin, Ilorin, Nigeria
drsikiruamoo@gmail.com, adisu@noun.edu.ng, asidowu@gmail.com

ABSTRACT
The study investigated effects of heat and mass transfer on convective Magnetohydrodynamics (MHD) slip flow over an inclined porous medium in the presence of variable viscosity and heat generations. The governing boundary layer equations of the model were transformed to a system of ordinary coupled differential equations. The coupled system of nonlinear equations were solved numerically using a fourth order Runge-Kutta method and method of shooting technique. A parametric study on the effect of variations of the radiation, magnetic, thermal conductivity grashof number, solutal grashof, pranddtl, schmidt, chemical species parameters and angle of inclination at the surface on velocity, temperature and concentration were presented graphically. Also, the effects of these paremeters were presented numerically for skin friction, Nusselt and Sherwood numbers.

Keywords: MHD slip flow, Variable viscosity, Inclined surface, Chemical Reaction, Porous Media

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INTRODUCTION

Heat flow over a moving stretching surface has important applications in electrochemistry and polymer processing. For example, (i) materials manufactured by extrusion processes and heat treated materials travelling between a feed roll and a windup roll or on a conveyor belt possess the characteristics of a moving stretching surface (Devi, Neeraj, and Reddy (2015)) and (ii) metallurgical processes involve the cooling of continuous strips or filaments by drawing them though a quiescent fluid and that in the process of drawing, these strips are sometimes stretched.

In view of the applications of the moving stretching surface, Mukhopadhyay (2012) investigatedthe slip effect on MHD boundary layer over exponentially stretching sheet. Mukhopadhyay and Gorla (2008) presented the effects of partial slip on boundary layer flow past a permeable exponentially stretching sheet in the presence of thermal radiation, heat and mass transfer. Shekhar (2014) carried out analysis on the boundary layer phenomena of MHD flow and heat transfer over an exponentially stretching sheet embedded in a thermally stratified medium. The researchers neglected the chemical reaction.

Ibrahim and Suneetha (2015) studied the effects of heat generation and thermal radiation on steady MHD flow near a stagnation point on a stretching sheet in porous medium and presence of variable thermal conductivity and mass transfer. Devi, Neeraj, and Reddy (2015) investigated radiation effect on MHD slip flow past a stretching sheet with variable viscosity and heat source/sink. Amoo, Babayo and Amoo (2017) considered nonlinear MHD boundary layer flow embedded in Darcy-Forcheimmer Porous Medium with Viscous dissipation and Chemical Reaction. All these studies are horizontally stretching surface.

However, the study of heat transfer through a porous medium is important, because of its applications in soil mechanics, water purification, underground water hydrology,

chemical engineering, petroleum engineering, ceramic engineering, metallurgical engineering, agricultural engineering and water irrigation process (Disu and Dada (2017)).

Despite the application of fluid flow through a porous medium, the study of the combination of heat and mass transfer effects using radiation and chemical reaction with MHD slip flow has drawn attention of few researchers (Amoo and Idowu (2017).

In view of the above studies, the present study investigated effects of heat and mass transfer on convective Magnetohydrodynamics (MHD) slip flow over inclined porous media in the presence of variable viscosity and heat generation.

Mathematical Analysis

Consider the heat and mass transfer of a two-dimensional MHD slip flow over an inclined porous medium in the present of radiation (**Figure 1**). A uniform transverse magnetic field $B(x)$ is applied perpendicular to the direction of the fluid flow. The flow is assumed to be in the x-direction with y-axis normal to it. The plate is maintained at the temperature and species concentration T_w, C_w and free stream temperature and species concentration T_∞, C_∞ respectively, while α is the angle of inclination. The equations governing the fluid flow are as follows:

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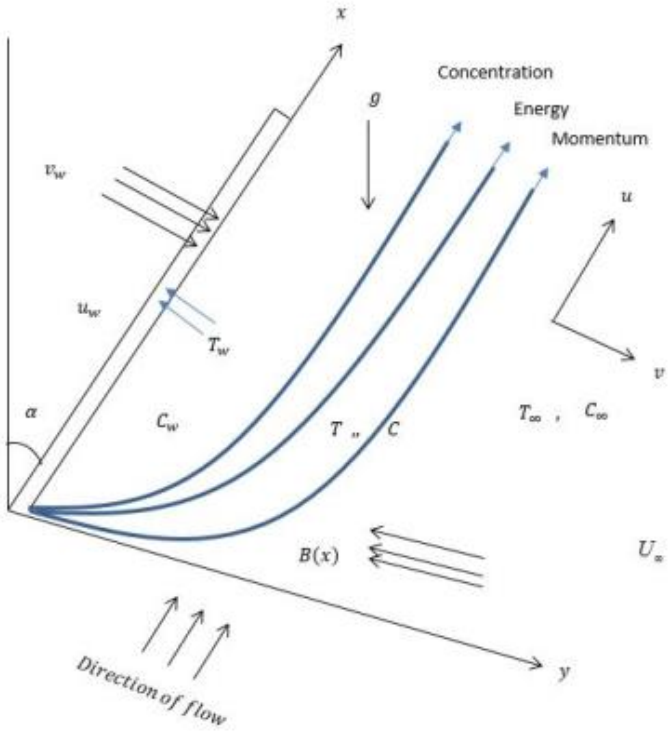

Figure 1: The physical model and coordinate system

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{\rho}\frac{\partial \mu}{\partial T}\frac{\partial T}{\partial y}\frac{\partial u}{\partial y}+\frac{\mu}{\rho}\frac{\partial^2 u}{\partial y^2}-\frac{1}{\rho}\sigma B^2(x)u+g\beta_T(T-T_\infty)\cos(\alpha)+g\beta_C(C-C_\infty)\cos(\alpha) \quad (2)$$

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\frac{\partial^2 T}{\partial y^2}-\frac{\partial q_r}{\partial y}+Q_0(T-T_\infty) \quad (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-\gamma(C-C_\infty) \quad (4)$$

Subject to the following boundary conditions:

$$u=U_0e^{\frac{x}{2L}}=\alpha x+L\frac{\partial u}{\partial y},v=-V_0e^{\frac{x}{2L}},T=T_w=T_\infty+T_0e^{\frac{x}{2L}},C=C_w=C_\infty+C_0e^{\frac{x}{2L}}\ at\ y=0$$
$$u\to 0,T\to T_\infty,C\to C_\infty\ as\ y\to\infty \quad (5)$$

where u , v , C , and T are velocity component in the x direction, velocity component

in the y direction, concentration of the fluid species and fluid temperature respectively. L is the reference length, $B(x)$ is the magnetic field strength, U_0 is the reference velocity and V_0 is the permeability of the porous surface. The physical parameters K, ρ, ν, σ, D, k, C_p, Q_0 and γ are the permeability of the porous medium, density, fluid kinematics viscosity, electric conductivity of the fluid, coefficient of mass diffusivity, thermal conductivity of the fluid, specific heat, rate of specific internal heat generation or absorption and reaction rate coefficient respectively. g is the gravitational acceleration, β_T and β_C are the thermal and mass expansion coefficients respectively and q_r is the radiative heat flux in the y direction.

Introducing the stream function $\psi(x, y)$ such that

By using the Rosseland approximation according to Ibrahim and Suneetha (2015). The radiative heat flux q_r is given by

$$q_r = -\frac{4\sigma_0}{3\delta}\frac{\partial T^4}{\partial y} \quad (6)$$

where σ_0 and δ are the Stefan-Boltzmann and the mean absorption coefficient respectively. Assume the temperature difference within the flow are sufficiently small such that T^4 may be expressed as a linear function of temperature, using Taylor series to expand T^4 about the free stream T_∞ and neglecting higher order terms, this gives the approximation

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \quad (7)$$

The magnetic field $B(x)$ is assumed to be in the form

$$B(x) = B_0 e^{\frac{x}{2L}} \quad (8)$$

where B_0 is the constant magnetic field.

$$u = \frac{\partial \psi}{\partial y} \quad , \quad v = -\frac{\partial \psi}{\partial x} \quad (9)$$

Temperature dependent viscosity according to Devi, *et al*. (2015) is of the form:

$$\mu = \mu_1 a + b(T_w - T) \quad (10)$$

Where μ_1 is the constant value of the coefficient of viscosity in the free stream and a, b are constants with $b(>0)$ having unit K^{-1} . Here viscosity temperature relation $\mu = a_1 - b_1 T$ which accords the relation $\mu = e^{-a_1 T}$ when second and higher order terms are neglected.

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Substituting (9) in (1), continuity equation satisfied Chauchy-Riemann equation and equations (2)-(4), give

$$\frac{\partial \psi}{\partial y}\frac{\partial T}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial T}{\partial y} = \left(\frac{k}{\rho C_p} + \frac{16\sigma_0 T_\infty^3}{3\rho C_p \delta}\right)\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho C_p}\left(T - T_\infty\right) \quad (11)$$

$$\frac{\partial \psi}{\partial y}\frac{\partial C}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - \gamma\left(C - C_\infty\right) \quad (12)$$

The corresponding boundary conditions become:

$$\frac{\partial \psi}{\partial y} = U_0 e^{\frac{x}{L}} = cx + L\frac{\partial u}{\partial y},\ \frac{\partial \psi}{\partial x} = V_0 e^{\frac{x}{L}}, T = T_w = T_\infty + T_0 e^{\frac{x}{2L}},$$
$$C = C_w = C_\infty + C_0 e^{\frac{x}{2L}} \ at\ y = 0$$
$$\frac{\partial \psi}{\partial y} \to 0, T \to T_\infty, C \to C_\infty \ as\ y \to \infty \quad (13)$$

In order to transform the equations (11), (12) and (13) as well as the boundary conditions (14) into an ordinary differential equations, the following similarity transformations variables are introduced following Sajid and Hayat (2008).

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$$\psi(x,y)=\sqrt{2\nu U_0 L}e^{\frac{x}{2L}}f(\eta),\eta=y\sqrt{\frac{U_0}{2\nu L}}e^{\frac{x}{2L}},T=T_\infty+T_0e^{\frac{x}{2L}}\theta(\eta),$$

$$C=C_\infty+C_0e^{\frac{x}{2L}}\phi(\eta) \quad (15)$$

The equation becomes

$$(a+A-A\theta)f'''+ff''-A\theta f'-f'^2-Mf'+G_r\theta\cos(\alpha)+G_c\phi\cos(\alpha)=0 \quad (16)$$

$$\left(1+\frac{4}{3}R\right)\theta''+P_r f\theta'-P_r f'\theta+P_rQ\theta=0 \quad (17)$$

$$\phi''+S_c f\phi'-S_c f'\phi-S_c\lambda\phi=0 \quad (18)$$

The corresponding boundary conditions take the form:

$$f=f_w, f'=1+\delta f'',\theta=1,\phi=1 \ at \ \eta=0$$
$$f'=0,\theta=0,\phi=0 \ as \ \eta\to\infty \quad (19)$$

where $\delta=L(\frac{c}{\upsilon_1})^{\frac{1}{2}}$ is the slip parameter, $A=b(T_w-T)$ is the viscosity parameter, $M=\frac{2\sigma LB_0}{\rho U_0}e^{\frac{x}{2L}}$ is the magnetic parameter, $Gc=\frac{2Lg\beta_T T_0}{U_0^2}e^{-\frac{3x}{2L}}$ is the thermal Grashof number, $Gc=\frac{2Lg\beta_C C_0}{U_0^2}e^{-\frac{3x}{2L}}$ is the solutal Grashof number, $Pr=\frac{\rho\nu C_p}{k}=\frac{\mu_1 c_\rho}{k}$ is the Prandtl number, $R=\frac{4\sigma_0 T_\infty^3}{\partial k}$ is the thermal radiation parameter, $Q=\frac{2LQ_0}{U_0\rho C_p}e^{-\frac{x}{L}}$ is the heat generation parameter, while α is the angle of inclination, $Sc=\frac{\nu_1}{D}$ is the Schmidt number, $\lambda=\frac{2L\gamma}{U_0}e^{-\frac{x}{L}}$ is the chemical reaction parameter, $f_w=V_0\sqrt{\frac{2L}{\nu U_0}}e^{-\frac{3x}{2L}}$ is the permeability of the plate. The skin friction coeficient was $C_f\left(\frac{\mathrm{Re}_x}{2}\right)^{\frac{1}{2}}=f''(0)$, the local Nusselt number was written as $Nu\left(\frac{\mathrm{Re}_x}{2}\right)^{-\frac{1}{2}}=-\theta'(0)$ and the local Sherwood number stood as $Sh\left(\frac{\mathrm{Re}_x}{2}\right)^{-\frac{1}{2}}=-\phi'(0)$

The equations (16), (17) and (18) are highly non-linear coupled differential equations and its satisfying the boundary conditions (19). The problem being a boundary value problem, applying a shooting technique (guessing the unknown values) to change the conditions to initial value problem. Equations (16-18) along with the boundary conditions (19) were solved numerically by applying Nachtsheim-Swigert shooting iteration technique along with Runge-Kutta fouth-order integration scheme. The computations were performed using a symbolic program and computational computer language Maple 18. The step size is taken to be $\Delta\eta = 0.001$ to satisfy the relative convergence requirement of 10^{-5} in all cases. The value of η_∞ is noticed to the iteration loop by $\eta_\infty = \eta_\infty + \Delta\eta$. The highest value of η_∞ to each parameter was determined when the values of the unknown boundary conditions at $\eta = 0$ did not change after successful loop with error less than 10^{-5}.

Results

The process of numerical computation showed the skin-friction coefficient, the local Nusselt number and the local Sherwood number, which were respectively proportional to $f''(0)$, $\theta'(0)$ and $\phi'(0)$, at the plate were examined for different values of the parameters. The comarison of the present study with the skin friction of the existing works are presented in Table 1 for values of δ when A=0.

Values	Present study	Devi *et al* (2015)	Bhattacharyya and Layek (2010).
Values	$f''(0)$	$f''(0)$	$f''(0)$
0.0	-0.000000	-1.000480	-1.000000
0.1	-0.876889	-0.872571	-0.872083
0.2	-0.788871	-0.776867	-0.776377
0.5	-0.646494	-0.591683	-0.591105

Table 1 shows numerical values of skin friction when compared with the existing literature and were in close agreement. The present study shows improvement over the previous studies. In our computattion, we set the flow parameters as: $a = 0.33,\ A = 0.21, \lambda = 0.50,\ Gr = 1, Gc = 0.01,\ Q = 0.5,\ M = 0.001,\ f_w = 1,\ R = 1,\ Sc = 0.35,\ \alpha = 5^0$, Ec.=0.05, $Pr = 0.72$. All graphs correspond to the value except otherwise indicated on the graph.

Table 2: Effect of f_w, G_r, G_c, S_c, P_r, and R on $f''(0)$, $\theta'(0)$ and $\phi'(0)$ (P-Parameters)

P	**Values**	***f ''(0)***	***-Θ' (0)***	***- $\phi'(0)$***	***P***	***Values***	***f ''(0)***	***-Θ' (0)***	$-\phi'(0)$
a	**0.33**	15.0980	*-1.29525*	1.93239	***A***	***2.1***	*9.09695*	*-1.24309*	1.86392
	0.35	*14.2211*	*-1.28665*	1.92702		***2.2***	*9.50230*	*-1.25326*	1.86734
	0.37	*13.4390*	*-1.27794*	1.92169		***2.3***	*9.90310*	*-1.26204*	1.87031
	0.39	*12.7367*	*-1.26912*	1.91643		***2.5***	*10.6906*	*-1.27621*	1.87519
M	0.001	0.01412	0.69831	0.68100	Sc.	0.35	5.62826	-1.16282	1.30661
	2.0	0.27422	-0.05178	0.72271		0.62	4.82978	-0.96109	1.78569
	3.0	0.35290	-0.63342	0.74226		1.50	4.03147	-0.78311	3.02227
	4.0	0.41963	-1.44956	0.76482		2.00	3.84534	-0.75063	3.64145

G_r	1.0	0.09698	0.55588	0.69198	P_r,	0.72	4.82978	-0.96109	1.78567
	2.0	0.49415	0.52775	0.71555		0.78	5.10741	-1.06232	1.79354
	3.0	0.89935	0.49261	0.73809		0.84	5.40764	-1.16452	1.80142
	4.0	1.75395	0.40082	0.78181		0.90	5.73259	-1.26808	1.80931
G_c.	0.01	-0.20669	0.43616	0.67722	R	0.5	4.82978	-0.96109	1.78567
	3.10	0.94207	0.25834	0.74706		1.7	3.53948	-0.35574	1.73692
	3.80	1.19933	0.21462	0.76003		4.7	2.99167	0.01182	1.70496
	5.00	1.64184	0.13830	0.78078		7.0	2.88026	0.09788	1.69712
f_w	1.00	4.82978	-0.96109	1.78567	Q	0.5	4.82978	-0.96109	1.78567
	2.00	3.31837	-0.03657	2.10685		0.8	5.64374	-1.26135	1.81537
	3.00	2.11475	0.75920	2.50962		1.0	6.29297	-1.47492	1.83622
	4.00	1.28080	1.40552	2.98273		1.5	8.31082	-2.05080	1.88944
λ	0.5	4.82978	-0.96109	1.78567	α	5^0	-0.48814	0.42069	0.65272

	1.5	4.69544	-0.93043	1.96359		8^0	-0.89544	0.40896	0.61814
	2.5	4.58568	-0.90575	2.12736		11^0	-0.74798	0.41526	0.63145
	4.0	4.45326	-0.87656	2.35225		14^0	-0.62291	0.41864	0.64199
Ec	0.05	1.92610	0.95675	1.61344	*Ec*	0.55	6.11630	-1.43313	1.83212
	0.50	4.82978	-0.96109	1.78567		0.57	6.77036	-1.64147	1.85182

DISCUSSION

Table 2 represents the numerical results of variation in Skin friction, Nusselt and Sherwood numbers at the surface with a, A, M, Gr, Gc, , f_w, Q, Sc, Pr, R, α and λ which are of physical and engineering interest. It could be observed from the results that an increase in the values of a, A, M, f_w, Sc and Pr. decreased the flow boundary layer while increase in M, Gc. Gr. Ec., Q and R increase the flow boundary layer. R, Sc., Q Ec., and a decreased thermal boudary layer. The table depicts that an increase in the values of M, Q, Gr, Gc, and R thicken the thermal boundary layer by reducing the rate at which heat diffuse out of the system while increase in f_w, Sc, λ and Pr reduce the thickness of the thermal boundary layer. Also, the results showed that increase in Pr, causes thinning in the concentration boundary layer while M, R, Gr, Gc, Sc, Q, fw, and λ thicken the mass boundary layer. Graphical interpretation of relevant parameters were equally presented in figures 2-14. Figure 2 showed the effect of slip conditions on the velocity, temperature and concentration profiles. The dimensionless parameter describing the slip condition at $a = 0$, suggest no

slip condition in the fluid flow. As we increased the parameter, it was discovered that the rate of flow decreased as well as thermal and concentration boundary layers too. Figure 3 illustrated the effects of *A* parameter on the rate of flow. It was discovered that as the parameter A increased, rate of flow increased as well as concentration profile with corresponding decreased in the thermal boundary layer. Figure 4 explained the effect of magnetic parameter M on the fluid flow. The effect of increased M led to the corresponding increase in skin friction, and sherwood number but decreased the Nusselt number or thermal boundary layer. The implication of this transport of fluid flow was that when magnetic field strength was applied tranversely to the flow, it gave rise to opposing force called Lorentz force.

Figure 5 showed the effects of thermal Grashoff number on the local velocity, temperature and concentration profiles. The influence showed that as we increased Gr. there were corresponding increase in fluid flow and mass boundary layer but decrease in thermal boundary layer hence law temperature profiles. Figure 6 depicted the effects of solutal Grashof number in the local skin friction, temperature profile and concentration. It was discovered that as we increased Gc. there was increase skin friction and sherwood numbers but a reverse in Nusselt number. Figure 7 illustrated effects of inclination on the MHD fluid with slip condition. It was found that increase in $\propto$ led to decrease in velocity and thermal boundary layers whereas its effect led to increase in concentration profile. Figure 8 showed the effect of heat source/sink on MHD slip flow. It was discovered that Q decreased thermal boundary layer but as we increased Q, the velocity and concentration profiles of the fluid increased correspondingly. Figure 9 depicted the effect of chemical reaction on the local velocity, temperature and concentration profiles. It was shown that chemical reaction decreased the velocity profile but increased the temperature and concentration of the fluid. Figure 10 described the effect of Schmidt number Sc. On the velocity, temperature and concentration profiles. It was observed that increased Sc. parameter decreased velocity

profile but increased thermal and concentration boundary layers.

Figure 11 showed the effect of Prandtl number Pr. on the velocity, temperature and concentration profiles respectively. The increase in Pr. caused decrease in temperature profile but the same increased the velocity and concentration. It is worth mentioning that figure 12 implemented the porosity at the plate thereby showing the effects on velocity, temperature and concntration profiles. The increase in fw showed decrease in velocity profile but increased the temperature and concntration profiles. The effects of thermal radiation R on velocity, temperature and concntration profiles was depicted in figure 13. When R was increased, it enhanced the heat flux from the plate and this was able to increase the velocity and temperature profiles. Howecer, its increase decreased the concentration profile. In figure 14 it was discovered that increase in Eckert number led to the increase velocity and concentration profile but decrease in temperature profile.

Conclusions

In this article, the steady case of MHD slip flows over inclined porous media was considered. The results obtained was compared with the existing result in literature and it was found to be in excellent agreement. The conclusions drawn from the study were:

- Increased slip condition parameter decreased velocity, temperature, time and concentration profiles
- Permeability decreased the velocity profile but increased the thermal concentration profiles
- Magnetic parameter increase both velocity and concentrationprofile but decreased temperature profile.
- Radiation increased both velocity and temperature profiles but not concentration profile.
- Eckert number increased both skin friction and Sherwood numbers but not solutal Grashof numbers
- Both thermal and solutal grashof numbers increased both velocity and concentration but both decreased the

thermal boundary layer or temperature profile. It was therefore remarkable to not that the study is recommended for use in industries.

Graphs

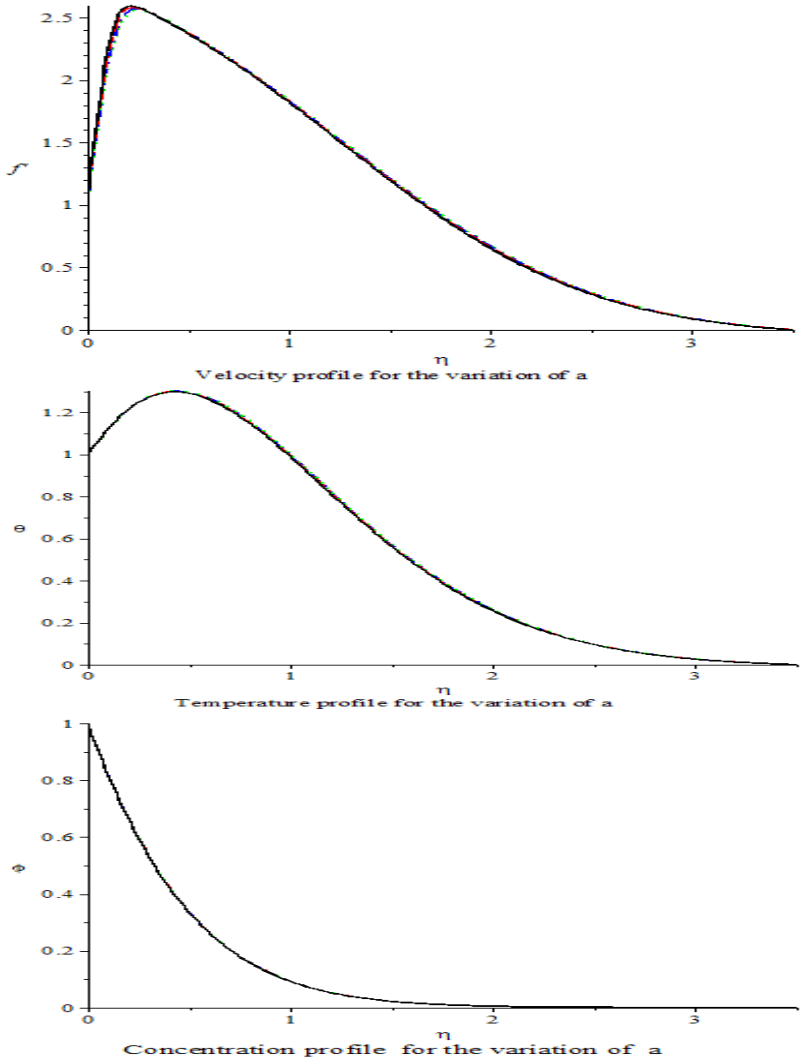
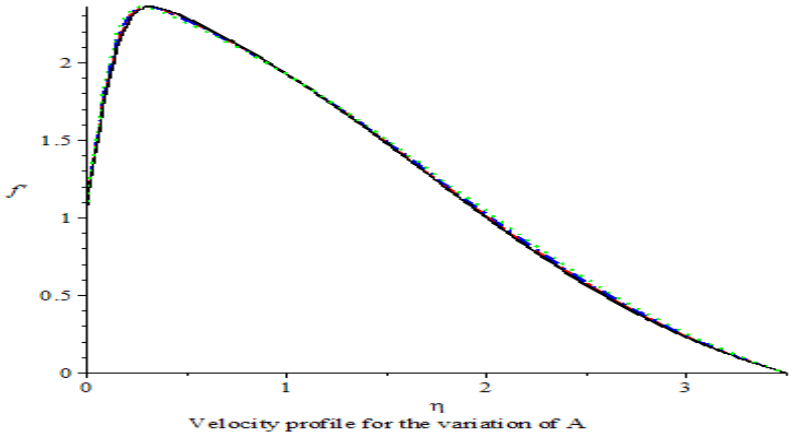
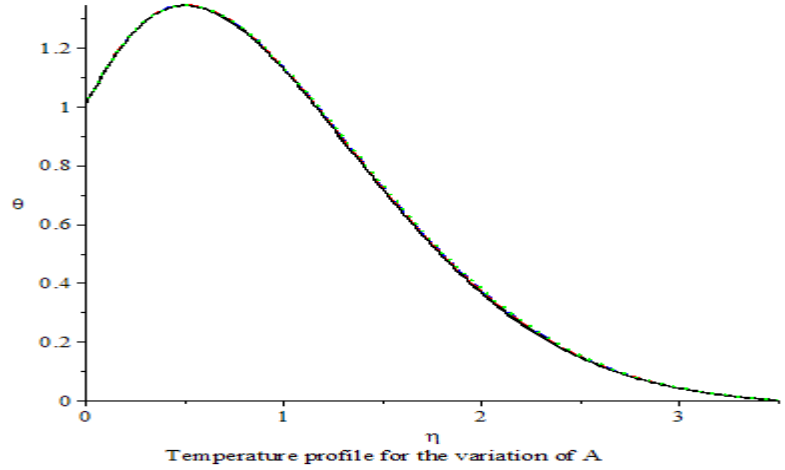


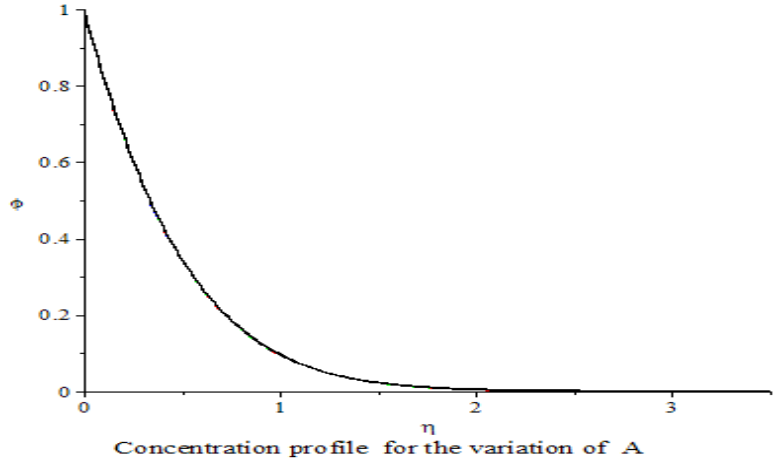
Figure 2: Effect on velocity, temperature and concentration profiles



Velocity profile for the variation of A

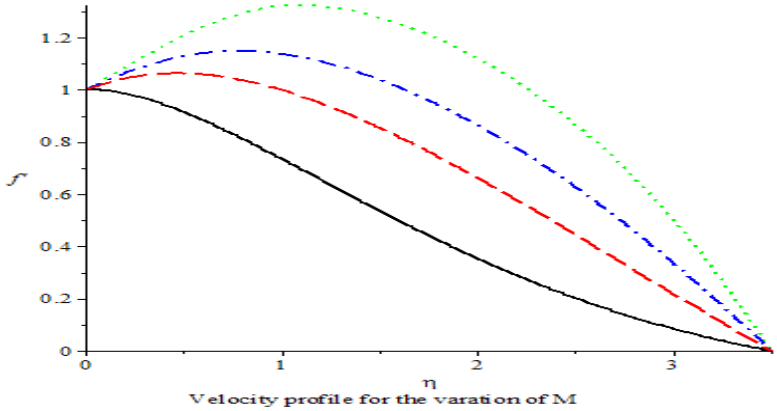


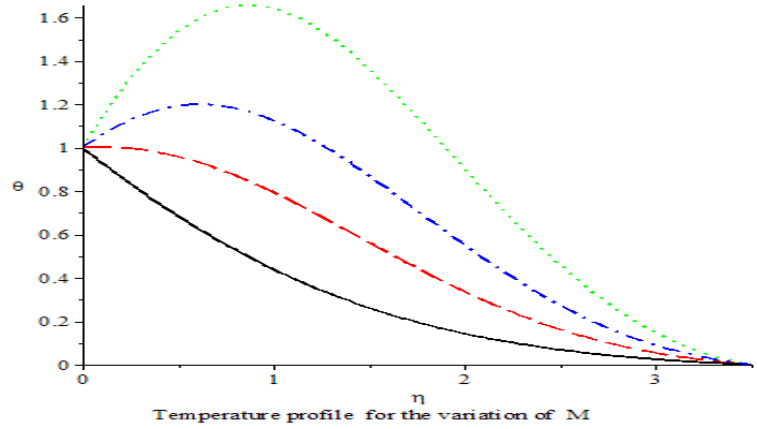
Temperature profile for the variation of A



Concentration profile for the variation of A

Figure 3: A effect on velocity, temperature and concentration profiles





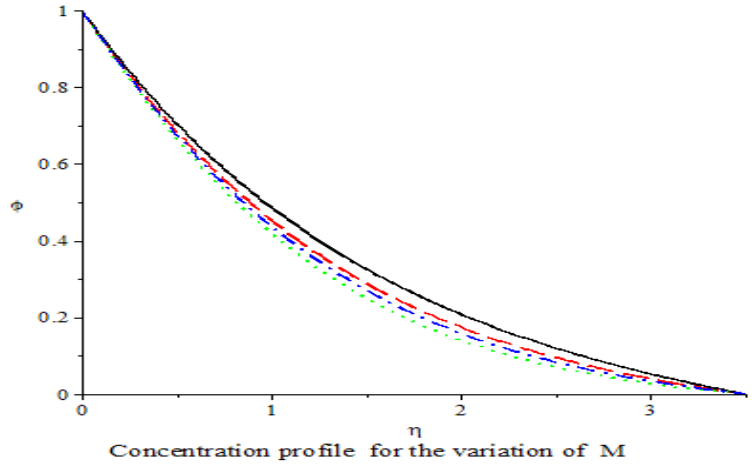
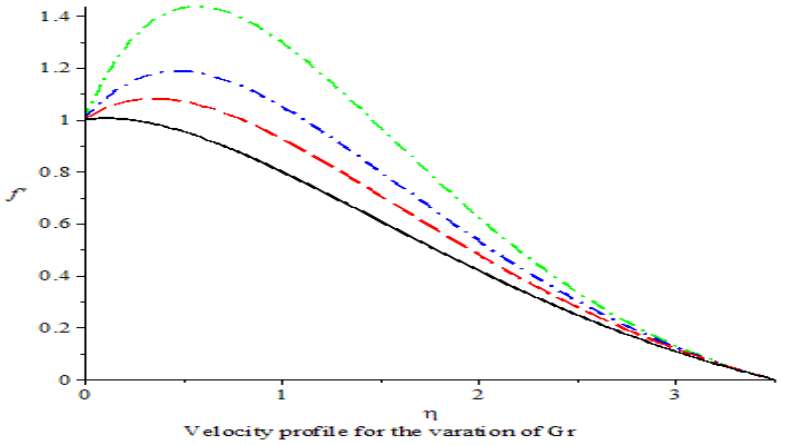
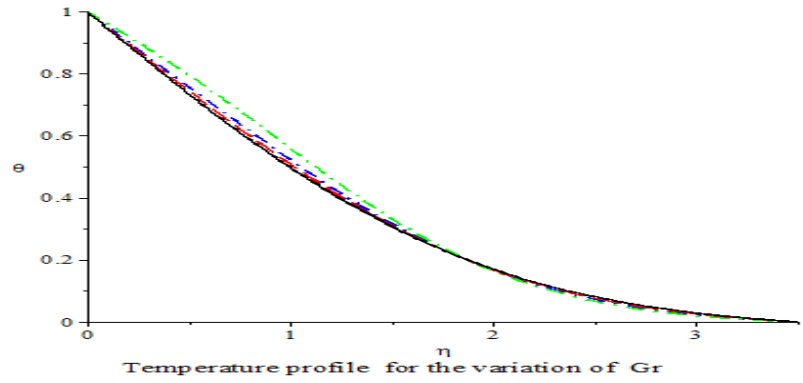


Figure 4: M effect on velocity, temperature and concentration profiles





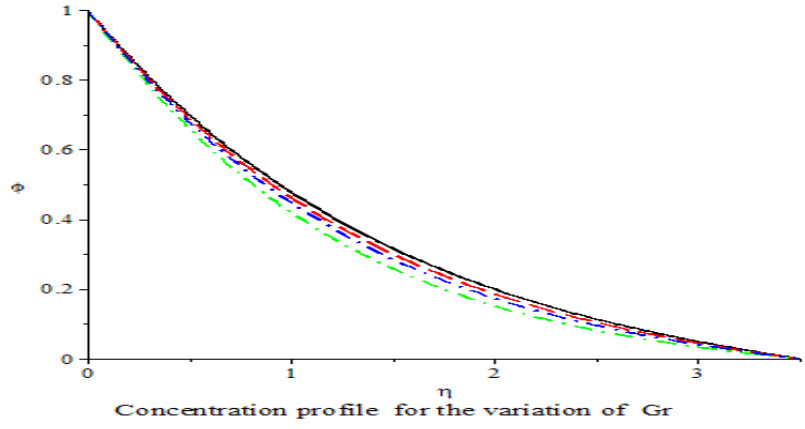
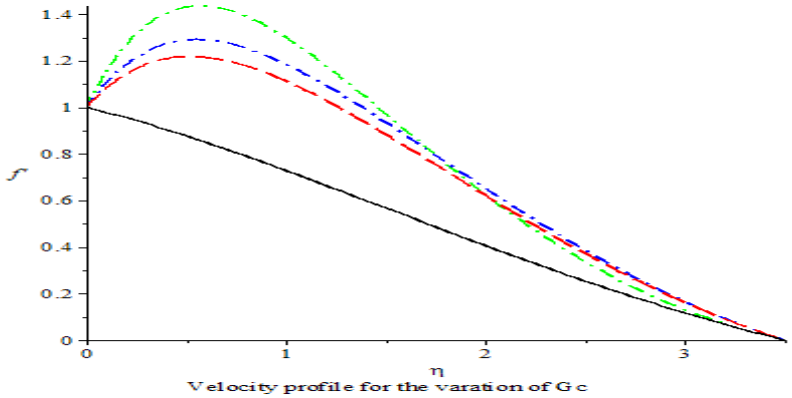
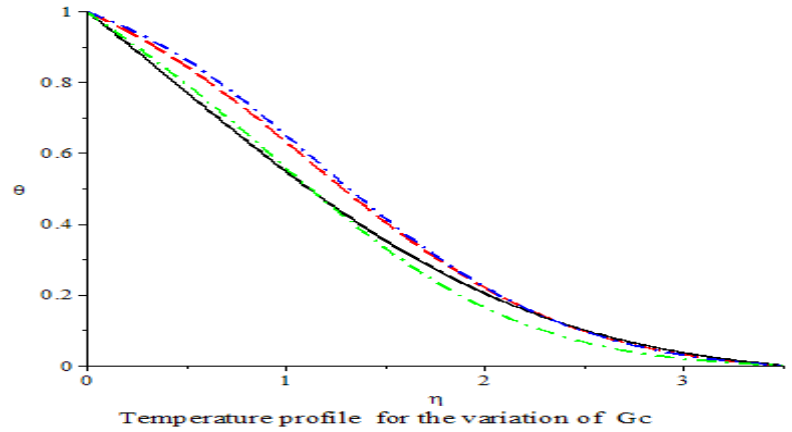


Figure 5: Gr effect on velocity, temperature and concentration profiles





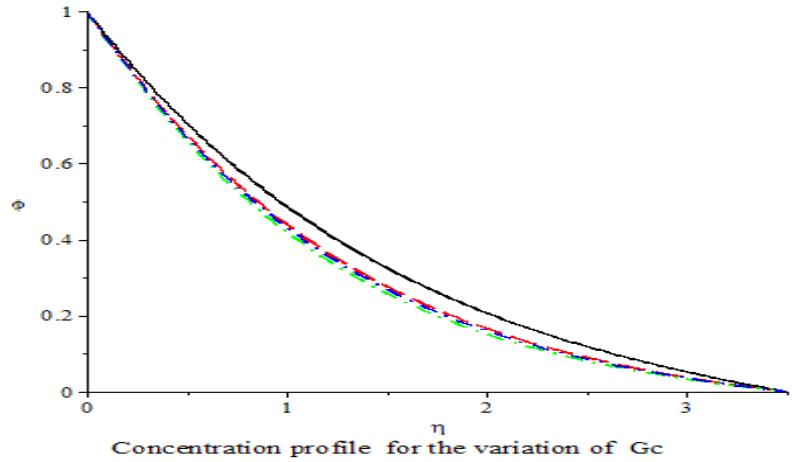


Figure 6: Gc effect on velocity, temperature and concentration profiles

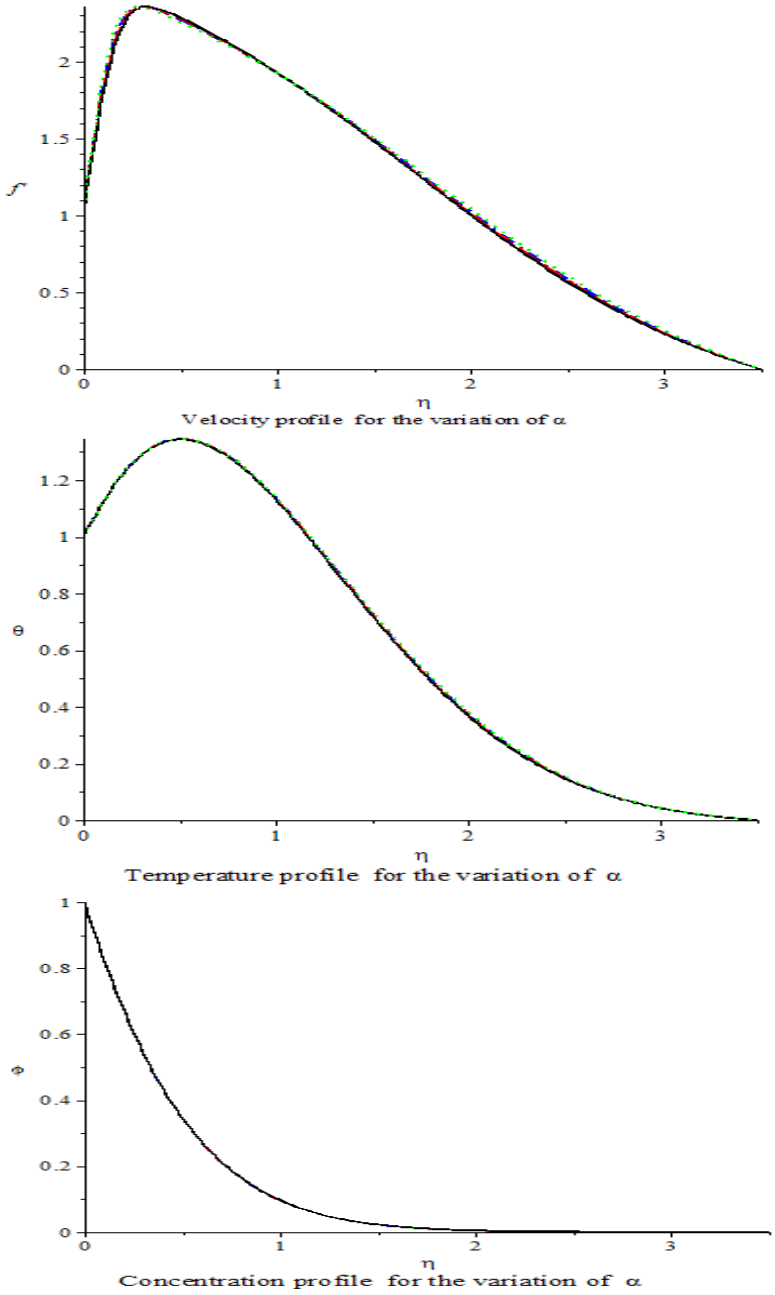


Figure 7: α effect on velocity, temperature and concentration profiles

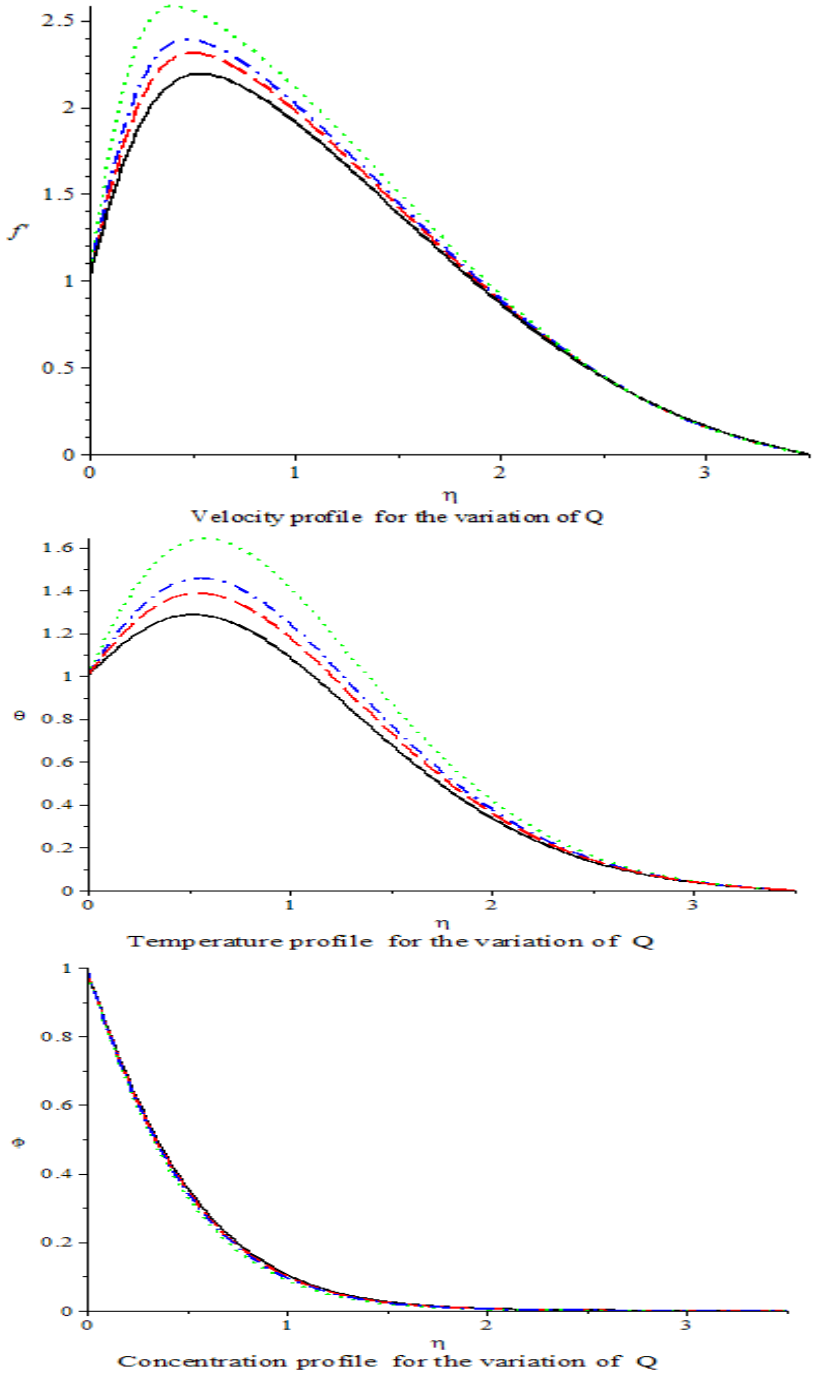
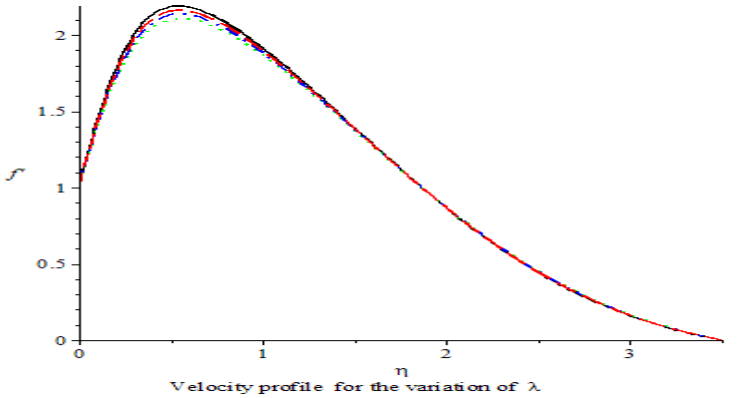
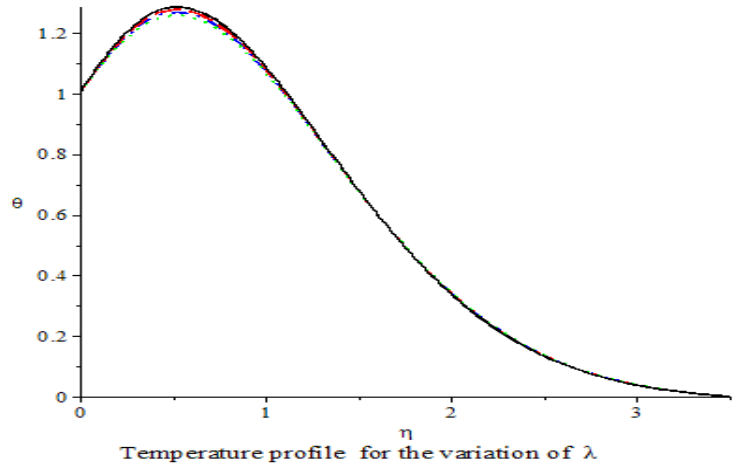


Figure 8: Q effect on velocity, temperature and concentration profiles





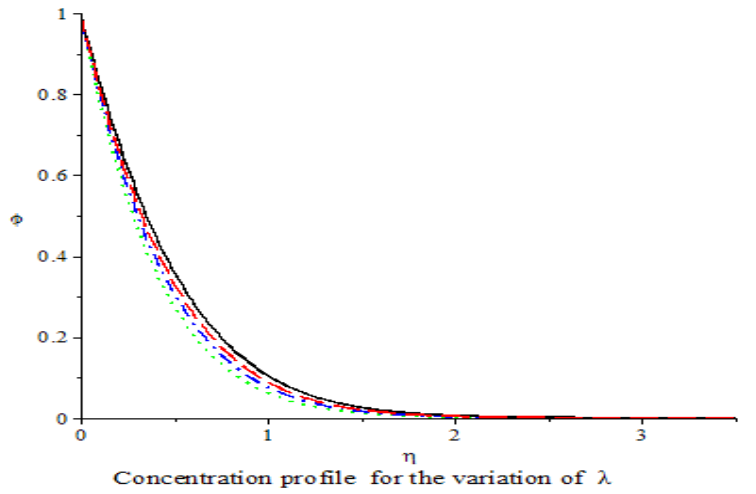
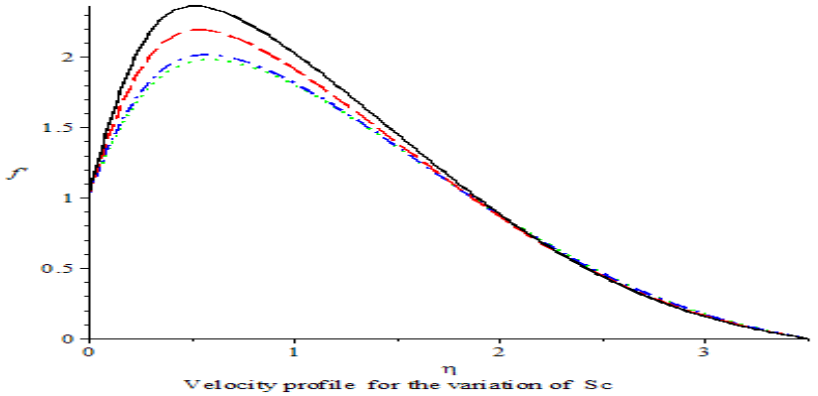
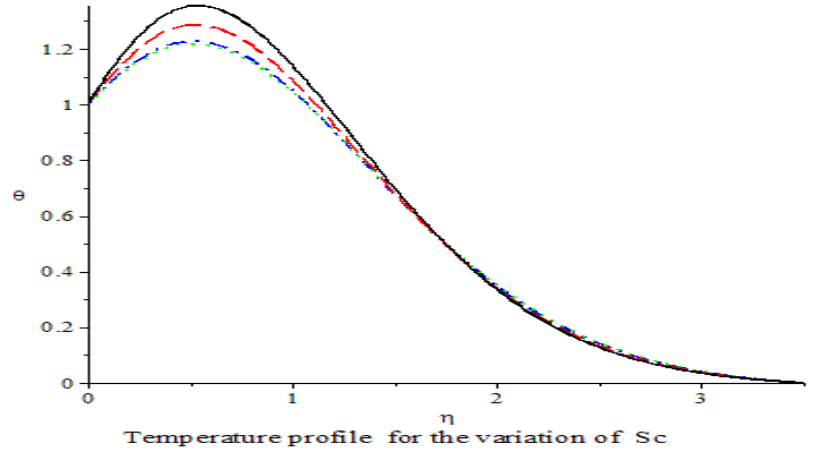


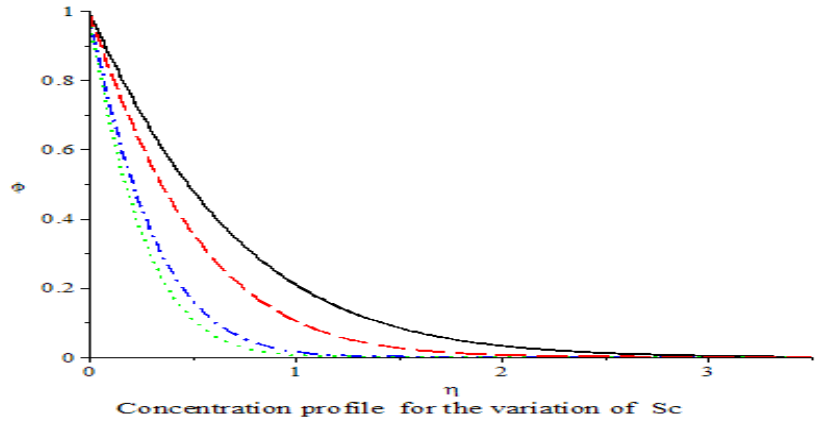
Figure 9: λ effect on velocity, temperature and concentration profiles



Velocity profile for the variation of Sc



Temperature profile for the variation of Sc



Concentration profile for the variation of Sc

Figure 10 Sc. effect on velocity, temperature and concentration profiles

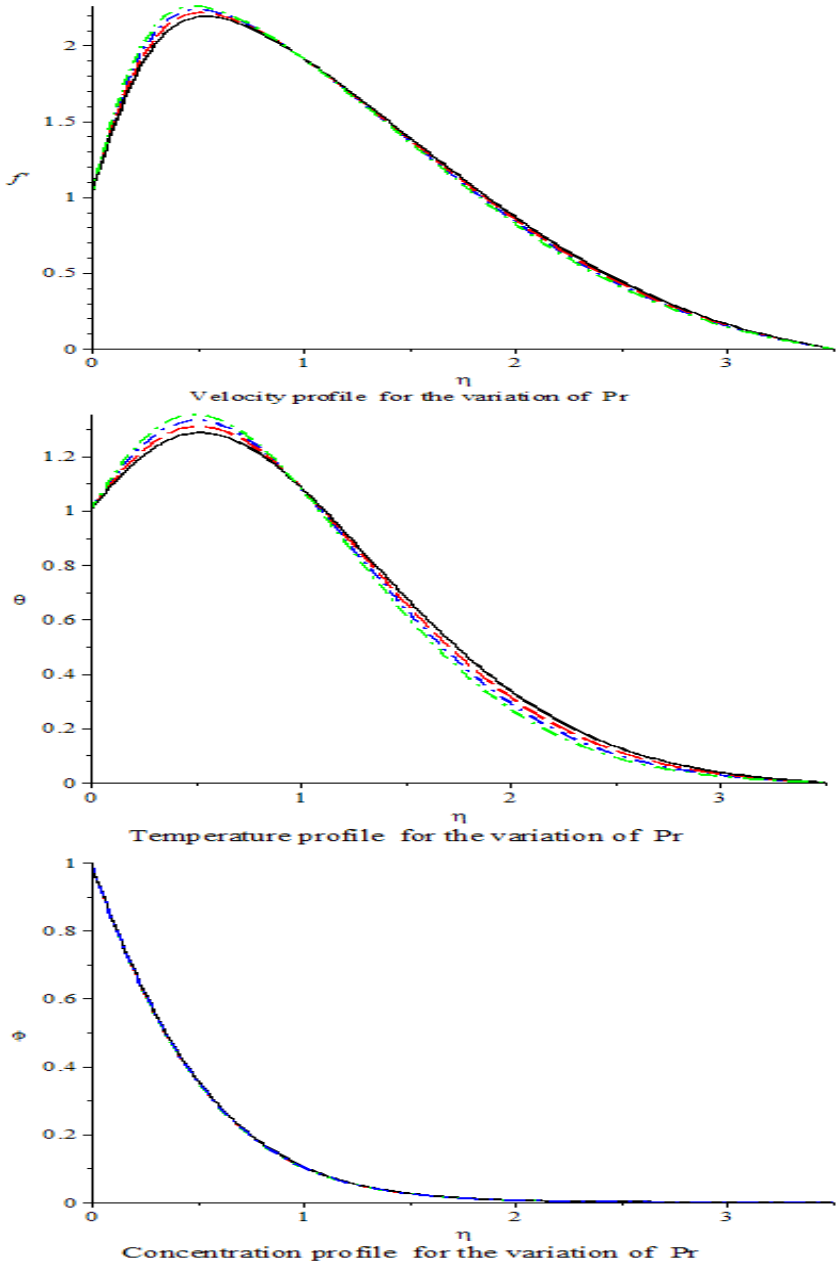


Figure 11: Pr. effect on velocity, temperature and concentration profiles

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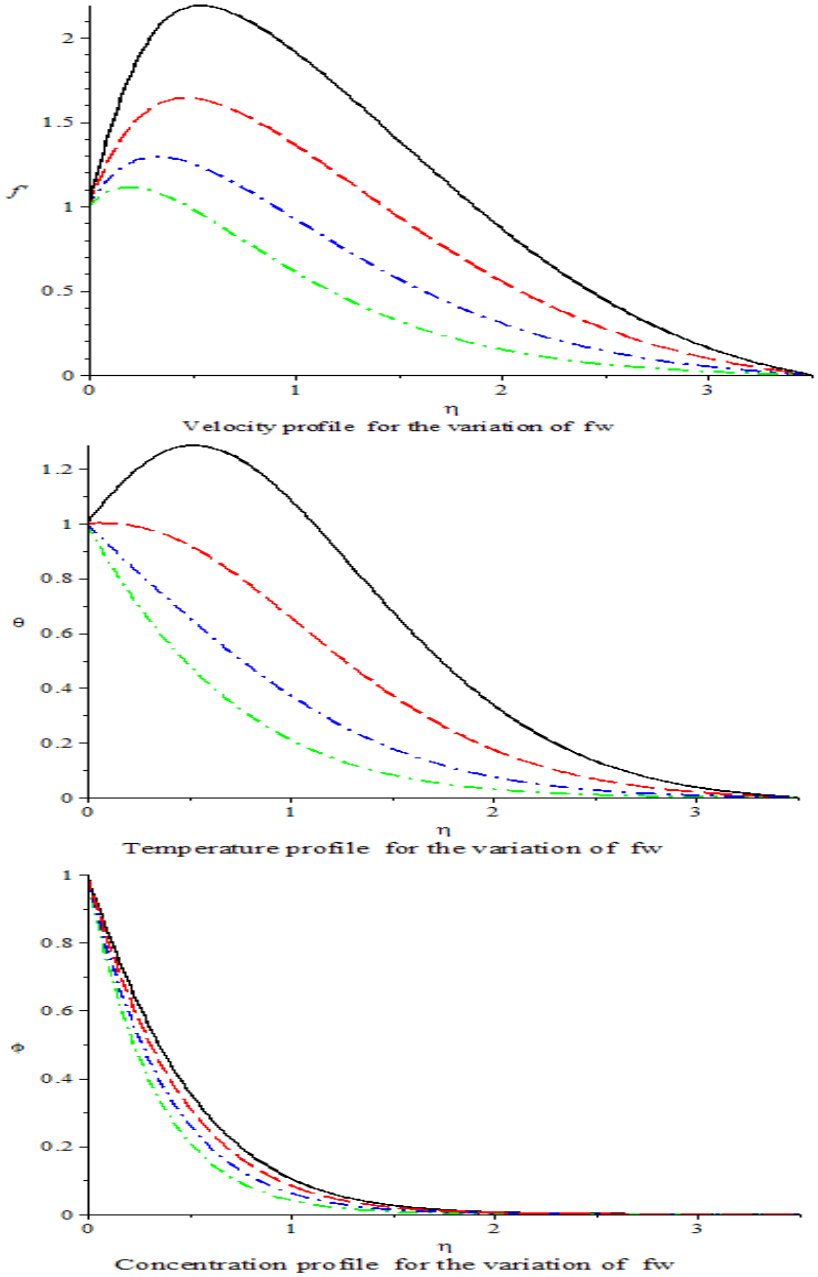
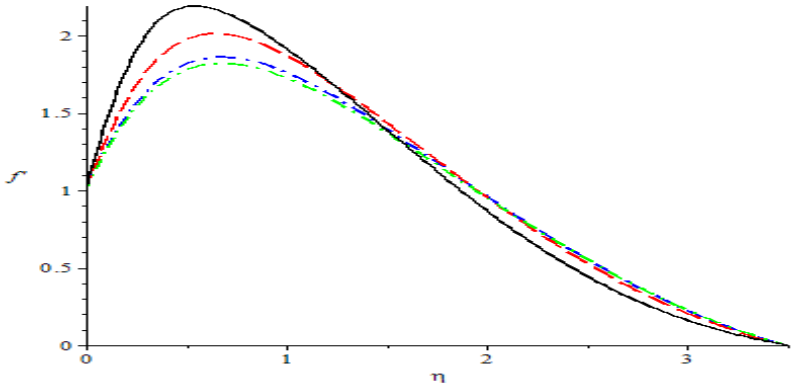
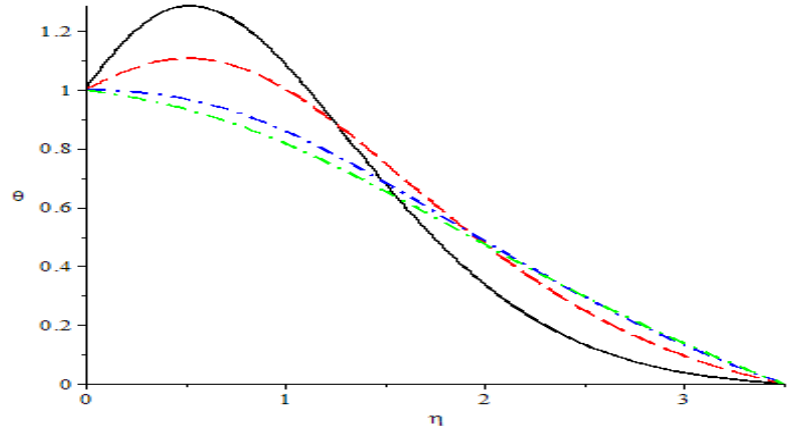


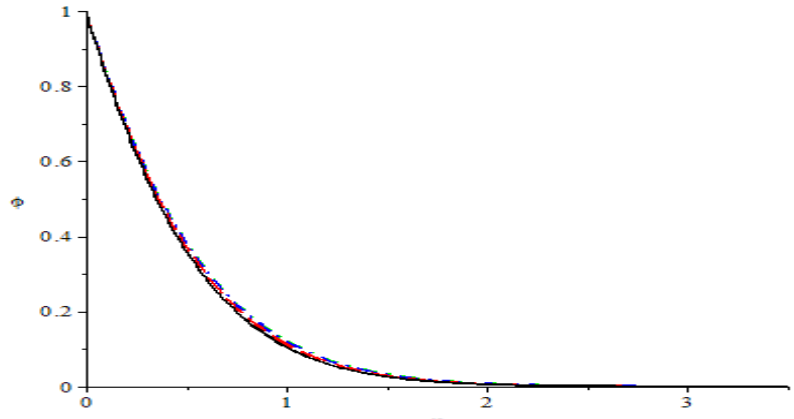
Figure 12: fw effect on velocity, temperature and concentration profiles



Velocity profile for the variation of R

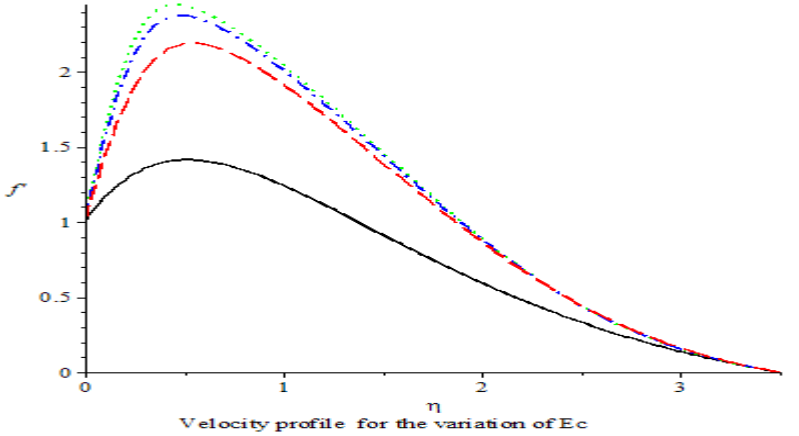


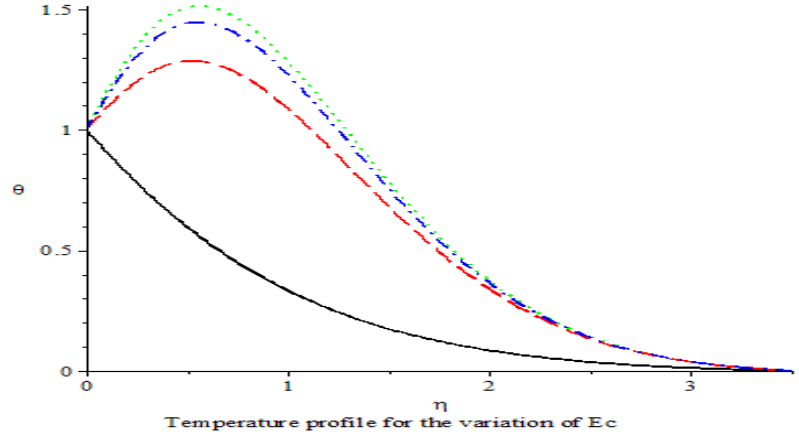
Temperature profile for the variation of R



Concentration profile for the variation of R

Figure 13: R effect on velocity, temperature and concentration profiles





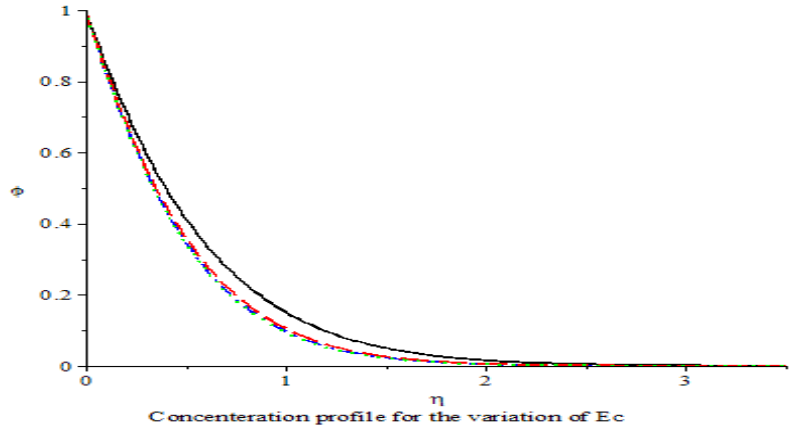


Figure 14: Ec. effect on velocity, temperature and concentration profiles

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