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Similarity Solution of Heat and Mass Transfer Flow over an Inclined Stretching Sheet with Viscous Dissipation and Constant Heat Flux in Presence of Magnetic Field

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Abstract

The present analysis of this paper is to examine the similarity solution of magnetohydrodynamics (MHD) free convection heat and mass transfer flow of an incompressible, electrically conducting and viscous fluid over an inclined stretching sheet with viscous dissipation and constant heat flux. So the present work is focused of the impact of the flow parameters on the velocity, temperature, and concentration are computed, discussed and have been graphically represented in figures and also the shearing stress, and rate of concentration shown in table 1 for various values of different parameters. The results presented graphically illustrate that velocity field decrease due to increasing of magnetic parameter, Prandtl number, Grashof number, and Eckert number whereas negligible increasing effects for Soret number, Schmidt number and noticeable increasing effect for angle of inclination but there is no effect for modified Grashof number. The temperature field decreases up to certain interval then increases in the presence of Magnetic parameter and reverse trend arise for Prandtl number but the temperature field increases for the remaining entering parameters. It is interesting to note that in a certain interval of η, the concentration profile is decreased and then increased but reverse trend arises in the case of Prandtl number and angle of inclination. By considering the hot plate the numerical results for the skin friction and the local Sherwood number are compared with the results reported by the other author when the magnetic field and modified Grashof number are absent. The present results in this paper are in good agreement with the work of the previous author.

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Keywords: MHD; heat and mass transfer; stretching sheet: angle of inclination; viscosity;

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1. Introduction

The steady MHD boundary layer flow over an inclined stretching sheet with suction and heat generation has much interested in last few decades. The effects of magnetic field on free convective flows are of importance in liquid metals, electrolytes, and ionized gases. Due to presence of a strong magnetic field the conduction mechanism in ionized gases is different from that in a metallic substance. An electric current in ionized gases is generally carried out by electrons which undergo successive collisions with other charged or neutral particles. However, in the presence of a strong electric field, the electrical conductivity is affected by a magnetic field. Also MHD laminar boundary layer flow over a stretching sheet has noticeable applications in glass blowing, continuous casting, paper production, hot rolling, wire drawing, drawing of plastic films, metal and polymer extrusion, metal spinning and spinning of fibbers. During its manufacturing process a stretched sheet interacts with the ambient fluid thermally and mechanically. Both the kinematics of stretching and the simultaneous heating or cooling during such processes has a decisive influence on the quality of the final products. In the extrusion of a polymer sheet from a die, the sheet is some time stretched. By drawing such a sheet in a viscous fluid, the rate of cooling can be controlled and the final product of the desired characteristics can be achieved. Raptiset et al. [1] have studied the viscous flow over a non-linearly stretching sheet in the presence of a chemical reaction and magnetic field. Tan et al. [2] studied various aspects of this problem, such as the heat, mass and momentum transfer in viscous flows with or without suction or blowing. Abel and Mahesh [3] presented an analytical and numerical solution for heat transfer in a steady laminar flow of an incompressible viscoelastic fluid over a stretching sheet with power-law surface temperature, including the effects of variable thermal conductivity and non-uniform heat source and radiation. Samad and Mohebujjaman [4] investigated the case along a vertical stretching sheet in presence of magnetic field and heat generation. Saleh Alharbi et.al [5] studied heat and mass transfer in MHD visco-elastic fluid flow through a porous medium over a stretching sheet with chemical reaction, Seddeek and Abdel Meguid [6] analyzed the effects of radiation and thermal diffusivity on heat transfer over a stretching surface with variable heat flux , Ali et al. [7] studied the Radiation and thermal diffusion effects on a steady MHD free convection heat and mass transfer flow past an inclined stretching sheet with Hall current and heat generation, Ibrahim and Shanker [8] investigated the unsteady MHD boundary layer flow and heat transfer due to stretching sheet in the presence of heat source or sink by Quasi-linearization technique. Ishak et al. [9] investigated the solution to unsteady mixed convection boundary layer flow and heat transfer due to a stretching vertical surface. Ebashbeshy and Aldawody [10] analyzed heat transfer over an unsteady stretching surface with variable heat flux in presence of heat source or sink, Fadzilah et al.[11] studied the steady MHD boundary layer flow and heat transfer of a viscous and electrically conducting fluid over a stretching sheet with an induced magnetic field, Rashidi et al. [12] find the solution of MHD flow in a laminar liquid film from a horizontal stretching surface by using differential transform method and Padé Approximant, later Rashidi et al. [13] showed a new analytical study of MHD stagnation–point flow in porous media with heat transfer also Rashidi et al. [14] studied the simultaneous effects of partial slip and thermal-diffusion and diffusion-thermo on steady MHD convective flow due to a rotating disk and Mohebujjaman et al. [15] studied MHD heat transfer mixed convection flow along a vertical stretching sheet with heat generation using shooting technique. All of the above researchers in their studies were not consider the inclination of angle of the sheet, viscous dissipation and constant heat flux. So the present work focused on similarity solution of heat and mass transfer flow over an inclined stretching sheet with viscous dissipation and constant heat flux in presence of magnetic field.

2. Mathematical formulation of the problem and similarity analysis

Let us consider a steady two dimensional laminar MHD viscous incompressible electrically conducting fluid along an inclined stretching sheet with an acute angle (γ), *X*- direction is taken along the leading edge of the inclined stretching sheet and *Y* is normal to it and extends parallel to *X*-axis. A magnetic field of strength B_0 is introduced to the normal to the direction to the flow. The uniform plate temperature T_w ($>T_\infty$), where T_∞ is the temperature of the fluid far away from the plate. Let *u* and *v* be the velocity components along the *X* and *Y* axis respectively in the boundary layer region. Under the above assumptions and usual boundary layer approximation, the dimensional governing equations of continuity, momentum, concentration and energy under the influence of externally imposed magnetic field are:

Equation of continuity:

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

Momentum equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=v\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_\infty)\cos\gamma+g\beta^*(C-C_\infty)\cos\gamma-\frac{\sigma B_0^2\, u}{\rho} \tag{2}$$

Energy Equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{v}{c_p}\left(\frac{\partial u}{\partial y}\right)^2,\alpha=\frac{k}{\rho c_p} \tag{3}$$

Concentration Equation:

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}+\frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

where *u* and *v* are the velocity components along x and y directions, T , T_w and T_∞ are the fluid temperature, the stretching sheet temperature and the free stream temperature respectively while C , C_w and C_∞ are the corresponding concentrations, k is the thermal conductivity of the fluid, C_p specific heat with constant pressure, α is thermal diffusivity, γ is the angle of inclination, μ is the coefficient of viscosity, ν is the kinematic viscosity , σ is the electrical conductivity, ρ is the fluid density, β is the thermal expansion coefficient, β * is the concentration expansion coefficient, B_0 is the magnetic field intensity, U_0 is the stretching sheet parameter, g is the acceleration due to gravity, q is the constant heat flux per unit area, D_m is the coefficient of mass diffusivity, K_T is the thermal diffusion ratio, T_m is the mean fluid temperature, respectively. The above equations are subject to the following boundary conditions:

$$u=U_0x,\ v=0,\ \frac{\partial T}{\partial y}=-\frac{q}{k},C=C_w \quad at \quad y=0\ and\ u=0,T=T_\infty,C=C_\infty\ as \quad y\to\infty \tag{5}$$

Introducing the stream function $\psi(x,y)$ as defined by $u=\frac{\partial\psi}{\partial y}$ and $v=-\frac{\partial\psi}{\partial x}$

To convert the governing equations into a set of similarity equations, we introduce the following similarity transformation:

$$\psi=x\sqrt{2v\,U_0}\,f(\eta),\eta=y\sqrt{\frac{U_0}{2v}},\ \theta(\eta)=\frac{k(T-T_\infty)}{q}\sqrt{\frac{U_0}{2v}},\varphi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}$$

From the above transformations, the non-dimensional, nonlinear and coupled ordinary differential equations are obtained as follows:

$$f''' + 4ff'' - 2f'^2 - Mf' + Gr\theta\cos\gamma + Gm\varphi\cos\gamma = 0 \quad (6)$$

$$\theta'' + 4\Pr f\theta' + \Pr Ecf''^2 = 0 \quad (7)$$

$$\varphi'' + 4Scf\varphi' + ScS_0\theta'' = 0 \quad (8)$$

The transform boundary conditions:

$$f = 0\ f' = 1, \theta' = -1, \varphi = 1\ at\ \eta = 0,\ and f' = 0, \theta = \varphi = 0\ as\ \eta \to \infty \quad (9)$$

Where f', θ and φ are the dimensionless velocity, temperature and concentration respectively, η is the similarity variable, η_∞ is the value of η at which boundary conditions is achieved, the prime denotes differentiation with respect to η. Also

$$M = \frac{2\sigma B_0^2}{\rho U_0}, Gr = \frac{2g\beta q}{U_0^2}\sqrt{\frac{2\nu}{xU_0}}, Gm = \frac{2g\beta^*(C_w - C_\infty)}{xU_0^2}, \Pr = \frac{\mu c_p}{k}, Ec = \frac{kU_0^2x^2}{qc_p}\sqrt{\frac{U_0}{2\nu}}, Sc = \frac{\nu}{D_m}$$

$$and\ S_0 = \frac{D_m K_T q}{kT_m(C_w - C_\infty)}\sqrt{\frac{2}{\nu U_0}}$$

are the magnetic parameter, Grashof number, modified Grashof number, Prandtl number, Eckert number, Schmidt number, and Soret number respectively. The important physical quantities of this problem are skin friction coefficient C_f and the local Sherwood number Sh which are proportional to rate of velocity and rate of concentration respectively.

3. Methodology

There are two asymptotic boundary conditions and hence two unknown conditions $f'(0), \theta'(0)$ are to be assumed to solve the boundary layer equations by using shooting method technique. Within the context of initial value method and Nachtsheim-Swigert iterations technique the outer boundary conditions may be functionally represented as:

$$f(\eta_{\max}) = f\ [f'(0), \theta'(0)] = \delta_1 \quad (10)$$

$$\theta(\eta_{\max}) = \theta\ [f'(0), \theta'(0)] = \delta_2 \quad (11)$$

with the asymptotic convergence criteria given by:

$$f'(\eta_{\max}) = f'\ [f'(0), \theta'(0)] = \delta_3 \quad (12)$$

$$\theta'(\eta_{\max}) = \theta'\,[f'(0), \theta'(0)] = \delta_4 \tag{13}$$

Let us choose $f'(0) = \Delta x,\ \theta'(0) = \Delta y$

Retaining only the first order terms from the Taylor's Series expansion from equations (10) – (13) yields:

$$f(\eta_{\max}) = f_c(\eta_{\max}) + f_x \Delta x + fy\,\Delta y = \delta_1 \tag{14}$$

$$\theta(\eta_{\max}) = \theta_c(\eta_{\max}) + \theta_x \Delta x + \theta y\,\Delta y = \delta_2 \tag{15}$$

$$f'(\eta_{\max}) = f'_c(\eta_{\max}) + f'_x \Delta x + f'y\,\Delta y = \delta_3 \tag{16}$$

$$\theta'(\eta_{\max}) = \theta'_c(\eta_{\max}) + \theta'_x \Delta x + \theta' y\,\Delta y = \delta_4 \tag{17}$$

where $x = f'(0),\ y = \theta'(0)$ and x, y are subscripts.

Indicate partial differentiation, e. g.:

$$f'_x = \frac{\partial f'(\eta_{\max})}{\partial f'(0)},\ f'_y = \frac{\partial f'(\eta_{\max})}{\partial \theta'(0)}$$

The subscript '*c*' indicates the value of the function at $\eta_{\max}$ determined from the trial integration. Solutions of these equations in a least square sense requires determining the minimum value of

$$E = \delta_1^2 + \delta_2^2 + \delta_3^2 + \delta_4^2 \tag{18}$$

Differentiation E with respect to x and y we get

$$\delta_1 \frac{\partial \delta_1}{\partial x} + \delta_2 \frac{\partial \delta_2}{\partial x} \delta_3 \frac{\partial \delta_3}{\partial x} \delta_4 \frac{\partial \delta_4}{\partial x} = 0 \tag{19}$$

$$\delta_1 \frac{\partial \delta_1}{\partial y} + \delta_2 \frac{\partial \delta_2}{\partial y} \delta_3 \frac{\partial \delta_3}{\partial y} \delta_4 \frac{\partial \delta_4}{\partial y} = 0 \tag{20}$$

using equations (14) –(17) in equation (19), we get

$$(f_x^2 + \theta_x^2 + f_x'^2 + \theta_x'^2)\,\Delta x + (f_x f_y + \theta_x \theta_y + f'_x f'_y + \theta'_x \theta'_y)\,\Delta y = -(f_c f_x + \theta_c \theta_x + f'_c f'_x + \theta'_c \theta'_x) \tag{21}$$

Similarly using equations (14) – (17) in equation (20), we get

$$(f_y^2 + \theta_y^2 + f_y'^2 + \theta_y'^2)\,\Delta y + (f_x f_y + \theta_x \theta_y + f'_x f'_y + \theta'_x \theta'_y)\,\Delta x = -(f_c f_y + \theta_c \theta_y + \theta'_c \theta'_y + f'_c f'_y) \tag{22}$$

we can write equation (21) and (22) in system of linear equations in the following form as:

$$a_{11}\Delta x + a_{12}\Delta y = d_1 \tag{23}$$

$$a_{21}\Delta x + a_{22}\Delta y = d_2 \tag{24}$$

where, $a_{11} = f_x^2 + \theta_x^2 + f_x'^2 + \theta_x'^2$

$$a_{12} = f_x f_y + \theta_x \theta_y + f_x' f_y' + \theta_x' \theta_y'$$

$$a_{21} = f_y^2 + \theta_y^2 + f_y'^2 + \theta_y'^2$$

$$a_{22} = f_x f_y + \theta_x \theta_y + f_x' f_y' + \theta_x' \theta_y'$$

$$d_1 = -(f_c f_x + \theta_c \theta_x + f_c' f_x' + \theta_c' \theta_y')$$

$$d_2 = -(f_c f_y + \theta_c \theta_y + \theta_c' \theta_y' + f_c' f_y')$$

The matrix from of (23) and (24) is

$$\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} \Delta x \\ \Delta y \end{pmatrix} = \begin{pmatrix} d_1 \\ d_2 \end{pmatrix} \tag{25}$$

We will solve the system of linear equations (25) by Cramers rule and thus we have

$$\Delta x = \frac{\det A_1}{\det A}, \quad \Delta y = \frac{\det A_2}{\det A}$$

where, det A = $\begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{12}a_{21}$

det A_1 = $\begin{vmatrix} d_1 & a_{12} \\ d_2 & a_{22} \end{vmatrix} = d_1 a_{22} - d_2 a_{12}$

det A_2 = $\begin{vmatrix} a_{11} & d_1 \\ a_{21} & d_2 \end{vmatrix} = d_2 a_{11} - d_1 a_{21}$

Then we obtain the unspecified missing values x and y as $x \equiv x + \Delta x$ and $y \equiv y + \Delta y$

Thus adopting this type of numerical technique described above, a computer program will be setup for the solution of the basic nonlinear differential equations of our problem where the integration technique will be adopted as the fourth order Runge-Kutta method along with shooting iterations technique. First of all, higher order non–linear differential equations are converted into simultaneous linear differential equations of first order and they are further transformed into initial value problem applying the shooting technique. Once the problem is reduced to initial value problem, then it is solved using Runge -Kutta fourth order technique. The effects of the flow parameters on the velocity, temperature and species concentration are computed, discussed and have been graphically represented in figures and also the shearing stress and rate of concentration shown in table 1 for various value of different parameters. In this regard, defining new variables by the equations

$$y_1 = f, y_2 = f', y_3 = f'', y_4 = \theta, y_5 = \theta', y_6 = \varphi, y_7 = \varphi'$$

The higher order differential equations (6), (7), (8) and boundary conditions (9) may be transformed to seven equivalent first order differential equations and boundary conditions respectively are given below:

$$dy_1 = y_2, dy_2 = y_3, dy_3 = -4y_1y_3 + 2y_2^2 + My_2 - Gr\cos\gamma\, y_4 - Gm\cos\gamma\, y_6, dy_4 = y_5,$$
$$dy_5 = -4\Pr y_1y_5 - \Pr Ecy_3^2, dy_6 = y_7, dy_7 = -4Scy_1y_7 + 4ScS_0\Pr y_1y_5 + ScS_0\Pr Ecy_3^2$$

And the boundary conditions are

$$y_1 = 0, y_2 = 1, y_5 = -1, y_6 = 0 \quad at\ \eta = 0,\ and\ y_2 = 0, y_4 = 0, y_6 = 0 \quad as \quad \eta \to \infty$$

4. Results and Discussion

Numerical calculation for the distribution of velocity, temperature and concentration profiles across the boundary layer for different values of the parameters are carried out. For the purpose of our simulation we have chosen *M = 0.5, S0= 0.2, Pr = 1.0, Gr = 2.0, Gm=2.0, Ec = 1.0, Sc= 0.22, and* $\gamma = 81^o$ while the parameters are varied over range as shown in the figures. Fig.1 clearly demonstrates that the velocity profile starts from maximum value at the surface and then decreasing until it reaches to the minimum value at the end of the boundary layer for all the values *M*. It is interesting to note that the effect of magnetic field is more prominent at the point of peak value, because the presence of *M* in an electrically conducting fluid introduces a force like Lorentz force which acts against the flow if the magnetic field is applied in the normal direction as in the present problem. As a result velocity profile is decreased. Similar effect is also observed in Fig. 2 and Fig. 5 with increasing values of *Gr* and *Ec*. Fig. 4, Fig. 6 and Fig.7 show the velocity profile for various values of S_0, *Sc* and γ, it is observed that an increasing in Soret number and Schmidt number lead to a negligible increasing effect on velocity profile whereas noticeable increasing effect for angle of inclination because of multiplication $\cos\gamma$ the effect of the buoyancy force increases for the increasing values of γ and therefore the velocity profile increases. But there is no effect of modified Grashof number on velocity profile which are shown in Fig. 3. Again, Fig. 8 – Fig. 14 show the temperature profile obtained by the numerical simulation for various values of entering parameters. From these figures it is clearly demonstrates that the thermal boundary layer thickness increases for the increasing values of *S0, Pr, Gr, Gm, Ec, Sc*. From Fig. 8 it is observed that in the certain interval of η, the temperature profile is increased and then decreased for increasing values of *M* which implies that the applied magnetic field normal to the flow of the fluid tends to heat the fluid and thus reduces the heat transfer rate from the sheet therefore temperature is increased but reverse trend arises for the increasing values of *Pr* which shown in Fig.14. That is, the thermal boundary layer thickness decreases as the *Pr* increases implying higher heat transfer. It is due to the fact that smaller values of *Pr* means increasing thermal conductivity and therefore it is able to diffuse away from the plate more quickly than higher values of *Pr*, hence the rate of heat transfer is reduced as a result the heat of the fluid in the boundary layer increases. The effect of *Gr* on temperature profile is shown in Fig. 9. From this figure it is observed that, the temperature profile increases for increasing values of *Gr*; because the increase of Grashof number results in the increase of temperature gradients, which leads to the enhancement of the velocity due to the enhanced convection and thus temperature profiles are increased. From Fig.12 it is seen that the temperature profile is increased for the increasing values of *Ec* due to the fact that heat energy is stored in the liquid due to the frictional heating. It is obvious that the increasing effect of *Ec* enhanced the temperature at any point of flow region for the case of salt water. From this figure it is concluded that greater viscous dissipative heat be the cause of increasing temperature profile. Again Fig.15-Fig. 22 shows the concentration profiles obtained by the numerical simulation for various values of entering non-dimensional parameters. Again, from Fig.15- Fig.18 and Fig. 22 it is observed that in a certain interval of η, the concentration profile is decreased and then increased it is due to the fact that the concentration buoyancy effects to decrease compliant a reduction in the fluid velocity. Thus the simultaneous reduction effects of velocity and concentration reduced the velocity and concentration boundary layer thickness but reverse trend arises in the case of *Pr* and γ are shown in Fig. 20 and Fig. 21. From Fig.19 it is seen that the concentration profile is increased for the effect of *Ec* due to the fact that heat energy is stored in the liquid due to the frictional heating. It is obvious that the increasing effect of *Ec* enhanced the concentration at any point of flow region for the case of salt water. From this figure it is concluded that greater viscous dissipative heat be the cause of increasing concentration profile. Further the numerical solutions for the skin friction and the local Sherwood number have been compared with those of D. Makinde [16].These results are given in Table.1 and it is observed that the present results and those of D. Makinde [16] are in good agreement.

5. Conclusions

Following are the conclusions made from above analysis:

- The magnitude of velocity decreases with increasing magnetic parameter causing of Lorentz force.
- It is interesting to note that, in the certain interval of η, the temperature profile is increased and then decreased for increasing values of *M* but reverse trend arises for the increasing values of Pr.
- The noticeable increasing effects of Prandtl number, Schmidt number, Eckert number and angle of inclination on concentration profile but reverse trend arises for the case of Grashof number, modified Grashof number and Soret number.
- To compare the skin friction and Sherwood number with previous results and get good agreement.

Table 1.Comparison of skin friction [$f''(0)$] and local Sherwood number [$-\varphi'(0)$] for different values of *M*, when $Pr = 1.0$, $Gr = -0.2$, $Gm = -0.2$, $S_0 = 0.2$, $Ec = 1.0$, $Sc = 0.22$, $\gamma = 81^o$

M	D. Makinde [16]		Present results	
	$-\mathrm{f}\ (0)$	$-\varphi\ (0)$	$-\mathrm{f}\ (0)$	$-\varphi\ (0)$
1.00	1.629178	0.561835	**1.619956**	**0.560545**
2.00	1.912620	0.554247	**1.912023**	**0.554767**
5.00	2.581130	0.541547	**2.57678**	**0.543557**
10.00	3.415289	0.531405	**3.422358**	**0.532425**

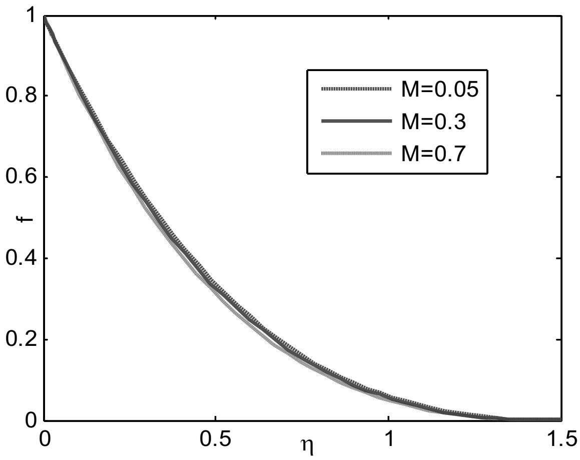

Fig.1. Velocity profile for various values of *M*

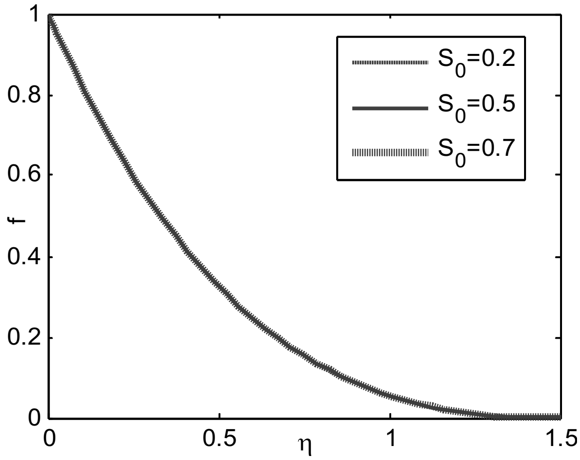

Fig.4. Velocity profile for various values of S_0

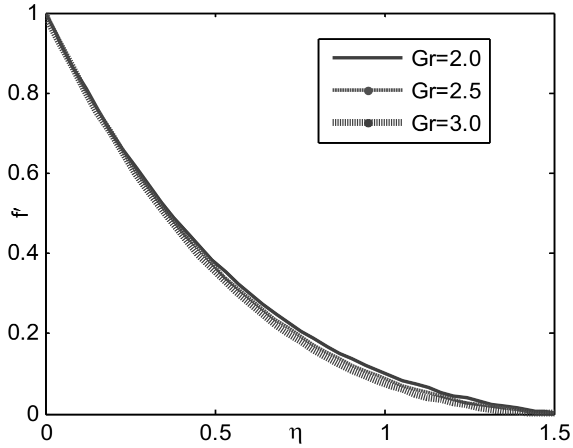

Fig.2. Velocity profile for various values of Gr

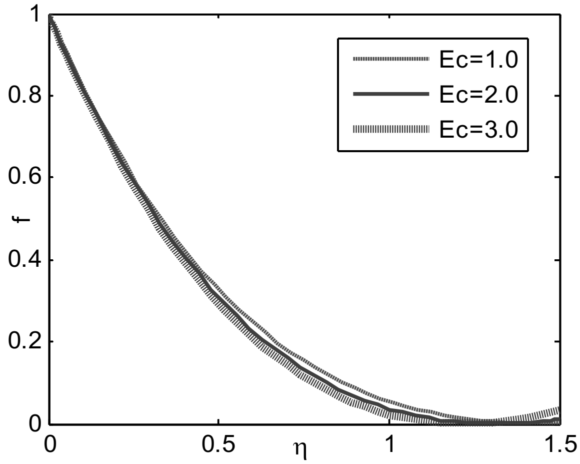

Fig.5. Velocity profile for various values of Ec

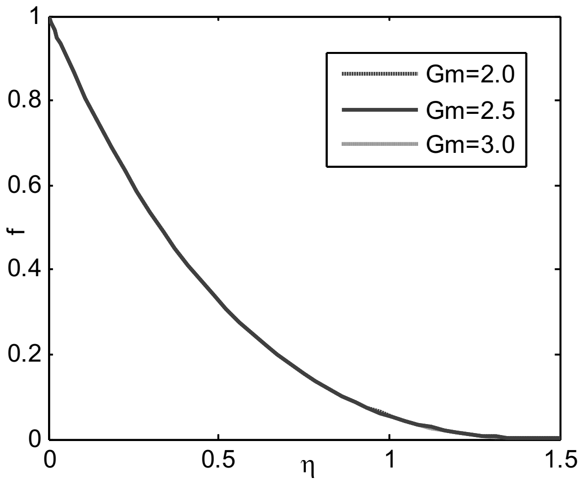

Fig.3. Velocity profile for various values of Gm

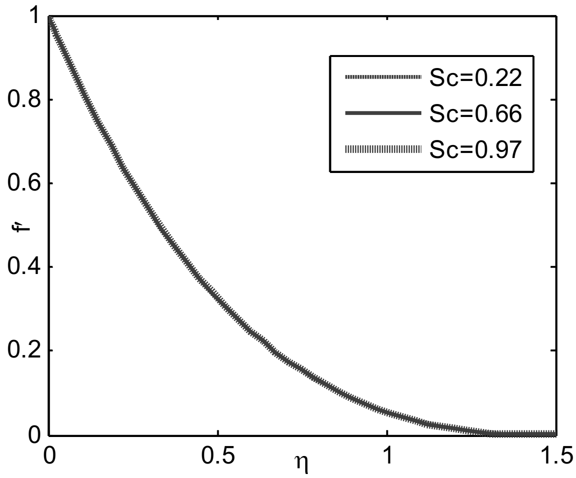

Fig.6. Velocity profile for various values of Sc

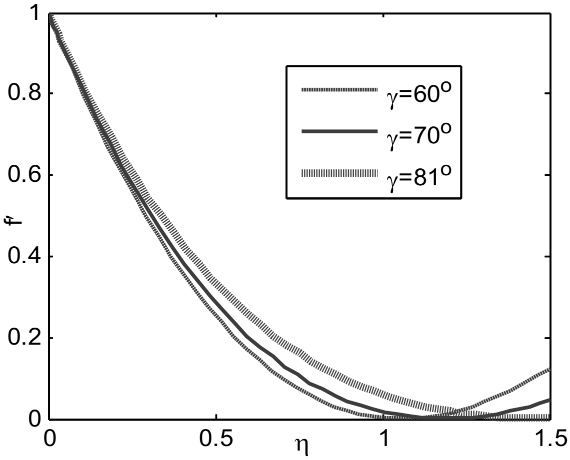

Fig.7. Velocity profile for various values of γ

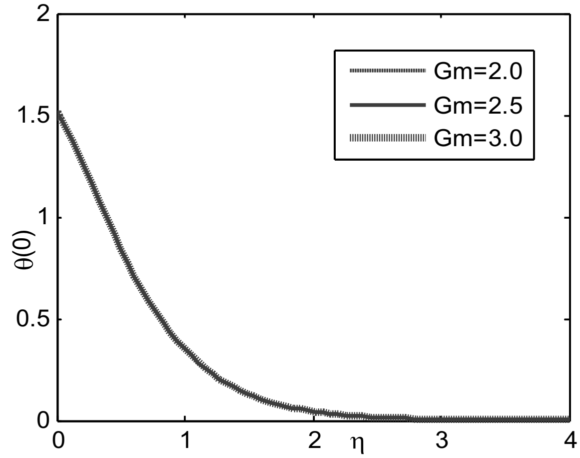

Fig.10. Temperature profile for various values of Gm

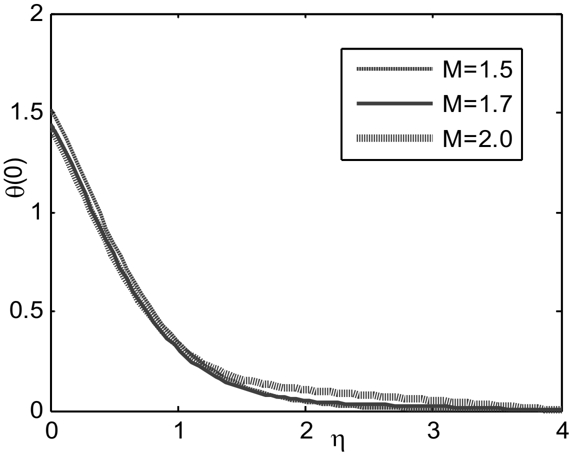

Fig.8. Temperature profile for various values of M

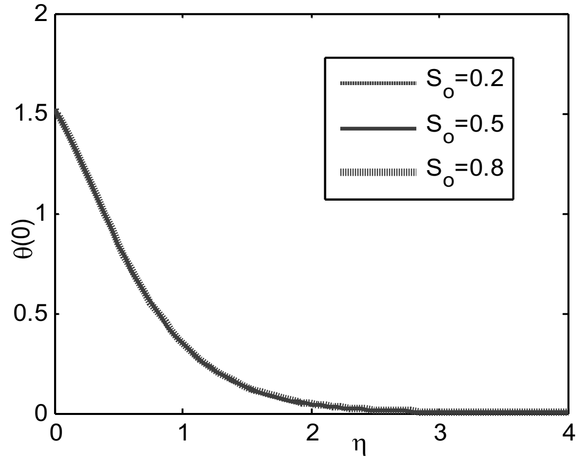

Fig.11. Temperature profile for various values of S0

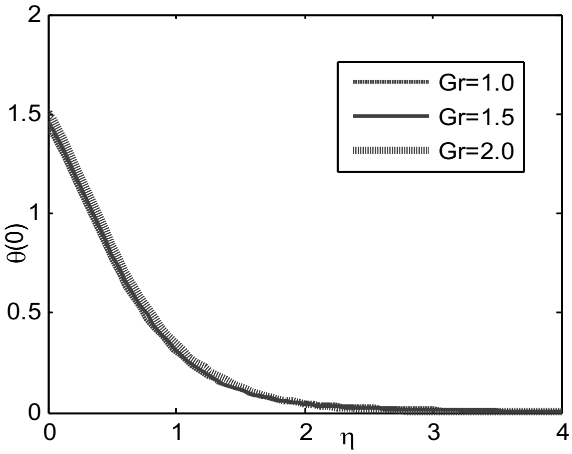

Fig.9. Temperature profile for various values of Gr

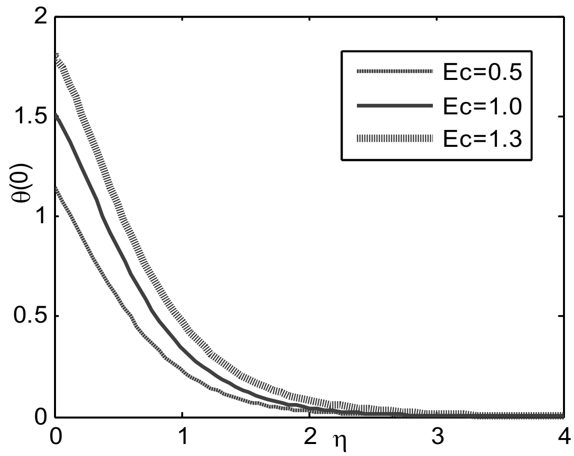

Fig.12. Temperature profile for various values of Ec

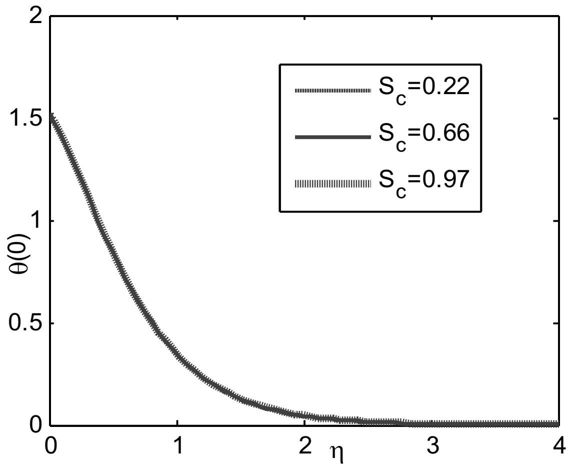

Fig.13. temperature profile for various values of Sc

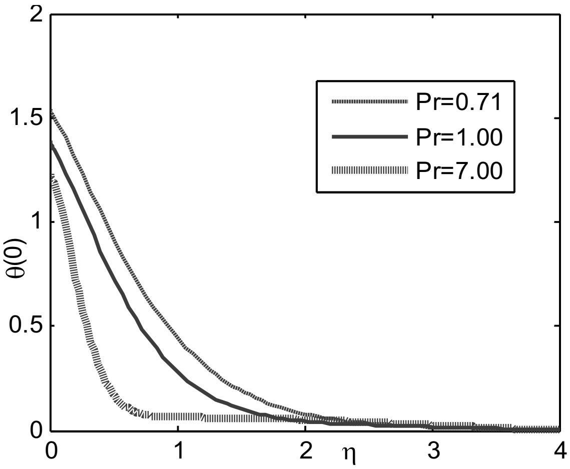

Fig.14. Temperature profile for various values of Pr

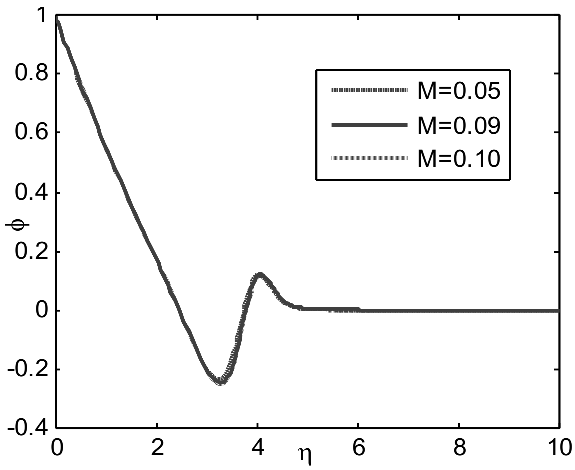

Fig.15. Concentration profile for various values of M

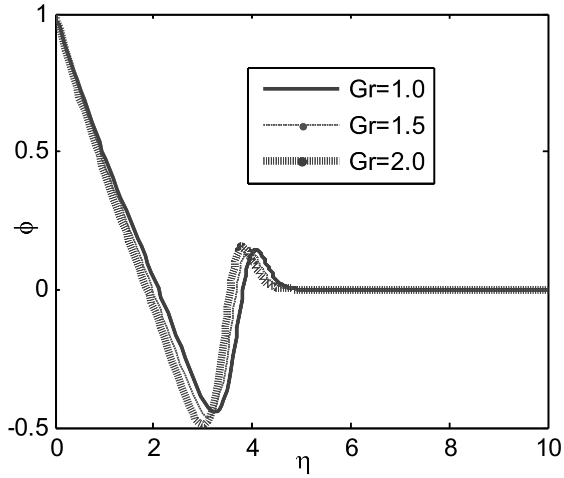

Fig.16. Concentration profile for various values of Gr

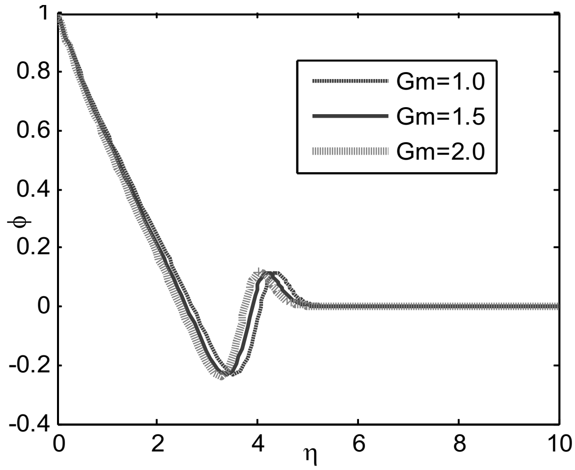

Fig.17. Concentration profile for various values of Gm

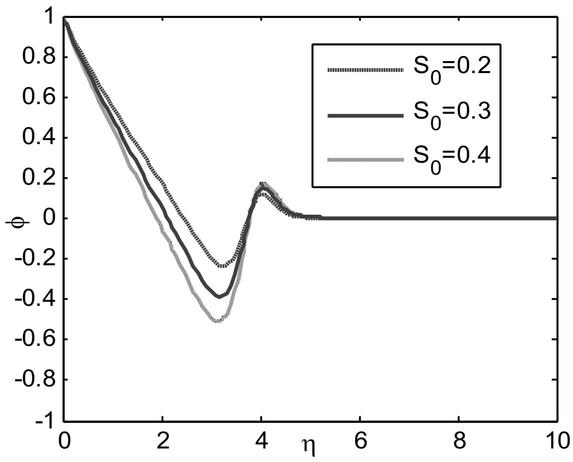

Fig.18. Concentration profile for various values of S0

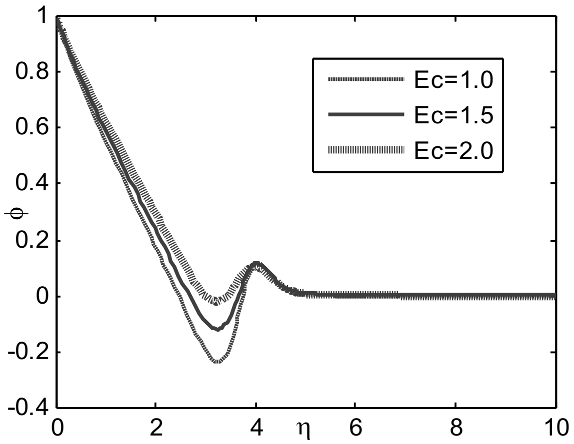

Fig.19. Concentration profile for various values of Ec

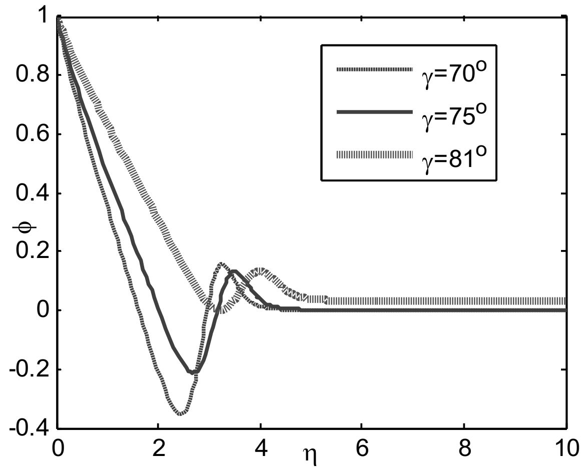

Fig.21. Concentration profile for various values of γ

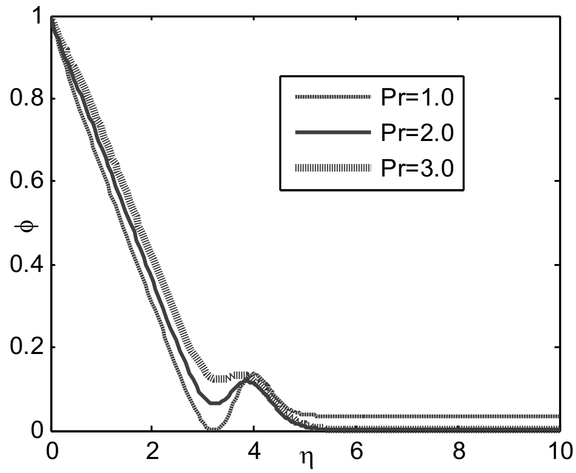

Fig.20. Concentration profile for various values of Pr

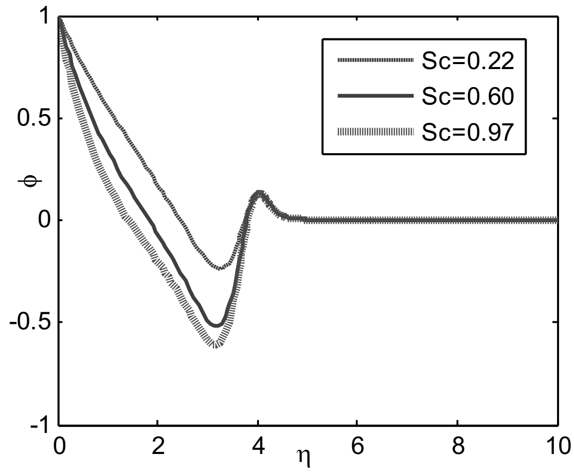

Fig.22. Concentration profile for various values of Sc

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