Magneto Hydrodynamic Free Convection Heat and Mass Transfer Flow of a Viscous, Conductive Fluid over an Inclined Stretching Sheet with Viscous Dissipation and Constant Heat Flux Using Homotophy Perturbation Method

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Abstract - *The present research article is to investigate the magnetohydrodynamic (MHD) free convective heat and mass transfer flow of viscous incompressible electrically conductive fluid over an inclined stretching sheet with viscous dissipation and constant heat flux with the help of homotophy perturbation technique. This paper gives the description of the effect of flow parameters on velocity, temperature and concentration, which is graphically represented in figures.*

Keywords - *MHD flow, Heat and Mass Transfer, inclined stretching sheet, concentration, angle of inclination.*

I. INTRODUCTION

In past decades the magnetohydrodynamic (MHD) flow over an inclined stretching sheet with viscous dissipation and heat generation gained lots of interest. It has importance in liquid metals, electrolytes and ionized gases. The presence of strong magnetic field effect, the conduction mechanism in ionized gases is differing from that in metallic substance. Generally in the ionized gases the electric current carried out by the electrons, which undergo the successive collision with other particles may be charged or neutral particles. In the presence of strong electric field, the conductivity is affected by a magnetic field. In many applications like glass blowing, continuous casting, paper production, hot rolling, drawing in plastic films, wire drawing, polymer extrusion, metal spinning and spinning of fibres are based on MHD laminar boundary layer flow over stretching sheet. During the process of manufacturing a stretched sheet interacts with the fluid thermally and mechanically. Kinematics of stretching and the simultaneous heating or cooling during this kind of process has a decisive influence on the quality of the final product. The sheet is stretched some times in the extrusion of a polymer sheet from a die. Drawing such a sheet in a viscous fluid, the rate of cooling can be controlled and the final product achieved with desired characteristics.

Raptis and Perdikis (2006) studied the viscous flow over a non-linearly stretching sheet in the presence of a chemical reaction and magnetic field. Tan, You, Hang and Liao (2008) investigate a new branch of the temperature distribution of boundary layer flows over an impermeable stretching plate. Abel and Mahesha (2008) studied the heat transfer in MHD visco-elastic fluid flow over a stretching sheet with variable thermal conductivity, non-uniform heat source and radiation. Samad and Mohebujjamanr (2009) discussed MHD heat and mass transfer free convection flow along a vertical stretching sheet in presence of magnetic field with heat generation. Heat and mass transfer in MHD visco-elastic fluid flow through a porous medium over a stretching sheet with chemical reaction analyzed by Alharbi, Saleh, Mohamed, Bazid and Mahmoud Gendy (2010). Seddeek and Abdelmeguid (2006) discussed the effects of radiation and thermal diffusivity on heat transfer over a stretching surface with variable heat flux. Ali, Alam, Alam, and Alim (2014) 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 (2012) discussed 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, Nazar and Pop (2009) analyzed boundary layer flow and heat transfer over an unsteady stretching vertical surface. Aldawody, Ebashbeshy (2010) also studied heat transfer over an unsteady stretching surface with variable heat flux in presence of heat source or sink. MHD boundary layer flow and heat transfer is discussed by many researchers like Fadzilah, Nazar, Norihan and Pop (2011), Mohebujjaman, Khalequ and Samad (2010), Elbashbeshy and Bazid (2004), Afify (2009), Mathew, Sudha, Nath, Raveendra and Rama Deva Prasad (2012) etc.

Rashidi (2010) studied the flow using differential transform method and Padé Approximant for solving MHD flow in a laminar liquid film from a horizontal stretching surface. Rashidi and Erfani (2011) again discussed a new analytical study of MHD stagnation–point flow in porous media with heat transfer. Simultaneous effects of partial slip and thermal-diffusion and diffusion-thermo on steady MHD convective flow due to a rotating disk was analyzed by Rashidi, Erfani, Hayat, Mohimanian, PourAwatif and A-Hendi (2011). Seini and Makinde (2013) discussed the MHD Boundary Layer Flow due to Exponential Stretching Surface with Radiation and Chemical Reaction. Kumar and Singh (2012) gives the Mathematical modeling of soret and hall effects on oscillatory MHD free convective flow of radiating fluid in a rotating vertical porous channel filled with porous medium. Grubka and Bobba (1985) discussed the heat transfer characteristics of a continuous stretching surface with variable temperature. Chen (1998) studied the laminar mixed convection adjacent to vertical, continuously stretching sheets. Most of the above researchers were not focused on the inclination of the angle of the sheet, constant heat flux and viscous dissipation.

Therefore the present work give emphasis on the heat and mass transfer MHD flow over an inclined stretching sheet with viscous dissipation and constant heat flux in the presence of magnetic field using similarity solution and homotophy perturbation technique.

II. FORMULATION OF THE PROBLEM

Let the flow considered to be two dimensional laminar MHD viscous incompressible electrically conducting fluid along an inclined stretching sheet. The leading edge of the inclined stretching sheet is along the X direction and Y is normal to the X axis. A magnetic field B_0 is applying normal to the direction of the flow and T_w ($T_w > T_\infty$) is the uniform temperature of the plate, where T_∞ is the temperature of the fluid away from the plate. Let α be the angle of inclination. Let u and v are the velocities along X and Y axis respectively. Using general boundary layer approximation and given assumptions the governing equations under the influence of external imposed magnetic field are given as:

Equation of continuity:

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

Equation of momentum:

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

Equation of energy:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{\nu}{c_p}\left(\frac{\partial u}{\partial y}\right)^2 \qquad ...(3)$$

Equation of concentration:

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

with the boundary conditions

$$\left.\begin{array}{ll} y=0: & u=U_0 x, v=0, \frac{\partial T}{\partial y}=-\frac{q}{k}, C=C_w \\ y\to\infty: & u=0, T=T_\infty, C=C_\infty \end{array}\right\} \qquad ...(5)$$

where T, T_w and T_∞ are the fluid temperature, the stretching sheet temperature and the free stream temperature respectively, C, C_w and C_∞ are corresponding concentration, κ is thermal conductivity, c_p is specific heat with constant pressure, $\alpha=\frac{k}{\rho c_p}$ is thermal diffusivity, μ is viscosity, ν is kinematic viscosity, σ is electrical conductivity, ρ is density, β is thermal expansion coefficient, β^* is concentration expansion coefficient, B_0 is magnetic field intensity, U_0 is stretching sheet parameter, g is acceleration due to gravity, q is constant heat flux per unit area, D_m is coefficient of mass diffusivity, K_T is thermal diffusion ratio, T_m is mean fluid temperature.

Now introducing the stream function $\Psi(x,y)$ such as

$$u=\frac{\partial\Psi}{\partial y} \text{ and } v=-\frac{\partial\Psi}{\partial x} \qquad ...(6)$$

Again introducing following similarity transformation:

$$\Psi=x\sqrt{2\nu U_0}f(\eta), \eta=\sqrt{\frac{U_0}{2\nu}}y, \theta(\eta)=\frac{k(T-T_\infty)}{q}\sqrt{\frac{U_0}{2\nu}}, \varphi(\eta)=\frac{C-C_\infty}{C_w-C_\infty} \qquad ...(7)$$

Using above similarity transformations in equation (2) to equation (4) we get the non dimensional, nonlinear and coupled differential equations as

$$f'''+2ff''-2f'^2-Mf'+Gr\theta\cos\gamma+Gm\varphi\cos\gamma=0 \qquad ...(8)$$

$$\theta''+2Prf\theta'+EcPrf''^2=0 \qquad ...(9)$$

$$\varphi''+2Scf\varphi'+ScS_0\theta''=0 \qquad ...(10)$$

Where f', θ and φ are non-dimensional velocity, temperature and concentration and η is similarity variable. And the Magnetic Parameter is$M=\frac{2\sigma B_0^2}{\rho U_0}$, the Grashof Number is $=\frac{2g\beta q}{xU_0^2}\sqrt{\frac{2\nu}{U_0}}$, the Modified Grashof Number $Gm=\frac{2g\beta^*(C_w-C_\infty)}{xU_0^2}$, the Prandtl Number $Pr=\frac{\mu c_p}{k}$, the Eckert Number is $Ec=\frac{kU_0^2x^2}{qc_p}\sqrt{\frac{U_0}{2\nu}}$, the Schmidt Number is $Sc=\frac{\nu}{D_m}$ and Soret Number is $S_0=\frac{D_mK_Tq}{k\mathrm{T_m}(C_w-C_\infty)}\sqrt{\frac{2}{\nu U_0}}$. And the transformed boundary conditions are

$$\left.\begin{array}{ll}\eta=0: & f'(\eta)=1,f(\eta)=0,\theta'(\eta)=-1,\varphi(\eta)=1\\ \eta\to\infty: & f'(\eta)=0,\theta(\eta)=0,\varphi(\eta)=0\end{array}\right\} \quad ...(11)$$

The homotopy for the above equations defined as

$$H(f,p)=(1-p)[f'''-Mf'-(3-\eta)e^{-\eta}+M(1-\eta)e^{-\eta}]+p[f'''+2ff''-2f'^2-Mf'+Gr\theta\cos\gamma+Gm\varphi\cos\gamma]=0 \quad ...(12)$$

$$H(\theta,p)=(1-p)[\theta''-e^{-\eta}]+p[\theta''+2Prf\theta'+EcPrf''^2]=0 \quad ...(13)$$

$$H(\varphi,p)=(1-p)[\varphi''-e^{-\eta}]+p[\varphi''+2Scf\varphi'+ScS_0\theta'']=0 \quad ...(14)$$

It is considered that

$$\left.\begin{array}{l}f=f_0+pf_1+p^2f_2+\cdots\\ \theta=\theta_0+p\theta_1+p^2\theta_2+\cdots\\ \varphi=\varphi_0+p\varphi_1+p^2\varphi_2+\cdots\end{array}\right\} \quad ...(15)$$

Substituting these assumptions in equation (12) to equation (14) and comparing the coefficients of like powers of p, we get

$$p^0: f_0'''-Mf_0'-[(3-\eta)-M(1-\eta)]e^{-\eta}=0 \quad ...(16)$$

$$p^1: f_1'''-Mf_1'+[(3-\eta)-M(1-\eta)]e^{-\eta}+2f_0f_0''-2f_0'^2+Gr\cos\gamma\,\theta_0+Gm\cos\gamma\,\varphi_0=0 \quad ...(17)$$

$$p^0: \theta_0''-e^{-\eta}=0 \quad ...(18)$$

$$p^1: \theta_1''+e^{-\eta}+2Prf_0\theta_0'+EcPrf_0''^2=0 \quad ...(19)$$

$$p^0: \varphi_0''-e^{-\eta}=0 \quad ...(20)$$

$$p^1: \varphi_0''+e^{-\eta}+2Scf_0\varphi_0'+ScS_0\theta_0''=0 \quad ...(21)$$

And the corresponding boundary conditions are

$$\left.\begin{array}{ll}\eta=0 & \left\{\begin{array}{l}f_0=0,f_1=0,\ldots\\ f_0'=1,f_1'=0,\ldots\\ \theta_0'=-1,\theta_1'=0,\ldots\\ \varphi_0=1,\varphi_1=0,\ldots\end{array}\right.\\ \eta\to\infty & \left\{\begin{array}{l}f_0'=0,f_1'=0,\ldots\\ \theta_0=0,\theta_1=0,\ldots\\ \varphi_0=0,\varphi_1=0,\ldots\end{array}\right.\end{array}\right\} \quad ...(22)$$

Solution of above equations (16) to (21) under the boundary conditions (22) are obtained as follows:

$$f_0=\eta e^{-\eta} \quad ...(23)$$

$$f_1=\frac{1}{\sqrt{M}}\left(\frac{M-2}{M-4}\right)\left(1-e^{-\sqrt{M}\eta}\right)+\frac{1}{\sqrt{M}}\left(\frac{Gr+Gm}{1-M}\right)\left(1-e^{-\sqrt{M}\eta}\right)\cos\gamma+\frac{1}{M-4}(e^{-2\eta}-1)+\left(\frac{Gr+Gm}{1-M}\right)(e^{-\eta}-1)\cos\gamma-\eta e^{-\eta} \quad ...(24)$$

$$\theta_0=e^{-\eta} \quad ...(25)$$

$$\theta_1=\frac{1}{2}Pr(\eta+1)e^{-2\eta}-\frac{1}{8}EcPr(2\eta^2-4\eta+3)e^{-2\eta}-e^{-\eta}+\left(\frac{1}{2}Pr-\frac{1}{8}EcPr-1\right)\eta \quad ...(26)$$

$$\varphi_0=e^{-\eta} \quad ...(27)$$

$$\varphi_1=\frac{1}{2}Sc(\eta+1)e^{-2\eta}-ScS_0e^{-\eta}-e^{-\eta}+1-\frac{1}{2}Sc+ScS_0 \quad ...(28)$$

The values of f, θ and φ are obtained as

$$f = lim_{p\to 1} f = f_0 + f_1 + f_2 + \cdots$$

$$\theta = lim_{p\to 1} \theta = \theta_0 + \theta_1 + \theta_2 + \cdots$$

$$\varphi = lim_{p\to 1} \varphi = \varphi_0 + \varphi_1 + \varphi_2 + \cdots$$

Therefore we obtained

$$f = \frac{1}{\sqrt{M}}\left(\frac{M-2}{M-4}\right)\left(1-e^{-\sqrt{M}\eta}\right) + \frac{1}{\sqrt{M}}\left(\frac{Gr+Gm}{1-M}\right)\left(1-e^{-\sqrt{M}\eta}\right)\cos\gamma + \frac{1}{M-4}\left(e^{-2\eta}-1\right) + \left(\frac{Gr+Gm}{1-M}\right)\left(e^{-\eta}-1\right)\cos\gamma \quad ...(29)$$

$$\theta = \frac{1}{2}Pr(\eta+1)e^{-2\eta} - \frac{1}{8}EcPr(2\eta^2 - 4\eta + 3)e^{-2\eta} + \left(\frac{1}{2}Pr - \frac{1}{8}EcPr - 1\right)\eta \quad ...(30)$$

$$\varphi = \frac{1}{2}Sc(\eta+1)e^{-2\eta} - ScS_0e^{-\eta} + 1 - \frac{1}{2}Sc + ScS_0 \quad ...(31)$$

Hence the velocities of the flow are given as

$$u = xU_0\left[\left(\frac{M-2}{M-4}\right)e^{-\sqrt{M}\sqrt{\frac{U_0}{2\nu}}y} + \left(\frac{Gr+Gm}{1-M}\right)e^{-\sqrt{M}\sqrt{\frac{U_0}{2\nu}}y} - \frac{2e^{-2\sqrt{\frac{U_0}{2\nu}}y}}{M-4}\cos\gamma - \left(\frac{Gr+Gm}{1-M}\right)e^{-\sqrt{\frac{U_0}{2\nu}}y}\cos\gamma\right] \quad ...(32)$$

$$v = -\sqrt{2\nu U_0}\left[\frac{1}{\sqrt{M}}\left(\frac{M-2}{M-4}\right)\left(1-e^{-\sqrt{M}\sqrt{\frac{U_0}{2\nu}}y}\right) + \frac{1}{\sqrt{M}}\left(\frac{Gr+Gm}{1-M}\right)\left(1-e^{-\sqrt{M}\sqrt{\frac{U_0}{2\nu}}y}\right)\cos\gamma + \frac{1}{M-4}\left(e^{-2\sqrt{\frac{U_0}{2\nu}}y}-1\right) + \left(\frac{Gr+Gm}{1-M}\right)\left(e^{-\sqrt{\frac{U_0}{2\nu}}y}-1\right)\cos\gamma\right] \quad ...(33)$$

The temperature is given as

$$T = \frac{q}{k}\sqrt{\frac{2\nu}{U_0}}\left[\frac{1}{2}Pr\left(\sqrt{\frac{U_0}{2\nu}}+1\right)e^{-2\sqrt{\frac{U_0}{2\nu}}} - \frac{1}{8}EcPr\left(2\frac{U_0}{2\nu}^2 - 4\sqrt{\frac{U_0}{2\nu}} + 3\right)e^{-2\sqrt{\frac{U_0}{2\nu}}} + \left(\frac{1}{2}Pr - \frac{1}{8}EcPr - 1\right)\sqrt{\frac{U_0}{2\nu}}\right] + T_\infty \quad ...(34)$$

The concentration of the flow is given as

$$C = (C_w - C_\infty)\left[\frac{1}{2}Sc\left(\sqrt{\frac{U_0}{2\nu}}+1\right)e^{-2\sqrt{\frac{U_0}{2\nu}}} - ScS_0e^{-\sqrt{\frac{U_0}{2\nu}}} + 1 - \frac{1}{2}Sc + ScS_0\right] + C_\infty \quad ...(35)$$

The important physical quantities are skin friction C_f and local Sherwood number S_h are defined as

$$C_f \propto f''(0)$$

$$C_f \propto -\sqrt{M}\left(\frac{M-2}{M-4}\right) + \frac{4}{M-4} + (1-\sqrt{M})\left(\frac{Gr+Gm}{1-M}\right)\cos\gamma \quad ...(36)$$

$$S_h \propto -\theta'(0)$$

$$S_h \propto 1 - \frac{9}{8}EcPr \quad ...(37)$$

III. RESULTS AND DISCUSSIONS

M	Gr	Gm	$-f''(0)$
0	-0.2	-0.2	1.3107
2	-0.2	-0.2	1.9137
2	-0.3	-0.2	2.1609
2	-0.2	-0.3	2.1609
3	-0.2	-0.2	2.3817
5	-0.2	-0.2	2.5823
10	-0.2	-0.2	3.4142

Table 1 : Skin friction coefficient $f''(0)$ for different values of M, Gr and Gm with $\gamma = 81^0$

Ec	Pr	$-\theta'(0)$
0.5	0.71	-0.6213
0.5	1	-0.8750
1	0.71	-0.8875

Table 2 : Rate of heat transfer (Nusselt Number) $-\theta'(0)$ for different values of Ec and Pr

Sc	So	$-\varphi'(0)$
0.2	0.2	0.5531
0.22	0.2	0.5543
0.2	0.3	0.5446

Table 3 : Rate of Mass Transfer (Sherwood Number) $-\varphi'(0)$ for different values of Sc and So

By Shooting Method		By Homotophy Perturbation Method	
$-f''(0)$	$-\varphi'(0)$	$-f''(0)$	$-\varphi'(0)$
1.912023 (M=2)	0.554767 (Sc=0.2,So=0.2)	1.9137 (M=2)	0.5531 (Sc=0.2,So=0.2)
2.57678 (M=5)	0.543557 (Sc=0.22,So=0.2)	2.5823 (M=5)	0.5543 (Sc=0.22,So=0.2)
3.422358 (M=10)		3.4142 (M=10)	

Table 4 : Comparison of Skin Friction Coefficient and Local Sherwood number for different Values of M, Sc and So

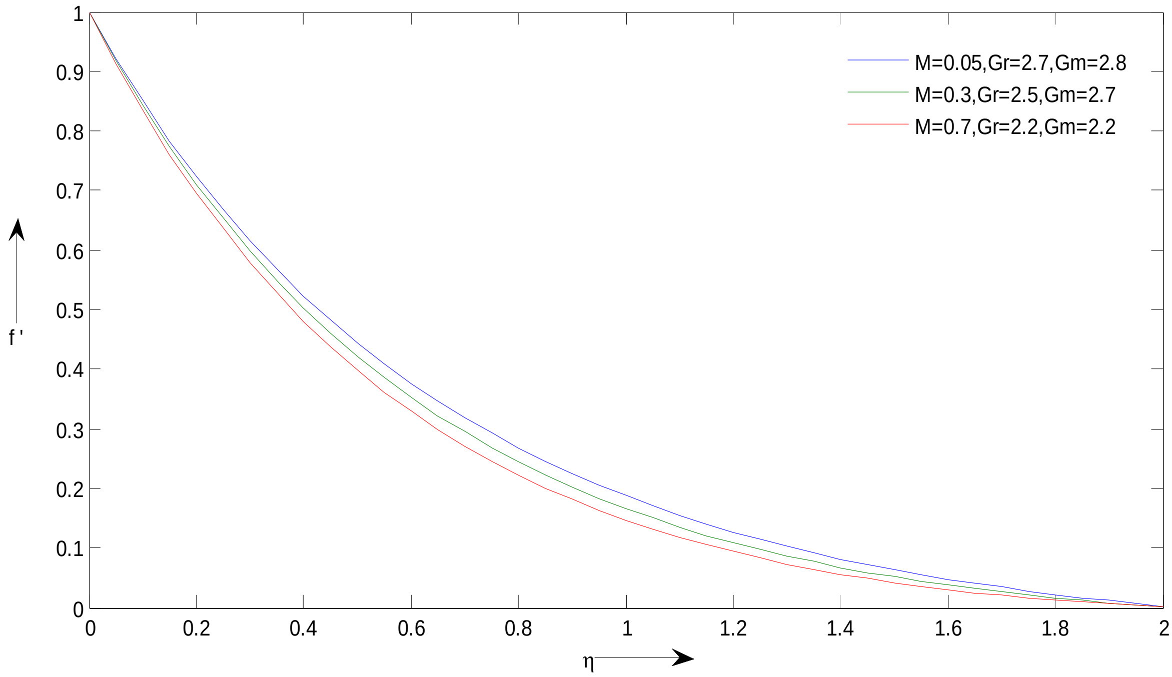

Figure 1 : Velocity f' distribution versus η for different values of M, Gr and Gm

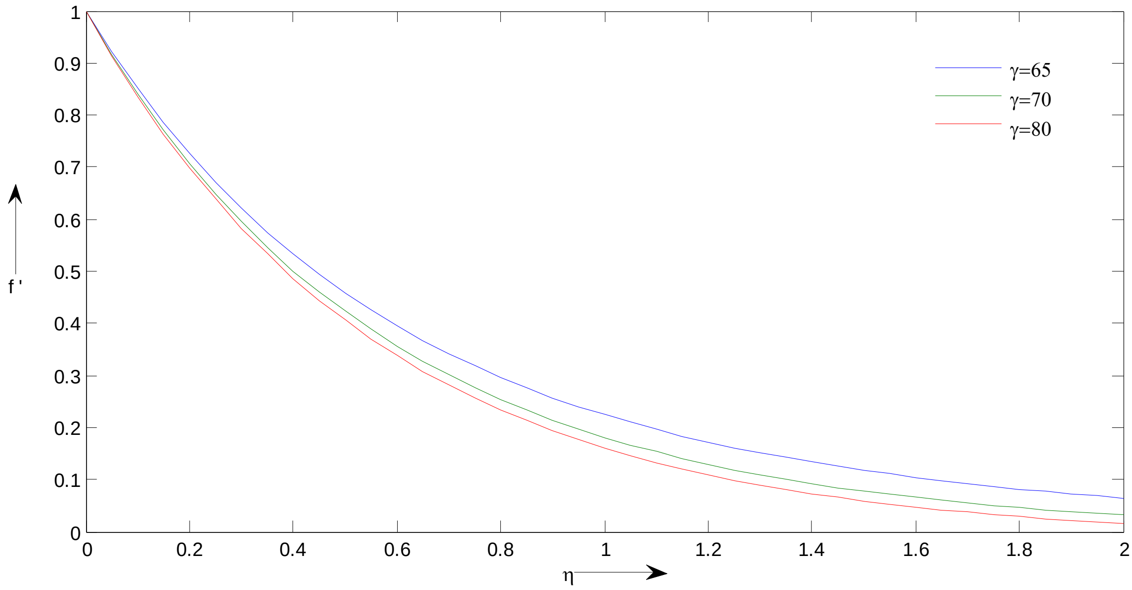

Figure 2 : Velocity f' distribution versus η for different values of γ the angle of inclination

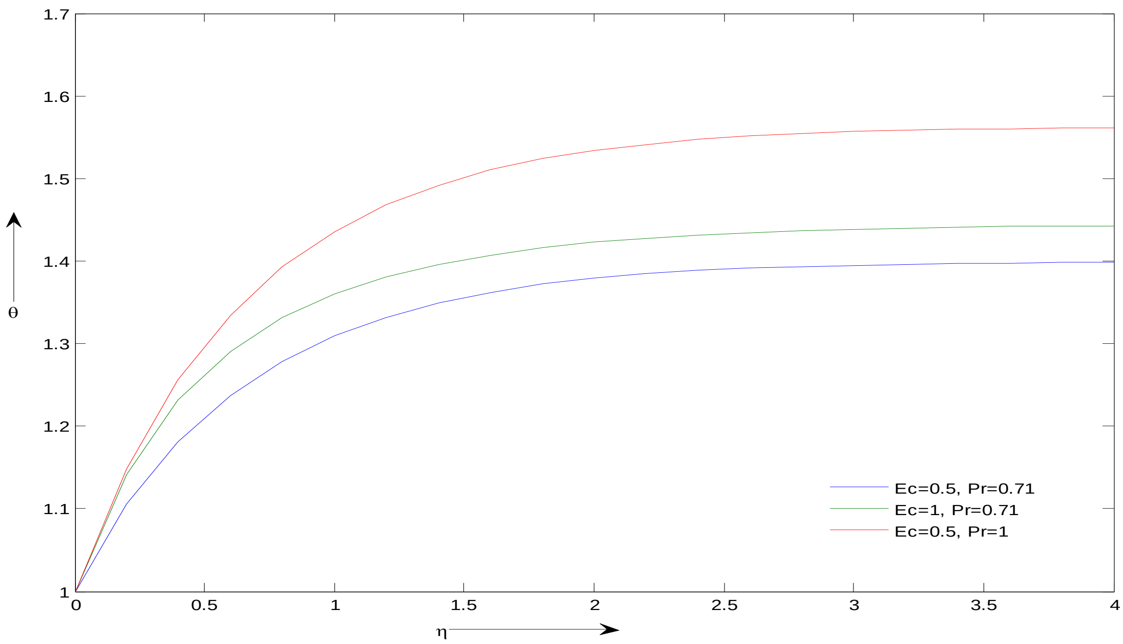

Figure 3 : Temperature θ profile against η for different values of Ec and Pr

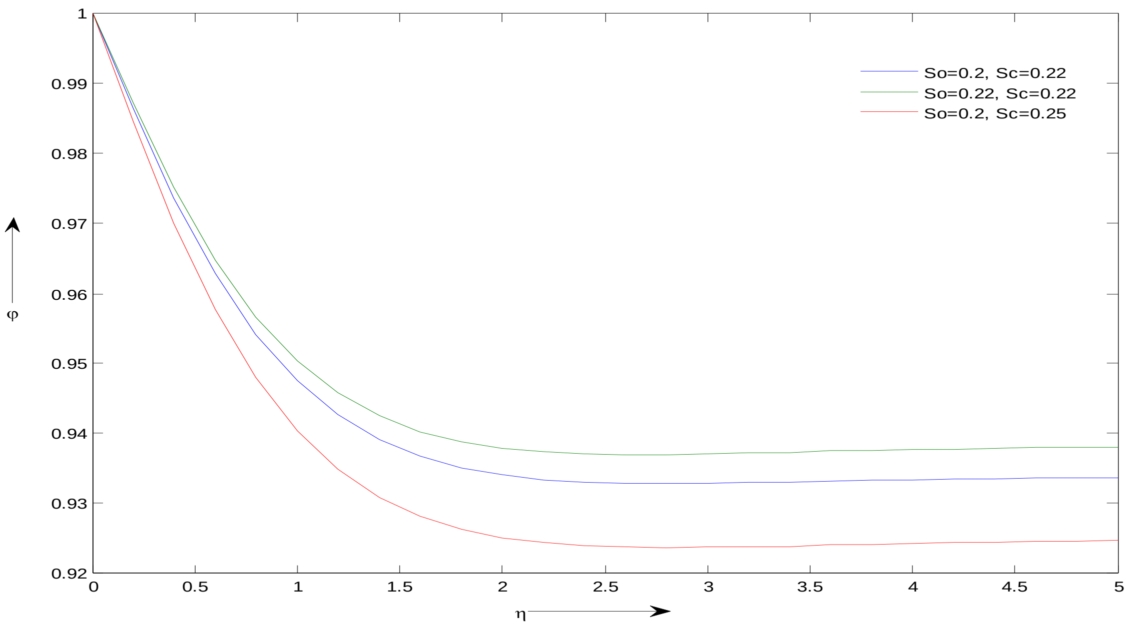

Figure 4 : Concentration φ profile against η for different values of Sc and So

Numerical observation for Skin Friction coefficient, Nusselt Number and Local Sherwood Number for different values of non-dimensional parameters are carried out. It is observed from Table 1 that coefficient of skin friction increases due to increase of magnetic parameter. Table 2 shows the effect of Prandtl number and Eckert Number on the rate of heat transfer. It is observed that Nusselt Number decreases due to increase of Prandtl number and Eckert Number. It is shown in the Table 3 that Local Sherwood Number increase due to increase of Schmidt Number. Table 4 shows the comparison between Shooting Method and Homotophy Perturbation Technique. It is observed from the table that result obtained by Schooting Method and HPM are in good agreement.

The observations and calculations for the velocity distribution, temperature and concentration profiles across the boundary layer for various values of parameters are carried out. Figure 1 displays the effect of Magnetic Parameter M, Grashof Number Gr and modified Grashof Number Gm on the velocity. It is observed that the velocity decreases due to increase in magnetic parameter and decreases due to decrease of Grashof Number. From the Figure 2 it is observed that velocity increases due to increase in angle of inclination.

Figure 3 shows the effect of Eckert Number and Prandtl Number on temperature. It is found that the temperature increase due to increase of Eckert Number and Prandtl number both. Figure 4 displays the concentration profile obtains by the variation in non-dimensional parameters. It is observed that in certain interval of η, the concentration profile decreased and then increased due to increase of Schmidt Number and Soret Number.

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