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Steady MHD Three Dimensional Flow of Jeffrey Fluid over an Exponentially Stretching Sheet with Slip Conditions

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Abstract: MHD three dimensional flow of Jeffrey fluid over an exponentially stretching surface with slip conditions are examined. The similarity transformations are used to convert the governing equations into a set of nonlinear ordinary differential equations and are solved numerically using fourth order Runge-Kutta method along with shooting technique. The effects of Jeffrey parameter, Hartmann number, temperature exponent, concentration exponent, heat source/sink, chemical reaction, Soret, Dufour and slip factors on velocity, temperature and concentration are shown graphically. The skin friction coefficient and the Nusselt number are examined numerically.
Key words: MHD, Jeffrey parameter, three dimensional flow, slip factors

I. INTRODUCTION

The MHD Boundary layer flow over a stretching sheet has gained considerable attention because of its applications in industry and manufacturing process such as MHD power generators, petroleum industries, plasma studies, geothermal energy extraction, the boundary layer control in the field of aerodynamics etc. The study of non Newtonian fluids is increasing substantially in the recent years. Many materials in nature like tomato paste, apple sauce, sugar solution, mud, emulsion, melts, shampoos, soaps, personal care products, blood at low shear rate, chyme etc., do not obey Newton’s law of viscosity. Such materials come under the category of non-Newtonian fluids. Hayat et al. [1] developed MHD three dimensional flow of Jeffrey fluid with Newtonian heating. Shafie et al. [2] discussed effects of soret and dufour on unsteady MHD flow by mixed convection over a vertical surface in porous media with internal heat generation, chemical reaction and hall current. Ahmad et al. [3] investigated mixed convection Jeffrey fluid flow over an exponentially stretching sheet with magneto hydrodynamic effect. Hayat et al. [4] discussed impacts of constructive and destructive chemical reactions in magneto hydrodynamic flow of Jeffrey liquid due to nonlinear radially stretched surface.Hayat et al. [5] studied unsteady MHD flow over an exponentially stretching sheet with slip conditions. Hayat et al. [6] investigated soret and dufour effects in three dimensional flow over an exponentially stretching surface with porous medium, chemical reaction and heat source/sink. Hayat et al. [7] discovered thermally stratified point flow of Casson fluid with slip conditions. Hayat et al. [8] developed MHD flow of Jeffrey fluid due to nonlinear radially stretched sheet in presence of Newtonian heating. Bhattacharyya et al. [9] reported slip effects on diffusion of chemically reactive species in boundary layer flow due to a vertical stretching sheet with suction or blowing. Shehzad et al. [10] developed soret and dufour effects on the stagnation point flow of Jeffrey fluid with convective boundary conditions. Makinde [11] studied computational modelling of MHD unsteady flow and heat transfer towards a flat plate with Navier slip and Newtonian heating. Satya Narayana et al. [12] developed numerical study of MHD heat and mass transfer of a Jeffrey fluid over a stretching sheet with chemical reaction and thermal radiation. Kalidas Das et al. [13] investigated radiative flow of MHD Jeffrey fluid past a stretching sheet with surface slip and melting heat transfer. Liu et al. [14] discovered flow and heat transfer for three dimensional flow over an exponentially stretching sheet. Magyari et al. [15] studied heat and mass transfer in the boundary layers on an exponentially stretching continuous surface. Hayat et al. [16] discussed radiative hydrodynamic flow of Jeffrey nanofluid by an exponentially stretching sheet. Hayat et al. [17] reported MHD three dimensional flow by an exponentially stretching surface with convective boundary condition. MHD stagnation point flow of Jeffrey fluid by a radially stretching surface with viscous dissipation and Joule heating was developed by Hayat et al. [18].Swatimukhopadyay[19] investigated slip effects on MHD boundary layer flow over an exponentially stretching sheet with suction/blowing and thermal radiation. Soret and Dufour effects on MHD radiative heat and mass transfer flow of a Jeffrey fluid over a stretching sheet and Joule heating effects on MHD mixed convection of a Jeffrey fluid over a stretching surface with power law heat flux were discussed by Satyanarayana et al. [20,21]. Gireesha et al. [22] studied influence of nonlinear thermal radiation and viscous dissipation on three dimensional flow of Jeffrey nanofluid over a stretching sheet in the presence of Joule heating. Gireesha et al. [23] developed combined effect of joule heating and viscous dissipation on MHD three dimensional flow of a Jeffrey nanofluid. Gireesha et al. [24] analyzed nonlinear thermal convection in Jeffrey liquid flow with cross diffusion effects past a stretched surface.

In the present study MHD three dimensional flow of Jeffrey fluid over an exponentially stretching surface with slip conditions is examined. The governing equations are solved numerically using fourth order Runge-Kutta method along with shooting technique. The effects of governing parameters on velocity, temperature and concentration are obtained graphically. The skin friction coefficient and Nusselt number are examined numerically.

II. MATHEMATICAL FORMULATION OF THE PROBLEM

Consider the steady MHD three dimensional flow of an incompressible Jeffrey fluid over an exponentially stretching surface. The sheet is stretched along the xy-plane while fluid is placed along the z-axis. Moreover the constant magnetic field is applied normal to the fluid flow and the induced magnetic field assumed to be negligible. The sheet at z = 0 is stretched in the x- and y-directions with velocities U_w and V_w respectively. The governing boundary layer flow equations are

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

$$u\frac{\partial u}{\partial x}+\upsilon\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\frac{\nu}{1+\lambda_1}\frac{\partial^2 u}{\partial z^2}-\frac{\sigma B_0^2}{\rho}u \quad (2)$$

$$u\frac{\partial \upsilon}{\partial x}+\upsilon\frac{\partial \upsilon}{\partial y}+w\frac{\partial \upsilon}{\partial z}=\frac{\nu}{1+\lambda_1}\frac{\partial^2 \upsilon}{\partial z^2}-\frac{\sigma B_0^2}{\rho}\upsilon \quad (3)$$

$$u\frac{\partial T}{\partial x}+\upsilon\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha_m\frac{\partial^2 T}{\partial z^2}+\frac{Dk_T}{c_s c_p}\frac{\partial^2 C}{\partial z^2}+\frac{Q}{\rho c_p}\left(T-T_\infty\right) \quad (4)$$

$$u\frac{\partial C}{\partial x}+\upsilon\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=D\frac{\partial^2 c}{\partial z^2}+\frac{Dk_T}{T_m}\frac{\partial^2 T}{\partial z^2}-K_1\left(C-C_\infty\right) \quad (5)$$

where u,υ and w are the velocity components corresponding to x-, y- and z- directions respectively. ρ is the fluid density, B_0 is the magnetic field strength, ν is the kinematic viscosity, λ_1 is the Jeffrey parameter, σ is the electrical conductivity of fluid, α_m is the thermal diffusivity, k_T is the thermal diffusion, T_m is the fluid mean temperature, Q is the heat generation/absorption parameter, c_p is the specific heat, c_s is the concentration susceptibility, T is represents the temperature of fluid, D is the diffusion coefficient, C is the concentration, K_1 is the reaction rate, C_∞ is the concentration far away from the surface and T_∞ is the is the temperature far away from the surface.

The associated with boundary conditions of equations (2)-(6) at the wall can be expressed as

$$\left.\begin{array}{l} u=U_w=U_0e^{\frac{x+y}{L}}+\alpha_1\dfrac{\partial u}{\partial z},\upsilon=V_w=V_0e^{\frac{x+y}{L}}+\alpha_2\dfrac{\partial \upsilon}{\partial z} \\ w=0,T=T_w=T_\infty+T_0e^{A\left(\frac{x+y}{2L}\right)}+\alpha_3\dfrac{\partial T}{\partial z},C=C_w=C_\infty+C_0e^{B\left(\frac{x+y}{2L}\right)}+\alpha_4\dfrac{\partial T}{\partial z} \end{array}\right\} at\ z=0 \quad (6a)$$

$$u=0,\upsilon=0,T\to T_\infty,C\to C_\infty\ as\ z\to\infty \quad (6b)$$

where U_w and V_w are the stretching velocities, U_0, T_0, C_0 and V_0 are constants, A and B are the temperature and concentration exponents, T_w is the surface temperature, T_0 is the reference temperature, T_∞ is the ambient temperature, L_1 and L_2 are temperature and concentration slip factors and L is the reference length.

In order to transform equations (2)-(6) to the dimensionless form, the following transforms are applied

$$\left.\begin{aligned} &u=U_0e^{\frac{x+y}{L}}f'(\eta),\ \upsilon=V_0e^{\frac{x+y}{L}}g'(\eta),\ w=-\left(\frac{vU_0}{2L}\right)^{\frac{1}{2}}e^{\frac{x+y}{L}}\left(f+\eta f'+g+\eta g'\right)\\ &\theta(\eta)=\frac{T-T_\infty}{T_0e^{\frac{A(x+y)}{2L}}},\phi(\eta)=\frac{C-C_\infty}{C_0e^{\frac{B(x+y)}{2L}}},\ \eta=\left(\frac{U_0}{2vL}\right)^{\frac{1}{2}}e^{\frac{x+y}{2L}}z\end{aligned}\right\}\quad(7)$$

where η is the similarity variable. Substituting equation (7) in (2)-(6), equation (1) is satisfied automatically and equations (2)-(6) are reduced to the following nonlinear ordinary differential equations

$$\frac{f'''}{1+\lambda_1}-2\left(f'+g'\right)f'+\left(f+g\right)f''-M^2f'=0\ (8)$$

$$\frac{g'''}{1+\lambda_1}-2\left(f'+g'\right)g'+\left(f+g\right)g''-M^2g'=0\ (9)$$

$$\theta''+\Pr\left[\left(f+g\right)\theta'-A\left(f'+g'\right)\theta+S\theta+Df\phi''\right]=0\ (10)$$

$$\phi''+Sc\left[\left(f+g\right)\phi'-B\left(f'+g'\right)\phi-\gamma\phi+Sr\theta''\right]=0\ (11)$$

The transformed boundary conditions can be written as

$$\left.\begin{aligned}&f(0)=0,\ f'(0)=1+\gamma_1f''(0),g(0)=0,g'(0)=\beta+\gamma_2g''(0),\theta(0)=1+\gamma_3\theta'(0),\phi(0)=1+\gamma_4\phi'(0)\\ &f'(\infty)\to0,g'(\infty)\to0,\theta(\infty)\to0,\phi(\infty)\to0\end{aligned}\right\}(12)$$

where prime denotes the differentiation with respect to the similarity variable η, $M=\frac{2\sigma B_0^2L}{\rho U_w}$ is the Hartmann number, $Sc=\frac{v}{D}$ is the Schmidt number, $\gamma=\frac{2K_1L}{U_w}$ is the chemical reaction parameters, $Df=\frac{Dk_T\left(C_w-C_\infty\right)}{c_sc_p\left(T_w-T_\infty\right)v}$ is the Dufour parameter, $Sr=\frac{Dk_T\left(T_w-T_\infty\right)}{T_m\left(C_w-C_\infty\right)v}$ is the Soret number, $S=\frac{2QL}{U_w\rho c_p}$ is the heat source/sink parameter, A and B are the temperature and concentration exponent $\Pr=\frac{v}{\alpha_m}$ is the Prandtl number, $\beta=\frac{V_0}{U_0}$ is the ratio parameter, $\gamma_1=\alpha_1\left(\frac{U_0e^X}{vL}\right)^{1/2}$ and $\gamma_2=\alpha_2\left(\frac{U_0e^X}{vL}\right)^{1/2}$ are the velocity slip parameters, $\gamma_3=\alpha_3\left(\frac{U_0e^X}{vL}\right)^{1/2}$ and $\gamma_4=\alpha_4\left(\frac{U_0e^X}{vL}\right)^{1/2}$ are the temperature slip parameter and the concentration slip parameter and λ_1 is the Jeffrey parameter.

The physical quantities of interest are the skin friction coefficients along the x - and y -directions are given by

$$C_{fx}=\frac{\frac{\mu}{1+\lambda_1}\left(\frac{\partial u}{\partial z}\right)_{z=0}}{\frac{1}{2}\rho U_w^2}\quad\text{and}\quad C_{fy}=\frac{\frac{\mu}{1+\lambda_1}\left(\frac{\partial\upsilon}{\partial z}\right)_{z=0}}{\frac{1}{2}\rho U_w^2}\quad(13)$$

the skin friction coefficients in dimensionless form are

$$C_{fx} = \left(\frac{\mathrm{Re}_{xy}}{2}\right)^{-1/2} e^{\frac{3(x+y)}{2L}} \frac{f''(0)}{1+\lambda_1} \text{ and } C_{fy} = \left(\frac{\mathrm{Re}_{xy}}{2}\right)^{-1/2} e^{\frac{3(x+y)}{2L}} \frac{g''(0)}{1+\lambda_1} \quad (14)$$

The local Nusselt number Nu_x and local Sherwood number Sh_x are defined as

$$Nu_x = -\frac{x}{T_w - T_\infty} \frac{\partial T}{\partial z}\bigg|_{z=0} = -\frac{x}{L}\left(\frac{\mathrm{Re}_{xy}}{2}\right)^{1/2} e^{\frac{(x+y)}{2L}} \theta'(0) \quad (15)$$

$$Sh_x = -\frac{x}{C_w - C_\infty} \frac{\partial C}{\partial z}\bigg|_{z=0} = -\frac{x}{L}\left(\frac{\mathrm{Re}_{xy}}{2}\right)^{1/2} e^{\frac{(x+y)}{2L}} \phi'(0) \quad (16)$$

where Re_{xy} is the Reynolds number defined by $\mathrm{Re}_{xy} = \frac{U_w L}{v}$.

III. RESULTS AND DISUCSSIONS

The present chapter deals with MHD three dimensional flow of Jeffrey fluid over an exponentially stretching surface with slip conditions. The effects of pertinent governing parameters such as Jeffrey parameter λ_1, Hartmann number M , heat source/sink S , chemical reaction γ , Soret Sr , ratio parameter β , Dufour Df , velocity slip factors γ_1 and γ_2 ,temperature exponent A , concentration exponent B ,temperature slip factor γ_3 and concentration slip factor γ_4 on flow velocity, temperature and concentration are depicted graphically.

The variation of Hartmann number M on velocity profiles $f'(\eta)$, $g'(\eta)$ are shown in Figure 1. It is observed that the velocity and the momentum boundary layer thickness reduce for enhancing Hartmann number. Hartmann number depends on Lorentz force and Lorentz force is an agent which resists the flow. When we increase the Hartmann number then Lorentz force increases which leads to a decrease in velocity of the fluid. Figure 2 depicts the influence of Jeffrey parameter λ_1 on velocity profiles $f'(\eta)$, $g'(\eta)$. We have seen that the velocity and the momentum boundary layer thickness decays with increasing λ_1. Figure 3 illustrates the behaviour of ration parameter β on the velocity components $f'(\eta)$, $g'(\eta)$. We observed that the velocity $f'(\eta)$ and the momentum boundary layer thickness reduce for higher values of β. It is noticed that an increment in β measures the stretching velocity in the y - direction has higher impact that the reference velocity in the x -direction and the opposite behaviour in the velocity $g'(\eta)$.The effect of velocity slip parameter γ_1 on velocity profiles $f'(\eta)$, $g'(\eta)$ are shown in Figure 4. We have seen that the velocity $f'(\eta)$ and the momentum boundary layer thickness reduce with increasing γ_1. In fact that the higher values of γ_1 the stretching velocity is partially transferred to the fluid and the opposite nature in the another velocity $g'(\eta)$.The impact of velocity slip parameter γ_2 on velocity profiles $f'(\eta)$, $g'(\eta)$ are demonstrated in Figure 5. The velocity $g'(\eta)$ and thickness of the boundary layer are decreased with increasing values of γ_2 and the opposite behaviour on another velocity $f'(\eta)$.

Figure 6 illustrates the ratio parameter β on temperature $\theta(\eta)$. We have seen that the temperature $\theta(\eta)$ and the thermal boundary layer thickness are reduces with increasing values of ratio parameter β. The impact of Prandtl number $\Pr$ on temperature $\theta(\eta)$ is displayed in Figure 7. We noticed that temperature $\theta(\eta)$ increases with increasing values of $\Pr$. This causes when $\Pr$ increases then the thermal diffusivity decreases further thickness of the thermal boundary layer decrease. Influence of heat source/sink S parameter on temperature $\theta(\eta)$ is shown in Figure 8. Here $S > 0$ is for heat source and $S < 0$ for heat sink. We observed that the temperature and thermal boundary layer thickness enhanced in the case of heat source when compare it with heat sink. The variation of Dufour effect Df on temperature distribution is displayed in Figure 9. It reveals that the temperature and thermal boundary layer enhanced with increasing Df . Figures 10 and 11 elucidate that an increase in temperature exponent A and temperature slip factor γ_3 on temperature distribution $\theta(\eta)$. We have seen that the temperature and thermal boundary layer are reduces for higher values of A and temperature slip factor γ_3.

The effects of Schmidt number Sc , Chemical reaction parameter γ , concentration exponent B and concentration slip factor γ_4 on concentration $\phi(\eta)$ are shown in Figures 12-15. From Figure 12 we have seen that the concentration and concentration boundary layer thickness reduces with increasing Schmidt number. In fact Schmidt number is inversely proportional to the diffusion coefficient. Hence an increase in Schmidt number corresponds to smaller diffusion coefficient. The concentration and concentration boundary layer thickness are decreases for higher values of chemical reaction parameter, concentration exponent and concentration slip factor are displayed in Figures 13-15. The effect of Soret parameter Sr on concentration $\phi(\eta)$ is shown in Figure 16. It is reveals that the concentration enhances with increasing Soret number.

The numerical values of the skin friction coefficients $-\frac{f''(0)}{1+\lambda_1}$ and $-\frac{g''(0)}{1+\lambda_1}$ are displayed in Table 1. We have seen that the skin friction coefficients are increasing for higher values of velocity ration parameter β. The rate of heat transfer $\theta'(0)$ is shown in table 2. It is decays via increasing in Prandtl number $\Pr$ .Table 1 and Table 2 illustrate the comparison of the present work with existing available results in limiting cases. These tables are confirming have been good agreement with the previous available results.

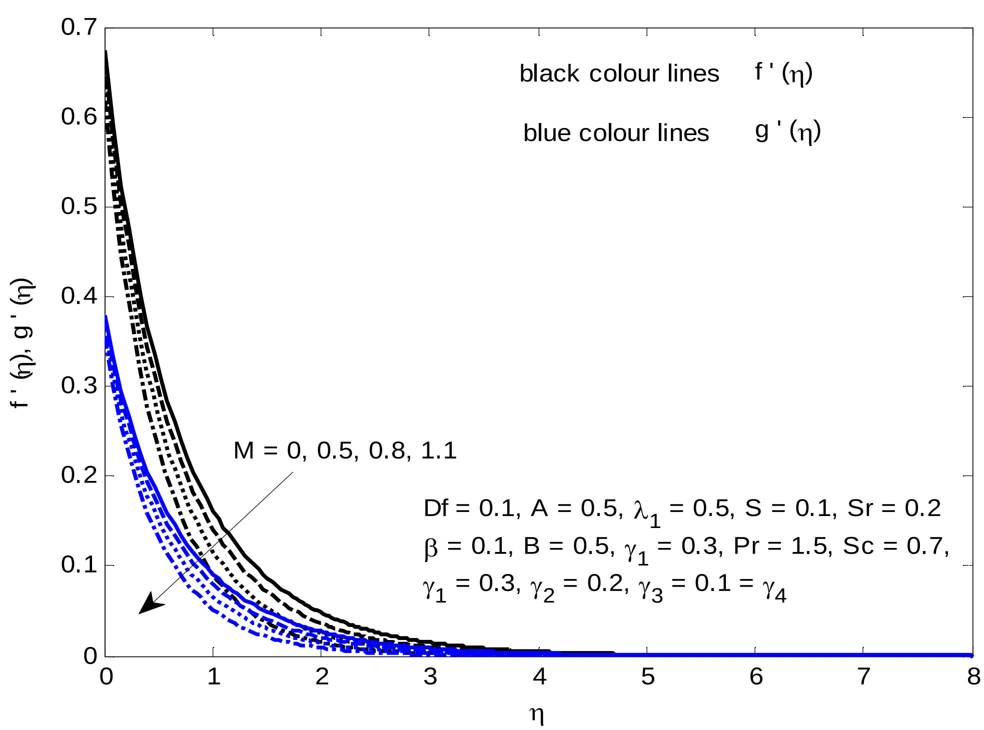

Figure 1. Velocity profiles $f'(\eta)$, $g'(\eta)$ for different values of M

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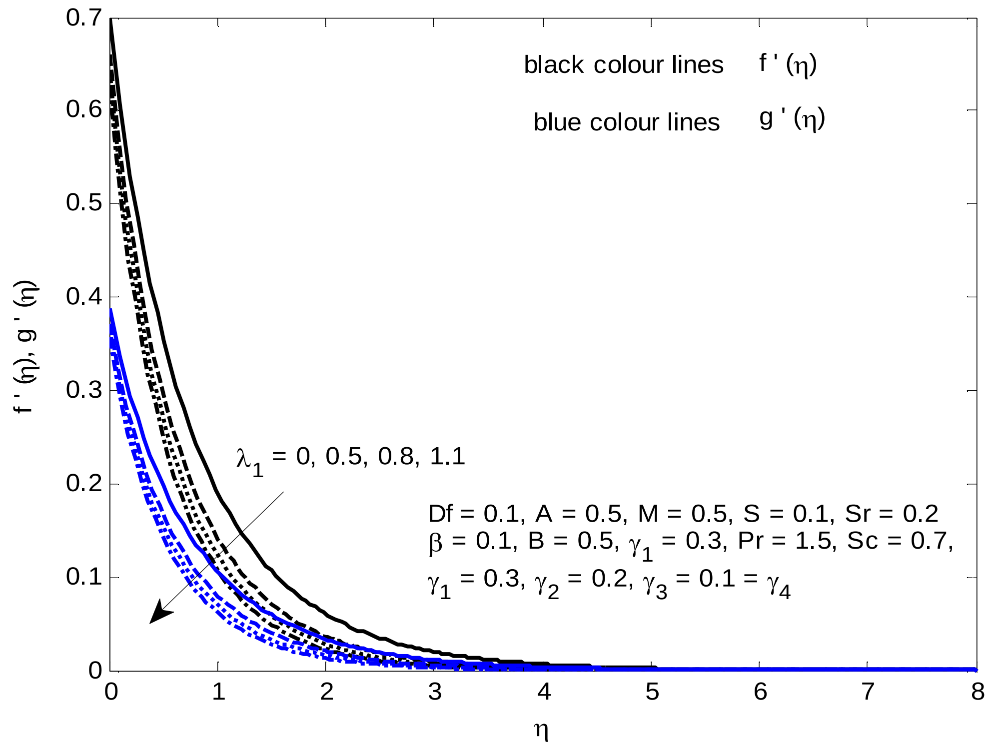

Figure 2. Velocity profiles $f'(\eta)$, $g'(\eta)$ for different values of λ_1

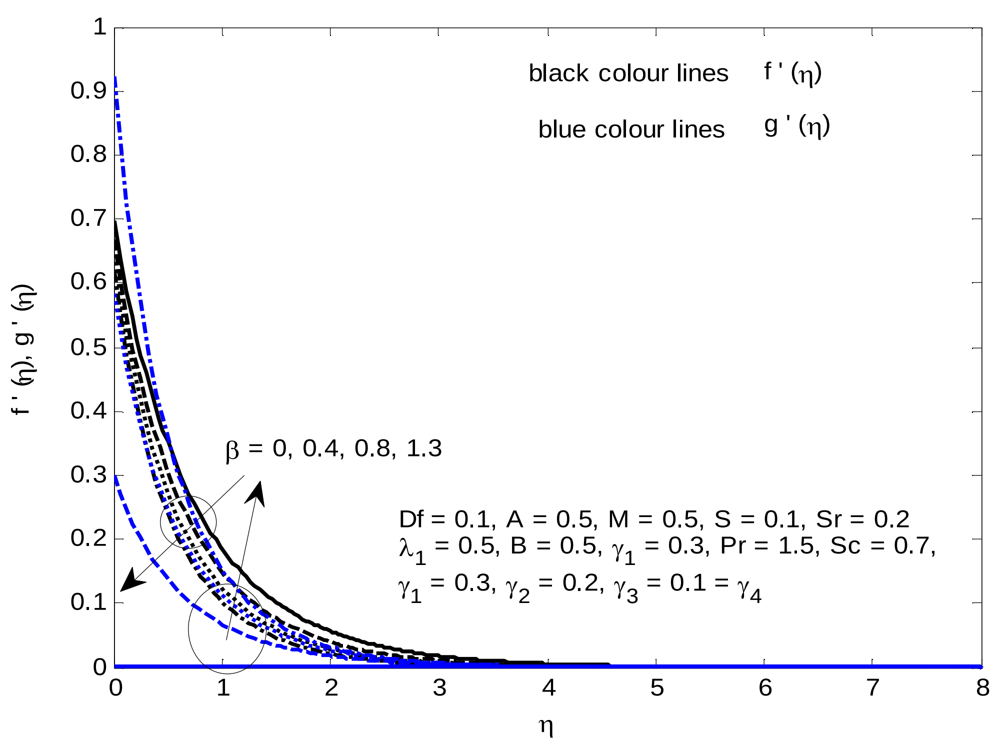

Figure 3. Velocity profiles $f'(\eta)$, $g'(\eta)$ for different values of β

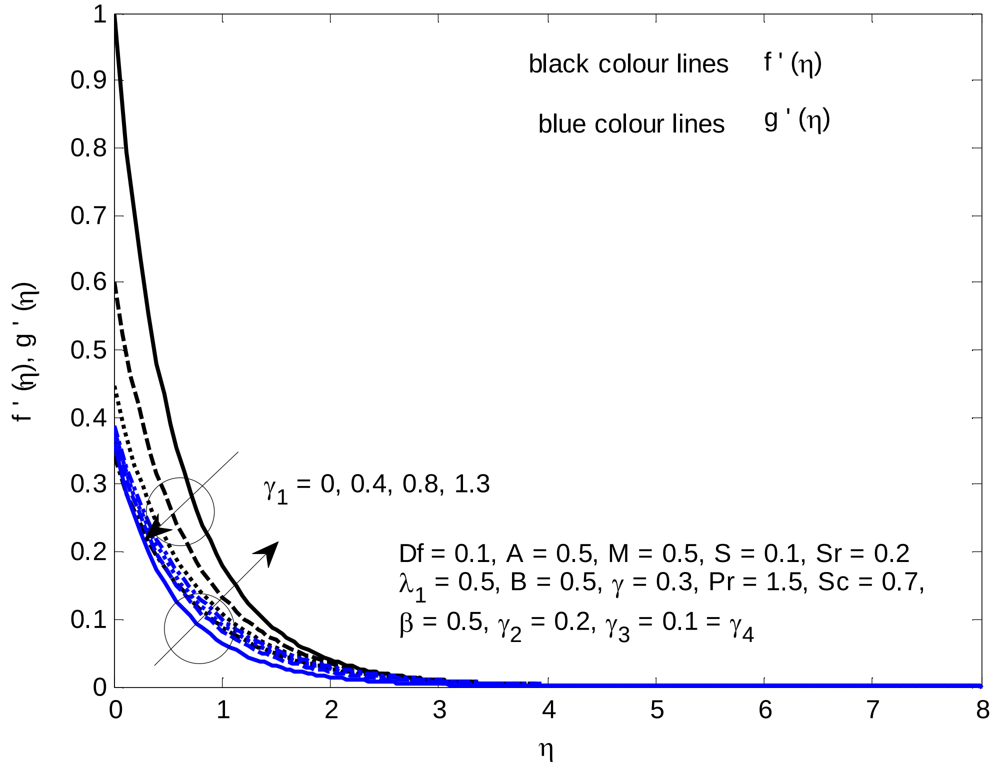

Figure 4. Velocity profiles $f'(\eta),\ g'(\eta)$ for different values of γ_1

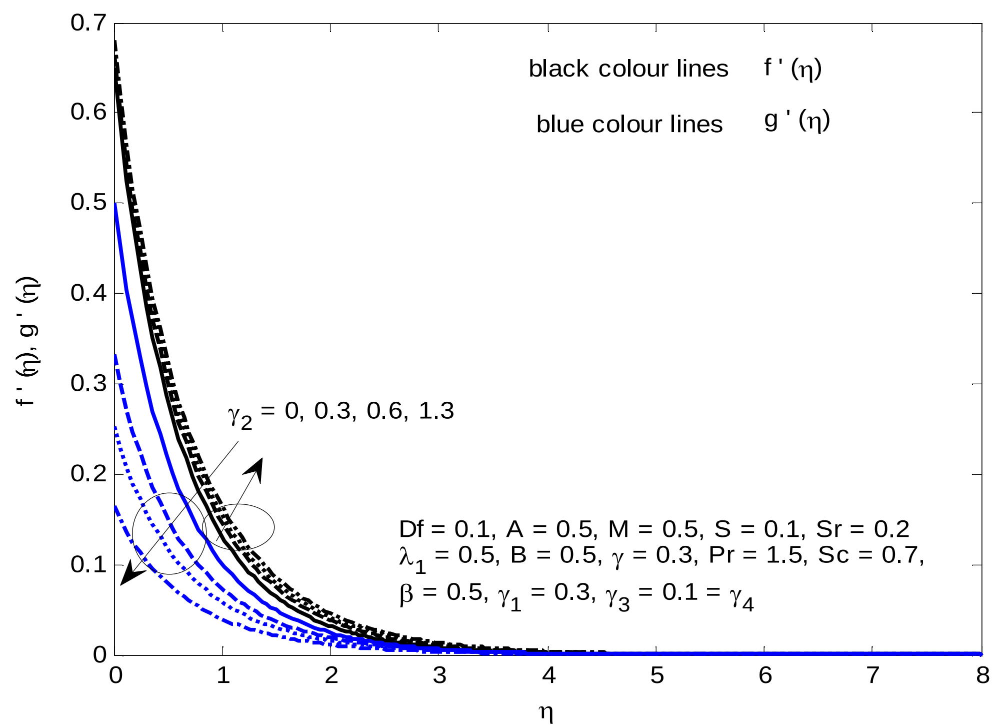

Figure 5. Velocity profiles $f'(\eta),\ g'(\eta)$ for different values of γ_2

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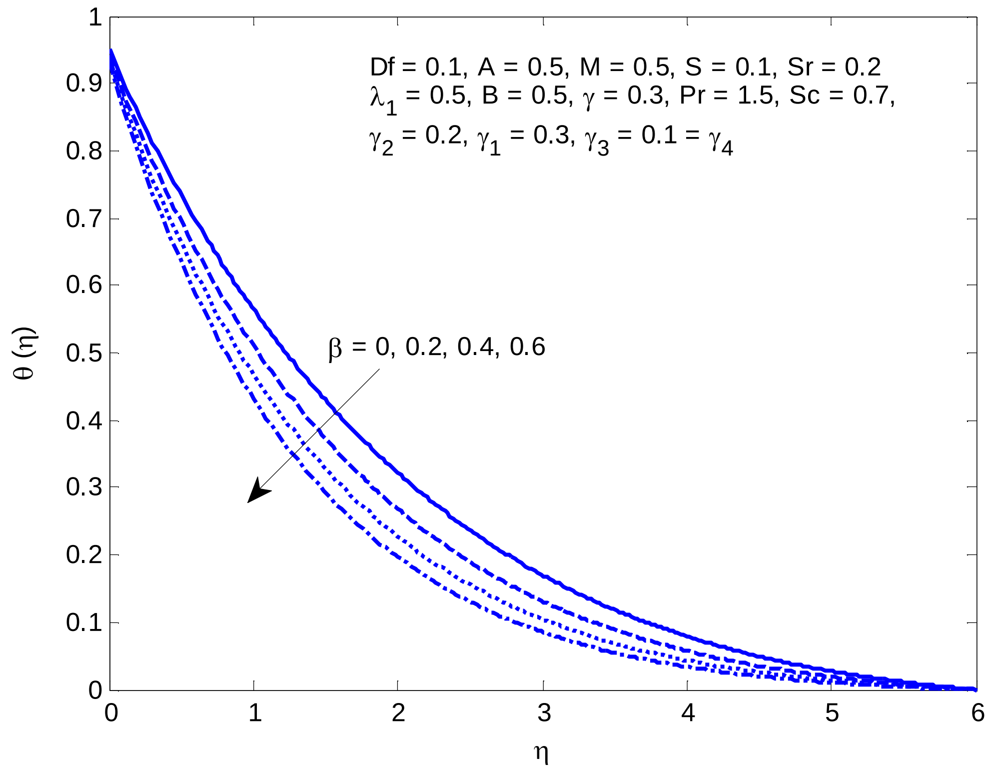

Figure 6. Temperature distribution $\theta(\eta)$ for different values of β

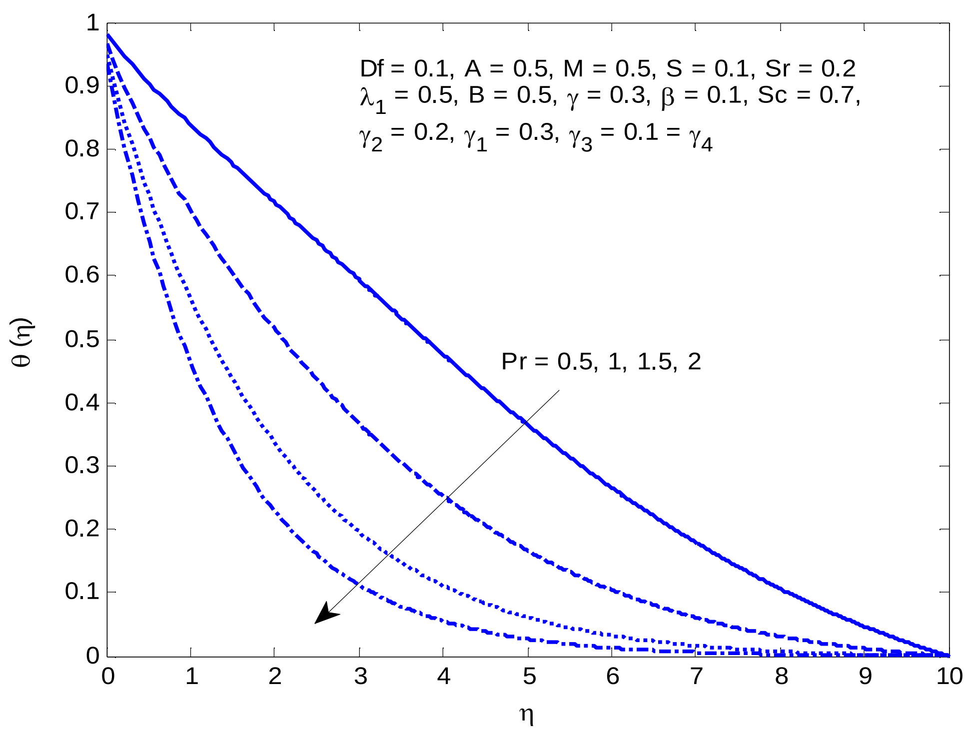

Figure 7. Temperature distribution $\theta(\eta)$ for different values of Pr

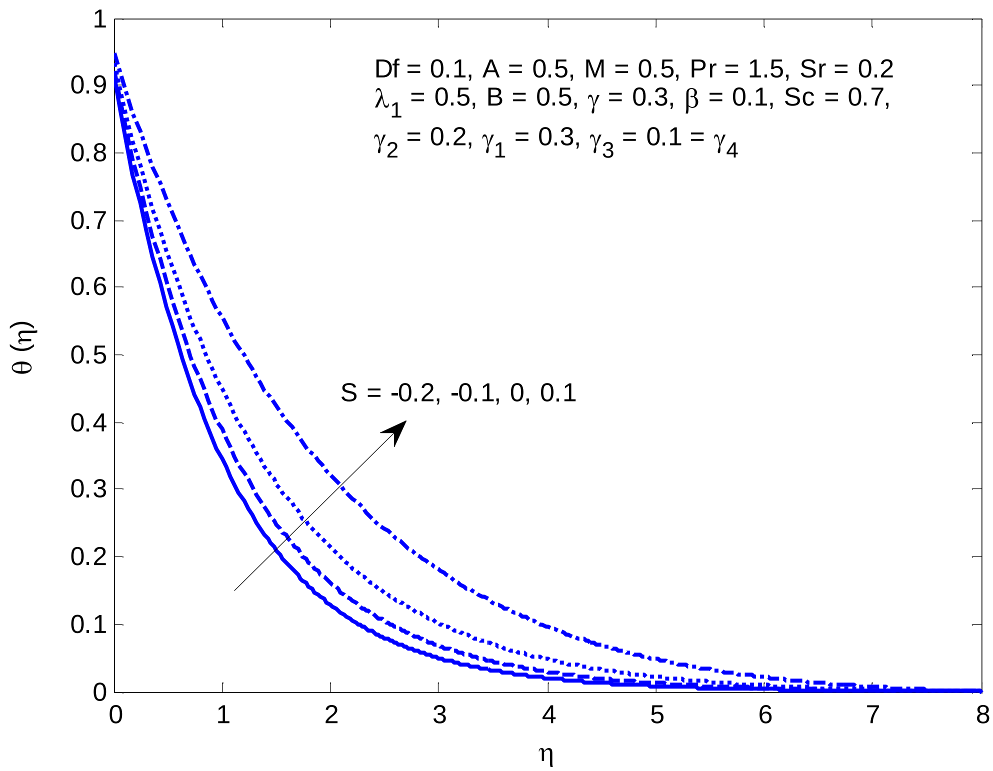

Figure 8. Temperature distribution $\theta(\eta)$ for different values of S

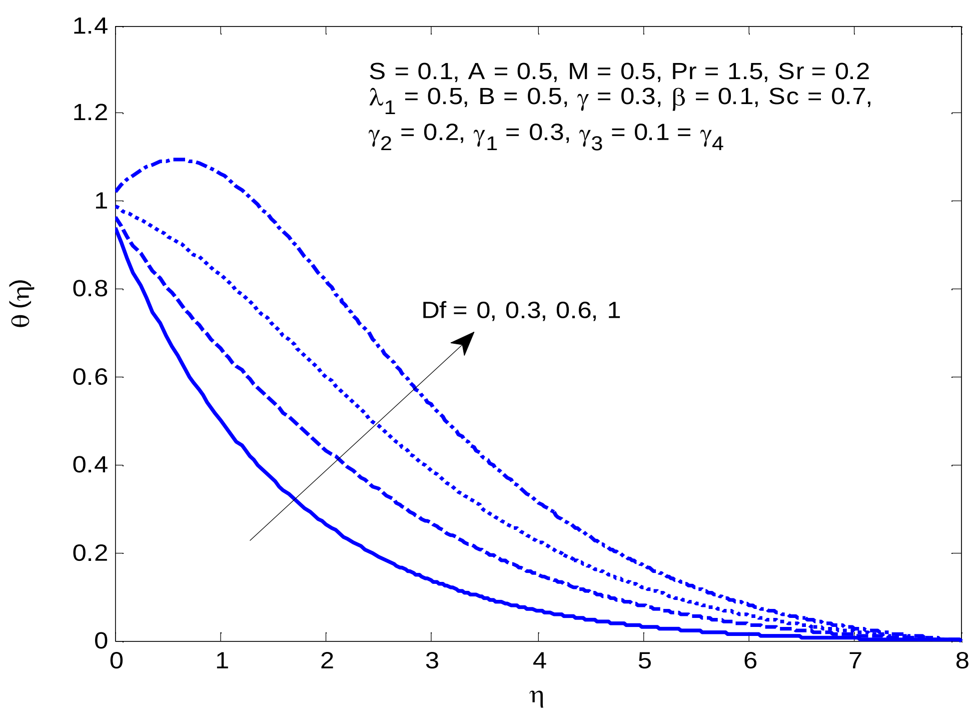

Figure 9. Temperature distribution $\theta(\eta)$ for different values of Df

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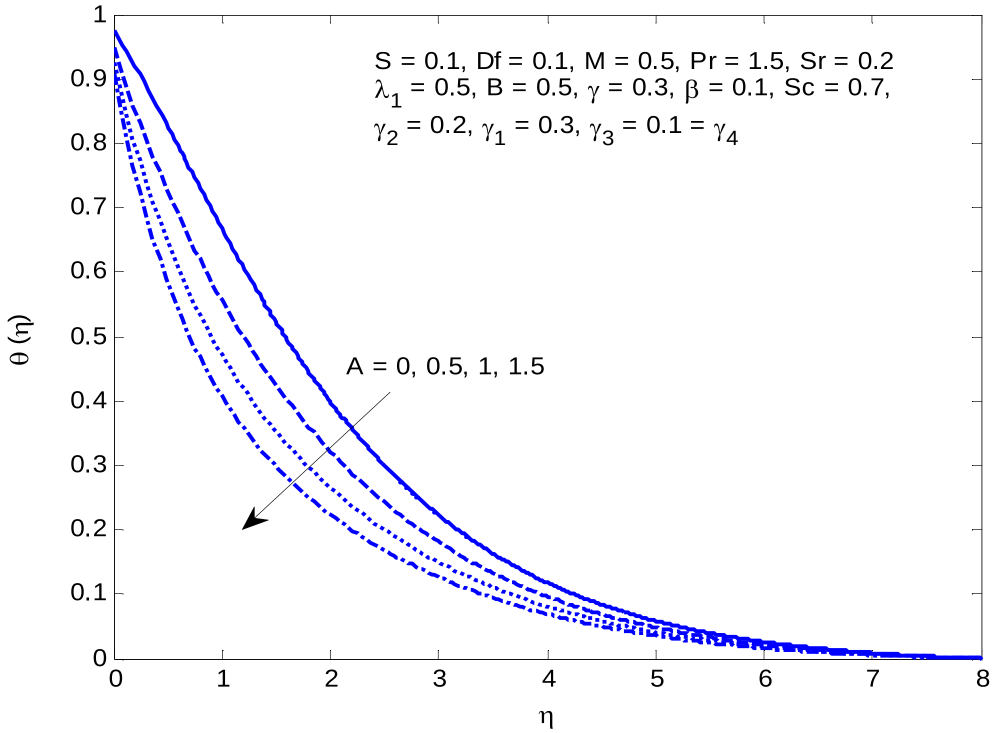

Figure 10. Temperature distribution $\theta(\eta)$ for different values of A

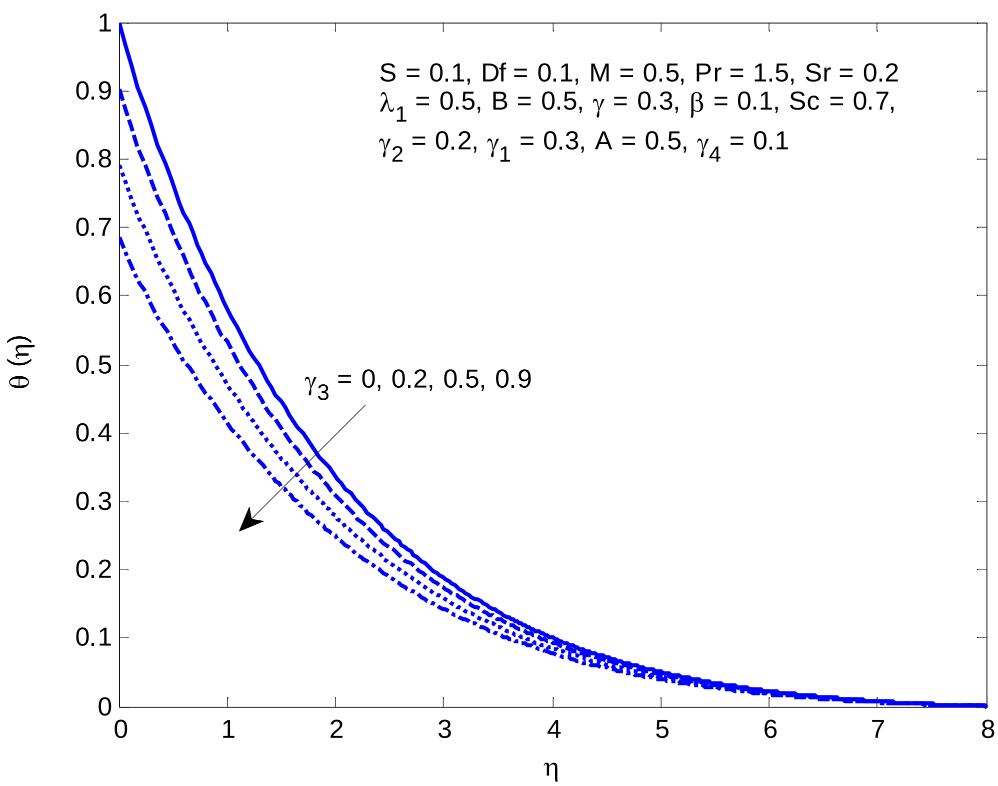

Figure 11. Temperature distribution $\theta(\eta)$ for different values of γ_3

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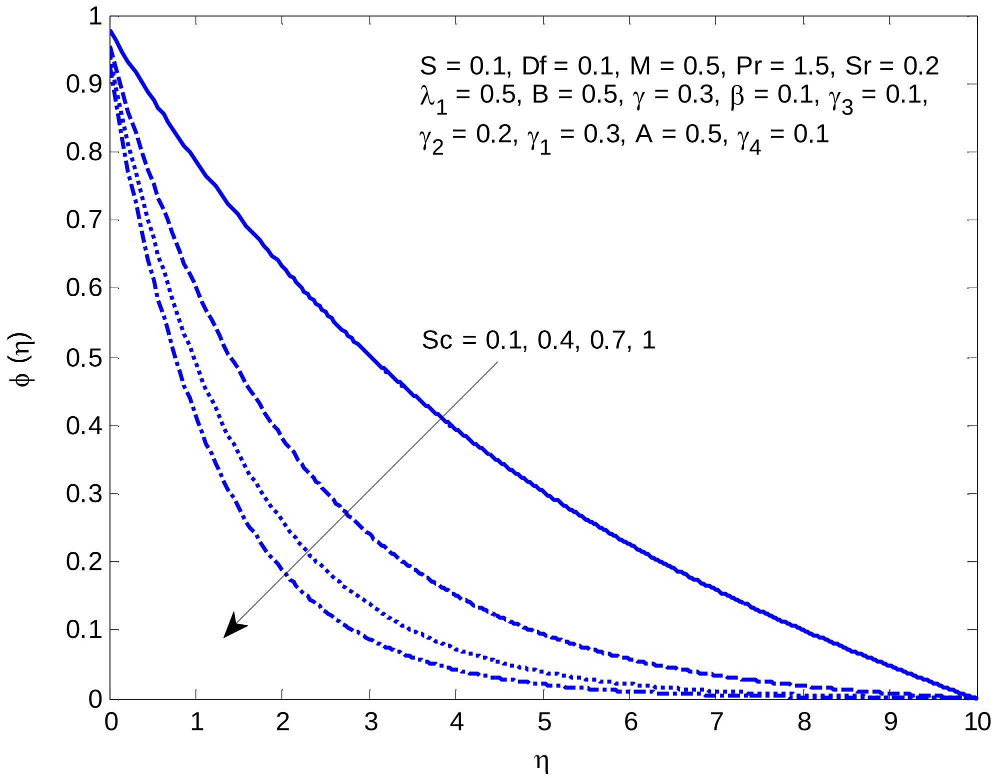

Figure 12. Concentration $\phi(\eta)$ for different values of Sc

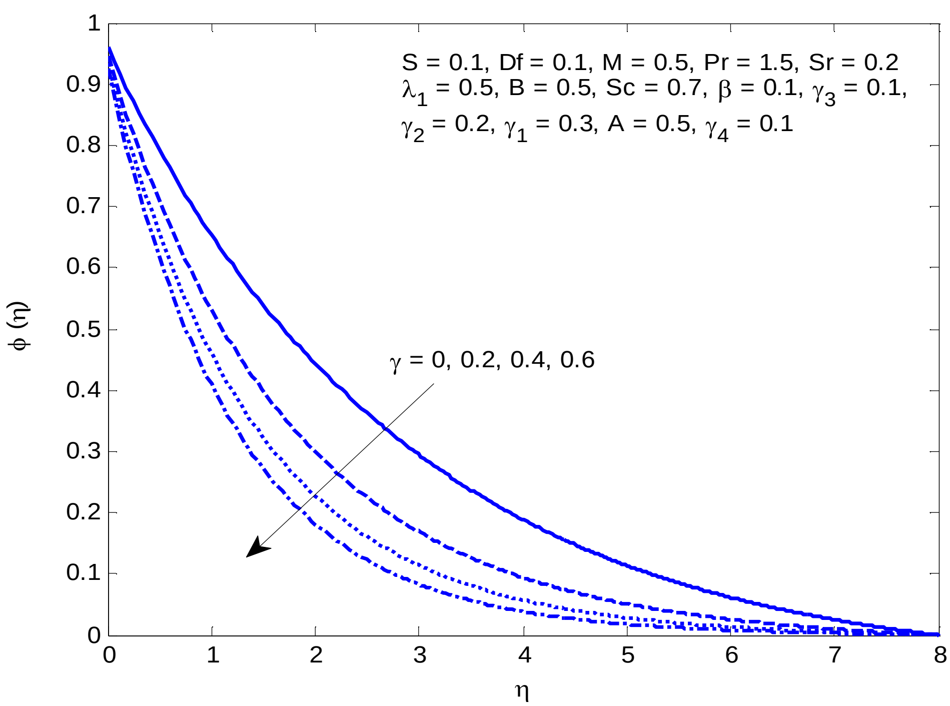

Figure 13. Concentration $\phi(\eta)$ for different values of γ

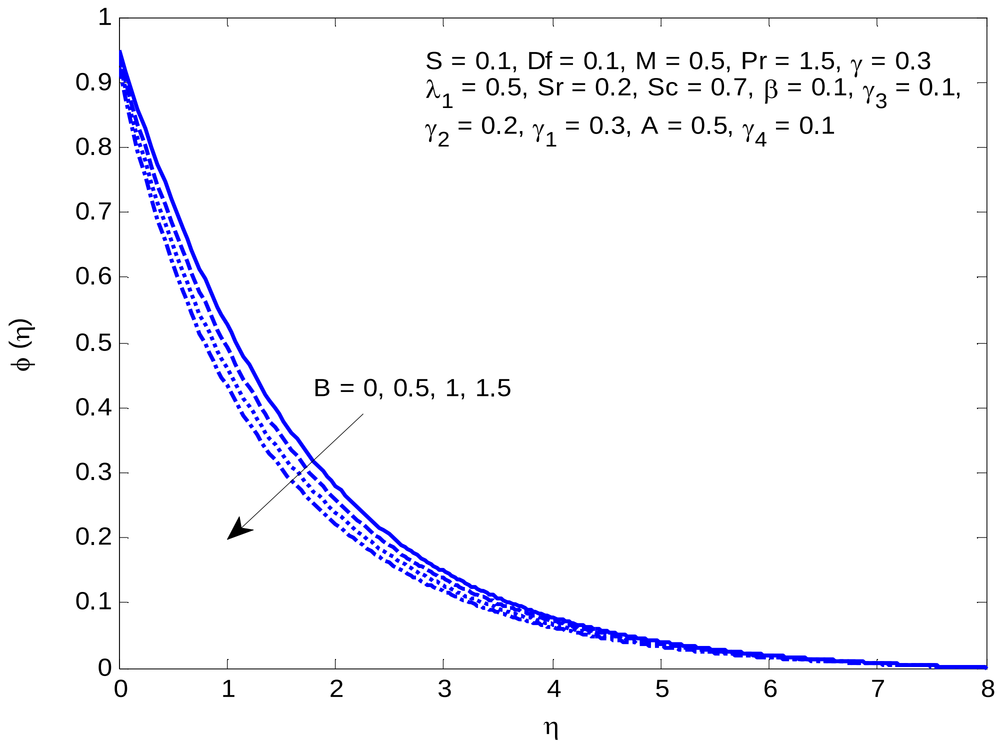

Figure 14. Concentration $\phi(\eta)$ for different values of B

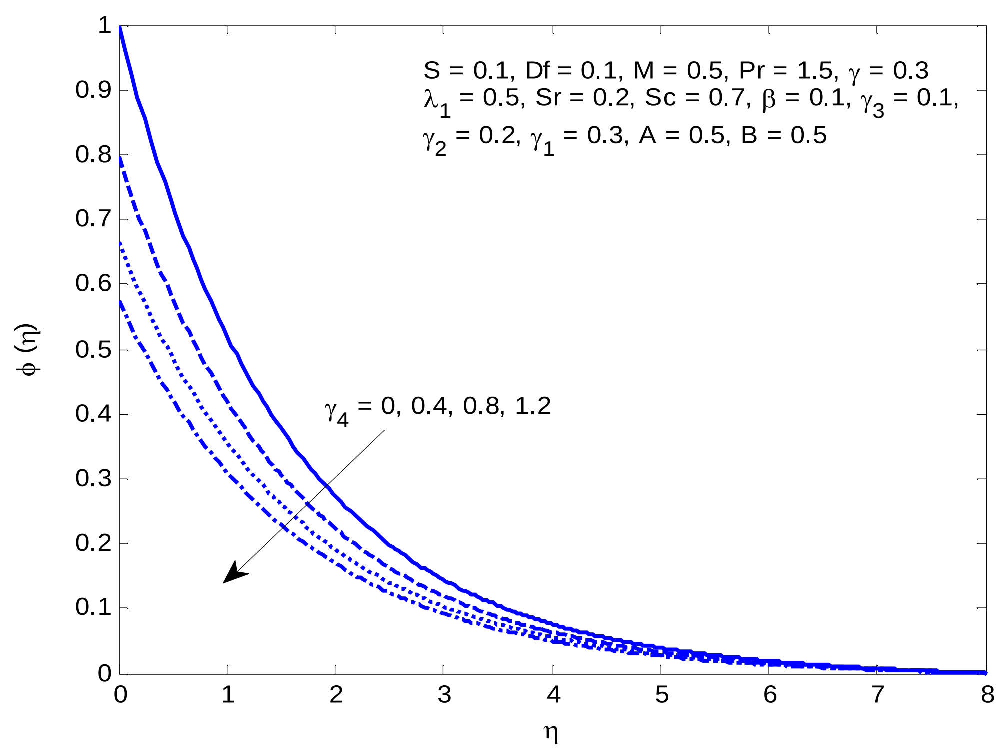

Figure 15. Concentration $\phi(\eta)$ for different values of γ_4

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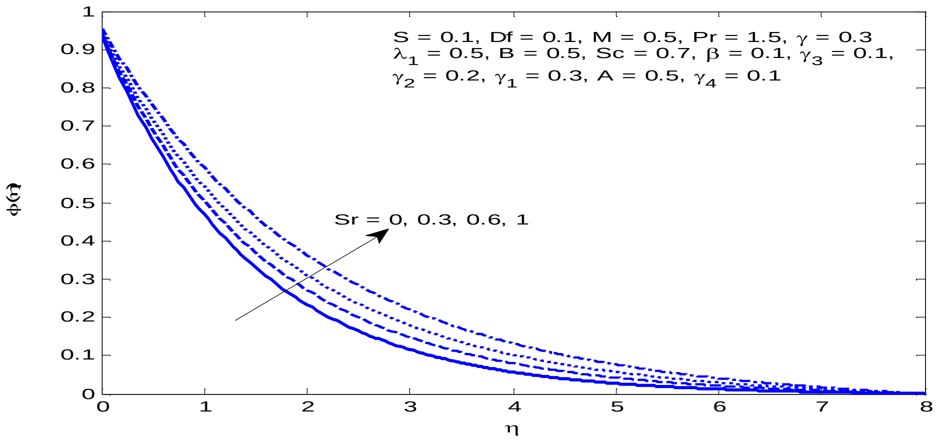

Figure 16. Concentration $\phi(\eta)$ for different values of Sr

Table 1: comparative table values of $-\frac{f''(0)}{1+\lambda_1}$ and $-\frac{g''(0)}{1+\lambda_1}$ for distinct values of β with $\Pr = 0.7, A = -2$ when $\lambda_1 = \gamma = Sr = Df = \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = M = 0$

β	Liu *et al* [14], Hayat *et al.* [6]		Present results	
	$-f''(0)$	$-g''(0)$	$-f''(0)$	$-g''(0)$
0	1.28180856	0	1.2818114	0
0.5	1.56988846	0.78494423	1.5699104	0.7849552
1.0	1.81275105	1.81275105	1.8127654	1.8127654

Table 2: comparison of $\theta'(0)$ of Magyari and Keller [15], Liu *et al.* [16] and Hayat *et al.* [6] with the present study for $\lambda_1 = \gamma = Sr = Df = \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = M = \beta = 0$

Pr	A	$\theta'(0)$		
		Magyari &Keller[15] Hayat *et al.* [6]	Liu *et al.* [14], Hayat *et al.* [6]	Present study
1	-1.5	0.377413	0.37741256	0.3774106
	0	-0.549643	-0.54964375	-0.5496460
	1	-0.954782	-0.95478270	-0.9547852
	3	-1.560294	-1.56029540	-1.5603044
5	-1.5	1.353240	1.35324050	1.3532396
	0	-1.521243	-1.52123900	-1.5212381
	1	-2.500135	-2.50013157	-2.500704
	3	-3.886555	-3.88655510	-3.8865583
10	-1.5	2.200000	2.20002816	2.2000298
	0	-2.257429	-2.25742372	-2.2574288
	1	-3.660379	-3.66037218	-3.6603259
	3	-5.635369	-5.62819631	-5.6281349

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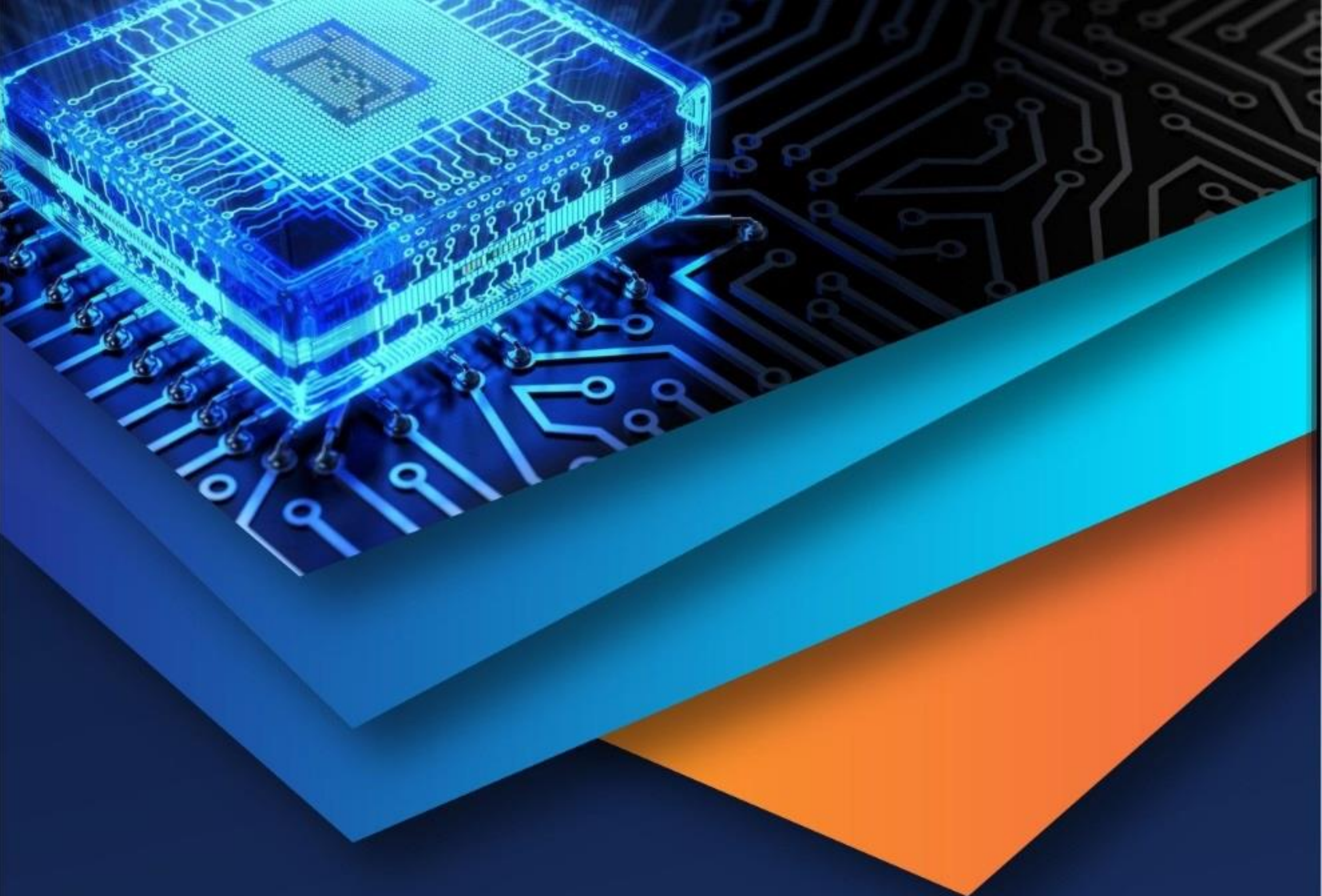

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