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Effect of Nonlinear Thermal Radiation on MHD Chemically Reacting Maxwell Fluid Flow Past a Linearly Stretching Sheet

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Abstract

This communication addresses the influence of nonlinear thermal radiation on magneto hydrodynamic Maxwell fluid flow past a linearly stretching surface with heat and mass transfer. The effects of heat generation/absorption and chemical reaction are taken into account. At first, we converted the governing partial differential equations into nonlinear ordinary differential equations with the help of suitable similarity transformations and solved by using Runge-Kutta based shooting technique. Further, the effects of various physical parameters on velocity, temperature and concentration fields were discussed thoroughly with the help of graphs obtained by using bvp5c MATLAB package. In view of many engineering applications we also computed the friction factor, heat and mass transfer coefficients and presented them in tables. Results indicate that an increase in thermal buoyancy parameter enhances the fluid velocity but suppresses the temperature. Deborah number have tendency to reduce the fluid velocity and mass transfer rate. It is also perceived that temperature ratio parameter has the propensity to enrich the fluid temperature.

Keywords: Maxwell fluid; Linear stretching sheet; Nonlinear thermal radiation; Chemical reaction

MSC 2010 No.: 76A05, 80A20, 80A32, 34B15, 35M13

Nomenclature:

a, b, c, d, e:	constants
B_0:	strength of the magnetic field
C:	concentration of the fluid in the boundary layer
C_0:	reference concentration
C_f:	skin friction coefficient
C_p:	specific heat at constant pressure
C_w:	concentration near the surface
C_∞:	concentration far away from the surface
D_B:	mass diffusivity
De:	Deborah number
f':	dimensionless velocity of the fluid
g:	acceleration due to gravity
K_l:	dimensionless chemical reaction parameter
k:	thermal conductivity of the fluid
k_1:	dimensional chemical reaction parameter
k^*:	mean absorption coefficient
M:	magnetic field parameter
N:	buoyancy ratio parameter
Nu_x:	local Nusselt number
$\Pr$:	Prandtl number
Q_1:	dimensional heat generation / absorption parameter
Q_h:	dimensionless heat generation / absorption parameter
q_w:	surface heat flux
q_m:	surface mass flux
R:	radiation parameter
Re_x:	Reynolds number
S_1, S_2	: thermal, concentration stratification parameters
Sc:	Schmidt number
Sh_x:	local Sherwood number
T:	temperature of the fluid in the boundary layer
T_0:	Deborah number
T_w:	temperature near the surface
T_∞:	temperature far away from the surface
u, v:	velocity components along $x, y-$ directions respectively
U_w:	velocity of the stretching surface

Greek symbols:

α:	thermal diffusivity
β_C:	coefficient of concentration expansion

β_T :	coefficient of thermal expansion
η:	similarity variable
λ :	thermal buoyancy parameter
λ_1:	relaxation time
υ:	kinematic viscosity of the fluid
ϕ:	dimensionless concentration of the fluid
ρ :	density of the fluid
σ :	electrical conductivity of the fluid
σ^*:	Stefan-Boltzman constant
θ:	dimensionless temperature of the fluid
θ_w :	temperature ratio parameter
τ_w:	wall shear stress

Subscripts:

w:	condition at the wall
∞:	condition at infinity

Superscripts:

$(\ )'$:	differentiation with respect to η

1. Introduction

Heat transfer occurs in many manufacturing processes such as hot rolling, extrusion, wire drawing, nuclear reactors and casting. The effects of heat and mass transfer on an unsteady flow past an impulsively vertical plate were studied by Muthucumarswamy et al. (2001). Muthucumarswamy and Velmurugan (2014) extended this work to examine the influence of chemical reaction. Further, the heat and mass transfer effects on the flow were analyzed by Kar et al. (2014) and Vedavathi et al. (2015) in their studies.

The study of flow past a stretching sheet has wide range of applications in polymer extraction, wire drawing and chemical processes. So, Crane (1970) introduced a mathematical model to investigate the flows over a stretching sheet. Heat transfer characteristics of a continuous stretching surface with variable temperature were examined by Grubka and Bobba (1985). Later, Chen (1998) extended this model to investigate the flow past a vertical and continuously stretching sheet. Chiam (1998) studied the heat transfer effects on the flow along a linearly stretching surface. The heat transfer effects on viscoelastic fluid flow over a stretching sheet were investigated by Abel et al. (2002). Elbashbeshy et al. (2010) discussed the heat generation/absorption on the flow past an unsteady stretching sheet. The researchers Mukhopadhyay (2012) and Bhattacharyya et al. (2013) discussed the flow over stretching surfaces with different assumptions on the flow.

Maxwell fluid is a non-Newtonian fluid. The usage of non-Newtonian fluids is increasing because of their tremendous applications in petroleum production, chemical and power engineering. Hakiem and Amin (2001) discussed the influence of mass transfer on non-Newtonian fluids past a vertical plate. Kumari and Nath (2001) investigated the boundary layer flow of power-law fluid over a moving surface. On the other hand, Elgazery (2008) proposed a mathematical model to investigate the effects of thermo diffusion and diffusion thermo on non-Newtonian fluid flow. Further, Chamkha (2010), Bhargava and Goyal (2014) studied the effects of heat source/sink on non-Newtonian fluids flow past different channels. Sandeep et al. (2015) described the Brownian motion of an unsteady flow with non-uniform heat generation/absorption. Rashidi et al. (2014) analyzed the MHD Viscoelastic fluid flow over a porous wedge with thermal radiation. The influence of viscous dissipation and chemical reaction on MHD Casson fluid flow past an exponentially stretching sheet was studied by Raju et al. (2016). The doubly stratified mixed convection flow of Maxwell fluid with heat source/sink was investigated by Abbasi et al. (2016). The researchers Siddiqa et al. (2013a), Saleem et al. (2014) and Hossain et al. (2013) have investigated the heat transfer characteristics of natural convective flow in presence of thermal radiation. Siddiqa and Hossain (2012) explored the flow and heat transfer behaviour of radiative optically dense gray fluid flow over a horizontal circular disk.

The study of magneto hydrodynamics has many applications in geophysics, astrophysics and in magnetic drug targeting. Owing to this importance many researchers like Mohamed (2009), Vempati and Narayana-Gari (2010), Pal and Mondal (2011), Nadeem et al. (2012) investigated the flow and heat transfer behaviour in the presence of magnetic field. Pal (2011) studied the effect of non-uniform heat source/sink on the flow over an unsteady stretching sheet. Siddiqa et al. (2013b) analyzed the free convection flow in presence of strong cross magnetic field and radiation. A short time ago, Ramana Reddy et al. (2016) described the influence of non-uniform heat source/sink on MHD nanofluid past a slendering stretching sheet. Mustafa et al. (2014) also analyzed the effect of non-uniform heat source/sink with various conditions on the flow. The effect of nonlinear thermal radiation on MHD non-Newtonian fluid flow was studied by Sulochana et al. (2015). Influence of thermal radiation on the boundary layer flow past a wavy horizontal surface was discussed by Siddiqa et al. (2014). Very recently, the behaviour of conjugate natural convective flow over a finite vertical surface with radiation was reported by Siddiqa et al. (2016). The effect of chemical reaction on the flow along a vertical stretching surface in presence of heat generation/absorption was investigated by Saleem and Aziz (2008). Krishnamurthy et al. (2016) discussed the impacts of radiation and chemical reaction on MHD Williamson fluid flow over a stretching sheet. Babu et al. (2016) studied the impact of nonlinear radiation effects on the stagnation point flow of ferro fluids and reported that nonlinear radiation parameter improves the fluid temperature.

2. Problem development

Here, two-dimensional laminar flow of Maxwell fluid over a linearly stretching sheet is considered. The sheet is taken along the direction of $x-$ axis. Magnetic field of strength B_0 is applied normal to the flow field in $y-$ axis direction. It is also assumed that the sheet is stretching with velocity $U_w(x)$. The physical geometry of the problem is depicted through Figure 1.

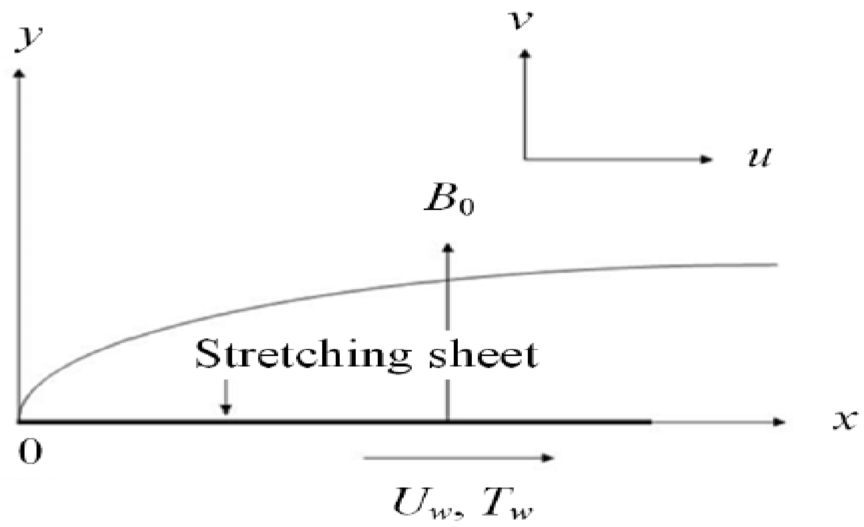

Figure 1. Physical geometry of the problem

The magnetic Reynolds number is chosen to be small. The induced magnetic field is smaller when compared to the applied magnetic field. Thus, the induced magnetic field is not considered for small magnetic Reynolds number. Electric field is absent. The effects of thermo diffusion and diffusion thermo are neglected in this study.

Therefore, the two-dimensional MHD boundary layer equations of an incompressible Maxwell fluid are, (See Abbasi et al. (2016) and Babu et al. (2016))

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+\lambda_1\left(u^2\frac{\partial^2 u}{\partial x^2}+v^2\frac{\partial^2 u}{\partial y^2}+2uv\frac{\partial^2 u}{\partial x\partial y}\right)=\upsilon\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^2}{\rho}\left(u+\lambda_1 v\frac{\partial u}{\partial y}\right) +g\left(\beta_T\left(T-T_\infty\right)+\beta_C\left(C-C_\infty\right)\right), \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{16\sigma^*}{3k^*\rho C_p}\frac{\partial}{\partial y}\left(T^3\frac{\partial T}{\partial y}\right)+\frac{Q_1}{\rho C_p}\left(T-T_\infty\right), \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}-k_1\left(C-C_\infty\right). \tag{4}$$

The boundary conditions for the presented analysis are

$$u=U_w(x)=cx, v=0, T=T_w=T_0+bx, C=C_w=C_0+dx \text{ at } y=0, \tag{5}$$

$$u\to 0, T\to T_\infty=T_0+ax, C\to C_\infty=C_0+ex \text{ as } y\to\infty, \tag{6}$$

where u and v are the velocity components in the $x-$ and $y-$ directions respectively, υ is the kinematic viscosity, λ_1 is the relaxation time, ρ is the density of the fluid, σ is the electrical conductivity of the fluid, g is the acceleration due to gravity, β_T is the thermal expansion coefficient, β_C is the concentration expansion coefficient, α is the thermal diffusivity, σ^* is the Stefan-Boltzmann coefficient, k^* is the mean absorption coefficient, C_p

is the specific heat at constant pressure, Q_1 is the dimensional heat generation/absorption parameter, k_1 is the dimensional chemical reaction parameter, D_B is the mass diffusivity, c is the stretching rate, a,b,d,e are dimensional constants and T_0, C_0 are the reference temperature and reference concentration, respectively.

Equations (2) - (6) can be made dimensionless by introducing the following similarity transformations

$$u = cxf'(\eta), v = -\sqrt{c\upsilon}\, f(\eta), \eta = y\sqrt{\frac{c}{\upsilon}},$$
$$T = T_\infty\left(1+(\theta_w - 1)\theta\right), \theta_w = \frac{T_w}{T_\infty}, \phi(\eta) = \frac{C - C_\infty}{C_w - C_0}, \tag{7}$$

The equations of momentum, energy and concentration in dimensionless form are given by,

$$f''' + De(2ff'f'' - f^2 f''') + (DeM + 1)ff'' - f'^2 - Mf' + \lambda(\theta + N\phi) = 0, \tag{8}$$
$$\theta'' + R\left(\left(1+(\theta_w - 1)\theta\right)^3 \theta'' + 3(\theta_w - 1)(\theta')^2\left(1+(\theta_w - 1)\theta\right)^2\right) + \Pr f\theta' + Q_h \Pr\theta = 0, \tag{9}$$
$$\phi'' + Scf\phi' - K_l Sc\phi = 0, \tag{10}$$

The corresponding boundary conditions are,

$$f = 0,\ f' = 1, \theta = 1 - S_1, \phi = 1 - S_2 \qquad \text{at } \eta = 0, \tag{11}$$
$$f' \to 0, \theta \to 0, \phi \to 0 \qquad \text{as } \eta \to \infty, \tag{12}$$

where

$De = \lambda_1 c$ is the Deborah number,

$M = \dfrac{\sigma B_0^2}{\rho c}$ is the magnetic field parameter,

$\lambda = \dfrac{g\beta_T (T_w - T_0)}{c^2 x}$ is the thermal buoyancy parameter,

$N = \dfrac{\beta_C (C_w - C_0)}{\beta_T (T_w - T_0)}$ is the buoyancy ratio parameter,

$R = \dfrac{16\sigma^* T_\infty^3}{3kk^*}$ is the Radiation parameter,

$\theta_w = \dfrac{T_w}{T_\infty}$ is the temperature ratio parameter,

$\Pr = \dfrac{\upsilon}{\alpha}$ is the Prandtl number,

$Q_h = \dfrac{Q_1}{c\rho C_p}$ is the heat generation $(Q_h > 0)$ or absorption $(Q_h < 0)$ parameter,

$Sc = \frac{\upsilon}{D_B}$ is the Schmidt number,

$K_l = \frac{k_1}{c}$ is the dimensionless chemical reaction parameter,

$S_1 = \frac{a}{b}$ is the thermal stratification parameter ,

$S_2 = \frac{e}{d}$ is the concentration stratification parameter.

The expressions for Skin friction coefficient, local Nusselt and Sherwood numbers are given below:

$$C_f = \frac{\tau_w}{\rho u_w^2}, Nu_x = \frac{xq_w}{k\left(T_w - T_0\right)}, Sh_x = \frac{xq_m}{D_B\left(C_w - C_0\right)}. \tag{13}$$

In the above expressions τ_w is the wall shear stress, q_w is the surface heat flux and q_m is the surface mass flux.

Now the Skin friction coefficient, local Nusselt and Sherwood numbers in dimensionless forms can be expressed as follows:

$$\mathrm{Re}_x^{1/2} C_f = \left(1 + De\right) f''(0), \frac{Nu_x}{\mathrm{Re}_x^{1/2}} = -\theta'\left(0\right), \frac{Sh_x}{\mathrm{Re}_x^{1/2}} = -\phi'\left(0\right), \tag{14}$$

where

$\mathrm{Re}_x = \frac{U_w x}{\upsilon}$ is the local Reynolds number.

3. Results and Discussion

The Equations (8) - (10) subject to the boundary conditions (11) - (12) are solved by using Runge-Kutta based shooting technique. Further, the effects of various physical parameters such as magnetic field parameter (M), thermal buoyancy parameter (λ), thermal buoyancy ratio parameter (N), Deborah number (De), Radiation parameter (R) and temperature ratio parameter (θ_w) etc. on velocity, temperature, concentration have been discussed in detail with the help of graphs. Table 1 gives the comparison of the present results for $-\theta'(0)$. We found a favourable agreement with the published results. Numerical values for skin friction coefficient, local Nusselt and Sherwood numbers are also given in Table 2. The results are obtained with the help of MATLAB bvp5c package. For numerical computations we consider the dimensionless parameter values as $M = 0.5, \lambda = 0.1, N = 5, \mathrm{Pr} = 6.8$, $Sc = 1$, $K_l = 0.5$, $Q_h = 0.5, K_l = 5, \theta_w = 1.1, R = 0.8$ and $S_1 = S_2 = 0.3$. These values have been kept in common for the entire study except the variations in the respective figures and tables.

Figures 2-17 are drawn to know the behaviour of velocity, temperature and concentration distribution under the influence of different governing parameters. Figures 2 and 3 depict the influence of magnetic field parameter (M) on velocity and temperature respectively. From Figure 2, it is clear that an increase in M slows down the fluid velocity. But from Figure 3, we observe an opposite phenomena in case of temperature distribution because, as we increase the values of M, 'Lorentz force' will be produced. This force has the capacity to reduce the fluid velocity. Also, the 'Lorentz force' produces heat to the flow. So we observe a hike in temperature profiles.

The influence of thermal buoyancy parameter (λ) on velocity, temperature and concentration fields is shown in Figures 4 - 6 respectively. From Figure 4, we examine that a hike in the values of λ improves the velocity of the fluid. Further, from Figures 5 and 6 we see that rising values of λ reduces the temperature and concentration profiles. Because, higher values of thermal buoyancy parameter corresponds to stronger buoyancy force and this force is responsible for a reduction in thermal and concentration boundary layer thicknesses. It is noteworthy to mention that temperature profiles are affected more than that of concentration in the presence of thermal buoyancy parameter.

The effect of buoyancy ratio parameter (N) on velocity and temperature distribution is shown in Figures 7 and 8 respectively. We found that rising values of N helps to enhance the fluid velocity but reduces the temperature of the fluid. Physically, increasing values of N means that temperature differences are small.

Figures 9 and 10 exhibit the effect of Deborah number (De) on velocity and temperature profiles. These figures enable us to conclude that, an increase in the values of De slows down the velocity profiles but enhances the fluid temperature significantly. Higher values of De correspond to more relaxation time which reduces the momentum boundary layer thickness and increases the temperature boundary layer thickness. Figures 11-13 give the variation in temperature profiles for different values of radiation (N), temperature ratio (θ_w) and heat generation parameters (Q_h), respectively. It is known that an increase in the values of R or θ_w or Q_h produces heat in the flow. So, we observe a hike in temperature profiles.

Figure 14 depicts the influence of Prandtl number ($\Pr$) on temperature distribution. It is evident that the fluids with higher values of $\Pr$ have lower temperature. Figures 15 and 16 are plotted to examine the behaviour of concentration for different values of profiles Schmidt number (Sc) and chemical reaction parameter (K_1) respectively. From these figures, we may observe that rising values of Sc or K_1 suppress the concentration distribution. From figure 17, we found that thermal stratification parameter (S_1) have tendency to increase the fluid temperature because increasing values of S_1 boost the thermal boundary layer thickness.

Table 2 presents the variations in skin friction coefficient (C_f), Nusselt number (Nu_x) and Sherwood number (Sh_x). From this table, we observe that an increase in the values of thermal buoyancy parameter (λ) or thermal ratio parameter (N) or thermal stratification parameter (

S_1) enhances the heat and mass transfer rates. Deborah number (β) increases the friction factor whereas an opposite result is observed in case of temperature ratio parameter (θ_w). Thermal radiation parameter (R) decreases the Nusselt number significantly but increases the Sherwood number.

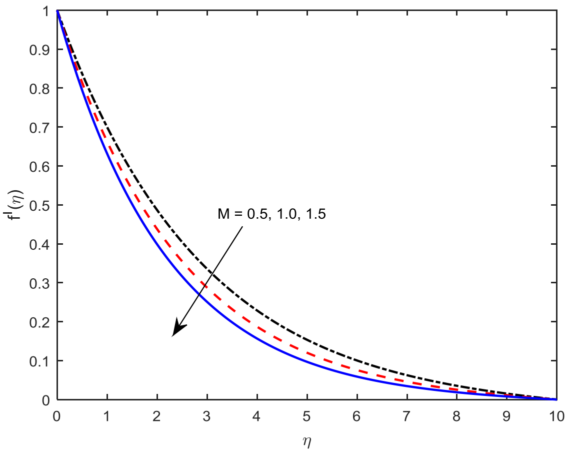

Figure 2. Velocity distribution for different values of M

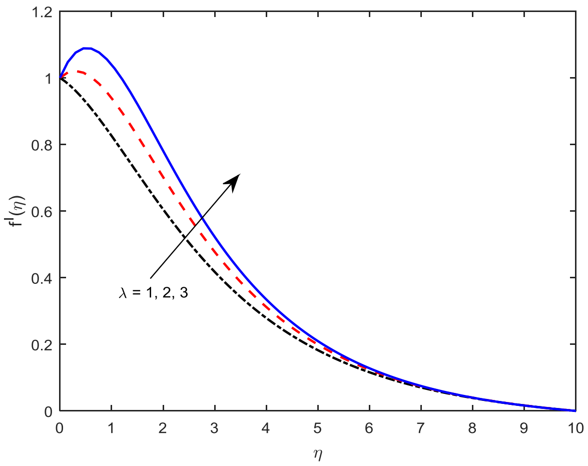

Figure 4. Velocity distribution for different values of λ

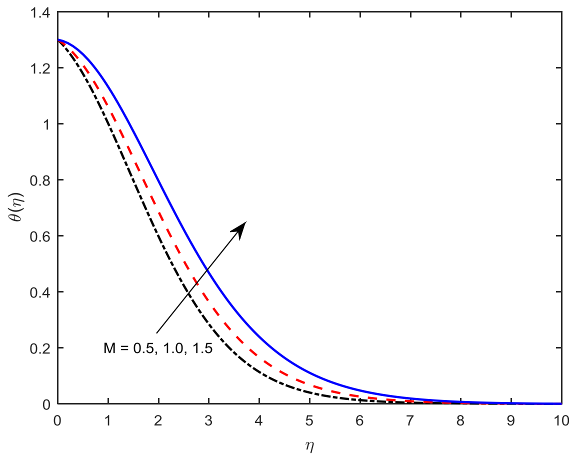

Figure 3. Temperature distribution for different values of M

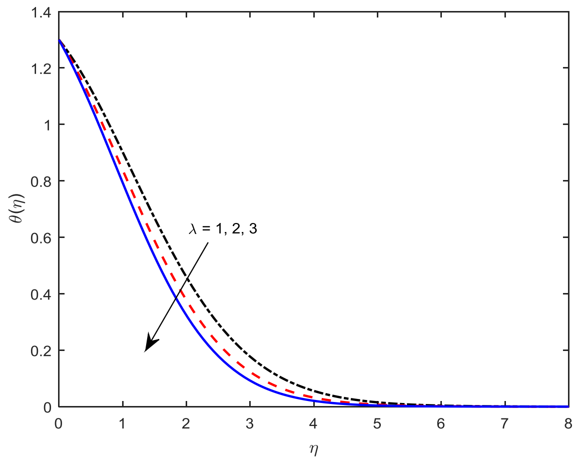

Figure 5. Temperature distribution for different values of λ

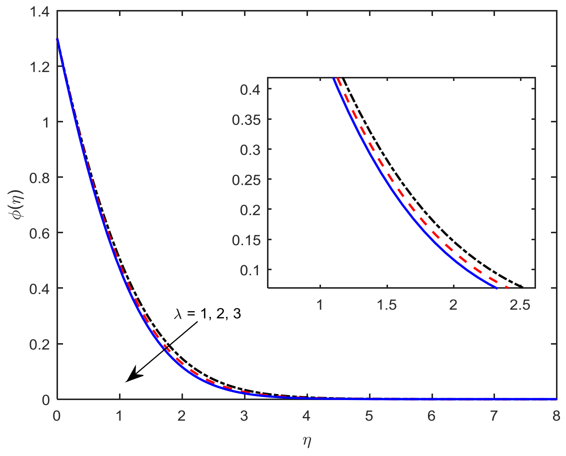

Figure 6. Concentration distribution for different values of λ

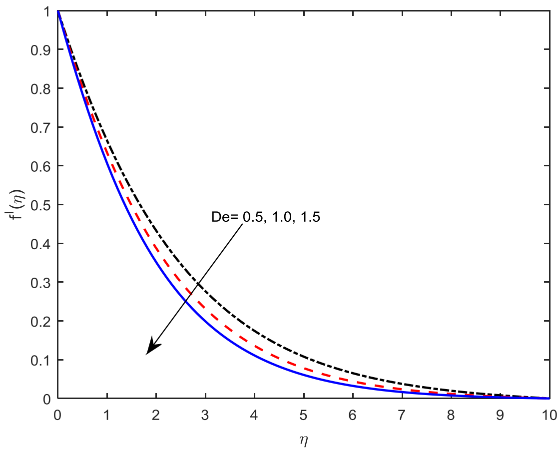

Figure 9. Velocity distribution for different values of De

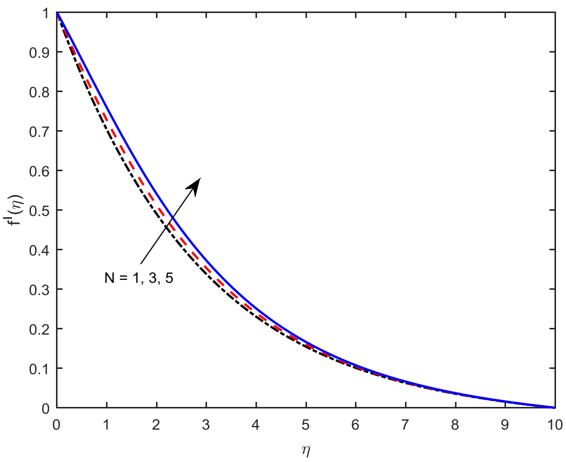

Figure 7. Velocity distribution for different values of N

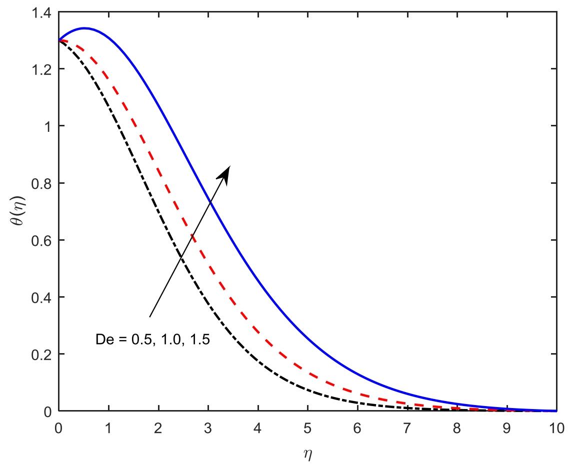

Figure 10. Temperature distribution for different values of De

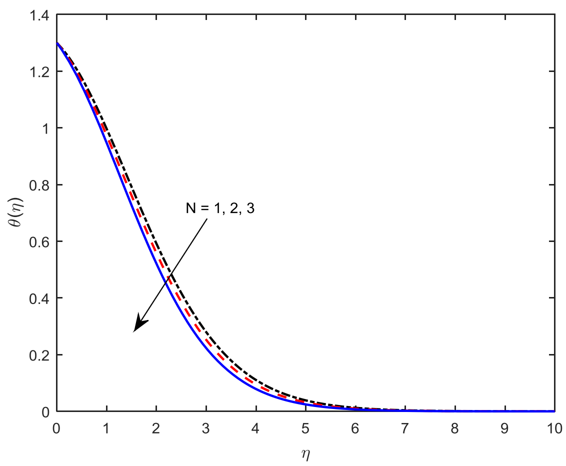

Figure 8. Temperature distribution for different values of N

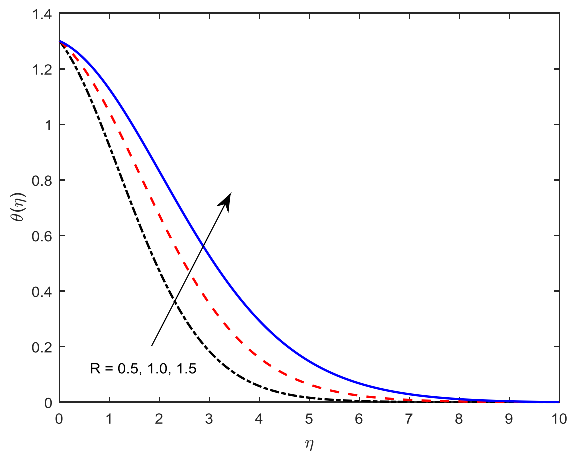

Figure 11. Temperature distribution for different values of R

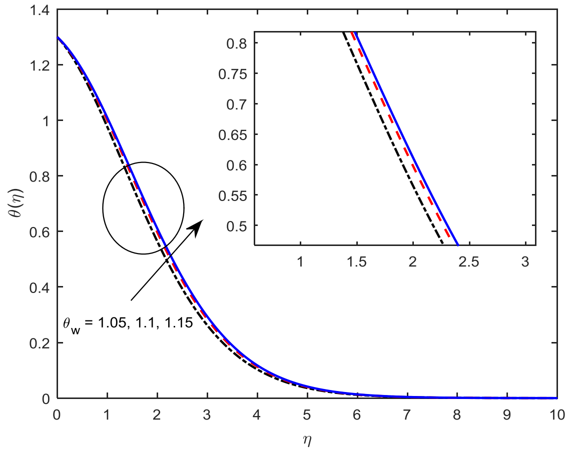

Figure 12. Temperature distribution for different values of θ_w

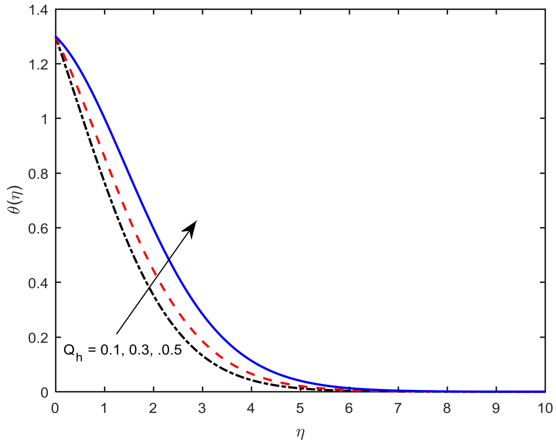

Figure 13. Temperature distribution for different values of Q_h

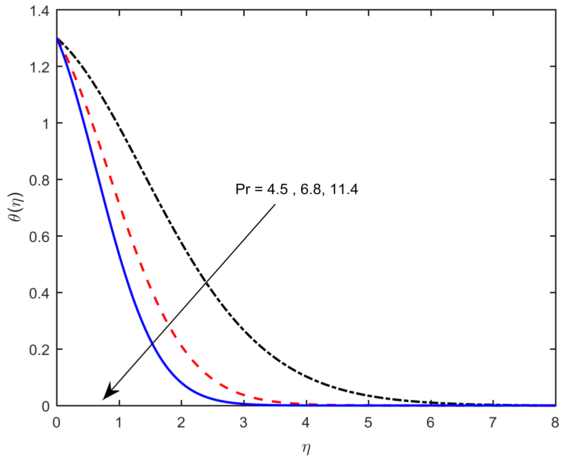

Figure 14. Temperature distribution for different values of Pr

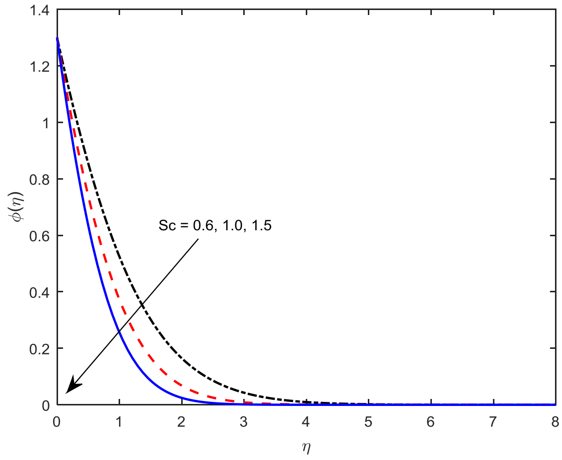

Figure 15. Concentration distribution for different values of Sc

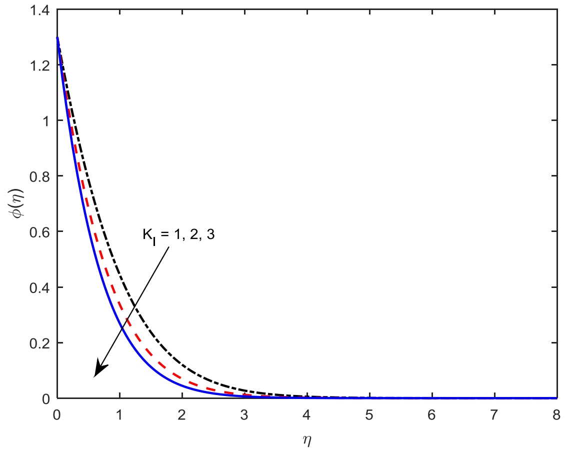

Figure 16. Concentration distribution for different values of K_l

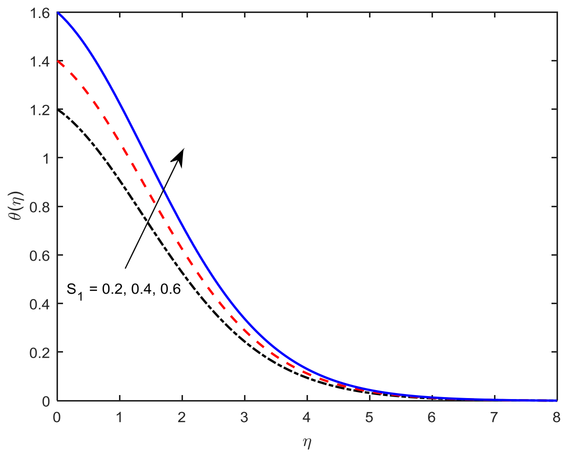

Figure 17. Temperature distribution for different values of S_1

Table 1. Comparison of the present results for $-\theta'(0)$ when $De = M = N = \lambda = R = \theta_w = Q_h = Sc = S_1 = S_2 = 0$

Pr	$-\theta'(0)$ Grubka and Bobba (1985) when $\gamma = 0$	$-\theta'(0)$ Present results
0.01	-0.0099	-0.0097
0.72	-0.4631	-0.4529
1.0	-0.5820	-0.5816
3.0	-1.1652	-1.1650
10.0	-2.3080	-2.3034

Table 2. Influence of various governing parameters on Skin friction coefficient, local Nusselt number and Sherwood number.

M	λ	N	De	R	θ_w	Q_h	Sc	Pr	K_l	S_1	C_f	Nu_x	Sh_x
0.5											-0.3549	0.1729	0.9944
1.0											-0.4107	0.1090	0.9863
1.5											-0.4601	0.0312	0.9793
	1.0										-0.1020	0.2796	1.0204
	2.0										0.1440	0.3485	1.0433
	3.0										0.3752	0.3978	1.0631
		1.0									-0.3472	0.1770	0.9952
		2.0									-0.2964	0.2021	1.0005
		3.0									-0.2299	0.2306	1.0072
			0.5								-0.3945	0.1009	0.9867
			1.0								-0.4310	-0.0011	0.9798
			1.5								-0.4639	-0.1629	0.9737
				0.5							-0.3564	0.2310	0.9941
				1.0							-0.3539	0.1416	0.9946
				1.5							-0.3516	0.0801	0.9951
					1.05						-0.3553	0.1906	0.9943
					1.10						-0.3549	0.1729	0.9944
					1.12						-0.3547	0.1660	0.9944
						0.1					-0.3582	0.5268	0.9938
						0.3					-0.3570	0.3779	0.9940
						0.5					-0.3549	0.1729	0.9944
							0.22				-0.3545	0.1734	0.5821
							0.60				-0.3549	0.1729	0.9944
							1.00				-0.3550	0.1897	1.3000
								4.5			-0.3201	0.3864	0.9973
								6.8			-0.3219	0.5255	0.9970
								11.4			-0.3186	0.2997	0.9976
									1.0		-0.3577	0.1684	1.2211
									2.0		-0.3578	0.1683	1.5824
									3.0		-0.3578	0.1682	1.8758
										0.6	-0.3159	0.1897	0.9981
										1.0	-0.3240	0.1823	1.3029
										1.5	-0.3294	0.1781	1.6074

4. Conclusions

The problem of two-dimensional flow, heat and mass transfer of Maxwell fluid over a linearly stretching sheet is investigated by considering the impact of nonlinear radiation. The modelled equations of the governing problem are numerically solved by the help of shooting method and the results are graphically displayed. The striking features of the analysis are presented below.

- Thermal buoyancy parameter enhances the fluid velocity but depreciates the fluid temperature.
- Deborah number effectively increases the temperature field, but an opposite trend is observed in the case of fluid velocity.
- Deborah number enriches the friction factor significantly whereas temperature ratio parameter and thermal stratification parameters show negligible effect.
- Temperature ratio parameter has tendency to reduce the heat transfer coefficient.
- As we expected, Lorentz force due to magnetic field parameter slows down the fluid motion but raises the temperature distribution.
- Thermal stratification parameter has tendency to increase the heat and mass transfer performance.
- Increasing values of either Chemical reaction parameter or Schmidt number reduces the concentration of the fluid.

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