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

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Received July 16, 2016; Accepted December 17, 2016

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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:

\begin{align*}
a, b, c, d, e : & \quad \text{constants} \\
B_0 : & \quad \text{strength of the magnetic field} \\
C : & \quad \text{concentration of the fluid in the boundary layer} \\
C_0 : & \quad \text{reference concentration} \\
C_f : & \quad \text{skin friction coefficient} \\
C_p : & \quad \text{specific heat at constant pressure} \\
C_w : & \quad \text{concentration near the surface} \\
C_{\infty} : & \quad \text{concentration far away from the surface} \\
D_b : & \quad \text{mass diffusivity} \\
De : & \quad \text{Deborah number} \\
f' : & \quad \text{dimensionless velocity of the fluid} \\
g : & \quad \text{acceleration due to gravity} \\
K_i : & \quad \text{dimensionless chemical reaction parameter} \\
k : & \quad \text{thermal conductivity of the fluid} \\
k_i : & \quad \text{dimensional chemical reaction parameter} \\
k^* : & \quad \text{mean absorption coefficient} \\
M : & \quad \text{magnetic field parameter} \\
N : & \quad \text{buoyancy ratio parameter} \\
Nu_x : & \quad \text{local Nusselt number} \\
Pr : & \quad \text{Prandtl number} \\
Q : & \quad \text{dimensional heat generation / absorption parameter} \\
Q_0 : & \quad \text{dimensionless heat generation / absorption parameter} \\
q_w : & \quad \text{surface heat flux} \\
q_m : & \quad \text{surface mass flux} \\
R : & \quad \text{radiation parameter} \\
Re_x : & \quad \text{Reynolds number} \\
S_1, S_2 : & \quad \text{thermal, concentration stratification parameters} \\
Sc : & \quad \text{Schmidt number} \\
Sh : & \quad \text{local Sherwood number} \\
T : & \quad \text{temperature of the fluid in the boundary layer} \\
T_0 : & \quad \text{Deborah number} \\
T_w : & \quad \text{temperature near the surface} \\
T_{\infty} : & \quad \text{temperature far away from the surface} \\
u, v : & \quad \text{velocity components along } x, y \text{ directions respectively} \\
U_w : & \quad \text{velocity of the stretching surface} \\
\end{align*}

Greek symbols:

\begin{align*}
\alpha : & \quad \text{thermal diffusivity} \\
\beta_c : & \quad \text{coefficient of concentration expansion} \\
\end{align*}
\( \beta_f \): coefficient of thermal expansion \\
\( \eta \): similarity variable \\
\( \lambda \): thermal buoyancy parameter \\
\( \lambda_1 \): relaxation time \\
\( \nu \): kinematic viscosity of the fluid \\
\( \phi \): dimensionless concentration of the fluid \\
\( \rho \): density of the fluid \\
\( \sigma \): electrical conductivity of the fluid \\
\( \sigma^* \): Stefan-Boltzman constant \\
\( \theta \): dimensionless temperature of the fluid \\
\( \theta_w \): temperature ratio parameter \\
\( \tau_w \): wall shear stress

Subscripts:

\( w \): condition at the wall \\
\( \infty \): condition at infinity

Superscripts:

\( (\cdot)' \): differentiation with respect to \( \eta \)

### 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

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.
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))

\[
\begin{align*}
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} &= 0, \\
u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \lambda_1 \left( u^2 \frac{\partial^2 u}{\partial x^2} + v^2 \frac{\partial^2 u}{\partial y^2} + 2uv \frac{\partial^2 u}{\partial x \partial y} \right) &= \nu \frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho} \left( u + \lambda_1 v \frac{\partial u}{\partial y} \right) + g \left( \beta_T (T - T_\infty) + \beta_C (C - C_\infty) \right), \\
u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} &= \alpha \frac{\partial^2 T}{\partial y^2} + \frac{16\sigma^*}{3k^* \rho C_p} \frac{\partial}{\partial y} \left( T^3 \frac{\partial T}{\partial y} \right) + \frac{Q_0}{\rho C_p} (T - T_\infty), \\
u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} &= D_u \frac{\partial^2 C}{\partial y^2} - k^* (C - C_\infty).
\end{align*}
\]

The boundary conditions for the presented analysis are

\[
\begin{align*}
u = &U_\infty(x) = cx, \quad v = 0, \quad T = T_w = T_0 + bx, \quad C = C_\infty = C_0 + dx \quad \text{at} \quad y = 0, \\
u \rightarrow &0, \quad T \rightarrow T_\infty = T_0 + ax, \quad C \rightarrow C_\infty = C_0 + ex \quad \text{as} \quad y \rightarrow \infty,
\end{align*}
\]

where \( u \) and \( v \) are the velocity components in the \( x \)- and \( y \)- directions respectively, \( \nu \) is the kinematic viscosity, \( \lambda_1 \) is the relaxation time, \( \rho \) is the density of the fluid, \( \sigma \) is the electrical conductivity of the fluid, \( g \) is the acceleration due to gravity, \( \beta_T \) is the thermal expansion coefficient, \( \beta_C \) is the concentration expansion coefficient, \( \alpha \) is the thermal diffusivity, \( \sigma^* \) is the Stefan-Boltzmann coefficient, \( k^* \) is the mean absorption coefficient, \( C_p \)
is the specific heat at constant pressure, \( Q_i \) is the dimensional heat generation/absorption parameter, \( k_t \) 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

\[
u = c x f' (\eta), \quad v = -\sqrt{c v f (\eta)} , \quad \eta = y \sqrt{\frac{c}{\nu}},
\]

\[
T = T_w \left(1 + (\theta_w - 1) \theta \right), \quad \theta_w = \frac{T_w}{T_\infty}, \quad \phi (\eta) = \frac{C - C_w}{C_w - C_0}.
\]

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

\[
f'' + De (2f f'' - f^2 f''') + (De M + 1)f f'' - f''^2 - MF' + \lambda (\theta + N \phi) = 0,
\]

\[
\theta'' + R \left( \left(1 + (\theta_w - 1) \theta \right)^3 \theta'' + 3 (\theta_w - 1) (\theta')^2 \left(1 + (\theta_w - 1) \theta \right) \right) + Pr \theta' + Q_n \theta = 0,
\]

\[
\phi'' + Scf \phi' - K, Sc \phi = 0,
\]

The corresponding boundary conditions are,

\[
f = 0, f' = 1, \theta = 1 - S_1, \phi = 1 - S_2 \quad \text{at} \quad \eta = 0, \quad f' \to 0, \theta \to 0, \phi \to 0 \quad \text{as} \quad \eta \to \infty,
\]

where

\[
De = \lambda c \quad \text{is the Deborah number},
\]

\[
M = \frac{\sigma B_0^2}{\rho c} \quad \text{is the magnetic field parameter},
\]

\[
\lambda = \frac{g \beta G (T_w - T_0)}{c^2} \quad \text{is the thermal buoyancy parameter},
\]

\[
N = \frac{\beta G (C_w - C_0)}{\beta G (T_w - T_0)} \quad \text{is the buoyancy ratio parameter},
\]

\[
R = \frac{16 \sigma T^3}{3 kk'} \quad \text{is the Radiation parameter},
\]

\[
\theta_w = \frac{T_w}{T_\infty} \quad \text{is the temperature ratio parameter},
\]

\[
Pr = \frac{\nu}{\alpha} \quad \text{is the Prandtl number},
\]

\[
Q_n = \frac{Q_i}{c \rho C_p} \quad \text{is the heat generation (} Q_n > 0 \text{) or absorption (} Q_n < 0 \text{) parameter},
\]
is the Schmidt number,

\[ K_l = \frac{k_l}{c} \] is the dimensionless chemical reaction parameter,

\[ S_i = \frac{a}{b} \] is the thermal stratification parameter,

\[ S_s = \frac{e}{d} \] is the concentration stratification parameter.

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

\[ C_f = \frac{\tau_w}{\rho u_w}, \quad Nu_x = \frac{xq_w}{k(T_w - T_0)}, \quad Sh_x = \frac{xq_m}{D_b(C_w - C_0)}. \]  

(13)

In the above expressions \( \tau_w \) 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:

\[ \text{Re}_{x}^{1/2} C_f = (1 + De) f^*(0), \quad \frac{Nu_x}{\text{Re}_{x}^{1/2}} = -\theta'(0), \quad \frac{Sh_x}{\text{Re}_{x}^{1/2}} = -\phi'(0), \]  

(14)

where

\[ \text{Re}_{x} = \frac{U_x x}{\nu} \] 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 \( (\lambda) \), thermal buoyancy ratio parameter \( (N) \), Deborah number \( (De) \), Radiation parameter \( (R) \) and temperature ratio parameter \( (\theta_w) \) 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 \( M = 0.5, \lambda = 0.1, N = 5, Pr = 6.8, Sc = 1, K_i = 0.5, Q_h = 0.5, K_f = 5, \theta_w = 1.1, R = 0.8 \) and \( S_i = S_s = 0.3 \). 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 \((\lambda)\) 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 \(\lambda\) improves the velocity of the fluid. Further, from Figures 5 and 6 we see that rising values of \(\lambda\) 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 \((\theta)\) and heat generation parameters \((Q)\), respectively. It is known that an increase in the values of \(Ror\theta\) or \(Q\) 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 \((K)\) respectively. From these figures, we may observe that rising values of \(Sc\) or \(K\) suppress the concentration distribution. From figure 17, we found that thermal stratification parameter \((S)\) have tendency to increase the fluid temperature because increasing values of \(S\) boost the thermal boundary layer thickness.

Table 2 presents the variations in skin friction coefficient \((C_f)\), Nusselt number \((Nu)\) and Sherwood number \((Sh)\). From this table, we observe that an increase in the values of thermal buoyancy parameter \((\lambda)\) or thermal ratio parameter \((N)\) or thermal stratification parameter \((S)\)
$S_i$) enhances the heat and mass transfer rates. Deborah number ($\beta$) increases the friction factor whereas an opposite result is observed in case of temperature ratio parameter ($\theta_w$). Thermal radiation parameter ($R$) decreases the Nusselt number significantly but increases the Sherwood number.

**Figure 2.** Velocity distribution for different values of $M$

**Figure 3.** Temperature distribution for different values of $M$

**Figure 4.** Velocity distribution for different values of $\lambda$

**Figure 5.** Temperature distribution for different values of $\lambda$
Figure 6. Concentration distribution for different values of $\lambda$

Figure 7. Velocity distribution for different values of $N$

Figure 8. Temperature distribution for different values of $N$

Figure 9. Velocity distribution for different values of $De$

Figure 10. Temperature distribution for different values of $De$

Figure 11. Temperature distribution for different values of $R$
Figure 12. Temperature distribution for different values of $\theta_w$.

Figure 13. Temperature distribution for different values of $Q_i$.

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 $K_i$.

Figure 17. Temperature distribution for different values of $S_i$. 
Table 1. Comparison of the present results for $-\vartheta'(0)$ when $De = M = N = \lambda = R = \theta_w = Q_s = Sc = S_1 = S_2 = 0$

<table>
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<th>Pr</th>
<th>$-\vartheta'(0)$ Grubka and Bobba (1985) when $\gamma = 0$</th>
<th>$-\vartheta'(0)$ Present results</th>
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Table 2. Influence of various governing parameters on Skin friction coefficient, local Nusselt number and Sherwood number.

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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.

REFERENCES


