Thermal radiation and cross diffusion effects on 3D convective flow of a viscoelastic fluid over a stretchy paper with chemical reaction

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Abstract. Effects of thermal radiation, Dufour and Soret numbers on 3D unsteady flow of a chemically reacting viscoelastic fluid over a stretchy paper with internal heat generation/absorption are investigated. The governing PDE models are transformed into an ODE models with suitable similarity variables and they are solved using homotopy analysis method (HAM). The influences of various parameters are analyzed. The Dufour effect boosted up the mass transfer rate and suppresses the heat transfer rate. The heat transfer rate enhances with Soret number and it diminishes on raising the Dufour number.

Keywords Heat transfer, radiation, chemical reaction, viscoelastic fluid, Soret/Dufour effect, heat generation or absorption

1. Introduction

The flow over a stretching surface has a developing area in recent years due to its many industrial applications, like continuous casting, fiber spinning, plastic sheet production, glass blowing, rolling and manufacturing plastic films. Wang [1] studied the 3D flow over a stretching flat surface. Other related analysis in this direction was presented by many authors, see ([2]-[8]). The Dufour and Soret effects are important in some situations. Alam et al. [9] analyzed the MHD flow over a porous plate. Few important studies in this directions are in Refs. ([10]-[18]).

In this paper, we investigate the Soret and Dufour effects on 3D flow of a chemically reacting viscoelastic fluid over a stretchy paper with radiation and heat absorption or generation. The governing equations are non-linear and it is very difficult to solve these nonlinear problems. The homotopy analysis method (HAM) is currently very popular and has been used by many researchers for the solutions of the non-linear problems, see ([19]-[22]). Therefore, the present problem is solved by using this method.

2. Mathematical Formulation

We consider the 3D unsteady flow of a viscoelastic fluid over a stretchy paper at $z = 0$. The $x$– and $y$– axes are chosen in the plane of the surface and the $z$– axis is taken normal to it. The surface is stretching with velocity $u_w$ in $x$-direction and $v_w$ in $y$-direction, respectively. The
effect of stretching ratio between $x$ and $y$ directions is examined here. Let $T_w$ & $C_w$ are the temperature & concentration at the surface and $T_\infty$ & $C_\infty$ are surrounding fluid temperature & concentration. It is assumed that the fluid generate heat internally. We incorporate the the thermo-diffusion effect in mass equation and diffusion-thermo effect in energy equation. There is a chemical reaction between the fluid and the foreign mass inside it. The governing equations with the above assumptions can be expressed as,

\[
\begin{align*}
  u_x + v_y + w_z &= 0 \\
  u_t + uu_x + v u_y + w u_z &= \nu u_{zz} \\
  v_t + w_x + v v_y + w v_z &= \nu v_{zz} \\
  C_t + u C_x + v C_y + w C_z &= DC_{zz} - K_0 (u_{zz} + w_{zz} - u_x u_{zz} - u_y u_{zz} - 2u_z u_{zz} - 2w_z u_{zz}) \\
  T_t + u T_x + v T_y + w T_z &= \alpha T_{zz} + \frac{Q}{\rho c_p} (T - T_\infty) + \frac{Dk_T}{T_m}T_{zz}
\end{align*}
\]

where $(u, v, w), (x, y, z), \nu, k_0, D, k_1, \alpha, Q, T_m, c_p$ are velocity components, direction co-ordinates, kinematic viscosity, material fluid parameter, diffusion coefficient, rate of chemical reaction, thermal diffusivity, internal heat absorption or generation, mean fluid temperature, density, thermal diffusion ratio, concentration susceptibility and specific heat.

Here the radiative heat flux term is simplified by using Rosseland approximation.

The boundary conditions are

\[
\begin{align*}
  z = 0 : & \quad u = \frac{ax}{1 - \alpha t}, v = \frac{by}{1 - \alpha t}, w = 0, C = C_w, T = T_w \\
  z \to \infty : & \quad u \to 0, v \to 0, u_z \to 0, v_z \to 0, C \to C_\infty, T \to T_\infty
\end{align*}
\]

where $a$ and $b$ are positive constants. The following similarity variables are used.

\[
\begin{align*}
  \eta &= \sqrt{\frac{a}{\nu (1 - \alpha t)}} z, \quad u = \frac{ax}{1 - \alpha t} f'(\eta), \quad v = \frac{by}{1 - \alpha t} g'(\eta), \\
  w &= -\sqrt{\frac{av}{1 - \alpha t}} (f(\eta) + g(\eta)), \quad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}, \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}
\end{align*}
\]

Finally we get,

\[
\begin{align*}
  f''' - f'^2 - \xi \left[ \frac{\eta}{2} f'' + f' \right] + \left[ f + g \right] f'' \\
  + K \left\{ -\xi \left[ \frac{\eta}{2} f'' + 2 f''' \right] + \left( f + g \right) f'' + \left( f''' - g'' \right) f'' - 2 \left( f' + g' \right) f''' \right\} &= 0 \\
  g''' - g'^2 - \xi \left[ \frac{\eta}{2} g'' + g' \right] + \left[ f + g \right] g'' \\
  + K \left\{ -\xi \left[ \frac{\eta}{2} g'' + 2 g''' \right] + \left[ f + g \right] g'' - \left[ f''' - g'' \right] g'' - 2 \left[ f' + g' \right] g''' \right\} &= 0 \\
  \phi'' + Sc \left[ f + g \right] \phi' - ScCr \phi - Sc \xi \eta \phi' + ScSr \phi'' &= 0 \\
  \left[ 1 + \frac{4}{3R_d} \right] \theta'' + Pr \left[ f + g \right] \theta' - Pr \xi \eta \theta' + Pr H \theta + Pr Df \phi'' &= 0
\end{align*}
\]
with boundary conditions,

\[ f(0) = 0, \quad g(0) = 0, \quad f'(0) = 1, \quad g'(0) = c, \quad \phi(0) = 1, \quad \theta(0) = 1, \]
\[ \phi(\infty) = 0, \quad \theta(\infty) = 0, \quad f'(\infty) = 0, \quad g'(\infty) = 0, \quad f''(\infty) = 0, \quad g''(\infty) = 0, \]

where \( K = \frac{b_0}{a_0} \) is the dimensionless viscoelastic parameter, \( \xi = \frac{a_1}{a} \) is the unsteady parameter, \( c = \frac{b}{a} \) is the stretching ratio, \( Sc = \frac{\nu}{Df} \) is the Schmidt number, \( Cr = \frac{b_1}{a_1} (1 - \alpha t) \) is the chemical reaction parameter, \( Sr = \frac{DK_T(T_w - T_\infty)}{T_m a_1 (C_w - C_\infty)} \) is the Soret number, \( Df = \frac{DK_T(C_w - C_\infty)}{\nu c w (T_w - T_\infty)(1 - \alpha t)} \) is the Dufour number, \( R_d = \frac{k^* k_T}{\dot{\alpha}_w T_\infty} \) is the radiation parameter, \( Pr = \frac{a}{\nu} \) is the Prandtl number and \( Hg = \frac{Q(1 - \alpha t)}{a \rho c_T} \) is the heat generation/absorption parameter.

Note that the two-dimensional can be considered when \( c = 0 \) and axisymmetric case when \( c = 1 \).

The dimensionless friction coefficients \( (C_{f_x} \& C_{f_y}) \), Sherwood \( (Sh) \) number and Nusselt number \((Nu)\) are defined as follows, see [12],

\[ C_{f_x} \sqrt{Re} = f''(0) + K \left\{ \frac{\xi}{2} \left[ 3f''(0) + \eta f'''(0) \right] + 3 \left[ f'(0) + g'(0) \right] f''(0) - \left[ f(0) + g(0) \right] f'''(0) \right\} \]
\[ C_{f_y} \sqrt{Re} = g''(0) + K \left\{ \frac{\xi}{2} \left[ 3g''(0) + \eta g'''(0) \right] + 3 \left[ f'(0) + g'(0) \right] g''(0) - \left[ f(0) + g(0) \right] g'''(0) \right\} \]
\[ Sh/\sqrt{Re} = -\phi'(0), \]
\[ Nu/\sqrt{Re} = \left[ 1 + \frac{4}{3R_d} \right] \theta'(0). \]

3. HAM Solutions

The governing system of equations (7)-(10) with (11) have been solved analytically by using HAM. The initial guesses are \( f_0(\eta) = 1 - \exp(-\eta), \quad g_0(\eta) = c(1 - \exp(-\eta)), \quad \phi_0(\eta) = \exp(-\eta) \) and \( \theta_0(\eta) = \exp(-\eta) \). These solution depends upon \( h_f, h_g, h_\phi \) and \( h_\theta \). The \( h \)-curves of \( f, g, \phi \) and \( \theta \) are plotted in figures 1(a,b). From figure 1(a), the range of \( h_f \) and \( h_g \) are \(-1.3 \leq h_f \leq -0.5 \) and \(-1.5 \leq h_g \leq -0.6 \). From figure 1(b), the range of \( h_\phi \) and \( h_\theta \) are \(-1.1 \leq h_\phi \leq -0.5 \) and \(-1.0 \leq h_\theta \leq -0.5 \). We choose \( h_f = h_g = h_\phi = h_\theta = -0.9 \) for the better solution.

4. Results and Discussion

The results are illustrated in figures 2-6, to show the influences of pertinent parameters on the flow as well as heat and mass transfer. The parameters involved in this study are the viscoelastic parameter \( K \), stretching ratio \( c \), unsteadiness parameter \( \xi \), Soret number \( Sr \), chemical reaction parameter \( Cr \), radiation parameter \( R_d \), Dufour number \( Df \) and heat generation/absorption parameter \( Hg \) with constant value \( Pr = 1.0 \) and \( Sc = 1.0 \) (Prandtl and Schmidt numbers).

Figures 2(a-d) show the effect of unsteady parameter on velocities, concentration and temperature profiles for both viscoelastic and viscous fluids. It is seen that the velocity in both directions are decrease by increasing the unsteady parameter. The fluid concentration and temperature increase by rising the unsteadiness of the flow. Also seen that the momentum boundary layers and thermal boundary layer thicknesses of viscoelastic fluid are small compared to viscous fluid due to the development of tensile stress. But the opposite trend is occur on solutal boundary layer. The variations of \( c \) on \( x \)-component & \( y \)-component velocities are plotted in figures 3(b-c). These graphs show that there is no much difference between steady and unsteady flows. Further scrutinizing these figures, the \( y \)-component velocity is more affected than the \( x \)-component velocity with stretching ratio parameter.
Figures 4(a-b) exhibit the variations of chemical reaction parameter on \( \phi \) of viscoelastic & viscous fluids for steady & unsteady flows and found that the solutal boundary layer thickness becomes thinner for rising \( Cr \) values for both fluids. It is also found that the solutal boundary layer thickness of steady flow is higher compared to the unsteady flow for Newtonian fluid. The solutal boundary layer overshoot near the surface when \( Cr \geq 0.5 \). The destructive chemical reaction(\( Cr < 0 \)) is more pronounced on concentration than the generative(\( Cr > 0 \)) chemical reaction parameter. The reverse phenomena are found for viscoelastic fluid. The effects of \( Hg \) on temperature profile of viscoelastic and viscous fluids for steady and unsteady flows. The presence of heat generation parameter boost up the fluid thermal state and this causes to rises the fluid temperature. However, the heat absorption parameter reduce the thermal state of the fluid and this reduces the fluid temperature. In addition, thickness of steady flow is larger compared to the unsteady flow for Newtonian fluid. However, the opposite trend is found for viscoelastic fluid.

Figures 6(a-b) depict the influence of \( Rd \) on \( \theta \) of viscoelastic and viscous fluids for both flows. It is found that the temperature reduces with radiation parameter for all cases considered here. Since, the large values of this parameter increases the conduction over radiation, this causes the thinning the thickness of thermal boundary layer. Table 2 shows the variation of \( C_{f_s}\sqrt{Re} \) and \( C_{f_s}\sqrt{Re} \) for various values of \( c \) and \( K \) for both flows and conclude that the both skin frictions are decreases on increasing the values of \( c \) and \( K \) for both flows. The variations of Sherwood number and Nusselt number for different values of \( Sr, Df, Hg, Rd \) and \( Cr \) for both flows are presented in Tables 3-4. We seen that the mass transfer rate develops on enlarging the value of \( Df, Hg \) and \( Cr \). However, it reduces on increasing the values of \( Cr \). The opposite trend is obtained in heat transfer case. In addition, the \( Sh/\sqrt{Re} \) and \( Nu/\sqrt{Re} \) raises on rising the value of radiation parameter, upto 3. After that, these numbers tends to decreases on increasing the radiation parameter.

5. Correlation Analysis
Thermal engineers implement the correlation equations to design the thermal system and analyze its performance. The correlation equation are derived using linear regression analysis. The correlation equations of \( C_{f_s}\sqrt{Re} \) and \( C_{f_s}\sqrt{Re} \), \( Sh/\sqrt{Re} \) and \( Nu/\sqrt{Re} \) for steady flow and unsteady flow are derived by:

**Steady flow:**
\[
\begin{align*}
C_{f_s}\sqrt{Re} & = -0.240297 - 0.938395c - 11.868233K \\
C_{f_s}\sqrt{Re} & = 1.271734 - 3.043985c - 8.116018K \\
Sh/\sqrt{Re} & = 0.591622 - 0.388394Sr + 0.096686Df + 0.133034Hg + 0.002473Rd + 0.695520Cr \\
Nu/\sqrt{Re} & = 0.050941 - 0.013095Sr - 0.879441Df - 1.406978Hg + 0.046395Rd - 0.059531Cr
\end{align*}
\]

**Unsteady flow:**
\[
\begin{align*}
C_{f_s}\sqrt{Re} & = -0.051107 - 0.9516667c - 15.130832K \\
C_{f_s}\sqrt{Re} & = 1.560449 - 3.1451499c - 11.587690K \\
Sh/\sqrt{Re} & = -0.050562 - 0.434874Sr + 0.039100Df + 0.110494Hg + 0.007968Rd + 1.317991Cr \\
Nu/\sqrt{Re} & = -0.165801 - 0.044384Sr - 0.905395Df - 1.873173Hg + 0.050332Rd - 0.105819Cr
\end{align*}
\]

The variables are used in the range of \( 0 \leq c \leq 1.5 \), \( 0 \leq K \leq 0.3 \), \( 0 \leq Sr \leq 0.9 \), \( 0 \leq Df \leq 0.9 \), \( -0.5 \leq Hg \leq 0.5 \), \( 1 \leq Rd \leq 10 \) and \( -0.5 \leq Cr \leq 1 \).
6. Conclusions
Analytical solutions are obtained for 3D viscoelastic fluid flow stretchy paper with radiation, chemical reaction, Soret and Dufour effects. The homotopy analysis method is used to solve governing equations. The following results are observed. The both velocities and its associated boundary layer thicknesses reduce with increasing the unsteady parameter. The solutal and thermal boundary layer thicknesses enlarge in unsteady flow and it suppresses in steady flow case. The destructive chemical reaction is more pronounced on concentration than the generative chemical reaction parameter. The temperature suppresses with rising the radiation parameter. The skin friction coefficient compresses on increasing the stretching ratio and viscoelastic parameter.

Table 1. Comparison of $-f''(0)$ and $-g''(0)$ for different $c$ values with Ref. [13].

| $c$  | Our study | Ref. [13] | Our study | Ref. [13] |
|------|-----------|-----------|-----------|-----------|
| 0.0  | 1.0000000 | 1.000000  | 0.0000000 | 0.000000  |
| 0.2  | 1.039495  | 1.039495  | 0.148737  | 0.148736  |
| 0.4  | 1.075788  | 1.075788  | 0.349209  | 0.349208  |
| 0.6  | 1.109947  | 1.109946  | 0.590529  | 0.590528  |
| 0.8  | 1.142489  | 1.142488  | 0.866684  | 0.866682  |
| 1.0  | 1.173712  | 1.173720  | 1.173712  | 1.173720  |

Table 2. Variation of the $C_{f_x} \sqrt{Re}$ & $C_{f_y} \sqrt{Re}$ for different parameters.

| $\xi$ | $c$ | $K$ | $C_{f_x} \sqrt{Re}$ | $C_{f_y} \sqrt{Re}$ |
|-------|-----|-----|---------------------|---------------------|
| 0.0   | 0.0 | 0.1 | -1.370320           | 0.000000            |
| 0.5   | 1.771246 | -0.780211 |
| 1.0   | -2.252807 | -2.252807 |
| 1.5   | -2.862666 | -4.501435 |
| 0.1   | 0.0 | 0.1 | -1.450284           | 0.000000            |
| 0.5   | -1.864647 | -0.830074 |
| 1.0   | -2.366984 | -2.366984 |
| 1.5   | -3.009172 | -4.705127 |
| 0.0   | 0.5 | 0.0 | -1.093095           | -0.465205           |
| 0.1   | -1.771246 | -0.780424 |
| 0.2   | -2.715729 | -1.305447 |
| 0.3   | -4.645470 | -3.076545 |
| 0.1   | 0.5 | 0.0 | -1.122876           | -0.481926           |
| 0.1   | -1.864647 | -0.830074 |
| 0.2   | -2.957389 | -1.454996 |
| 0.3   | -5.662016 | -4.160667 |
Figure 1. $h$ curves of $f''(0)$ & $g''(0)$ (a) and $\phi'(0)$ & $\theta'(0)$ (b) with $\xi = 0.1$, $K = 0.1$, $c = 0.5$, $Cr = 1.0$, $Sr = 0.2$, $Rd = 10.0$, $Hg = -0.5$ and $Df = 0.2$.

Figure 2. $x$– component velocity (a), $y$– component velocity (b), concentration profile (c) and temperature profile (d) for different values of $\xi$ and $K$ with $c = 0.5$, $Cr = 1.0$, $Sr = 0.2$, $Rd = 10.0$, $Hg = -0.5$ and $Df = 0.2$.

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Table 3. Variation of the Sherwood number and Nusselt number for different parameters with $\xi = 0$

| $Sr$ | $Df$ | $Hg$ | $Rd$ | $Cr$ | $Sh/\sqrt{Re}$ | $Nu/\sqrt{Re}$ |
|------|------|------|------|------|----------------|----------------|
| 0.0  | 0.2  | -0.5 | 10.0 | 1.0  | 1.249833       | 0.919235       |
| 0.3  |      |      |      |      | 1.144574       | 0.935436       |
| 0.6  |      |      |      |      | 1.032036       | 0.952921       |
| 0.9  |      |      |      |      | 0.911191       | 0.971877       |
| 0.2  | 0.0  | -0.5 | 10.0 | 1.0  | 1.161419       | 1.076941       |
| 0.3  |      |      |      |      | 1.190321       | 0.853802       |
| 0.6  |      |      |      |      | 1.221743       | 0.614226       |
| 0.9  |      |      |      |      | 1.256070       | 0.355792       |
| 0.2  | 0.2  | -0.5 | 10.0 | 1.0  | 1.180424       | 0.929902       |
|      |      |      |      |      | 1.197633       | 0.796988       |
|      |      |      |      |      | 1.228654       | 0.545009       |
|      |      |      |      |      | 1.276674       | 0.098946       |
|      |      |      |      |      | 1.349099       | -0.775663      |
| 0.2  | 0.2  | -0.5 | 1.0  | 1.0  | 1.139542       | 0.136871       |
| 3.0  |      |      |      |      | 1.193495       | 1.038875       |
| 5.0  |      |      |      |      | 1.186724       | 0.978404       |
| 10.0 |      |      |      |      | 1.180424       | 0.929902       |
| 0.2  | 0.2  | -0.5 | 10.0 | -0.5 | -0.545922      | 1.173486       |
|      |      |      |      |      | 0.182992       | 1.085522       |
|      |      |      |      |      | 0.576328       | 1.028251       |
|      |      |      |      |      | 0.929192       | 0.971920       |
|      |      |      |      |      | 1.180424       | 0.929902       |

Figure 3. $x-$ component velocity (a) and $y-$ component velocity (b) for different values of $c$ and $\xi$ with $K = 0.1$, $Cr = 1.0$, $Sr = 0.2$, $Rd = 10.0$, $Hg = -0.5$ and $Df = 0.2$. 
Table 4. Variation of the Sherwood number and Nusselt number for different parameters with ξ = 0.1

| Sr | Df | Hg | Rd | Cr | Sh/√Re  | Nu/√Re |
|----|----|----|----|----|---------|--------|
| 0.0| 0.2| -0.5| 10.0| 1.0| 1.233696| 0.896519|
| 0.3|    |    |    |    | 1.131390| 0.912345|
| 0.6|    |    |    |    | 1.021972| 0.929424|
| 0.9|    |    |    |    | 0.904439| 0.947942|
| 0.2| 0.0| -0.5| 10.0| 1.0| 1.147344| 1.053240|
| 0.3|    |    |    |    | 1.176077| 0.831217|
| 0.6|    |    |    |    | 1.207316| 0.592821|
| 0.9|    |    |    |    | 1.241446| 0.335643|

| ξ  | η | φ(η) | Cr = −0.5, −0.3, 0.0, 0.3, 0.5 |
|-----|----|------|--------------------------------|
| 0.0 | 0.5| 1.5   |                                 |
| 0.1 | 0.5| 1.5   |                                 |

Figure 4. Concentration profile for Newtonian fluid (a) and viscoelastic fluid (b) for different values of Cr and ξ with K = 0.1, c = 0.5, Sr = 0.2, Rd = 10.0, Hg = −0.5 and Df = 0.2.
Figure 5. Temperature profile for Newtonian fluid (a) and viscoelastic fluid (b) for different values of $Hg$ and $\xi$ with $K = 0.1$, $c = 0.5$, $Cr = 1.0$, $Sr = 0.2$, $Rd = 10.0$ and $Df = 0.2$. 

Figure 6. Temperature profile for Newtonian fluid (a) and viscoelastic fluid (b) for different values of $Rd$ and $\xi$ with $K = 0.1$, $c = 0.5$, $Cr = 1.0$, $Sr = 0.2$, $Hg = -0.5$ and $Df = 0.2$.

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