Effect of Thermo Diffusion and Chemical Reaction on Heat and Mass Transfer in a Power Law Fluid over a Flat Plate with Heat Generation

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Abstract. The present study examines the convection heat and mass transfer in a power law fluid over a flat plate in the presence of adverse pressure gradient, heat generation, diffusion - thermo effect and chemical reaction. The governing coupled non-linear partial differential equations describing the flow problem are transformed into non-linear ordinary differential equations by method of similarity transformation. The resulting similarity equations are solved numerically using Runge-Kutta shooting method. The results are presented as velocity, temperature and concentration profiles for pseudoplastic fluid and for different values of parameters entering into the problem. The skin friction, rate of heat transfer and mass transfer are presented numerically in tabular form. In addition, the results obtained showed that these parameters have significant influence on the flow, heat and mass transfer.

Keywords: power law fluid, heat and mass transfer, pressure gradient, heat generation, diffusion - thermo effect, chemical reaction

1 Introduction

It is well known that most fluids which are encountered in chemical and allied processing applications do not adhere to the classical Newtonian viscosity postulate and are accordingly known as non-Newtonian fluids. One particular class of materials which are of considerable practical importance is that in which the viscosity depends on the shear stress or on the flow rate. Most slurries, suspensions and dispersions, polymer solutions, melts and solutions of naturally occurring high-molecular-weight, synthetic polymers, pharmaceutical formulations, cosmetics and toiletries, paints, biological fluids, synthetic lubricants and foodstuffs, exhibit complex rheological behaviour which is not experienced when handling ordinary low-molecular-weight Newtonian fluids such as air, water, silicon oils, etc.

Due to the importance of the applications of non-Newtonian fluids for the design of equipment and in industrial processing, considerable efforts have been directed towards the analysis and understanding of such fluids. Non-Newtonian fluid behaviour has been the subject of recent researches by engineers and scientists. Historically, the boundary layer flow past a flat plate was first example considered by Blasius to illustrate the application of Prandtl’s boundary layer theory. Ali [1] discussed the problem of coupled heat and mass transfer by natural convection from a vertical impermeable semi-infinite flat plate embedded in a non-uniform non-metallic porous medium in the presence of thermal dispersion effects. It is found that the variable porosity of the porous medium and the effect of thermal dispersion result in an increase in the local Nusselt number. Acrivos et. al [2] considered the momentum and heat transfer for a non-Newtonian fluids past arbitrary external surfaces.

Afify [3] investigated the effect of chemical reaction on free convective flow and mass transfer of a viscous incompressible fluid and electrically conducting fluid over a stretching in the presence of a constant transverse magnetic field. Ahmet and Muharrem [4] investigated the pressure gradient flow rate relationship for steady state non-isothermal pressure driven flow of a non-Newtonian fluid in a channel including the effect of viscous heating. The viscosity of the fluid depends on both temperature and shear rate. The effects of the activation energy parameter and the Brinkman number as well as the power law index and material time constant on the flow are studied. Ali [5] presented the numerical solution

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of the problem of steady, laminar, buoyancy-induced flow by natural convection along a vertical permeable surface immersed in a thermally-stratified environment in the presence of magnetic field and heat generation or absorption effects. Ali [6] studied the asymptotic solution for small and large values of the distance from the leading edge of the plate for the analysis of the problem the convection-radiation interaction heat transfer in boundary-layer flows over a semi-infinite flat plate with temperature dependent effective viscosity embedded in a fluid-saturated porous medium in the presence of a magnetic field.

Ali [7, 8] investigated hydromagnetic flow and heat transfer over a non-isothermal permeable surface stretching with a power-law velocity with heat generation and suction/injection effects and in the presence of a non-uniform transverse magnetic field and boundary-layer flow of a viscous, incompressible, electrically conducting and heat-absorbing fluid along a semi-infinite vertical permeable moving plate in the presence of a uniform transverse magnetic field and thermal and concentration buoyancy effects respectively. Ali and Abdul-Rahim [9] examined the problem of coupled heat and mass transfer by mixed convection in a linearly stratified stagnation flow in the presence of an externally applied magnetic field and internal heat generation or absorption effect. Also, Ali and Ali [10] investigated the problem of coupled heat and mass transfer by natural convection from a permeable sphere in the presence of an external magnetic field and thermal radiation effect.

Bird [12] examined unsteady pseudoplastic flow near a moving wall. The power-law index ranges from $n = (\frac{1}{3})$ to $n = (\frac{2}{3})$. He estimated for each $n$ the similarity value $r_1$ for which the fluid velocity has fallen off to 1% of the velocity of the moving wall. The result shows that $r_1$ decreases as $n$ increases.

Chung and Wuladana [13] examined the non-linear stability of steady flow and temperature distribution of a Newtonian fluid in a channel heated from below where the viscosity is a function of temperature. Hassanien et al. [14] presented a boundary layer analysis for the problem of flow and heat transfer from a power law fluid to a continuous stretching sheet with variable wall temperature. Their result showed that the friction factor and heat transfer rate depend strongly on the flow parameters. Howell et al. [15] examined the momentum and heat transfer occurring in the laminar boundary layer on a continuously moving and stretching two dimensional surface in non-Newtonian fluid. Their results include situation when the velocity is nonlinear and when the surface is stretched linearly. Ibrahim et al. [16] investigated the method of similarity reduction for problems of radiative and magnetic field effect on free convection and mass transfer flow past a semi-infinite flat plate. Kelly et al. [17] studied a non-conventional fluid dynamic problem by means of the boundary layer approximation. They presented analysis of the asymptotic behaviour of the solutions for small and high values of the non-dimensional numbers that govern the energy and diffusion equation.

Makinde [18] examined the free convection flow with thermal radiation and mass transfer past a moving vertical porous plate. The plate is maintained at a uniform temperature with uniform species concentration and the fluid is considered to be gray, absorbing-emitting. Marusic - Paloka [19] examined the steady flow of a dilatant non-Newtonian fluid obeying the power law in unbounded channels and pipes. A proof of existence and uniqueness of the solution for Leray's problem is given as well as the delay estimate for the solution. For the existence result, he applied Galerkins procedure using monotonicity of the principal of the operator and the continuity of the inertial term. The effect of the thermal radiation, suction, thermal diffusion and heat generation on convection heat and mass transfer in a power law fluid were also investigated in [20–24]. Pascal [25] investigated the spread of a gravity current consisting of a fluid of Non-Newtonian power law rheology along a rigid horizontal plane under a shallow layer with a free theory approximation to establish a two layer model which couples the dynamics of the two layers. Sivasankaran et al. [26] investigated the natural convection heat and mass transfer fluid past an inclined semi-infinite porous surface with heat generation using Lie group analysis. Their result revealed that the velocity and temperature of the fluid increases with the heat generation parameter. Also, the velocity of the fluid increases with the porosity parameter and temperature and concentration decreases with the increase in the porosity parameter.

Schowalter [27] applied the boundary layer theory to power law pseudoplastic fluids and developed the two-dimensional and three dimensional boundary layer equations for the momentum transfer. Uzun [28] presented the finite difference solution for laminar heat transfer of a non-Newtonian power law fluid in the thermal entrance region of arbitrary cross sectional ducts with constant wall temperature. In his study, the effects of axial heat conduction, viscous dissipation and thermal energy sources with the fluid were neglected. Yu - shu and Karsten [29] reviewed their previous work relying on the development of a three dimensional, fully implicit, integral finite difference simulation for simple and multi-phase flow of non-Newtonian fluids in porous fractured media. Yurusoy and Pakdemirli [30] examined the exact solution of boundary layer equations of a non-Newtonian fluid over a stretching sheet by the method of lie group analysis and they found that the boundary layer thickness increases when the non-Newtonian behaviour increases. Over the years, a con-
A steady two dimensional laminar boundary layer flow of an incompressible reacting power law fluid over a flat plate with velocity

\[ u(x) = U_0 x^{\alpha - 1} \]  

(1)
is considered. The pressure gradient along the plate can be computed from Euler’s equation, so that

\[ \frac{\partial p}{\partial x} = -\rho \left( \frac{\alpha - 1}{2} \right) U_0 x^{\alpha - 2} \]  

(2)

In a region of decreasing pressure along the flow direction, the net pressure acting on the fluid tends to accelerate it; in which case the pressure is called favourable. In a region in which pressure increases along the flow direction, it is called an adverse pressure gradient. Thus, (2) implies that, for a pseudoplastic flow in the presence of an adverse pressure gradient, the pressure is called favourable. In a region in which pressure increases along the flow direction, the relations between the fluxes and the driven potential are important. It has been found that an energy flux can be generated not only by temperature gradients but by composition gradient as well. The energy caused by a composition gradient is called the Dufour or the diffusion-thermo effect, also the mass fluxes can also be created by the temperature gradients and this is called the Soret or thermal diffusion effect, the thermal diffusion effect is neglected in this study because it is of a smaller order of magnitude than the magnitude of rate of chemical reaction which exerts a stronger effect on the mass flux.

This paper extends earlier works by examining the combined effect of heat generation, diffusion thermo effect and chemical reaction on the convection heat and mass transfer in a power law fluid over a vertical flat plate in the presence of pressure gradient. The numerical results are presented as velocity, temperature and concentration profiles for pseudoplastic fluid and for different values of parameters entering into the problem. The skin friction, rate of heat transfer and mass transfer are presented numerically in tabular form.

### 2 Formulation of the problem

A steady two dimensional laminar boundary layer flow of an incompressible reacting power law fluid over a flat plate past a flat plate, especially in Newtonian fluids and to a limited extent in power-law fluids. However, the flow over a flat plate in the presence of adverse pressure gradient is encountered in various applications such as lift designs. Most of the work above have neglected pressure gradient. It should be noted that numerous fluids of industrial importance display shear-thinning characteristics which are conveniently approximated by the power law model. Indeed, many of these fluids (polymer melts, polymer, solutions, food, emulsions, suspensions, and biological fluids) exhibit a value of the power-law index, \( n \), typically in the range of 0 and 1. When heat and mass transfer occur simultaneously in a moving fluid, the relations between the fluxes and the driven potential are important. It has been found that an energy flux can be generated not only by temperature gradients but by composition gradient as well. The energy caused by a composition gradient is called the Dufour or the diffusion-thermo effect, also the mass fluxes can also be created by the temperature gradients and this is called the Soret or thermal diffusion effect, the thermal diffusion effect is neglected in this study because it is of a smaller order of magnitude than the magnitude of rate of chemical reaction which exerts a stronger effect on the mass flux.
And the appropriate boundary conditions are:

\[ u = U, \quad v = v_w(x), \quad T = T_w, \quad C = C_w \text{ at } y = 0 \]

\[ u \to 0, T \to T_\infty, \quad C \to C_\infty \quad \text{as } y \to \infty \]  

(7)

3 Method of Solution

Introduce the stream function formulation,

\[ u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x}, \]  

(8)

the continuity equation (2) is automatically satisfied.

Define a similarity variable:

\[ \eta = Ay^{-\frac{1}{n-1}} \]  

(9)

such that

\[ \psi = U f(\eta), \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty} \text{ and } \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty} \]  

(10)

Therefore, equations (4), (5), (6) together with the boundary and initial conditions (7) become:

\[ \nu n (2n - 1) U^{n-2} A^{2n-1} (-f''')^{-1} f''' + U_0^2 - f'^2 - G r_n \theta - G c_n \phi = 0 \]  

(11)

\[ \frac{\nu}{P r_n} (2n - 1) \theta''' - H_n \theta + D_n \phi'' = 0 \]  

(12)

\[ (2n - 1) \phi'' + R_n S c_n \phi' = 0 \]  

(13)

\[ \begin{aligned}
    f &= f_w, \quad f' = 1, \quad \theta = 1, \quad \phi = 1 \text{ at } \eta = 0 \\
    f' &= 0, \quad \theta = 0, \quad \phi = 0 \text{ as } \eta \to \infty
\end{aligned} \]  

(14)

And the dimensionless parameters introduced in equations (11), (12), (13) are as defined below:

\[ G r_n = \frac{x^{2n+1} g \beta (T_w - T_\infty)}{U^2 A^2} \]  

is the thermal Grashof number,

\[ G c_n = \frac{x^{2n+1} g \lambda (C_w - C_\infty)}{U^2 A^2} \]  

is the mass Grashof number,

\[ P r_n = \frac{\nu p c U}{\kappa A x^{2n+1}} \]  

is the mass Grashof number,

\[ H e = \frac{Q (2n - 1) x^{2n+1} \rho c A}{p c U} \]  

is the heat generation parameter,

\[ S c_n = \frac{x^{2n-1}}{D m A^2} \]  

is the Schmidt number,

\[ D_n = \frac{D_n K T (2n - 1) (C_w - C_\infty)}{p c (T_w - T_\infty)} \]  

is the Dufour number,

\[ R_n = \frac{R (2n - 1)}{2 \nu} \]  

is the chemical reaction parameter.
Remark(s): (i) Similarity solution exists for $\alpha = \frac{2n-3}{2n-1}$.

(ii) In the presence of an adverse pressure gradient $\alpha < 1$; $\frac{\partial p}{\partial x} > 0$ implies that $\frac{1}{2} < n < 1$, hence solution exists for pseudoplastic power law fluid. The set of the coupled non-linear differential equations (11), (12), (13) are resolved into system of equations as follow;

$$\begin{pmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4 \\
x_5 \\
x_6 \\
x_7 \\
x_8 \\
\end{pmatrix} = \begin{pmatrix}
\eta \\
f \\
f' \\
f'' \\
\theta \\
\theta' \\
\phi \\
\phi' \\
\end{pmatrix}$$

(15)

Taking the first derivatives of the system of equations (15), then equations (11), (12), (13) together with conditions (14) become

$$\begin{pmatrix}
x_1' \\
x_2' \\
x_3' \\
x_4' \\
x_5' \\
x_6' \\
x_7' \\
x_8' \\
\end{pmatrix} = \begin{pmatrix}
1 \\
x_3 \\
x_4 \\
x_5 \\
x_6 \\
x_7 \\
x_8 \\
\end{pmatrix} + \begin{pmatrix}
\frac{x_2^2 + Gr_n x_5 + Gr_n x_7 - U_0^2}{v n U_0 A^{2n-1}(2n-1)(-x_4)^{n-1}} \\
-x_6 \frac{Pr_n x_2 H \tau}{v(2n-1)} + \frac{2Pr_n D_n Sc_n R_n x_7}{v(2n-1)^2} \\
-x_8 \frac{R_n Sc_n x_5}{(2n-1)} \\
\end{pmatrix}$$

(16)

And the initial conditions in (12) become

$$\begin{pmatrix}
x_1(0) \\
x_2(0) \\
x_3(0) \\
x_4(0) \\
x_5(0) \\
x_6(0) \\
x_7(0) \\
x_8(0) \\
\end{pmatrix} = \begin{pmatrix}
0 \\
1 \\
1 \\
-\gamma \\
1 \\
-\Gamma \\
1 \\
-\beta \\
\end{pmatrix}$$

(17)

Where $\gamma$, $\Gamma$ and $\beta$ are constants to be determined. Problem (16) together with the initial conditions (17) is solved numerically using Runge-Kutta shooting method.

In a shooting method, the missing (unspecified) initial condition at the initial point of the interval is assumed, and the differential equation is then integrated numerically as an initial valued problem to the terminal point. The accuracy of the assumed missing initial condition is then checked by comparing the calculated value of the dependent variable at the terminal point with its given value there. If a difference exists, another value of the missing initial condition must be assumed and the process is repeated. This process is continued until the agreement between the calculated and the given condition at the terminal point is within the specified degree of accuracy. The numerical result is presented as velocity and temperature profiles in figures 1 - 9.

In practical applications, the physical quantities of principal interest are the local skin friction coefficient, local Nusselt number and the Sherwood number which indicate(s) the physical wall shear stress, rate of heat transfer and the

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Figure 1: Velocity profile for various values of the power law exponent.

Figure 2: Velocity profile for various values of Schmidt number.

Figure 3: Velocity profile for different values of the reaction parameter.

Figure 4: Temperature profile for various values of power law exponent.

Figure 5: Temperature profile showing the effect of heat generation parameters.

Figure 6: Temperature profile for different values of the Dufuor effects.

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rate of mass transfer respectively. The local wall shear stress is defined as

\[ \tau_w = \left( -m \frac{\partial u}{\partial y} \right)_{y=0} \]  

And the skin-friction coefficient, \( C_f \) is given by,

\[ C_f = \frac{2\tau_w}{\rho U^2} \quad \text{or} \quad \frac{1}{2} C_f Re = (-f''(0))^n \]  

where \( Re = \frac{\rho U^2}{\mu x} \) is the Reynolds number.

The heat flux, \( q_w \) at the wall is given by,

\[ q_w = -k \left( \frac{\partial T}{\partial y} \right)_{y=0} \]  

And the Nusselt number is given by

\[ Nu = \frac{\frac{U x}{k} q_w}{\kappa \Delta T} = -\theta'(0) \]  

where \( \Delta T = T_w - T_\infty \)

Figure 7: Concentration profiles for various values of the power law exponents with Sc=0.75, R=0.5.

Figure 8: Concentration profile of a pseudoplastic fluid of various values of Schmidt number with Rn=0.5.

Figure 9: Concentration profiles of a pseudoplastic fluid of various values of Reaction rate parameter R with Sc=0.75.
concentration increases with increase in the rate of chemical reaction. Therefore, the velocity decreases with increase in the power law exponents and the velocity increases with increase in the Schmidt number.

R shows that the heat generation parameter increases. Therefore, the velocity decreases with increase in the power law exponents but the mass transfer is low and the skin friction is high. Though, the heat transfer rate is high for a large number of the power law exponents but the mass transfer is low and the skin friction is high.

Table 1: For various values of power law exponents

<table>
<thead>
<tr>
<th>n</th>
<th>Rn</th>
<th>Scn</th>
<th>Hn</th>
<th>Prn</th>
<th>Dn</th>
<th>Grn</th>
<th>Gcn</th>
<th>Sh</th>
<th>Nu</th>
<th>Cf</th>
</tr>
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<tr>
<td>0.6</td>
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<td>0.75</td>
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<td>0.0042397410</td>
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</table>

Table 1: For various values of power law exponents

The mass flux $M_w$ at the wall are given by,

$$M_w = -D_M \left( \frac{\partial C}{\partial y} \right) = -D_M A \Delta C \phi'(0)$$ (22)

And the Sherwood number is given by

$$Sh = \frac{x M_w}{AD_M \Delta C} = -\phi'(0)$$ (23)

where, $\Delta C = C_w - C_\infty$. The skin friction coefficient, Nusselt number and the Sherwood number are obtained numerically and the result is presented in tables 1 - 5.

4 Results and Discussion

Convection heat and mass transfer in reactive power law fluid over a flat plate in the presence of an adverse pressure gradient, chemical reaction, heat generation and thermo diffusion effect have been studied. Figure 1 shows the velocity profile for different values of the power law exponent $n$, $n = 0.6, 0.7, 0.8$ and $0.9$, it is observed that the boundary layer increases with increase in the power law exponents. Figures 2 and 3 show the velocity profile for different values of the Schmidt number $Sc_n$, $Sc_n = 0.75, 1.5, 2.25$ and $3.0$ and different values of the rate of chemical reaction $R_n$, $R_n = 0.5, 0.75, 1.0$ and $1.5$ respectively. It is observed from the figures that the boundary layer grows thicker with decrease in the Schmidt number. The boundary layer decreases with increase in the rate of the chemical reaction. Therefore, the velocity decreases with increase in the power law exponents and the velocity increases with increase in the Schmidt and rate of chemical reaction.

Figure 4 shows that the thermal boundary layer increases with increase in the power law exponents. Figures 5 and 6 display the temperature profiles for different values of diffusion thermo (Dufour) effect $D_n$, $D_n = 0.02, 0.04, 0.08$ and $0.12$ and heat generation parameter $H_n$, $H_n = 0.06, 0.12, 0.18$ and $0.24$ respectively. It is observed from the figures 5 and 6 that as the Dufour number $D_n$ increases the temperature decreases and thermal boundary layer decreases slightly. And, as heat generation increases the temperature increases and thermal boundary layer decreases with increase in the heat generation parameter. Figure 7 shows the concentration profile for various values of the power law exponent $n$, $n = 0.6, 0.7, 0.8$ and $0.9$ and it is observed that the concentration decreases with increase in the power law exponents. Figure 8 shows that the concentration increases with increase in the values of the Schmidt number. Figure 9 shows that concentration increases with increase in the rate of chemical reaction.

Tables 1 - 5 show the effect of power law exponents, heat generation, Schmidt number, diffusion thermo (Dufour) and rate of chemical reaction on the shearing stress, heat transfer and mass transfer which are measured in terms of the skin friction, Nusselt number and Sherwood number respectively.

From table 1, it is observed that the Sherwood number decreases with increase in the power law exponent, the Nusselt number and the skin friction increases with increase in the power law exponent. Thus, a power law fluid with low values of power law exponent gives a high rate of mass transfer and low skin friction. Though, the heat transfer rate is high for large number of the power law exponents but the mass transfer is low and the skin friction is high.

Table 2 clearly shows that, at a constant value of thermal radiation parameter, a low value of heat generation is necessary for high mass transfer and heat transfer, since the skin friction increases and the Nusselt number decreases as the heat generation parameter increases.

It is observed from table 3 that increase in the diffusion thermo (Dufour number) effect enhances increase heat transfer and mass transfer.
### Table 2: Effects of Heat Generation.

<table>
<thead>
<tr>
<th>n</th>
<th>$R_n$</th>
<th>$Sc_n$</th>
<th>$H_n$</th>
<th>$Pr_n$</th>
<th>$D_n$</th>
<th>$Gr_n$</th>
<th>$Gr_n$</th>
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### Table 3: Effect of diffusion thermo (Dufour)

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### Table 4: Effect of Schmidt number

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### Table 5: Effect of Chemical reaction

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<th>$D_n$</th>
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Table 4 shows that increase in the Schmidt number causes an increase in the rate of mass transfer, a decrease in the rate of heat transfer and skin friction.

Table 5 shows that the Sherwood number increases with increase in the rate of chemical reaction. The Nusselt number and skin friction decreases with increase in the rate of chemical reaction.

5 Conclusion

The combined effect of heat generation, diffusion thermo effect and chemical reaction on the convection heat and mass transfer in a reactive power law fluid over a flat plate in the presence of pressure gradient have been studied. From the study, the following conclusion(s) may be drawn:

- The higher the power law exponent, the lower the rate of mass transfer and the higher the rate of heat transfer.

- A high rate of mass transfer and heat transfer is achievable at simultaneous increase in the thermal radiation and heat generation parameters.

- A high diffusion thermo (Dufour number) effect enhances high rate of mass transfer and heat transfer.

- Increase in Schmidt number enhances high rate of mass transfer and a low rate of heat transfer.

- With high rate of chemical reaction, the rate of mass transfer is high and the rate of heat transfer is low.

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References


