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Diffusion of a chemically reactive species of a power-law fluid past a stretching surface

K. Vajravelu [a,*], K.V. Prasad [b], N.S. Prasanna Rao [c]

[a] Department of Mathematics, University of Central Florida, Orlando, FL 32816, USA

[b] Department of Mathematics, Central College Campus, Bangalore University, Bangalore 560001, India

[c] Department of Mechanical Engineering, RNS Institute of Technology, Channasandra, Bangalore 560061, India

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ABSTRACT

A numerical solution for the steady magnetohydrodynamic (MHD) non-Newtonian power-law fluid flow over a continuously moving surface with species concentration and chemical reaction has been obtained. The viscous flow is driven solely by the linearly stretching sheet, and the reactive species emitted from this sheet undergoes an isothermal and homogeneous one-stage reaction as it diffuses into the surrounding fluid. Using a similarity transformation, the governing non-linear partial differential equations are transformed into coupled nonlinear ordinary differential equations. The governing equations of the mathematical model show that the flow and mass transfer characteristics depend on six parameters, namely, the power-law index, the magnetic parameter, the local Grashof number with respect to species diffusion, the modified Schmidt number, the reaction rate parameter, and the wall concentration parameter. Numerical solutions for these coupled equations are obtained by the Keller–Box method, and the solutions obtained are presented through graphs and tables. The numerical results obtained reveal that the magnetic field significantly increases the magnitude of the skin friction, but slightly reduces the mass transfer rate. However, the surface mass transfer strongly depends on the modified Schmidt number and the reaction rate parameter; it increases with increasing values of these parameters. The results obtained reveal many interesting behaviors that warrant further study of the equations related to non-Newtonian fluid phenomena, especially shear-thinning phenomena. Shear thinning reduces the wall shear stress.

1. Introduction

During the past three decades, the study of heat, mass, and momentum transfer in boundary layer flow over a continuously moving surface through a quiescent liquid has attracted considerable attention. This interest is due to several important applications in electrochemistry and polymer processing (see [1,2]) industries. Flows due to a continuously moving surface are often encountered in the aerodynamic extrusion of plastic sheets, the boundary layer along liquid film in condensation processes, the cooling and drying of papers and textiles, and glass fiber production. In view of these applications, Sakiadis [3] initiated a theoretical study for the momentum transfer occurring in the boundary layer adjacent to a continuous surface moving steadily through an otherwise quiescent fluid environment, and this was experimentally verified by Tsou et al. [4]. Crane [5] extended the work of Sakiadis by assuming that the velocity of the sheet varies linearly with the distance from the slit. Thereafter, numerous investigations were made on the stretching sheet problem with linear

* Corresponding author.
E-mail address: vajravel@mail.ucf.edu (K. Vajravelu).

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Nomenclature

b	Stretching rate, a positive constant
B_0	Magnetic field
C	Species concentration in the fluid
C_w	Species concentration near the plate
C_f	Skin friction
C_∞	Species concentration with fluid far away form the plate
D	Chemical molecular diffusivity
E	Constant
f	Dimensionless velocity variable
g	Acceleration due to gravity
Gc_x	Modified Grashof number
$h(x)$	Heat transfer coefficient
H_0	Applied transverse magnetic field
k_1	Chemical reaction parameter
l	Characteristic length
Mn	Magnetic parameter
n	Power-law index
Nsc	Generalized modified Schmidt number for power-law fluids
Re_x	Local Reynolds number
r	Species concentration parameter
$\mathrm{Sh}_w(x)$	Sherwood number
x	Horizontal distance
y	Vertical distance
u	Velocity in the x-direction
U	Velocity of the sheet
v	Velocity in the y-direction

Greek symbols

β^*	Coefficient of expansion with concentration
β	Chemical reaction rate parameter
η	Similarity variable
γ	Kinematic viscosity
ψ	Stream function
ρ	Density
σ	Electrical conductivity
τ_{xy}, τ_{ij}	Shear stress
ϕ	Dimensionless concentration variable
δ_{ij}	Kronecker delta
μ^*	Consistency index of the power-law fluid

Subscripts

w, ∞	Conditions at the surface and in the free stream
η	Differentiation with respect to η

stretching under different physical situations [6–9]. It is well known that a number of industrial fluids such as molten plastics, polymeric liquids, and foodstuffs (or slurries) exhibit non-Newtonian fluid behavior. Therefore, heat and mass transfer in non-Newtonian fluids is of practical importance. Many different types of non-Newtonian fluid exist, but the simplest and most common type is the power-law fluid for which the rheological equation of state between the stress components τ and strain components e is defined by (see [10])

$$\tau_{ij} = -P\delta_{ij} + K\left|\sum\sum e_{lm}e_{lm}\right|^{\frac{n-1}{2}} e_{ij},$$

where P is the pressure, δ_{ij} is the Kronecker delta, and K and n are respectively the consistency and the flow behavior indices of the fluid. Such fluids are known as power-law fluids. For $n > 1$, the fluid is said to be a dilatant or shear-thickening fluid; for $n < 1$, the fluid is called a shear-thinning or pseudo-plastic fluid, and for $n = 1$, the fluid is simply a Newtonian fluid. Several studies in the literature suggest the range $0 < n < 2$ for the value of power-law index n. Schowalter [11]