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Computational study of Jeffrey's non-Newtonian fluid past a semi-infinite vertical plate with thermal radiation and heat generation/absorption

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Abstract The nonlinear, steady state boundary layer flow, heat and mass transfer of an incompressible non-Newtonian Jeffrey's fluid past a semi-infinite vertical plate is examined in this article. The transformed conservation equations are solved numerically subject to physically appropriate boundary conditions using a versatile, implicit finite-difference Keller box technique. The influence of a number of emerging non-dimensional parameters, namely Deborah number (De), ratio of relaxation to retardation times (λ), Buoyancy ratio parameter (N), suction/injection parameter (f_w), Radiation parameter (F), Prandtl number (Pr), Schmidt number (Sc), heat generation/absorption parameter (Δ) and dimensionless tangential coordinate (ξ) on velocity, temperature and concentration evolution in the boundary layer regime is examined in detail. Also, the effects of these parameters on *surface heat transfer rate, mass transfer rate* and *local skin friction* are investigated. This model finds applications in metallurgical materials processing, chemical engineering flow control, etc.

1. Introduction

Non-Newtonian transport phenomena arise in many branches of process mechanical, chemical and materials engineering. Such fluids exhibit shear-stress-strain relationships which diverge significantly from the classical Newtonian (Navier-Stokes) model. Most non-Newtonian models involve some form of modification to the momentum conservation equations. These include power-law fluids [1], viscoelastic fluid model [2], Walters-B short memory models [3], Oldroyd-B models [4], differential Reiner-Rivlin models [5,6], Bingham plastics [7], tangent hyperbolic models [8], Eyring-Powell

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Nomenclature

C	concentration
C_f	skin friction coefficient
c_p	specific heat parameter
De	Deborah number
D_m	mass (species) diffusivity
f	non-dimensional steam function
F	thermal radiation
$\mathbf{g}$	acceleration due to gravity
Gr	Grashof number
K	thermal diffusivity
k	thermal conductivity
k^*	mean absorption coefficient
L	characteristic length
m	pressure gradient parameter
Nu	heat transfer rate (local Nusselt number)
Pr	Prandtl number
q_r	radiative heat flux
$\mathbf{S}$	Cauchy stress tensor
Sc	local Schmidt number
Sh	mass transfer rate (Sherwood number)
T	temperature of the fluid
u, v	non-dimensional velocity components along the x- and y-directions, respectively
x	streamwise coordinate
y	transverse coordinate

Greek symbols

α	thermal diffusivity
β	coefficient of thermal expansion
β^*	coefficient of concentration expansion
λ	ratio of relaxation to retardation times
λ_1	retardation time
η	dimensionless radial coordinate
μ	dynamic viscosity
ν	kinematic viscosity
θ	non-dimensional temperature
ϕ	non-dimensional concentration
ρ	density of fluid
ξ	dimensionless tangential coordinate
ψ	dimensionless stream function
Δ	heat generation (source)/heat absorption (sink) parameter
σ^*	Stefan-Boltzmann constant

Subscripts

w	surface conditions
∞	free stream conditions

models [9], nano non-Newtonian fluid models [59] and Maxwell models [10].

Among the several non-Newtonian models proposed, Jeffrey's fluid model is significant because Newtonian fluid model can be deduced from this as a special case by taking $\lambda_1 = 0$. Further, it is speculated that the physiological fluids such as blood exhibit Newtonian and non-Newtonian behaviors during circulation in a living body. As with a number of rheological models developed, the Jeffrey's model has proved quite successful. This simple, yet elegant rheological model was introduced originally to simulate earth crustal flow problems [11]. This model [12] constitutes a viscoelastic fluid model which exhibits shear thinning characteristics, yield stress and high shear viscosity. The Jeffrey's fluid model degenerates to a Newtonian fluid at a very high wall shear stress i.e. when the *wall stress is much greater than yield stress*. This fluid model also approximates reasonably well the rheological behavior of other liquids including physiological suspensions, foams, geological materials, cosmetics, and syrups. Interesting studies employing this model include peristaltic transport of Jeffery fluid under the effect of magnetohydrodynamic [13], peristaltic flow of Jeffery fluid with variable-viscosity [14], Radiative flow of Jeffery fluid in a porous medium with power law heat flux and heat source [15]. Vajravelu et al. [16] presented the influence of free convection on nonlinear peristaltic transport of Jeffrey fluid in a finite vertical porous stratum using the Brinkman model. Lakshminarayana et al. [17] discussed the influence of slip and heat transfer on the peristatic transport of Jeffrey fluid in a vertical asymmetric channel in porous medium. The governing equations are solved using perturbation technique. The peristaltic flow of a conducting Jeffrey fluid in an inclined asymmetric channel was investigated by K. Vajravelu et al. [18] using perturbation technique. Vajravelu et al. [19] reported the peristaltic flow of Jeffrey fluid in a vertical porous stratum with heat transfer under long wavelength and low Reynolds number assumptions.

The heat transfer analysis of boundary layer flow with radiation is important in various material processing operations including high temperature plasmas, glass fabrication, and liquid metal fluids. When coupled with thermal convection flows, these transport phenomena problems are highly nonlinear. At a high temperature the presence of thermal radiation changes the distribution of temperature in the boundary layer, which in turn affects the heat transfer at the wall. A number of studies have appeared that consider multi-physical radiative-convective flows. Recently, Nadeem et al. [20] reported the magnetic field effects on boundary layer flow of Eyring-Powell fluid from a stretching sheet. Noor et al. [21] used the Rosseland model to study radiation effects on hydromagnetic convection with thermophoresis along an inclined plate. Further, studies employing the Rosseland model include Gupta et al. [22] who examined on radiative convective micropolar shrinking sheet flow, Cortell [23] who investigated non-Newtonian dissipative radiative flow, and Bargava et al. [24] who studied radiative-convection micropolar flow in porous media. Akbar et al. [25] reported the dual solutions in MHD stagnation-point flow of a Prandtl fluid past a shrinking sheet by shooting method.

Convective boundary-layer flows are often controlled by injecting or withdrawing fluid through a heat surface. This can lead to enhanced heating or cooling of the system and can help to delay the transition from laminar to turbulent flow.