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ORIGINAL ARTICLE

Numerical study of entropy generation for forced convection flow and heat transfer of a Jeffrey fluid over a stretching sheet

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Jeffrey fluid;
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Abstract Entropy generation for the steady two-dimensional laminar forced convection flow and heat transfer of an incompressible Jeffrey non-Newtonian fluid over a linearly stretching, impermeable and isothermal sheet is numerically investigated. The governing differential equations of continuity, momentum and energy are transformed using suitable similarity transformations to two nonlinear coupled ordinary differential equations (ODEs). Then the ODEs are solved by applying the numerical implicit Keller's box method. The effects of various parameters of the flow and heat transfer including Deborah number, ratio of relaxation to retardation times, Prandtl number, Eckert number, Reynolds number and Brinkman number on dimensionless velocity, temperature and entropy generation number profiles are analyzed. The results reveal that the entropy generation number increases with the increase of Deborah number while the increase of ratio of relaxation to retardation times causes the entropy generation number to reduce. A comparative study of the numerical results with the results from an exact solution for the dimensionless velocity gradient at the sheet surface is also performed. The comparison shows excellent agreement within 0.05% error.

1. Introduction

During the last few decades, researchers have shown much interest in the flows of non-Newtonian fluids. The reason for such accelerating interest is in fact due to the wide range of applications of non-Newtonian fluids. The non-Newtonian fluids have applications in various areas such as in chemical and petroleum industries, geophysics and biological sciences. The flows of non-Newtonian fluids have governing equations which are more complex than the Navier–Stokes equations. The governing equations for flows of non-Newtonian fluids are in fact the consequence of the constitutive relations which are used to predict the rheological behavior of these fluids. Due to versatile nature of the non-Newtonian fluids, various constitutive relations have been considered in the literature. One of the various constitutive relations used for non-Newtonian fluids is the Jeffrey fluid model. The Jeffrey fluid model is a linear

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Nomenclature

a	stretching rate (s^{-1})
Br	Brinkman number ($=\mu\cdot(u_w)^2/k\cdot\Delta T$) (–)
$C_{f,x}$	local skin friction coefficient ($=(1+\beta)f''(0)/(1+\lambda)Re_x^{0.5}$) (–)
C_p	specific heat at constant pressure of the fluid (J kg^{-1} K^{-1})
Ec	Eckert number ($=(u_w)^2/C_p(T_w-T_\infty)$) (–)
f	dimensionless velocity variable ($=-v/(a\upsilon)^{0.5}$) (–)
k	thermal conductivity (W m^{-1} K^{-1})
m	power of exact solution in Eq. (12) (–)
Nu_x	local Nusselt number ($=-\theta'(0)/Re_x^{-0.5}$) (–)
N_S	entropy generation number (–)
Pr	Prandtl number ($=\mu C_p/k$) (–)
Re_x	local Reynolds number ($=u_w x/\upsilon$) (–)
S_{gen}	local volumetric entropy generation rate (W m^{-3} K^{-1})
$(S_{gen})_0$	characteristic entropy generation rate (W m^{-3} K^{-1})
T	temperature variable (K)
T_w	given temperature of the sheet (K)
T_∞	temperature of fluid far away from the sheet (K)
ΔT	sheet and free-stream temperature difference ($=T_w-T_\infty$) (K)
u	velocity in x-direction (m s^{-1})
u_w	velocity of the sheet (m s^{-1})
v	velocity in y-direction (m s^{-1})
x	horizontal coordinate (m)
y	vertical coordinate (m)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	Deborah number ($=a\lambda_1$) (–)
η	similarity variable ($=y(a/\upsilon)^{0.5}$) (–)
θ	dimensionless temperature variable ($=T-T_\infty/T_w-T_\infty$) (–)
λ	ratio of relaxation to retardation times (–)
λ_1	relaxation time (s)
μ	dynamic viscosity (N s m^{-2})
υ	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
ψ	stream function (m^2 s^{-1})
Ω	dimensionless temperature difference ($=\Delta T/T_\infty$) (–)

Subscripts

∞	infinity
f	fluid
w	sheet surface

model which uses time derivatives instead of convected derivatives which are used for example in the Maxwell fluid model.

The area of non-Newtonian fluid flow and heat transfer has been given much attention in the last few years. For instance, Molla and Yao [1] investigated mixed convection heat transfer of non-Newtonian fluids over a flat plate using a modified power-law viscosity model. They solved the boundary layer equations by marching from the leading edge downstream and presented the numerical results for a shear-thinning fluid in terms of velocity and temperature distribution. Hayat et al. [2] studied the magneto-hydrodynamic (MHD) flow of a Jeffery fluid in a porous channel. They constructed series solutions to the nonlinear problem by using the homotopy analysis method (HAM). Sahoo [3] considered the flow and heat transfer of a non-Newtonian third grade fluid due to a linearly stretching plate with partial slip. He adopted a second order numerical scheme to solve the differential equations and obtained the combined effects of the partial slip and the third grade fluid parameter on velocity and temperature fields. Prasad et al. [4] considered the steady viscous incompressible two-dimensional MHD flow of an electrically conducting power law fluid over a vertical stretching sheet. They assumed the stretching of surface velocity and the prescribed surface temperature to vary linearly with the distance from the slit and solved the boundary layer equations by Keller's box method. Hayat et al. [5] investigated the three-dimensional flow of Jeffery fluid over a linearly stretching surface and solved the nonlinear coupled system of governing equations using a homotopy analysis method. Hayat et al. [6] studied the unsteady boundary layer flow and heat transfer of an incompressible Jeffery fluid over a linearly stretching sheet. They obtained the analytical solutions of the arising differential system by homotopy analysis technique. Khan et al. [7] presented a mathematical model for unsteady stagnation point flow of a linear viscoelastic fluid bounded by a stretching/shrinking sheet. They solved the resulting nonlinear problems by a homotopy analysis approach. Malik et al. [8] considered the Jeffrey fluid flow with a pressure-dependent viscosity. They numerically solved two types of flow problem, namely, Poiseulle flow and Couette flow for the Jeffrey fluid. Hayat et al. [9] examined the flow and heat transfer of an incompressible Jeffery fluid over a stretching surface with power law heat flux and heat source in the presence of thermal radiation. They developed homotopic solutions for velocity and temperature fields. Hayat et al. [10] investigated the boundary layer stretched flow and heat transfer of a Jeffrey fluid subject to convective boundary conditions. They solved the governing dimensionless equations by using the homotopy analysis approach. They analyzed the influence of embedded parameters and found that the temperature is an increasing function of the Biot number. Turkyilmazoglu and Pop [11] investigated the flow and heat transfer of a Jeffrey fluid near the stagnation point over a stretching/shrinking sheet with a parallel external flow. They indicated that structure of the analytical solutions strongly depends on a parameter measuring the ratio of strength of the external flow to surface stretching/shrinking. Goyal and Bhargava [12] analyzed the effect of velocity slip on the MHD flow and heat transfer of non-Newtonian nanofluid over a stretching sheet with a heat source/sink. They also considered the Brownian motion and thermophoresis effects and solved the differential equations by the variational finite element method. Qasim [13] studied the combined effects of heat and mass transfer in Jeffrey fluid over a stretching sheet in the presence of heat source/sink.

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