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Entropy analysis for magnetohydrodynamic flow and heat transfer of a Jeffrey nanofluid over a stretching sheet

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ABSTRACT

Entropy generation for steady laminar two-dimensional forced convection magnetohydrodynamic (MHD) boundary layer flow, heat transfer and mass transfer of an incompressible non-Newtonian nanofluid over a linearly stretching, impermeable and isothermal sheet with viscous dissipation is numerically studied. The nanofluid model is considered by using the Brownian motion and thermophoresis effects. The Jeffrey model is used to denote the non-Newtonian fluid. The boundary layer continuity, momentum, energy, and concentration equations are transformed by using appropriate similarity transformations to three nonlinear coupled ordinary differential equations (ODEs). Then, the ODEs are solved by applying an implicit Keller's box numerical algorithm. The influence of various controlling parameters including ratio of relaxation to retardation times, Deborah number, Eckert number, Brownian motion parameter, thermophoresis parameter, and Lewis number on flow, heat transfer, mass transfer, and entropy generation characteristics is examined and discussed. Graphical presentation of the numerical examination is performed to illustrate the influence of various parameters on velocity, temperature, nanoparticles volume fraction, and entropy generation number profiles. The results reveal that the entropy generation number strongly varies by variations in Reynolds number, Prandtl number, Lewis number, and thermophoresis parameter. A comparative study of our numerical results with the results from previous works is also performed which shows excellent agreement.

1. Introduction

It is known that many fluids behavior used in industry differ deeply from the Newtonian fluids in their rheology. These kinds of fluids, called non-Newtonian fluids, have wide and practical applications in various branches of science and engineering, for instance, in wire and blade coating, plastics manufacturing, dying of papers and textiles, food processing, movement of biological fluids, etc. Therefore, non-Newtonian fluids rheology has attracted the attention of researchers during the past few decades. However, the Navier–Stokes equations cannot effectively describe the flow of non-Newtonian fluids. Also, such fluids cannot be analyzed by a single constitutive relationship between shear stress and rate of strain. Thus, there is no model which can lonely foretell the behavior of all these fluids. Due to this reason, several models of such fluids have been suggested in the literature. Among the various non-Newtonian fluid models, the Jeffrey model is a linear one for which time derivatives are used instead of convected derivatives.

Literature survey indicates that interest in investigating the behavior of non-Newtonian fluids flow in different geometries and applications has grown in the last decade [1–13]. Kothandapani and Srinivas [14] studied the peristaltic flow of a Jeffrey fluid in an asymmetric channel under long wavelength and low Reynolds number assumptions. They constructed analytical expressions for streamfunction, axial velocity and axial pressure gradient. They found that the axial velocity for the magnetohydrodynamic (MHD) fluid flow is less when compared with hydrodynamic fluid flow in the central part of the channel. Hayat et al. [15] analyzed the MHD flow of Jeffery fluid in a porous channel by homotopy analysis method (HAM). Nadeem and Akram [16] studied the peristaltic flow of a Jeffrey fluid in a rectangular duct. They found the exact solutions of velocity and

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pressure gradient under the assumptions of long wave length and low Reynolds number. They also numerically evaluated the expression for pressure rise in the rectangular duct. Hayat et al. [17] studied the three-dimensional rotational flow of non-Newtonian fluid over a shrinking surface with suction. They considered the Jeffrey model in their investigation. They found that the magnitude of the velocity components increases with an increase in the suction parameter. They also observed that the applied magnetic field retards the flow near the shrinking sheet. In Ref. [18], Hayat et al. studied the flow and heat transfer characteristics over a continuously moving surface in the presence of a free stream velocity where the Jeffrey fluid was treated as a rheological model. They found that the boundary layer thickness is an increasing function of local Deborah number. In Ref. [19], Hayat et al. investigated the boundary layer flow and heat transfer of an incompressible Jeffrey fluid. They obtained exact solutions of the momentum equation and numerical solutions of the dimensionless energy equations for the steady-state case. Their results indicated an increase in the velocity and the boundary layer thickness by increasing the elastic parameter (Deborah number) for a Jeffrey fluid. Akbar and Nadeem [20] considered the Jeffrey fluid model of blood flow through a tapered artery with a stenosis and variable viscosity. They calculated the analytical solutions of the governing equations along with the boundary conditions of stenosed symmetric artery. They noticed that the impedance resistance increases for converging tapering, diverging tapering, and non-tapered arteries when they increase retardation time and stenosis shape, while decreases when they increase relaxation time and viscosity parameter. In Ref. [21], Akbar and Nadeem investigated the slip and heat transfer effects on the peristaltic flow of a six constant Jeffrey's model in an inclined asymmetric channel. They derived the governing equations of the six constant Jeffrey model for two-dimensional and two directional flows in a Cartesian coordinate system. Hayat et al. [22] investigated the three-dimensional flow of incompressible Jeffrey fluid over a linearly stretching surface by using HAM. Domairry et al. [23] investigated the natural convection of a non-Newtonian copper-water nanofluid between two infinite parallel vertical flat plates. They analytically solved the governing differential equations using the differential transformation method (DTM) and indicated that as the nanoparticles volume fraction increases, the momentum boundary layer thickness increases whereas the thermal boundary layer thickness decreases. Turkyilmazoglu and Pop [24] investigated the flow and heat transfer of a Jeffrey fluid near the stagnation point on a stretching/shrinking sheet with a parallel external flow. Their main concern was to analytically investigate the structure of the solutions which might be unique or multiple. They showed that structure of the solutions strongly depends on a parameter measuring the ratio of strength of the external flow to surface stretching/shrinking. Akbar et al. [25] studied the Jeffrey fluid model for the peristaltic flow of chyme in a small intestine. They formulated the problem using two non-periodic sinusoidal waves of different wavelengths propagating with the same speed along the outer wall of the tube. It was seen that magnetic field highly influenced the peristaltic flow problem. Qasim [26] studied the combined effects of heat and mass transfer in Jeffrey fluid flow over a stretching sheet in the presence of heat source/sink. He observed that the velocity increases with an increase in Deborah number. He also indicated that the temperature is a decreasing function of Deborah number and the thermal boundary layer thickness decreases by increasing the wall temperature and heat sink parameters. Akram and Nadeem [27] discussed the peristaltic motion of a two-dimensional Jeffrey fluid in an asymmetric channel under the effects of induced magnetic field and heat transfer. They simplified the problem by using long wavelength and low Reynolds approximations. They observed that the pressure rise for sinusoidal wave is less than trapezoidal wave and greater than triangular wave in a Jeffrey fluid. Nadeem et al. [28] studied the steady flow of a Jeffrey fluid in the presence of nanoparticles. They discussed the pertinent parameters of nano non-Newtonian fluid. They found that reduced Nusselt number is decreasing function and reduced Sherwood number is increasing function of Brownian motion parameter N_b and thermophoresis parameter N_t.

Many researchers, in the last decade, have investigated the entropy generation in flow and heat transfer over surfaces. For instance, Aiboud and Saouli [29] studied entropy generation analysis in viscoelastic MHD flow over a stretching surface. Butt et al. [30] presented the effects of velocity slip on entropy generation in the boundary layer flow over a vertical sheet with convective boundary condition. Noghrehabadi et al. [31] considered entropy generation of a nanofluid flow over a stretching sheet with heat generation/absorption. Rashidi et al. [32] considered the first and second law analyzes of an electrically conducting fluid past a rotating disk in the presence of a uniform vertical magnetic field, analytically via HAM, and then applied Artificial Neural Network and Particle Swarm Optimization algorithm in order to minimize the entropy generation. Abolbashari et al. [33] employed the HAM to study the entropy generation in an unsteady MHD nanofluid flow adjacent to a stretching surface with the water as the base fluid and different types of nanoparticles. Further literature survey reveals that, so far, the entropy generation has not been investigated for the flow and heat transfer of a Jeffrey nanofluid over a stretching surface.

The purpose of the present study is to numerically investigate the entropy generation for steady 2-D laminar MHD flow, heat and mass transfer of an incompressible Jeffrey nanofluid over a linearly stretching sheet. To the best of the authors' knowledge, no paper in the literature has so far studied entropy generation in Jeffrey nanofluid over a stretching sheet. In this regard, the proper similarity transformations have been utilized for the reduction of governing partial differential equations into ordinary differential equations. The obtained solution has been analyzed by plotting graphs of dimensionless velocity, temperature, nanoparticles volume fraction, and entropy generation.

2. Mathematical formulation

A steady 2-D laminar forced convection flow of an incompressible Jeffrey nanofluid past a linearly stretching impermeable isothermal sheet in the region $y > 0$ is considered. The origin of the coordinates is fixed and the x- and y-directions of axes are applied along and perpendicular to the sheet, respectively. The velocity of the stretching sheet is considered to change linearly with the distance along the sheet ($u_w(x) = ax$; in which $a > 0$ is a constant). A constant magnetic field B_0 is imposed on the fluid flow in the y-direction. The nanofluid model is taken into account by using the Brownian motion and thermophoresis effects. It is assumed that the nanoparticles have a uniform size and shape. In addition, both the fluid phase and nanoparticles are assumed in thermal equilibrium state. Also, the nanoparticles are assumed to be very small in sizes, therefore the slip velocity between the phases is presumed to be negligible. In the presence of magnetic field and viscous dissipation, the continuity, momentum, energy, and concentration equations can be expressed as follows [28,30]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$