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Forced convective heat transfer to Sisko nanofluid past a stretching cylinder in the presence of variable thermal conductivity

Masood Khan [a], Rabia Malik [a,b,*]

[a] Department of Mathematics, Quaid-i-Azam University, Islamabad 44000, Pakistan
[b] Department of Mathematics and Statistics, International Islamic University, Islamabad 44000, Pakistan

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ABSTRACT

This article investigates the influence of variable thermal conductivity on the heat transfer to Sisko nanofluid past a horizontally stretching cylinder in the presence of convective boundary and nanoparticle flux conditions. The local-similarity transformation is used to transfer the governing partial differential equations into the ordinary differential equations. Further, these higher order differential equations are converted into seven first order differential equations which are then solved numerically by employing shooting technique. Interestingly, the analysis reveals that the temperature and concentration profiles are larger in case of flow past a cylinder as compared to the flat plate. In addition, with the increasing N_b the concentration profile decreases but the temperature profile remains unaffected. To prove the authenticity of the obtained numerical results a comparison is made with the HAM results.

1. Introduction

The heat transfer aspect in various manufacturing processes possesses vast applications including microelectronics, fuel cells, hybrid powered engines nuclear reactors, transportations, biomedicine/pharmaceutical processes and pasteurization of food and so forth. In heat transfer process the various thermophysical properties such as thermal conductivity are often considered constant. However, practical situations demand variable behavior from such properties. The thermal conductivity is one of the properties which vary with temperature in an approximately linear manner for liquid metals from 0°F to 400°F [1–4].

On the other hand, due to the growing demands of new technologies such as, microelectronics, chemical production and power station, there is a necessity to develop novel types of fluids which transfer heat more effectively. Heat transfer efficiency of working fluid can likewise be enhanced by increasing the thermal conductivity. In general commonly used heat transfer fluids (e.g. water, ethylene glycol, and engine oil) possess low thermal conductivities when contrasted with the thermal conductivity of solids. The addition of small particles of solids possessing high thermal conductivities to fluids can enhance the thermal conductivity of the fluid. The practicality of the usage of such suspensions of solid particles was investigated by several researchers and huge points of interest were observed [5]. Researchers are permitted because of the recent advances in nanotechnology to study the next generation heat transfer nanofluids, a term first introduced by Choi [6]. Numerous sorts of liquids, such as water, ethylene glycol, engine oil, pump oil and glycerol have been used as host liquids in nanofluids. Whereas, nanoparticles used in nanofluids are of different materials having better thermal conductivity than base fluid. Owing to this, many researchers are persuaded and revolutionary work has been done by them. Rana and Bhargava [7] scrutinized numerically the flow induced by a flat plate stretching with the non-linear velocity in a nanofluid by using variational finite element method. The analysis of slip effects on the boundary layer flow and heat transfer over a linearly stretching surface in the presence of nanoparticle fractions has been made by Noghrehabadi et al. [8]. Heat and mass transfer over a stretching sheet subject to hydromagnetic, viscous dissipation, chemical reaction and Soret effects in Cu–water and Ag–water nanofluids is investigated by Kameswaran et al. [9]. They found that the heat and mass transfer rates at the surface were higher when considering Cu–water nanofluid when compared to a Ag–water nanofluid. Khan et al. [10] obtained the non-similar solutions for the problem of unsteady boundary-layer flows of a nanofluid over a stretching sheet in the presence of magnetic field and thermal radiation by using explicit finite difference method with stability and convergence analysis. Ibrahim et al. [11] analyzed numerically the influence of magnetic field on stagnation point flow and heat transfer towards a stretching sheet due to nanofluid. They found that when the free stream velocity exceeds the stretching velocity the rate of heat transfer at the boundary increases with the magnetic parameter and reverse behavior appears otherwise. Khan et al. [12] addressed the problem of steady three-dimensional flow of an Oldroyd-B nanofluid over a bidirectional stretching surface in the presence of heat generation/absorption effects.

* Corresponding author at: Department of Mathematics, Quaid-i-Azam University, Islamabad 44000, Pakistan.
E-mail address: rabiamalik.qau@gmail.com (R. Malik).

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Observations revealed that with the Brownian motion parameter and thermophoresis parameter temperature profile increases; however, opposite behavior appeared for concentration profile. Khan and Khan [13] explored the steady flow of Burgers' nanofluid over a stretching surface in the presence of heat generation/absorption effects by utilizing homotopy analysis method. Khan et al. [14] scrutinized the two-dimensional boundary layer flow and heat transfer to Sisko nanofluid over a stretching sheet in the concerned study. Their secured results showed that temperature distribution increased with the thermophoresis and Brownian motion parameters and concentration distribution increased with the thermophoresis parameter but decreased with the Brownian motion parameter. The entropy generation for the forced convection MHD boundary layer flow, heat and mass transfers of Jeffrey nanofluid over a linearly stretching sheet with viscous dissipation is numerically studied by Dalir et al. [15]. Their results revealed that the entropy generation number strongly depends on the Reynolds number, Prandtl number, Lewis number, and thermophoresis parameter. Analytical solutions are provided by Abolbashari et al. [16] for the flow, heat and mass transfers and entropy generation for the steady Casson nanofluid flow induced by a stretching sheet in the presence of velocity slip and convective surface boundary conditions by using optimal homotopy analysis method. Series solution for the forced convective analysis for generalized Burgers nanofluid flow over a stretching sheet is determined by Khan and Khan [17].

All the above investigations by various researchers were restricted to the two-dimensional flow and heat transfer of nanofluid over a stretching sheet. However, not much attention is paid to the more intricate problem of the two-dimensional axisymmetric flow due to a stretching cylinder. The main purpose of this study is therefore to investigate the steady two-dimensional flow and heat transfer of Sisko nanofluid past a stretching cylinder with the convective boundary conditions. It is worth pointing out that Sisko fluid is a special case of GNL (Generalized Newtonian Fluid) which predicts shear thinning and shear thickening nature of fluids. Originally, it was introduced to predict the behavior of greases but later it was found that the behavior of cement slurries was also predictable by this model. Its industrial applications include drilling fluids, cement slurries and waterborne coatings etc. Here, the realistic concentration boundary conditions are also used which are introduced by Kuznetsov and Nield [18,19]. The non-similar solutions are obtained numerically by using the shooting technique for shear thinning and shear thickening fluids. These solutions are presented graphically and in tabular form to show the effects of different emerging parameters.

2. Problem formulation

2.1. Governing equations

Consider a steady and axisymmetric boundary layer flow of an incompressible Sisko nanofluid along a continuously stretching horizontal cylinder of radius d with velocity $U = cx$ (see Fig. 1). The cylinder is being stretched and nanofluid is being moved along the axial direction x. The radial coordinate r is measured perpendicular to the cylinder axis. An assumption is made that the cylinder is in contact with a hot fluid at temperature T_f which provides a heat transfer coefficient h_f. Under these assumptions, the governing partial differential equations of the problem under consideration are as follows:

$$\frac{\partial(rv)}{\partial r} + \frac{\partial(ru)}{\partial x} = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial r} = \frac{a}{\rho r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) - \frac{b}{\rho r}\left(-\frac{\partial u}{\partial r}\right)^n + \frac{bn}{\rho}\left(-\frac{\partial u}{\partial r}\right)^{n-1}\frac{\partial^2 u}{\partial r^2}, \tag{2}$$

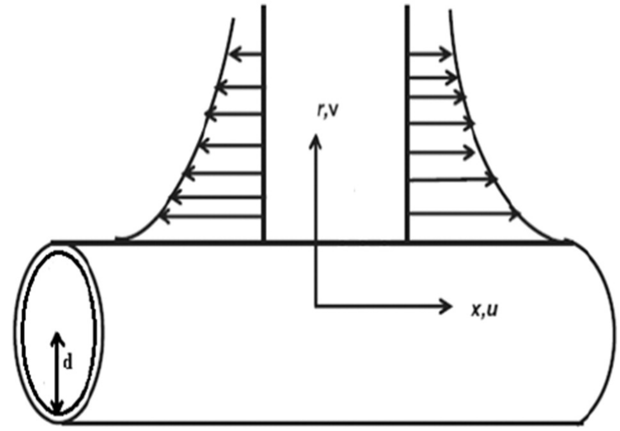

Fig. 1. Physical model and coordinate system.

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial r} = \frac{1}{\rho c_p}\frac{1}{r}\frac{\partial}{\partial r}\left[K(T)r\frac{\partial T}{\partial r}\right] + \tau\left[D_B\frac{\partial C}{\partial r}\frac{\partial T}{\partial r} + \frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial r}\right)^2\right], \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial r} = D_B\frac{\partial^2 C}{\partial r^2} + \frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial r^2}. \tag{4}$$

Here u, v, T and C represent the velocity components along the axial and radial directions, temperature of the fluid and concentration of the species, respectively, n (≥0), a and b represent the material constants associated to the Sisko fluid. We have denoted the fluid density by ρ, specific heat of fluid at constant pressure by c_p, the ratio of effective heat capacity of the nanoparticle material to the heat capacity of the fluid by τ, the Brownian diffusion coefficient by D_B and thermophoresis diffusion coefficient by D_T. The thermal conductivity of the fluid $K(T)$ is assumed to vary linearly with temperature in the form

$$K(T) = k_\infty\left(1 + \varepsilon\left(\frac{T - T_\infty}{\Delta T}\right)\right), \tag{5}$$

where k_∞ represents the thermal conductivity of the fluid far away from the cylinder surface, $\Delta T = T_f - T_\infty$ represents the cylinder surface — fluid temperature difference and ε is a small parameter known as thermal conductivity parameter.

2.2. Boundary conditions

The associated boundary conditions are given as

$$u = U = cx, v = 0, k\frac{\partial T}{\partial r} = -h_f\left[T_f - T\right], D_B\frac{\partial C}{\partial r} + \frac{D_T}{T_\infty}\frac{\partial T}{\partial r} = 0 \text{ at } r = d, \tag{6}$$

$$u \to 0, T \to T_\infty, C \to C_\infty \text{ as } r \to \infty. \tag{7}$$

Here c represents a positive real number, h_f, T_f and T_∞ represent the heat transfer coefficient, hot fluid temperature which heats up the surface of the cylinder and the ambient temperature of the fluid, respectively.

2.3. Local-similarity transformations

The local-similarity transforms are introduced as follows

$$\eta = \frac{r^2 - d^2}{2dx}Re_b^{\frac{1}{n+1}}, \psi = -Udx Re_b^{-\frac{1}{n+1}}f(\eta), \theta(\eta) = \frac{T - T_\infty}{T_f - T_\infty}, \varphi = \frac{C - C_\infty}{C_\infty}. \tag{8}$$