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ORIGINAL ARTICLE

Transpiration effect on stagnation-point flow of a Carreau nanofluid in the presence of thermophoresis and Brownian motion

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Abstract The effect of transpiration on magnetohydrodynamic stagnation-point flow of a Carreau nanofluid toward a stretching/shrinking sheet in the presence of thermophoresis and Brownian motion was investigated numerically. The transformed governing partial differential equations are solved using Runge–Kutta coupled with shooting technique. The effect of pertinent parameters on velocity, temperature and concentration profiles along with the friction factor, local Nusselt and Sherwood numbers is presented graphically and through tables. It is observed that, increasing values of the thermophoresis parameter enhances the heat and mass transfer rate, whereas the Weissenberg number enlarges the momentum boundary layer thickness along with the heat and mass transfer rate. A good agreement of the present results has been observed by comparing with the published results.

1. Introduction

The problem of convective heat and mass transfer past a permeable stretching/shrinking sheet plays a vital role in manufacturing industries in design of reliable equipments. The study of fluid flow through a stretching sheet is a wide area of research, and it has gained the attention of many researchers due to its enormous industrial and engineering applications such as extrusion of plastic and rubber sheets, glass blowing, cooling/drying of papers and textiles, hot rolling polymer processing industries, glass fiber and textile production, petroleum production, crystal growing, wire drawing, fiber spinning, and the cooling of nuclear reactors. In view of these wide varieties of applications Crane [1] has pioneered the work on steady two-dimensional flow over a permeable stretching sheet. Sandeep and Sulochana [2] studied the influence of chemical reaction on MHD mixed convective micropolar fluid flow through a stretching/shrinking surface in the presence of non-uniform heat generation/absorption and observed the dual solutions. Singh and Chamkha [3] observed the dual solutions for viscous fluid flow and heat transfer toward a linearly shrinking plate with second order slip. Nadeem et al. [4] discussed the suction/injection effects on MHD Casson nanofluid flow through

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a nonlinearly shrinking surface in the presence of convective boundary conditions. This study was further extended by many authors such as Mansur et al. [5], Qasim and Noreen [6], Robert et al. [7], Lok and Pop [8], Mahapatra and Samir Kumar [9], Sharma et al. [10], Makinde et al. [11], Raju et al. [12], Bhattacharyya [13], Prakash et al. [14], Yacob et al. [15], and Wahiduzzaman et al. [16] to investigate several aspects such as suction/blowing, viscous dissipation, thermal radiation, Buoyancy effects, chemical reaction, and heat generation over a stretching/shrinking surface.

In the recent years, the problem of stagnation point flow has received tremendous research interest. Stagnation-point flow is seen in every type of flow whenever the fluid impinges on a solid object. Then, the fluid velocity reduces to zero and the fluid pressure and heat mass transfer rates are highest at the stagnation point area. The studies of stagnation-point flow toward a stretching or shrinking sheet are classic in fluid mechanics because of its enormous practical applications in industry and engineering, such as cooling of nuclear reactors and cooling of electronic devices by fans, in the design of radial diffusers and thrust bearings, drag reduction and many hydrodynamic processes. In view of aforesaid applications Wang [17] studied the stagnation point flow through a shrinking sheet and observed that due to increase in boundary layer thickness the heat transfer rate decreases with the rate of shrinking. The effect of induced magnetic field on MHD stagnation point flow and heat transfer of an viscous incompressible fluid through a stretching surface is studied by Ali et al. [18] and they compared their results in the absence of magnetic field parameters with previously derived results and the results are found to be good. Akbar et al. [19] analyzed the influence of Brownian motion, thermophoresis and radiation effects on steady two-dimensional stagnation point flow of nanofluid past a stretching cylinder in the presence of convective boundary conditions. Rushi Kumar et al. [20] studied the effect of chemical reaction on MHD flow through a vertical cone with variable electrical conductivity. A lot of work on stagnation-point flow is done by the researchers [21–34].

Moreover, shear stress is directly proportional to shear rate of both Newtonian and non-Newtonian fluids. Carreau fluid is a type of Newtonian fluid. The study of peristaltic flow of a Carreau fluid attracted the attention of many researchers because of its wide applications in the field of science and technology viz. Physiology, treatment of diagnostic diseases, neurological treatment, cancer treatment. The effect of magnetic field on a Carreau (Newtonian) fluid has been used for treatment of gastronomic pathologies, hypertension, cancer tumor treatment, hyperthermia, blood reduction during surgeries, etc. Although many researchers such as Raju et al. [35,36], Akbar et al. [37], Riaz et al. [38], Jasmine Benazir et al. [39] and Nadeem et al. [40] addressed the non-Newtonian fluid through different channels, in all the aforesaid investigations, a less work has been available on the flow of Carreau fluids past a stretching/shrinking sheet. Very recently, the researchers [41–44] investigated the heat and mass transfer in magnetohydrodynamic flows by considering the Buongiorno's model.

In this study, we investigated the influence of transpiration on the flow of a Carreau nanofluid near a stagnation-point toward a stretching/shrinking sheet in the presence of Brownian motion and thermophoresis effects. The governing partial differential equations are transformed into nonlinear ordinary differential equations by using appropriate similarity transformations and then solved numerically. The influence of non-dimensional governing parameters namely magnetic field parameter, power-law index, Weissenberg number, Brownian motion, thermophoresis and stretching/shrinking parameter on velocity, temperature and concentration profiles along with friction factor, local Nusselt and Sherwood numbers is discussed and presented through graphs and tables for both suction and injection cases and obtained the dual solutions.

2. Mathematical formulation

Consider a steady two dimensional stagnation point flow of an incompressible Carreau nanofluid over a wall coinciding with plane $y = 0$, and the flow is being confined to $y > 0$. A magnetic field of strength B_0 is applied along x-direction as displayed in Fig. 1. Induced magnetic field is neglected in this study. Thermophoresis and Brownian motion effects are taken into account. The flow is generated due to the linear stretching. Extra stress tensor for Carreau fluid is [16],

$$\bar{\tau}_{ij} = \eta_0\left[1+\frac{(n-1)}{2}(\Gamma\bar{\dot{\gamma}})^2\right]\bar{\dot{\gamma}}_{ij} \tag{1}$$

In which $\bar{\tau}_{ij}$ is the extra stress tensor, η_0 is the zero shear rate viscosity, Γ is the time constant, n is power law index and $\bar{\dot{\gamma}}_{ij}$ is defined as

$$\bar{\dot{\gamma}} = \sqrt{\frac{1}{2}\sum_i\sum_j\bar{\dot{\gamma}}_{ij}\bar{\dot{\gamma}}_{ji}} = \sqrt{\frac{1}{2}\prod}. \tag{2}$$

Here $\prod$ is the second invariant strain tensor. The physical model of the problem is displayed in Fig. 1.

Flow equation for Carreau fluid model after applying the boundary layer approximations can be defined as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y} = 0, \tag{3}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y} = \nu_f\frac{\partial^2 u}{\partial y^2}+\nu_f\frac{3(n-1)\Gamma^2}{2}\left(\frac{\partial u}{\partial y}\right)^2\frac{\partial^2 u}{\partial y^2} + \frac{\sigma\beta_0^2}{\rho_f}(u_e-u)+u_e\frac{\partial u_e}{\partial x}, \tag{4}$$

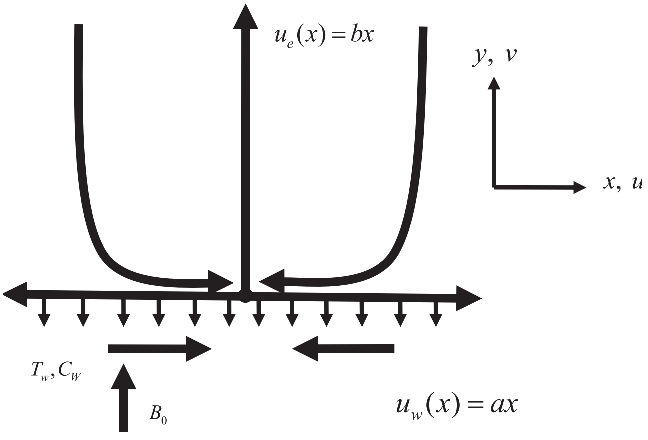

Figure 1 Physical model of the problem.

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