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Unsteady MHD flow of an UCM fluid over a stretching surface with higher order chemical reaction

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Chemically reactive species;
Shooting method

Abstract The objective of this paper was to illustrate the frequent and wide occurrence of unsteady two dimensional MHD flow of an UCM fluid over a stretching surface in the presence of higher order chemical reaction in a diverse range of applications, both in nature and in technology. The governing partial differential equations are converted into ordinary differential equations by using similarity transformation. The ordinary differential equations were numerically solved by using shooting technique. The effects of different governing parameters on the flow field and mass transfer are shown in graphs and tables. The governing physical parameters significantly influence the flow field and mass transfer. Also, existing results in the literature are compared with the present study as a special case. In addition to practical applications in foams, suspensions, polymer solutions and melts, the present study also contributed to the existing literature.
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1. Introduction

The boundary layer flows of non-Newtonian fluid have received much importance due to its numerous industrial and engineering applications. In view of non-Newtonian fluids diverse rheological properties cannot be examined through one constitutive relationship between shear stress and rate of strain. For any boundary layer, Maxwell model is used to predict stress relaxation and also excludes the effects of shear dependent viscosity. Sakiadis [1] first investigated the boundary layer flow of a viscous fluid, and the flow is caused due to the motion of the rigid plane sheet in its own plane. Due to entrainment to ambient fluid, this situation represents a different class of boundary-layer problem which has a solution substantially different from that of boundary-layer flow over a semi-infinite flat plate. Erickson et al. [2] extended this problem to the moving surface in the presence of suction or blowing. Crane [3] considered the moving sheet, and the velocity is proportional to the distance from the slit. In general, these types of flows occur in the drawing of plastic films and artificial fibers. Gupta and Gupta [4] investigated heat and mass transfer over a stretching sheet with suction or blowing. Similarity solution of MHD boundary layer flow problem of an electrically conducting incompressible fluid over a stretching surface

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in the presence of transverse magnetic field was studied by pavlov [5]. Chakrabarti and Guptav [6] extended the problem to the temperature distribution in the MHD boundary layer flow due to stretching surface with suction.

Non-Newtonian fluids with convective heat and mass transfer finds many industrial applications such as nuclear fuel slurries, paper coating, liquid metals, movement in biological fluids, plastic extrusion, material processing and crystal growing. The behavior of non-Newtonian fluid has been characterized by upper-convected Maxwell model. The Rayleigh-Stokes problem and the Maxwell fluid flow past an infinite plate were investigated by Fatecau and Fatecau [7,8]. Sadeghy and Sharifi [9] presented a comparative analysis for Sakiadis flow of an Upper-Convected Maxwell (UCM) fluid on a fixed plate and concluded that the Deborah number increases with decrease in skin friction at the wall. Mass transfer phenomenon is the movement of mass from one region to another region in the system. This physical process is applied in several scientific fields such as variable systems and chemical change that affect molecular and convective diffusion of atoms and molecules. The driving force for movement of mass is a difference in concentration, and the random motion of molecules causes a net movement of mass from a high concentration region to the low concentration region. Liu [10] and Cortell [11] investigated the heat and mass transfer in the presence of the hydromagnetic flow over a stretching surface. Momentum and mass transfer characteristics of chemical reactive species with first and higher order reactions for electrically conducting viscoelastic fluid are influenced by a porous stretching sheet. Andersson et al. [12] discussed the momentum and mass diffusion of the flow with chemical reactive species over a stretching sheet. Takhar et al. [13] presented the mass transfer with magnetohydrodynamic (MHD) flow in a viscous electrically conducting fluid by a stretching sheet with nonzero velocity. The problem of second grade fluid with a porous medium was extended by Akyildiz et al. [14]. The effects of suction/blowing with heat absorption/generation over a porous stretching surface in the presence of boundary layer flow were analyzed by Layek et al. [15]. Hayat et al. [16] studied the magnetohydrodynamic boundary layer flow of a Jeffery fluid bounded by a stretching sheet and solved the governing equations by using homotopy analysis method. Different analytical techniques such as LSM, DTM, OHAM, and HPM, were studied by Ghasemi et al. [19,20], Vatani et al. [21] and Mohammadian et al. [22].

The effects of combined heat and mass transfer of third grade nanofluids over a convectively heated stretching permeable surface were studied by Khan et al. [23]. Their study is based on Buongiorno model for the nanofluids. Various boundary layer flow problems on past a stretching sheet and vertical porous plate were studied by Makinde [24], Makinde and Sibanda [25], Makinde and Olanrewaju [26] and Anver Beg and Makinde [27].

In this paper our aim was to investigate unsteady boundary layer MHD flow and mass transfer of an UCM fluid in the presence of higher order chemical reaction. The rest of this paper is organized as follows: Section 2 is devoted to the mathematical formulation of the problem. Section 3 deals with the exact solutions in certain cases. In Section 4, the numerical solution of the problem is introduced. Section 5 deals with the results and discussion. Section 6 gives the conclusion.

2. Mathematical formulation

2.1. Transient unsteady-state flow and mass transfer ($t > 0$)

We consider the unsteady and incompressible MHD flow and mass transfer of an electrically conducting upper convected Maxwell fluid over a stretching surface. The flow is induced due to the stretching surface by applying equal and opposite forces by the x-axis and considering the flow to be bounded to the region $y > 0$. The mass flow and unsteady fluid start at $t = 0$. The sheet appears out of a slit at origin and moves with velocity $U(x,t) = \frac{bx}{1-\alpha t}$ where b and α are positive constants both having dimensions $(time)^{-1}$, b is the rate of stretching and $\frac{b}{1-\alpha t}$ is the rate of stretching with time. In case of polymer, the material properties of the sheet vary with time. A uniform magnetic field of strength B_0 is along the y-axis. The induced magnetic field is trifling, which is a valid assumption on a scale under the small magnetic Reynolds number and the external field is zero. The problem of mass transfer in the flow along a flat plate that contains a species, say A is slightly soluble in B. C_w be the concentration at the plate surface and C_∞ be the solubility of A in B and in the concentration of species far away from the plate is A. Let the rate of reaction of the species A with B be an nth-order homogenous chemical reaction with constant k_n. The flow geometry and coordinate system is shown in Fig. 1.

It is desirable to study the system by the boundary layer analysis [17]. The governing equations of the model [18] are expressed as

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

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + \lambda\left(u^2\frac{\partial^2 u}{\partial x^2} + v^2\frac{\partial^2 u}{\partial y^2} + 2uv\frac{\partial^2 u}{\partial x \partial y}\right) = v\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}u, \tag{2}$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - K_n(C - C_\infty)^n, \tag{3}$$

The initial conditions are as follows:

$$u(x,0) = u(x), \quad v(x,0) = -v_0, \quad C(x,0) = C_w(x), \tag{4}$$

The appropriate boundary conditions for Eqs. (1)–(3) have the form:

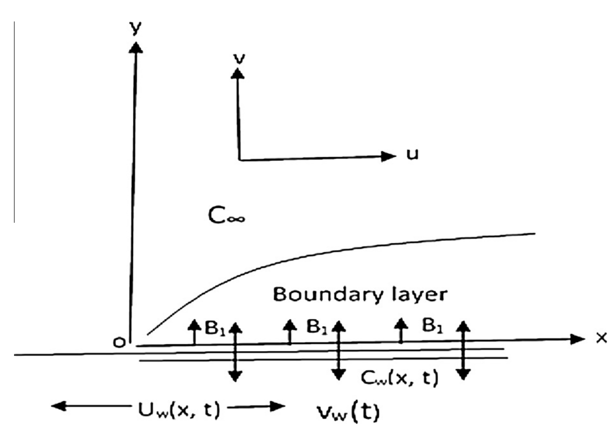

Figure 1 Flow model and physical coordinate system.

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