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ORIGINAL ARTICLE

Numerical study of magnetohydrodynamics (MHD) boundary layer slip flow of a Maxwell nanofluid over an exponentially stretching surface with convective boundary condition

P. Bala Anki Reddy[a,*], S. Suneetha[b], N. Bhaskar Reddy[c]

[a]Department of Mathematics, S.A.S., VIT University, Vellore 632014, India
[b]Department of Applied Mathematics, Yogi Vemana University, Kadapa 516003, India
[c]Department of Mathematics, S.V. University, Tirupati 517502, India

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Abstract This paper focuses on a theoretical analysis of a steady two-dimensional magnetohydrodynamic boundary layer flow of a Maxwell fluid over an exponentially stretching surface in the presence of velocity slip and convective boundary condition. This model is used for a nanofluid, which incorporates the effects of Brownian motion and thermophoresis. The resulting non-linear partial differential equations of the governing flow field are converted into a system of coupled non-linear ordinary differential equations by using suitable similarity transformations, and the resultant equations are then solved numerically by using Runge-Kutta fourth order method along with shooting technique. A parametric study is conducted to illustrate the behavior of the velocity, temperature and concentration. The influence of significant parameters on velocity, temperature, concentration, skin friction coefficient and Nusselt number has been studied and numerical results are presented graphically and in tabular form. The reported numerical results are compared with previously published works on various special cases and are found to be an in excellent agreement. It is found that momentum boundary layer thickness decreases with the increase of magnetic

*Corresponding author. Tel.: +91 8870933848.
E-mail address: pbarmaths@gmail.com (P. Bala Anki Reddy).

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parameter. It can also be found that the thermal boundary layer thickness increases with Brownian motion and thermophoresis parameters.

1. Introduction

The flow of a non-Newtonian fluid over a stretching sheet has attracted considerable attention during the last two decades due to its vast applications in industrial manufacturing such as hot rolling, wire drawing, glass fiber and paper production, drawing of plastic films, polymer extrusion of plastic sheets and manufacturing of polymeric sheets. For the production of glass fiber/plastic sheets, thermo-fluid problem involves significant heat transfer between the sheet and the surrounding fluid. Sheet production process starts solidifying molten polymers as soon as it exits from the slit die. The sheet is then collected by a wind-up roll upon solidification. To improve the mechanical properties of the fiber/plastic sheet we use two ways, the extensibility of the sheet and the rate of cooling. Crane [1] was the first who reported the analytical solution for the laminar boundary layer flow past a stretching sheet. Several researchers viz. Gupta and Gupta [2], Dutta et al. [3], Chen and Char [4] extended the work of Crane by including the effects of heat and mass transfer under different situations.

In almost all investigations on the flow past a stretching sheet, the flow occurs because of the linear stretching velocity of the flat sheet. However, the boundary layer flow induced by an exponentially stretching/shrinking sheet is not studied much, though it is very important and realistic flow frequently appears in many engineering processes. However, all these studies are restricted to linear stretching of the sheet. It is worth mentioning that the stretching need not necessarily be linear. In view of this, Ali [5] has investigated the thermal boundary layer. The heat and mass transfer on boundary layer flow due to an exponentially continuous stretching sheet was considered by Magyari and Keller [6]. Elbashbeshy [7] added a new dimension to the study of Ali, by considering exponentially continuous stretching surface. Partha et al. [8] reported a similarity solution for mixed convection flow past an exponentially stretching surface. Srinivas et al. [9] studied on non-Darcian unsteady flow of a micro polar fluid over a porous stretching sheet with thermal radiation and chemical reaction.

In recent years, investigations on the boundary layer flow problem with a convective surface boundary condition have gained much interest among researchers, since first introduced by Aziz [10], who considered the thermal boundary layer flow over a flat plate in a uniform free stream with a convective surface boundary condition. Ishak [11] obtained the similarity solutions for the steady laminar boundary layer flow over a permeable plate with a convective boundary condition. Makinde and Aziz [12] investigated numerically the effect of a convective boundary condition on the two dimensional boundary layer flows past a stretching sheet in a nano fluid.

There has been a renewed interest is studying magnetohydrodynamic flows and heat transfer due to the effect of magnetic fields on the boundary layer flow control and on the performance of many systems involving electrically conductive flows. In addition, this type of flow finds applications in many engineering problems such as magnetohydrodynamics (MHD) generators, Plasma studies, Nuclear reactors, and Geothermal energy extractions. Al-Odat et al. [13] analyzed the thermal boundary layer on an exponentially stretching continuous surface in the presence of magnetic field effect. Bhattacharyya and Pop [14] showed the effect of external magnetic field on the flow over an exponentially shrinking sheet. Recently, Nadeem and Lee [15] obtained analytic solutions of boundary layer flow of nanofluid over an exponentially stretching surface using homotopy analysis method (HAM). The buoyancy effects on MHD stagnation point flow and heat transfer of a nanofluid past a convectively heated stretching/shrinking sheet was discussed by Makinde et al. [16]. Nadeem et al. [17] investigated the numerical study of MHD boundary layer flow of a Maxwell fluid past a stretching sheet in the presence of nanoparticles. Akbar et al. [18] analyzed the numerical solutions of Magneto hydrodynamic boundary layer flow of tangent hyperbolic fluid towards a stretching sheet. Akbar et al. [19] studied the radiation effects on MHD stagnation point flow of nano fluid towards a stretching surface with convective boundary condition. The numerical solutions for the g-jitter induced magnetohydrodynamic boundary layer flow of water based nanofluid were discussed by Uddin et al. [20]. Uddin et al. [21] studied the two dimensional magneto hydrodynamics viscous incompressible free convective boundary layer flow of an electrically conducting, chemically reacting nanofluid from a convectively heated permeable vertical surface. The magnetohydrodynamic flow and heat transfer for Maxwell fluid over an exponentially stretching sheet through a porous medium in the presence of non-uniform heat source/sink with variable thermal conductivity was analyzed by Vijendra Singh and Shweta Agarwal [22].