Ain Shams Engineering Journal (2014) 5, 1337–1342

Ain Shams University

Ain Shams Engineering Journal

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ENGINEERING PHYSICS AND MATHEMATICS

Radiation effect on boundary layer flow of an Eyring–Powell fluid over an exponentially shrinking sheet

Asmat Ara [a], Najeeb Alam Khan [b,*], Hassam Khan [b], Faqiha Sultan [c]

[a] Department of Mathematical Sciences, Federal Urdu University Arts, Science and Technology, Karachi 75300, Pakistan
[b] Department of Mathematical Sciences, University of Karachi, Karachi 75270, Pakistan
[c] Department of Sciences and Humanities, National University of Computer and Emerging Sciences, Karachi 75030, Pakistan

Received 27 February 2014; revised 15 May 2014; accepted 12 June 2014
Available online 10 July 2014

KEYWORDS

Boundary layer flow;
Eyring–Powell model;
Thermal radiation

Abstract The aim of this paper was to examine the steady boundary layer flow of an Eyring–Powell model fluid due to an exponentially shrinking sheet. In addition, the heat transfer process in the presence of thermal radiation is considered. Using usual similarity transformations the governing equations have been transformed into non-linear ordinary differential equations. Homotopy analysis method (HAM) is employed for the series solutions. The convergence of the obtained series solutions is carefully analyzed. Numerical values of the temperature gradient are presented and discussed. It is observed that velocity increases with an increase in mass suction S. In addition, for the temperature profiles opposite behavior is observed for increment in suction. Moreover, the thermal boundary layer thickness decreases due to increase in Prandtl number Pr and thermal radiation R.
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1. Introduction

Viscous boundary layer flow due to a stretching/shrinking sheet is of significant importance due to its vast applications. Aerodynamic extrusion of plastic sheets, glass fiber production, paper production, heat treated materials traveling between a feed roll and a wind-up roll, cooling of an infinite metallic plate in a cooling bath and manufacturing of polymeric sheets are some examples for practical applications of non-Newtonian fluid flow over a stretching/shrinking surface. The quality of the final product depends on the rate of heat transfer at the stretching surface. This stretching/shrinking may not necessarily be linear. It may be quadratic, power-law, exponential and so on.

Over the last few decades, in nearly all investigations on the flow past a stretching/shrinking sheet, the flow occurs due to linear stretching/shrinking velocity of the flat sheet. However, boundary layer flow induced by an exponentially stretching/shrinking sheet is not studied much. Crane [1] firstly investigated the steady boundary layer flow of the incompressible flow. Gupta and Gupta [2] and Chen and Char [3] extended the work of Crane under various physical conditions. Hayat et al. [4] examined the unsteady three dimensional flow of couple stress fluid over a stretching surface with chemical reaction.

* Corresponding author. Tel.: +92 3333012008.
E-mail address: njbalam@yahoo.com (N.A. Khan).
Peer review under responsibility of Ain Shams University.

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http://dx.doi.org/10.1016/j.asej.2014.06.002

Hamad [5] found the analytical solution of natural convection flow of a nanofluid over a linearly stretching sheet in the presence of magnetic field. Bachok et al. [6] described stagnation-point flow over a stretching/shrinking sheet in a nanofluid. Bhattacharyya [7] considered heat transfer analysis in unsteady boundary layer stagnation-point flow toward a shrinking/stretching sheet. Numerical study of MHD boundary layer flow of a maxwell fluid past a stretching in the presence of nanoparticles has been carried out by Nadeem et al. [8]. Mehmood et al. [9] examined the non-orthogonal flow of a second grade micropolar fluid toward a stretching sheet, they also have taken heat transfer analysis into account. Moreover, Nadeem et al.[10] have recently analyzed the non-orthogonal stagnation point flow of a third order fluid toward a stretching surface in the presence of heat transfer. Magyari et al. [11] obtained the boundary layer flow due to exponentially stretching sheet. Elbashbeshy [12] numerically explained the flow and heat transfer over an exponentially stretching surface considering wall mass suction. The MHD boundary layer flow of a viscous fluid over an exponentially stretching sheet with effects of radiation was studied by Ishak [13]. Al-Odet et al. [14] examined the effect of magnetic field on thermal boundary layer flow on an exponentially stretching continuous surface with an exponentially temperature distribution. Sajid et al. [15] found the influence of thermal radiation on the boundary layer flow past an exponentially stretching sheet and they reported series solutions for the velocity and temperature by employing HAM. Bhattacharyya [16] discussed the boundary layer and heat transfer over an exponentially shrinking sheet.

Up to date not much study has been carried out for the two dimensional flow of the Eyring–Powell fluid. Although this fluid model has many advantages over the non-Newtonian fluids models. Firstly, it is extracted from the kinetic theory of liquids rather than the empirical relation. Secondly, for low and high shear rates it correctly reduces to Newtonian behavior. Eyring–Powell fluid model [17] a complete mathematical model proposed by Powell and Eyring in 1944. Hayat et al. [18] analyzed steady flow of an Eyring–Powell fluid over a moving surface with convective boundary conditions. Malik et al. [19] presented boundary layer flow of an Eyring–Powell model fluid due to a stretching cylinder with variable viscosity. Nabil et al. [20] studied numerical study of viscous dissipation effect on free convection heat and mass transfer of MHD Eyring–Powell fluid flow through a porous medium. Javed et al. [21] investigated flow of an Eyring–Powell non-Newtonian fluid over a stretching sheet. Characteristics of heating scheme and mass transfer on the peristaltic flow an Eyring–Powell fluid in an endoscope discussed by Nadeem et al. [22] However, to the best of our knowledge no attempt has been made to study Eyring–Powell fluid over an exponentially shrinking sheet.

Thus current work presents a theoretical study Eryning Powell flow of over an exponentially shrinking sheet. A mathematical model has been prepared in the presence of radiation effects. We developed series solutions for the resulting problems by using the homotopy analysis method [23–27]. Results for the velocity and temperature are constructed. Convergence criteria for the derived series solutions are established. The velocity and temperature are analyzed to gain thorough insight toward the physics of the problem for various parameters of interest. Numerical values of the temperature gradient are presented and discussed.

2. Mathematical formulation

Consider the steady two dimensional boundary layer flow of an Eyring–Powell fluid with heat transfer in the presence of thermal radiation over an exponentially shrinking sheet (see Fig. 1). The stress tensor of an Eyring–Powell model [28] is expressed as

$$A = -pI + \tau \tag{1}$$

where extra stress tensor τ_{ij} is given by

$$\tau_{ij} = \mu\frac{\partial u_i}{\partial x_j} + \frac{1}{\beta}\sinh^{-1}\left(\frac{1}{d}\frac{\partial u_i}{\partial x_j}\right). \tag{2}$$

In accordance with the boundary layer approximations, the governing equations for the flow are

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{-1}{\rho}\frac{\partial p}{\partial x}+\left(\nu+\frac{1}{\rho\beta d}\right)\left(\frac{\partial^2 u}{\partial y^2}\right)-\frac{1}{2\rho\beta d^3}\left(\frac{\partial u}{\partial y}\right)^2\left(\frac{\partial^2 u}{\partial y^2}\right) \tag{4}$$

$$\frac{\partial p}{\partial y}=0 \tag{5}$$

Eqs. (4) and (5) show that the pressure is independent of y. Since the lateral velocity is zero far away from the sheet and the pressure is uniform, then Eq. (4) takes the form

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\left(\nu+\frac{1}{\rho\beta d}\right)\frac{\partial^2 u}{\partial y^2}-\frac{1}{2\rho\beta d^3}\left(\frac{\partial u}{\partial y}\right)^2\left(\frac{\partial^2 u}{\partial y^2}\right) \tag{6}$$

The equations representing temperature with heat radiation may be written in usual notation as below:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\kappa}{\rho C_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \tag{7}$$

where u and v are the velocity components, ν is the kinematic viscosity, ρ is the fluid density, β and d are the fluid parameters of Eyring–Powell model, d has the dimension of $(time)^{-1}$. κ is the fluid thermal conductivity and C_p is the specific heat constant. The radiative heat flux, q_r is given by $q_r = -\frac{4\sigma\partial T^4}{3K\partial y}$, where σ is Stefan–Boltzman constant and K is Rosseland mean absorption coefficient.

The boundary conditions are given by

$$u = U_w(x), v = v_w \text{ at } y = 0; u \to 0 \text{ as } y \to \infty \tag{8}$$

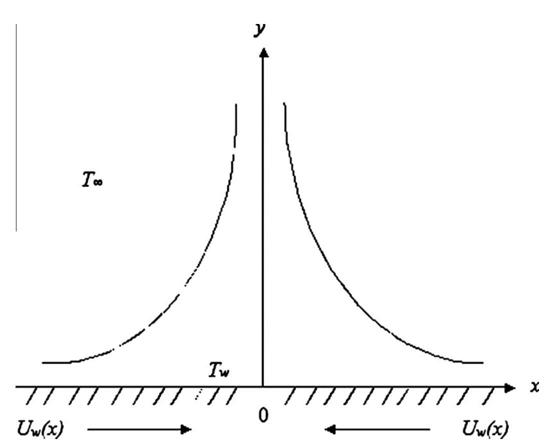

Fig. 1 Physical model of the fluid.

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