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On Cattaneo–Christov heat flux model for Carreau fluid flow over a slendering sheet

Hashim *, Masood Khan

Department of Mathematics, Quaid-i-Azam University, Islamabad 44000, Pakistan

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ABSTRACT

The underlying intentions of this article are to investigate the impact of non-Fourier heat flux model on the stagnation-point flow of non-Newtonian Carreau fluid. In this study, the innovative Cattaneo–Christov constitutive model is introduced to study the characteristics of thermal relaxation time. The flow is impelled by a slendering surface which is of the variable thickness. In the model, the physical mechanism responsible for homogeneous–heterogeneous reactions are further taken into account. Also, the diffusion coefficients of the reactant and auto catalyst are considered to be equal. The governing non-linear partial differential equations consisting of the momentum, energy and concentration equations are reduced to the coupled ordinary differential equations by means of local similarity transformations. The transformed ODEs are tackled numerically by employing an effective shooting algorithm along with the Runge–Kutta Fehlberg scheme. The physical characteristics of the fluid velocity, temperature and concentration profiles are illuminated with the variation of numerous governing factors and are presented graphically. For instance, our result indicates that the temperature and thermal boundary layer thickness are lower in case of Cattaneo–Christov heat flux model when compared to classical Fourier's heat model. Meanwhile, the rate of heat transfer is significantly improved by a high wall thickness parameter and an opposite influence is found due to the thermal relaxation parameter. We further noticed that a higher value of homogeneous and heterogeneous reaction parameter corresponds to a deceleration in the concentration field and it shows an inverse relation for the Schmidt number. A correlation with accessible results for specific cases is found with fabulous consent.

Introduction

In the most recent couple of decades, numerous investigators have shown fantastic energy in exploring the heat propagation by means of a wave mechanism rather than essentially by diffusion. Late studies affirm this is not just a low temperature phenomenon, but rather one which has possible imperative real applications. This subject got uncommon consideration because of its bounteous applications in engineering and modern industrial procedures. Case of such applications incorporates in skin burns and nanofluids, cooling of electronic devices, food technology, nuclear reactor cooling, power generation, heat propagation in tissues and many more. It is a most prone to comprehend that the natural phenomenon of heat exchange happens, if there is a temperature contrast between objects or between different parts of the same objects. Just about 200 years prior, Fourier [1] proposed the heat conduction model in the matter and has been the best model to give a knowledge to comprehend the heat exchange mechanism in various situations. In any case, the primary inadequacy of the Fourier's laws negates the rule of causality. Later on, in 1948, Cattaneo [2] presented a modification of Fourier's law for heat conduction in an inflexible body. He modifies the Fourier's law through the inclusion of thermal relaxation time term to present the "thermal inertia", which is known as Maxwell–Cattaneo law. Christov [3] has returned to the point that the objective derivative one should use while dealing with a Cattaneo type theory for a fluid. In addition, he changed the time derivative in the Maxwell–Cattaneo model by the Oldroyd upper-convected derivative which has successfully preserved the material-invariant formulation. The uniqueness and structural stability of the solutions for the temperature governing equations with Cattaneo–Christov heat flux model in some initial and boundary problem, have been proved by Straughan [4]. Additionally, steadiness of structure of Cattaneo–Christov heat flux model with uniqueness is exhibited by Ciarletta and Straughan [5]. Tibullo and Zampoli [6] explored the conduct of the Cattaneo–Christov condition when connected to incompressible liquids, acquiring,

* Corresponding author.
E-mail address: hashim@math.qau.edu.pk (Hashim).

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specifically, a uniqueness result. Straughan [7] and Haddad [8] procured the numerical solutions for thermal convection of an incompressible Newtonian fluid with Cattaneo–Christov heat flux model by utilizing the D_2 Chebyshev tau method. Starting late, Hayat et al. [9] got the analytic solution utilizing the homotopy analysis technique for the flow over a variable thickness sheet in the presence of Cattaneo–Christov heat flux model. As of late, an interest has been connected with the problem of the flow and heat transfer over stretching sheet by employing both the Fourier heat flux model and Cattaneo–Christov heat flux model [10–12].

With the rapid progress of modern engineering technology, there has been an enormous amount of efforts put in the fluid flow and heat transfer over a stretching surface near the stagnation-point by the various researchers owing to their wide applications in aerospace engineering and industry. The flow in the neighborhood of a stagnation-point has awesome significance in that the stagnation-point represents the location of high pressure and, in thermally active flows, the higher heat transfer rate. Initially, Hiemenz [13] done pioneering work to investigate the two-dimensional stagnation-point flow for viscous fluid. Later on, the problem of stagnation-point flow towards a stretching surface has been investigated by Chiam [14]. In this analysis, he considered the stretching velocity of the plate equal to the straining velocity of the stagnation-point flow and show that no boundary layer structure exists near the surface. Hayat et al. [15] studied a two-dimensional model for the steady flow of an incompressible Burgers fluid in the region of stagnation-point. Further, the impact of the magnetic field on the stagnation-point flow and mass transfer of Burgers fluid over a shrinking sheet has been scrutinized by Alsaedi et al. [16]. Recently, reviews on the flow of Newtonian and non-Newtonian fluids in the region of stagnation point have been presented by Akbar et al. [17], Hayat et al. [18,19], Khan et al. [20] and Majeed et al. [21] etc.

These days, a developing interest has been shown in the flows of non-Newtonian fluids alongside chemical reactions that involve both the homogeneous and heterogeneous reactions. Homogeneous–heterogeneous reactions happen in numerous, chemically reacting frameworks, for instance, in combustion, nourishment, earthenware production, atmospheric flows, chemical processing, catalysis and biochemical systems. There are numerous responses with the capacity to advance gradually or not, at one spot aside from an association of a catalyst. The cooperations between the heterogeneous and homogeneous responses are amazingly mind boggling and have gotten expanding consideration, be that as it may, it is still not clear. It has been exhibited that these connections incorporate the promotion of homogeneous reactions because of chemically affected exothermicity and the restraint of heterogeneous reactions on the homogeneous reactions for the most part brought about by competition of fuels and oxidizers of the heterogeneous reactions versus homogeneous reactions [22]. On account of the significance of homogeneous–heterogeneous reaction processes, broad hypothetical and experimental works have been done to give knowledge into the correlation of homogeneous and heterogeneous reactions. Merkin [23] basically constructed a simple model for homogeneous–heterogeneous reactions of stagnation-point flow. Chaudhary and Merkin [24] inspected the homogenous-heterogeneous reactions in point of boundary layer flow of viscous fluid. In this study, they got the numerical solution near the principle edge of flat plate. A two dimensional stagnation-point stream over a permeable sheet within the sight of homogeneous–heterogeneous reactions was reviewed by Khan and Pop [25]. Likewise, Bachok et al. [26] considered stagnation-point stream towards a stretching surface with h omogeneous–heterogeneous reactions impacts. Also, homoge neous–heterogeneous responses in micropolar liquid flow in a permeable medium have been examined by Shaw et al. [27]. The impact of homogeneous–heterogeneous reactions in the stretched flow of ferro-fluid due to a rotating disk long is studied by Hayat et al. [28].

The purpose of this note is to conduct a numerical study to see the impact of Cattaneo–Christov heat flux model on the flow of Carreau fluid over a slendering sheet with variable thickness. In addition, the influence of homogeneous–heterogeneous reactions are examined. Of particular interest in the current work is to examine and review the local similar solutions of the governing non-linear partial differential equations using the shooting method for some values of the governing parameters. In light of these solutions a comprehensive analysis is performed to research the impacts of various flow parameters on the velocity, temperature and concentration fields, skin friction coefficient and Nusselt number.

Mathematical modeling

Problem statement

We have considered, an incompressible, two-dimensional, stagnation-point flow of a Carreau fluid over a continuous moving sheet with a variable thickness. It is assumed that the sheet is not flat with a given profile and its thickness is given by $y = A_1(x+b)^{\frac{1-m}{2}}$. Further, it is taken that the coefficient A_1 is as small that the sheet is adequately thin and m represents the velocity power index. Additionally, the impacts of homogeneous–hetero geneous reactions are taken into account. We single out the Cartesian coordinates x-axis and y-axis along the sheet and orthogonal to the sheet, respectively, as seen in Fig. 1. The sheet is kept at constant temperature T_w although T_∞ being the ambient temperature such that $T_w > T_\infty$.

Cattaneo–Christov heat flux model

In abstract vector notations, valid in any coordinate system, the upper-convective material time derivative of a vector has the form [3]

$$\frac{d\mathbf{F}}{dt} = \frac{\partial \mathbf{F}}{\partial t} + \mathbf{V}\cdot\nabla\mathbf{F} - \mathbf{F}\cdot\nabla\mathbf{V} + (\nabla\cdot\mathbf{V})\mathbf{F}. \tag{1}$$

Following established terminology, $\mathbf{V}$ means the velocity vector and $\mathbf{F}$ is a vector which can be replaced by the heat flux vector or the mass flux vector.

We consider the Cattaneo–Christov heat flux model [2,3], which is the generalization of Fourier's law, is given by the expression:

$$\mathbf{q} + \lambda\left(\frac{\partial \mathbf{q}}{\partial t} + \mathbf{V}\cdot\nabla\mathbf{q} - \mathbf{q}\cdot\nabla\mathbf{V} + (\nabla\cdot\mathbf{V})\mathbf{q}\right) = -k\nabla T, \tag{2}$$

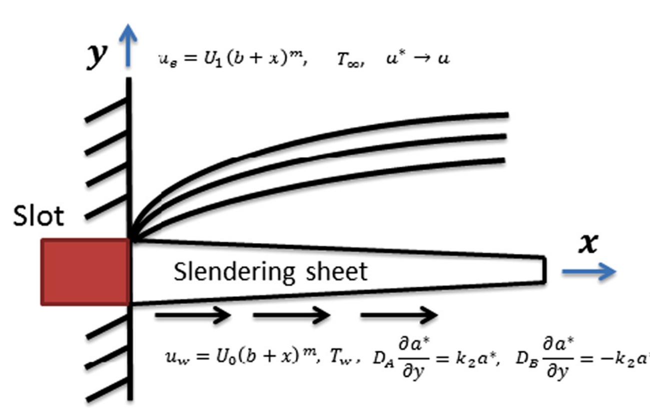

Fig. 1. Geometry of the problem.