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ORIGINAL ARTICLE

Newtonian heating effect on unsteady hydromagnetic Casson fluid flow past a flat plate with heat and mass transfer

M. Das [a,*], R. Mahato [a], R. Nandkeolyar [b]

[a] Department of Mathematics, School of Applied Sciences, KIIT University, Bhubaneswar 751024, India
[b] School of Mathematics, Thapar University, Patiala 147004, India

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Abstract The influence of Newtonian heating on heat and mass transfer in unsteady hydromagnetic flow of a Casson fluid past a vertical plate in the presence of thermal radiation and chemical reaction is studied. The Casson fluid model is used to distinguish the non-Newtonian fluid behavior. The fluid flow is induced due to periodic oscillations of the plate along its length and a uniform transverse magnetic field is applied in a direction which is normal to the direction of fluid flow. The partial differential equations governing the flow, heat, and mass transfer are transformed to non-dimensional form using suitable non-dimensional variables which are then solved analytically by using Laplace transform technique. The numerical values of the fluid velocity, fluid temperature, and species concentration are depicted graphically whereas the values of skin-friction, Nusselt number, and Sherwood number are presented in tabular form. It is noticed that the fluid velocity and temperature decrease with increasing values of Casson parameter while concentration decreases with increasing values of chemical reaction parameter and Schmidt number. Such a fluid flow model has several industrial and medical applications such as in glass manufacturing, paper production, purification of crude oil and study of blood flow in the cardiovascular system.

1. Introduction

The combined effects of mass and heat transfer with chemical reaction on the hydromagnetic flow of a viscous, incompressible, and electrically conducting fluid have attracted many researchers due to its wide range of engineering and industrial applications such as in MHD generators, plasma studies, nuclear reactors and geothermal energy extractions. Das et al. [1] studied the first-order chemical reaction effect on the flow past an impulsively started infinite vertical plate with constant mass transfer and heat flux. Anjali Devi and Kandasamy [2] contemplated the mass and heat transfer on steady laminar flow along semi-infinite horizontal plate in the presence of chemical reaction. Andersson [3] studied the effect of magnetic field on the flow of a viscoelastic fluid past

* Corresponding author.
E-mail addresses: mrutyunjay0307@gmail.com (M. Das), rumam488@gmail.com (R. Mahato), rajnandkeolyar@gmail.com (R. Nandkeolyar).
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a stretching sheet. Nandkeolyar et al. [4] investigated the unsteady hydromagnetic heat and mass transfer flow of a heat radiating and chemically reactive fluid past a flat porous plate with ramped wall temperature. Reddy et al. [5] presented a theoretical investigation of convective mass as well as heat transfer of unsteady MHD flow past a vertical semi-infinite porous plate with different viscosity and thermal conductivity.

In recent years non-Newtonian fluids have outspread applications in chemical, pharmaceutical and cosmetic industries such as in the production of several chemicals, oil, gas, paint, syrup, juice, cleanser, and deodorizer [6]. In Newtonian fluid the viscous stresses arising from its flow, at every point are linearly proportional to the local strain rate and they have limited applications. They cannot describe various facts noticed for the fluids in industrial and other technological applications such as blood, soap, certain oils, paints, and many emulsions. It is well known that the mechanics of non-Newtonian fluids present a special challenge to engineers, physicists and mathematicians. Navier–Stokes' equations are not able to describe the properties of such fluids and no single constitutive equation is accessible which exhibits the properties of all fluids. Rheological properties of non-Newtonian fluids are described by their constitutive equations. Due to complex behavior of fluids, a number of non-Newtonian fluid models have been proposed such as viscoplastic [7], Bingham plastic [8], Brinkman type [9], power law [10], Oldroyd-B [11] and Walter-B [12] models. There is a popular non-Newtonian model, which was originally introduced by Casson for the forecast of flow behavior of pigment-oil suspension [13] and the model known as Casson model. In the earlier studies on Casson fluid, Fredrickson [14] investigated its steady flow in a tube. Boyd et al. [15] described the steady and oscillatory flow of blood flow by taking into account Casson fluid model. Mernone et al. [16] described the peristaltic flow of a Casson fluid in a two dimensional channel. Mustafa et al. [17] studied the unsteady boundary layer flow and heat transfer of a Casson fluid over a moving flat plate with a parallel free stream using homotopy analysis model (HAM). Mukhopadhay [18] described the effects of thermal radiation on Casson fluid flow and heat transfer over an unsteady stretching surface. Hayat et al. [19] examined the mixed convection stagnation point flow of Casson fluid with convective boundary conditions. Bhattacharyya [20] investigated the boundary layer stagnation point flow of Casson fluid and heat transfer toward a shrinking/stretching sheet. Pramanik [21] studied the Casson fluid flow and heat transfer past an exponentially porous stretching surface in the presence of thermal radiation. Mukhopadhay and Mondal [22] studied the forced convection flow of a Casson fluid past with surface heat flux over a symmetric porous wedge. The heat transfer aspects of the Casson fluid flow is an important research area due to its relevance to the optimized processing of chocolate, toffee and other foodstuffs [23]. Recently, Akbar and Khan [24] studied the metachronal beating of cilia under the influence of Casson fluid and magnetic field. Again Akbar [25] investigated the influence of magnetic field on peristaltic flow of a Casson fluid in an asymmetric channel an application in crude oil refinement. Physiological transportation of Casson fluid in a plumb duct was investigated by Akbar and Butt [26]. A theoretical investigation on oblique stagnation point flow of a Casson-Nano fluid toward a stretching surface with heat transfer was presented by Nadeem et al. [27], and in the same year again Nadeem et al. [28] studied the MHD three dimensional boundary layer flow of Casson nanofluid past a linearly stretching sheet with convective boundary condition.

In many realistic cases, the heat transfer from the surface is proportional to the local surface temperature. Such an effect is known as Newtonian heating effect. Merkin [29] investigated conjugate convective flow with Newtonian heating. Due to various applications researchers are attracted to consider the Newtonian heating condition in their problems. Hussanan et al. [30] presented an exact analysis of mass and heat transfer past a vertical plate with Newtonian heating. Recently, the unsteady boundary layer flow and heat transfer of a Casson fluid under the Newtonian heating boundary condition for non-Newtonian fluid was investigated by Hussanan et al. [31].

Motivated by the above investigations, the present analysis is focused on the study of unsteady MHD heat and mass transfer flow of a Casson fluid past a vertical plate with Newtonian heating in the presence of thermal radiation and chemical reaction. Exact solutions are obtained by using Laplace transform technique. The numerical results of skin friction, Nusselt number, and Sherwood number are presented in tabular form whereas the graphical results are presented and discussed for various physical parameters influencing the fluid flows and heat and mass transfer characteristics of the Casson fluid. Exact solutions obtained in this paper are useful for explaining the flow physics in detail.

2. Mathematical formulation

Consider the unsteady free convection heat and mass transfer flow of a viscous, incompressible, electrically conducting, heat radiating, and chemically reactive Casson fluid along an infinite non-conducting vertical flat plate in the presence of a uniform magnetic field B_0 applied in a transverse direction to the fluid flow. Let x'-axis be along the plate in upward direction, y'-axis is normal to it and z'-axis is normal to $x'y'$-plane.

Initially, when $t' \leqslant 0$, both the fluid and plate are at stationary condition having constant temperature T_∞ and species concentration C_∞. When $t' > 0$, the plate begins to oscillate in its plane having velocity $u' = U_0 \cos(w't')$ against the gravitational field, where U_0 denote the amplitude of the plate oscillations. Simultaneously, there is a direct proportionality relation between the local surface temperature T' and the heat transfer from the plate to the fluid and the concentration level near the plate is raised from C'_∞ to C'_w. A uniform magnetic field B_0 is applied in the y direction, it is assumed that induced magnetic field is negligible in comparison with the applied magnetic field, hence it is neglected. Since the plate is of infinite extent in x' and z' directions and is electrically nonconducting, all the physical quantities except pressure are function of y' and t' only. Assuming the rheological equation for an incompressible and isotropic Casson fluid, represented by Casson [13], is

$$\tau = \tau_0 + \mu\alpha^{\cdot}, \tag{1}$$

equivalently,

$$\tau_{ij} = \begin{cases} 2\left(\mu_B + \frac{p_y}{\sqrt{2\pi}}\right)e_{ij}, \pi > \pi_c \\ 2\left(\mu_B + \frac{p_y}{\sqrt{2\pi_c}}\right)e_{ij}, \pi < \pi_c \end{cases} \tag{2}$$