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## ORIGINAL ARTICLE

# Numerical exploration of a non-Newtonian Carreau fluid flow driven by catalytic surface reactions on an upper horizontal surface of a paraboloid of revolution, buoyancy and stretching at the free stream

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*Uhspr*;  
 Boundary layer analysis

**Abstract** Geometrically, the upper pointed surface of an aircraft and bonnet of a car are examples of upper horizontal surfaces of a paraboloid of revolution (*uhspr*). The motion of these objects strongly depends on the boundary layer that is formed within the immediate space on it. However, each of these surfaces is neither a horizontal/vertical nor cone/wedge and neither a cone nor a wedge. This article presents the motion of 2-dimensional Blasius flow of Carreau fluid on the surface of such object. The case in which the reaction between the Carreau fluid and catalyst at the surface produces significant temperature differences which consequently set up buoyancy-driven flows within the boundary layer is investigated. Single first-order Arrhenius kinetics is adopted to model the reaction on the surface of the catalyst situated on *uhspr* which initiates the free convection. Suitable similarity variables are applied to non-dimensionalized, parameterized and reduce the governing partial differential equations to a coupled ordinary differential equations (BVP). The BVP is solved numerically using the shooting technique. Temperature distribution in the flow of viscoelastic Carreau fluid is greater than that of a Newtonian fluid. Local heat transfer rate decreases faster when the Carreau fluid is characterized as shear-thinning. Maximum concentration is guaranteed at a small value of power-law index  $n$  and large value of thickness parameter.

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## 1. Introduction

Transmutation of any chemical substance into another is referred to as a chemical reaction. There exist different kinds of a chemical reaction due to the fact that this transmutation

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strongly depends on the particular portion of space occupied by electrons during the formation and breaking down of chemical bonds between atoms but no change in nuclei. In 300AD, Egyptian alchemist Zosimos of Panopolis and Stockholm Papyrus proposed some theories of chemical reaction. In the late 8th century, Hermes Trismegistus and Jabir ibn Hayyan deliberated on the concept rigorously; see Grethe [1], Rose and Gasteiger [2]. The statement of Wei and Prater [3] “*many chemical reaction systems which are of interest to engineers in the industry can be closely approximated by first-order reactions*” attracted some researchers to model selected occurrences of a chemical reaction within boundary layer as first order. Hayat et al. [4] deliberated on the effects of first order chemical reaction in the flow of upper convected Maxwell (UCM) magnetohydrodynamic (MHD) within the boundary layer. Krishna et al. [5] deliberated on the first-order chemical reaction within boundary layer flow of dusty viscous fluid using the perturbative technique. The influence of  $n$ th order chemical reaction when plastic dynamic viscosity and thermal conductivity of Casson fluid is temperature dependent has been reported by Animasaun [6]. Another occurrence of a chemical reaction within boundary layer is of an exothermic and endothermic kind. This kind of chemical reactions in which energy is absorbed from the surrounding (endothermic reactions) and the opposite case in which energy is released into the surroundings (exothermic reactions) attracted Maleque [7] to investigate the effects of exothermic/endothermic chemical reactions with Arrhenius activation energy on MHD free convection and mass transfer flow in presence of thermal radiation. Omowaye et al. [8] focused on the relevance of exothermic/endothermic kind of chemical reactions in the flow of Casson fluid over a thermally stratified melting surface of a paraboloid of revolution. Traced to the fact that some transmutations between chemical substance within the fluid (i.e. homogeneous bulk fluid) and catalyst on a solid object (heterogeneous) requires heat and/or accelerator (i.e. catalyst), the case of cubic and quartic autocatalytic kind of homogeneous-heterogeneous chemical reaction during the flow of various fluid has been deliberated in Refs. [9–17]. In most cases of boundary layer flow, wall temperature and free stream temperature satisfies  $T_w > T_\infty$  and this often initiates buoyancy. Chaudhary and Merkin [18,19] remarked that in certain cases, boundary-layer flow can be driven by catalytic surface reactions.

Boundary layer flow of different fluids driven by buoyancy due to the fact that  $T_w > T_\infty$  has been investigated by various authors. It is a well-known fact that when positive temperature and/or concentration difference(s) occurs within a fluid, the corresponding change in the fluid density gradients may be caused by the differences in the molecular weight of the reactants and the products or by non-reversible chemical reaction in the system Animasaun [20]. However, it was remarked that when  $T_w < T_\infty$  modification of Boussinesq approximation suggested by Oberbeck [21,22] and presented by Boussinesq [23,24] is needed. Related articles (flow of a thin liquid film of a fluid containing both nanoparticles and microorganism downwards along a vertical surface) in which modification of Boussinesq approximation could be easily deduced; see Raees [25], Motsa and Animasaun [26]. However, many chemical reactions are carried out in the combustion, biochemical industries, and chemical industries. When a slow reaction is witnessed, experts often subject the chemical reaction to flow

over a solid catalyst and Pop and Ingham [27] remarked that in most cases of reactant species at different rates both on the catalytic surface and within the fluid results in significant temperature variations within the reactant fluid and consequently modifies the fluid motion. In this case, wall temperature  $T_w$  is undefined but certainly, the whole of the reaction occurs within a boundary-layer region on the catalytic surface and temperature differences set up substantial buoyancy-driven flows within the boundary-layer. This contribution to the body of knowledge earns the interest of Bond [28] and Scott [29] to present an elaborate discussion on catalysts and production of heat energy. Chaudhary et al. [30], Refs. [18,19] presented a suitable model to investigate free convection boundary layers which are generated purely by the heat supplied to the surrounding fluid by an exothermic surface reaction. It is worth mentioning that the influence of this kind of chemical reaction in the flow of fluid when the viscosity is defined over an infinite range of shear rates is an open question. In the flow of either gases or liquids, the movement of groups of molecules is inevitable. However, the convection may take place through diffusion, advection or both. Moreover, one of the types of heat transfer and a major mode of mass transfer is convection. This has attracted the attention of various experts [31–44] to investigate either free convection, forced convection or mixed convection within the boundary layer. In all the published articles on free convection, it is worth pointing out that the effects of increasing buoyancy parameter in the flow of viscoelastic-Carreau fluid flow driven by catalytic surface reactions on an upper horizontal surfaces of a paraboloid of revolution also remains an open question.

The flow of fluids may be categorized into a Newtonian fluid flow, viscoelastic fluid flow, a flow of non-Newtonian fluid with time-dependent viscosity and the flow of non-Newtonian fluids with time independent viscosity. However, there exist no fluid flow which accurately fits the definition of a Newtonian fluid flow (i.e. shear stress is proportional to the rate of deformation). Meanwhile, many common liquids and gasses such as air and water have been only assumed to be shear stress is proportional to the rate of deformation for theoretical study and practical study. When fluid flow experiences large differences in shear rate, Newtonian model is violated and another material model is strongly needed. Many rheological models had been tried until 1972 to describe adequately the behavior of this kind of non-Newtonian viscoelastic materials. In the year 1972, Pierre J. Carreau a modern rheologist proposed the model of Carreau fluid; see Carreau [45] and Carreau et al. [46]. It was noticed that the material model generates a curve that will characterize the viscosity over an infinite range of shear rates. In the Carreau model, viscosity of the fluid is modeled as function depending on shear rate (popularly written as  $\dot{\gamma}$ , viscosity at infinite shear rate ( $\mu_\infty$ ), viscosity at zero shear rate ( $\mu_0$ ), relaxation time ( $\lambda$ ) and power law index which measures the degree of non-Newtonian behavior. Using the theory, Olajuwon [47] remarked that the constitutive equation for a Carreau fluid describes the behavior of a purely viscous fluid whose viscosity changes with increasing rate of deformation. Unlike the power-law or Ostwald-De Waele model, it predicts a viscosity that remains finite as the shear rate approaches zero. Pantokratoras [48] explained the Carreau fluid model using the controlling parameter  $n$ . It was stated that the fluid is characterized as shear-thinning for  $0 < n < 1$ , shear-thickening for

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