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ORIGINAL ARTICLE

47nm alumina–water nanofluid flow within boundary layer formed on upper horizontal surface of paraboloid of revolution in the presence of quartic autocatalysis chemical reaction

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 Volume fraction;
 Buoyancy induced model

Abstract In this article, a modified version of buoyancy-induced model is considered to investigate the flow of 47nm alumina–water nanofluid along an upper surface of horizontal paraboloid of revolution in the presence of nonlinear thermal radiation, Lorentz force and quartic autocatalysis kind of homogeneous heterogeneous chemical reaction. The case of unequal diffusion coefficients of reactant A (bulk fluid) and B (high concentration of catalyst at the surface) in the presence of bio-convection is considered. Governing equation suitable to unravel the thermophoresis which takes place within the boundary layer is presented. Since chemical reactant B is of higher concentration at the surface more than the concept described as cubic autocatalytic, the suitable schemes are herein described as isothermal quartic autocatalytic reaction and first order reaction. The viscosity and thermal conductivity are assumed to vary with volume fraction (ϕ) and suitable models for the case $0\% \leq \phi \leq 0.8\%$ are adopted. The transformed governing equations are solved numerically using Runge–Kutta fourth order along with shooting technique (RK4SM). Good agreement is obtained between the solutions of RK4SM and MATLAB `bvp5c` for a limiting case. The influence of some pertinent parameters on velocity, temperature, diffusion of motile microorganism, concentration of bulk fluid and catalyst is illustrated graphically and discussed.

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1. Introduction

Aerosol can be described as a suspension of fine liquid droplets or solid particles in air or liquid. Practically speaking, small particle(s) can be driven from a hot surface towards a cold surface. For instance, small particles (e.g. dry dust) when suspended in a gas (e.g. air) with a temperature gradient, experience a force in the direction of the temperature gradient

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(migrate towards the direction of decreasing temperature). In this situation, the velocity of such particle(s) which drives it from the region of hot surface to the region of cold surface is called thermophoretic velocity. The force experienced by the suspended particle(s) due to the temperature gradient is called thermophoretic force. This concept was first observed and reported by John Tyndall (Physicist/Chemist from Ireland) in the year 1870. Thereafter, John William Strutt (3rd Baron Rayleigh) explained this report in such a way that scientists deeply understood the contribution of John Tyndall; see Davis [1]. A common example of the phenomenon is the blackening of the glass globe of a kerosene lantern; the temperature gradient established between the flame and the globe drives the carbon particles produced in the combustion process towards the globe where they deposit; Talbot et al. [2]. Another occurrence of thermophoresis can be found at the edge of fluorescent bulb. According to Tsai et al. [3] on combined effects of thermophoresis and electrophoresis on particle deposition onto a thin slice of semiconductor material used in electronic for fabrication of integrated circuits; the deposition mechanisms for particles include Brownian diffusion, convection, thermophoresis and electrophoresis. Thermophoresis is of practical importance in many industrial applications, such as in aerosol collection (thermal precipitator), micro contamination control, removing small particles from gas streams, nuclear reactor safety, in studying the particulate material deposition on turbine blades, and also in determining exhaust gas particle trajectories from combustion devices. Animesaun [4] reported the dynamics of unsteady magnetohydrodynamic fluid flow with thermophoresis of particles past a vertical porous plate moving through a binary mixture in an optically thin environment. Sandeep et al. [5] deliberated on boundary layer flow of a thermophoretic MHD dissipative nanofluid over an unsteady stretching sheet in a porous medium.

Nanoparticles can be described as particles between 1nm and 100nm in size. Nanoparticle research is currently an area of intense scientific interest due to a wide variety of potential applications in engineering and biomedical. When nanoparticles are controllably dispersed in base fluid, it enhances the properties of the so-called multi-component fluid or two-phase fluid. The term “*nanofluid*” was proposed by Choi [6], referring to dispersions of nanoparticles in the base fluid such as water. Nguyen et al. [7] reported that sedimentation, shear stress and agglomeration are few problems that can be referred to as an agent which may limit the mixtures of nanoparticles in a nanofluid. Sandeep et al. [8] reported stagnation point flow, heat and mass transfer behavior of MHD Jeffrey nanofluid in the presence of induced magnetic field. The word “*Bioconvection*” was first introduced in the report of James Henry Platt with the aim to call the attention of other researchers to the physics of streaming patterns observed in dense cultures of free-swimming organisms. According to Platt [9], the moving polygonal patterns in dense cultures of *Tetrahymena* and other *ciliates* and *flagellates* look like “Benard cells” but are not due to thermal convection. There exist many bacteria (organisms) and it is a well-known fact that many bacteria can be damaged and sometimes killed if exposed to high temperature. In contrary, thermophile is an organism commonly found in various heated regions of the earth. Ghorai and Hill [10] further explained that bioconvection is the term used to describe the phenomenon of spontaneous pattern formation in suspensions of microorganisms such as bacteria and algae. Bioconvection

can now be described as the macroscopic convective motion of fluid caused by density gradient and is created by collective swimming of motile microorganisms. Like natural convection, bioconvection is caused by unstable density stratification. Kuznetsov and Avramenko [11] explained that if bioconvection develops, it enhances mixing and slows down the settling of the particles which may be of importance in pharmaceutical applications. Khan and Makinde [12] investigated nanofluid bioconvection due to gyrotactic microorganisms and remarked that these self-propelled motile microorganisms may increase the density of the base fluid by swimming in a particular direction, thus causing bioconvection. For more related contributions on heterogeneous mixed convection of alumina/water nanofluid, nanofluid flow inside porous micro-channel in the presence and absence of heat source/sink, heat convection inside concentric annulus filled with alumina–water nanofluid and unsteady motion of vertically falling spherical particles see Refs. [13–17]. Recently, Raees et al. [18] reported that bioconvection in nanofluids has great potential in Colibri microvolumes spectrometer and also to improve the stability of nanofluids.

Chemical reaction can be explained as an interaction between two or more chemicals which produces either one or more new chemical compounds. An example is n th order of chemical reaction which may not require catalyst. Animesaun [19] analyzed such effects in MHD dissipative Casson fluid flow in the presence of thermophoresis. Many chemical reactions actually require heat and accelerator (i.e. catalyst). A chemical reaction in which catalyst is in the same phase (i.e. in the same state of matter) as the reactant(s) is known as homogeneous catalytic reaction. Reactions between two gases and between two liquids are typical examples of homogeneous catalytic reactions. Another example is the mixture of household cooking gas with oxygen gas leading to flame. In heterogeneous catalytic reaction, catalyst and reactants are in different phases (i.e. different states of matter). Examples of heterogeneous catalytic reactions are chemical reactions between gas & liquid, gas & solid and liquid & solid. In addition to this example, a chemical reaction in which one or more reactants undergo chemical change at an interface (i.e. on the surface of a solid catalyst) is called heterogeneous catalytic reaction. When fluid moves along a surface, a thin layer is formed in the vicinity of a surface bounding the fluid; Ludwig Prandtl called it “*boundary layer*”. Chaudhary and Merkin [20] introduced a simple model for homogeneous heterogeneous reactions in stagnation-point boundary-layer flow in which the homogeneous (bulk) reaction is assumed to be given by isothermal cubic autocatalator kinetics and the heterogeneous (surface) reaction by first order kinetics. Scott [21] considered quadratic and cubic autocatalytic together with rates of their chemical reaction; then coupled the equation with the diffusion of the reactants through a permeable boundary from an external reservoir where the concentrations are held constant. Motsa et al. [22] investigated the case of equal diffusion coefficients of chemical species A and B in the stagnation point nanofluid flow in the presence of homogeneous heterogeneous reactions using successive linearization method (SLM). Sandeep et al. [23] explained the effects of induced magnetic field on cubic autocatalytic reaction which often occurs in viscoelastic fluid flows toward a stagnation point. In most cases when the concentration of homogeneous species B is highly substantial, the cubic autocatalator kinetics may not be sufficient;

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