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Gyrotactic bioconvection flow of a nanofluid past a vertical wavy surface

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ABSTRACT

In this paper bioconvection flow with heat and mass transfer of a water-based nanofluid containing gyrotactic microorganisms over a vertical wavy surface is investigated. The coupled nonlinear set of equations comprised of velocity, temperature, nanoparticle concentration and density of microorganisms is solved numerically by using implicit finite difference method. Flow characteristics are obtained in terms of skin friction coefficient, Nusselt number, Sherwood number and density number of microorganisms coefficient and are presented graphically by varying several controlling parameters. Interesting observations are recorded for the parameters: *a*, *Nr*, *Lb* and *Rb*. It is observed that the amplitude of the wavy surface has pronounced influence on the rates of heat and mass transfer, skin friction coefficient and density number of the microorganisms coefficient and all these quantities get augmented as the amplitude increases.

1. Introduction

Bioconvection is a macroscopic convection motion of the fluid originated due to the density gradient created by collective swimming of microorganisms (such as bacteria and algae) [1–6]. These self-propelled motile microorganisms increase the density of the base fluid by swimming in a particular direction, thus causing bioconvection. Although bioconvection systems can be distinguished on the basis of the mechanism of directional motion of different types of microorganisms, but on the average they swim upward (more denser than the base fluid) and the reason for up-swimming may be different for different species. Microorganisms respond to certain stimuli by tending to swim in particular directions. These responses are called taxes, examples being gravitaxis, gyrotaxis, phototaxis, and chemotaxis. In this paper, we deal with the gyrotactic bioconvection in which direction of swimming is determined by the balance of gravitational and viscous torques (for example see Refs. [7–9]). Bioconvection found its applications in biomicrosystems and biotechnology. For example, in biomicrosystems mass transport enhancement and mixing is caused due to bioconvection (see Refs. [10,11]).

The concept of nanofluid bioconvection basically describes the spontaneous pattern formation and density stratification caused by the simultaneous interaction of the denser self-propelled microorganisms, nanoparticles and buoyancy forces. Nanofluids are preferred since they can be used to enhance the thermal conductivity of the base fluid(s). Such fluids found their applications in many industrial processes. In a broader perspective, nanofluids are observed to be more stable fluids having better wetting, spreading and dispersion properties on solid surfaces (see Refs. [12,13]). The motion of the nanoparticles is caused due to the Brownian motion and thermophoresis, taking place within the nanofluids, which conclude that the motion of the nanoparticles is independent of the motion of motile microorganisms. Therefore, combined interaction of nanofluids and bioconvection becomes significant for microfluidic devices. In order to keep the microorganisms alive, the presence of water in the nanofluid/base fluid is important. Nanofluid bioconvection seems possible only when the concentration of nanoparticles is small enough so that nanoparticles do not enhance the viscosity of the base fluid [14]. The nanofluid bioconvection of gyrotactic microorganisms was initially examined by Refs. [14–21].

In many engineering problems heat transfer enhancement is of

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great interest from energy saving perspective. Several different methods are used for the enhancement of heat transfer, namely, changing flow geometry, boosting thermal conductivity of the fluid, or by changing boundary conditions. In literature, it has been reported that heat transfer characteristics of the base fluid can be enhanced by suspending higher thermal conductivity microsolid particles. The size of the suspended particles is small enough (like nanofluids) in order to avoid microchannels clogging and erosion. As mentioned earlier, irregular surfaces can be used for the enhancement of heat transfer rate. For instance, solar collectors, condensers in refrigerators, cavity wall insulating systems, grain storage containers, and industrial heat radiators are a few of many applications of rough surfaces through which small as well as the large scale heat transfer is encountered. Study of heat transfer along a wavy surface has been exploited by several authors under several different circumstances (see Refs. [22–30]). In the present study, nanofluid bioconvection flow is investigated with gyrotactic microorganisms over the vertical wavy surface. These motile microorganisms are self-propelled and therefore they can swim in the base fluid due to the presence of stimuli like gravity. The nanoparticles carried by the base fluid are set in motion due to Brownian motion and thermophoresis. In the later sections, the problem is formulated mathematically and solved numerically in the light of important physical parameters.

2. Flow analysis

Consider a 2D bioconvection flow of a water based nanofluid containing gyrotactic microorganisms past a vertical wavy surface. The wavy surface is maintained at constant temperature T_w, the nanoparticle volume fraction φ_w, and the density of microorganisms n_w, whereas the ambient values of temperature, nanoparticle volume fraction and density of the microorganisms are denoted as T_∞, φ_∞ and n_∞, respectively. The wavy surface is considered to be heated, i.e., $T_w > T_\infty$. It is assumed that the nanoparticles do not have any influence on microorganism's swimming direction and also on their swimming velocity. Bioconvection can only be induced in modestly diluted cell (nanoparticle) suspension; otherwise, a large concentration of nanoparticles would result in a large suspension viscosity, which would suppress bioconvection. The physical model and the coordinate system are shown in Fig. 1. The governing equations are obtained by using the Oberbeck-Boussinesq approximation and are based on the theory of bioconvection in suspensions of gyrotactic microorganisms, as proposed by Buongiorno [12] and Kuznetsov [14]. These equations are related to conservation of mass, momentum, thermal energy, nanoparticle volume fraction and microorganisms and can be written as:

$$\nabla \cdot \vec{U} = 0 \tag{1}$$

$$\vec{U} \cdot \nabla \vec{U} = -\frac{1}{\rho_f} \nabla \bar{p} + \nu_f \nabla^2 \vec{U} + \frac{1}{\rho_f} \Big[\rho_f \beta (1 - \varphi_\infty)(T - T_\infty) - \left(\rho_p - \rho_f\right)(\varphi - \varphi_\infty) - \gamma \left(\rho_m - \rho_f\right)(n - n_\infty) \Big] \vec{g} \tag{2}$$

$$\vec{U} \cdot \nabla T = \alpha \nabla^2 T + \tau D_B \nabla \varphi \cdot \nabla T + \frac{\tau D_T}{T_\infty} \nabla T \cdot \nabla T \tag{3}$$

$$\vec{U} \cdot \nabla \varphi = D_B \nabla^2 \varphi + \frac{D_T}{T_\infty} \nabla^2 T \tag{4}$$

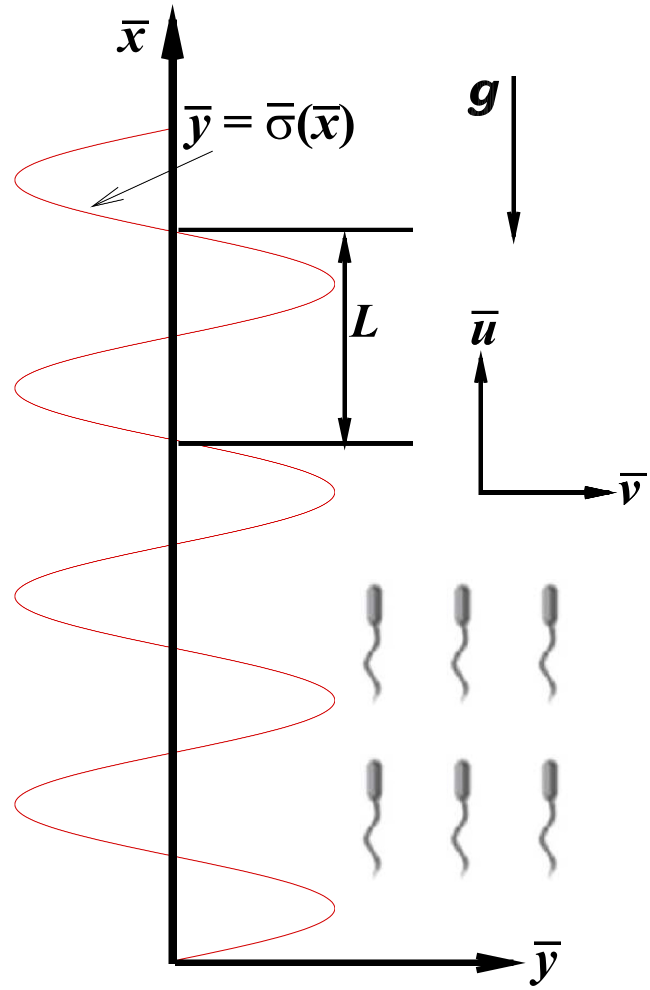

Fig. 1. Physical model.

$$\nabla \cdot \vec{j} = 0 \tag{5}$$

where $\vec{U} = (\bar{u}, \bar{v})$ is the velocity vector of the nanofluid flow in the $(\bar{x}, \bar{y})$ directions, $\bar{p}$ the pressure, T the temperature, φ the nanoparticles concentration, n the concentration of microorganisms, $\vec{j}$ the flux of microorganisms due to fluid convection, self-propelled swimming and diffusion, ν_f the kinematic viscosity of the suspension of nanofluid and microorganisms, ρ_f the density of the base fluid, ρ_p the density of the nanoparticles, ρ_m the microorganisms density, $(\rho_m - \rho_f)$ the density difference between a cell and a base fluid, β the volumetric coefficient of thermal expansion of the base fluid, $\vec{g}$ the gravity vector, γ the average volume of a microorganism, α the thermal diffusivity of the nanofluid, $\tau = (\rho c)_p/(\rho c)_f$ defines the ratio of heat capacity of the nanoparticle to the heat capacity of the base fluid, D_B the Brownian diffusion coefficient and D_T the thermophoretic diffusion coefficient. Furthermore, the flux of microorganisms, $\vec{j}$, is defined as (see Ref. [14]):

$$\vec{j} = n\vec{U} + n\vec{\hat{U}} - D_{m0} \nabla n \tag{6}$$

where