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Hydromagnetic bioconvection of nanofluid over a permeable vertical plate due to gyrotactic microorganisms

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ABSTRACT

In this paper, we investigate the bioconvection induced by the hydromagnetic flow of a novel type of a water based nanofluid containing nanoparticles and motile microorganisms past a permeable vertical moving surface. Nanofluid bioconvection is generated by the combined effects of buoyancy forces and magnetic field on the interaction of motile microorganisms and nanoparticles. Both Brownian motion and thermophoresis effects are incorporated into the model nonlinear differential equations.Using appropriate similarity transformation and shooting quadrature coupled with Runge–Kutta–Fehlberg integration scheme, the model boundary value problem is tackled numerically. A parametric study of the entire flow regime is carried out to illustrate the effects of the governing parameters, namely bioconvection Lewis number *Lb*, traditional Lewis number *Le*, bioconvection Péclet number *Pe*, buoyancy ratio parameter *Nr*, bioconvection Rayleigh number *Rb*, Brownian motion parameter *Nb*, thermophoresis parameter *Nt*, Hartmann number *Ha*, Grashof number *Gr*, Eckert number *Ec*, the microorganisms concentration difference parameter Ω and the suction/injection parameter f_w on the velocity, temperature, nanoparticles volume fraction and motile microorganisms density profiles as well as the skin friction coefficient, the local Nusselt number, the local Sherwood number and the local density number of the motile microorganisms.

1. Introduction

The concept of boundary layer flow past a permeable media has many applications in mechanical, chemical and civil engineering such as cooling systems for electronic devices, furnace engineering, solar energy collectors, thermal insulation of buildings, geophysical systems, non-Newtonian chemical processes, electromagnetic fields and underground disposal of nuclear or non-nuclear waste applications among others. In all these systems, heat transfer enhancement is of a major contemporary interest from an energy saving perspective. There exists different ways of enhancing heat transfer such as changing flow geometry, boundary conditions, or by enhancing thermal conductivity of the fluid. Various theoretical and experimental studies have shown that base fluid heat transfer characteristics are enhanced, by suspending higher thermal conductivity microsolid particles. However, owing to the large size of the suspended particles, microchannels logging and erosion occurs. To overcome this problem, the use of smaller sized particles (nanoparticles) was proposed as in the case of nanofluids. The term "nanofluid" was coined by Choi [1] to refer to a colloidal suspension of submicronic solid particles (nanoparticles) having higher thermal conductivity in a base fluid. The typical length of a nanoparticle is on the order 1–50 nm. The nanoparticles used are ultrafine, therefore, nanofluids appear to behave more like a single-phase fluid than a solid–liquid mixture. The nanoparticles used in nanofluids are typically made of chemically stable metals (Al, Cu, Ag, Au, Fe), oxides (Al_2O_3, CuO, TiO_2, SiO_2), carbides (SiC), nitrides (AlN, SiN), or non-metals (graphite, carbon nanotubes), and the base fluid is usually a conductive fluid, such as water, ethylene glycol (or other coolants), oil (and other lubricants), polymer solutions, bio-fluids and other common fluids. Experimental studies have shown that the thermal conductivity of nanofluids depends on several parameters; nanoparticle material, particle volume fraction, spatial distribution, particle size, particle shape, base-fluid type, temperature, and pH value. According to Lee et al. [2] and Eastman et al. [3], metallic nanoparticles enhance the thermal and electrical conductivity of the base fluid as well as the overall heat transfer rate compared to non-metallic ones. They also found that nanofluids' heat transfer rate increases with

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increase in nanoparticle volume fraction. This unique property makes nanofluids applicable as a means of heat removal in numerous thermal–fluid microsystems such as microheat pipes, microchannel heat sinks, microreactors among others. As proposed by Buongiorno [4], the convective transport process in nanofluids is mainly attributed to Brownian diffusion and thermophoresis, which necessitates their inclusion in the conservation equations for mass and energy. The concept of convective transport in nanofluids taking into consideration these physical mechanisms has been widely investigated [5–8].

MHD flow past a flat surface is of a special technical significance because of its frequent occurrence in many technological and industrial applications such as MHD pumps, micro-mixing of physiological samples, biological transportation and drug delivery. The flow and heat transfer in any electrically conducting fluid flow system may be controlled by the application of an external magnetic field. The presence of the nanoparticles enhances the electrical conductivity property of nanofluids, hence making them more susceptible to the influence of the magnetic field as compared to the conventional base fluids. Studies on MHD free convective boundary-layer flow of nanofluids [9–12], autonomously pointed out that, magnetic nanofluids have many industrial, engineering and biomedical applications such as magnetofluidic leakage free seals, magnetogravimetric separations, aerodynamic sensors, smartfluids for vibration damping, MHD blood flow meters, magnetic drug targeting and nanocryosurgery.

Bioconvection has many applications in biological systems and biotechnology. The concept of nanofluid bioconvection which is the focus of the study therein describes the spontaneous pattern formation and density stratification caused by the simultaneous interaction of the denser self-propelled microorganisms, nanoparticles, and buoyancy forces. These microorganisms may include gravitaxis, gyrotaxis or oxytaxis organisms. The benefits of adding motile microorganisms to the suspension include enhanced mass transfer, microscale mixing, especially in microvolumes and improved nanofluid stability [13]. The hydrodynamic convection caused by the oxytactic microorganisms leads to a flow system which transport cells and oxygen from the upper fluid region to the lower fluid regions. Unlike motile microorganisms, the nanoparticles are not self-impelled, and their motion is driven by Brownian motion and thermophoresis taking place within the nanofluid. It is thus apparent that motion of the motile microorganisms is independent of the motion of nanoparticles. A combination of a nanofluid and bioconvection is consequently quite alluring for novel microfluidic devices. It is assumed that the presence of nanoparticles has no effect on the directional locomotion of the self-propelled microorganisms. It is worth noting that, since the motile microorganisms have to be able to live in the base fluid, the nanofluid has to be water-based. Bioconvection has many applications in bio-microsystems, such as enzyme biosensors and biotechnology due to the mass transport enhancement and mixing, which are important issues in many micro-systems. Nanofluid bioconvection is predicted to be possible if the concentration of nanoparticles is small, so that nanoparticles do not cause any significant increase in the viscosity of the base fluid [14]. The problem of bioconvection of gyrotactic microorganisms in nanofluids was first considered in [15–17]. The theory of suspensions was further advanced by Kuznetsov [18], who, applied Buongiorno's [4] concept of convective transport in nanofluids which took into account Brownian motion and thermophoresis. Aziz et al. [19] extended the work of Kuznetsov [20] by considering free convection boundary layer flow past a horizontal plate embedded in a porous medium filled by a nanofluid containing both nanoparticles and gyrotactic microorganisms. Further work revealed that nanofluid stability depended on: the nanoparticle distribution and the density stratification induced by either the vertical temperature gradient or the upswimming of oxytactic microorganisms, while the effect of microorganisms on the stability of the suspension depended on the value of bioconvection Peclet number [21,22]. Inspite of the aforementioned studies already devoted to understanding nanofluid bioconvection, no attempt has been made in the literature to investigate the effects of magnetic field on nanofluid bioconvection. Such analysis may give some insight into the complex dynamics of self-propelled microorganisms in nanofluid under the influence of external magnetic field for application purpose (see Fig. 1).

This present study aims to extend the recent work of Olanrewaju and Makinde [5] to include hydromagnetic nanofluid bioconvection over a permeable vertical plate with gyrotactic microorganisms. Since motile microorganisms are self-propelled they can actively swim in the fluid in response to such stimuli as gravity, light or chemical attraction. On the contrary, nanoparticles just move due to such phenomena as Brownian motion and thermophoresis and are carried by the flow of the base fluid. In the following sections, the model is formulated, analysed and numerically solved. Pertinent results are presented graphically and discussed.

2. Model formulation

A steady boundary layer flow of a water-based electrically conducting nanofluid containing gyroytactic microorganisms past a permeable vertical flat plate is considered. The flow is subjected to a uniform transverse magnetic field of strength B_0. There is no applied voltage and the magnetic Reynolds number is small, hence the induced magnetic field and Hall effects are negligible. As earlier mentioned, the presence of nanoparticles is assumed to have no effect on the direction of microorganisms' swimming and on their swimming velocity. It is assumed that the nanoparticle suspension is stable (there is no nanoparticle agglomeration) and dilute (the concentration of nanoparticles is than 1%). This is a logical assumption, since nanofluid bioconvection is expected to occur only in a dilute suspension of nanoparticles; otherwise, a large concentration of nanoparticles would result in increased viscosity of the base fluid, which would suppress bioconvection [14]. Adopting the

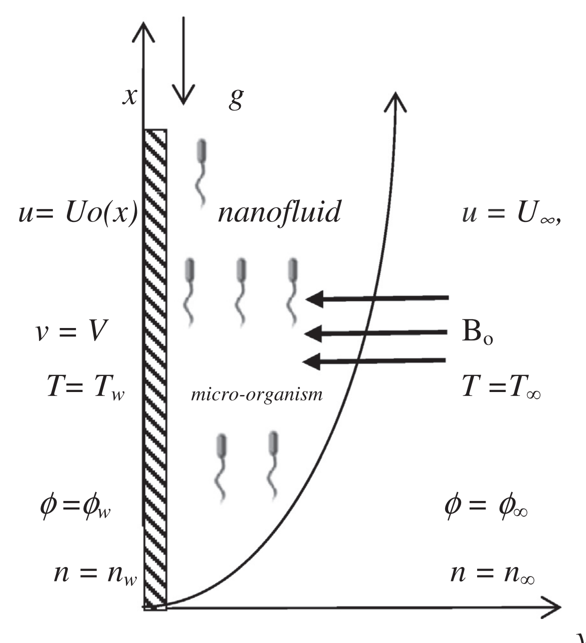

Fig. 1. Schematic diagram of the problem.