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ORIGINAL ARTICLE

Flow and heat transfer characteristics of nanofluids in a rotating frame

Kalidas Das *

Department of Mathematics, Kalyani Government Engineering College, Kalyani, Nadia, West Bengal 741235, India

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Abstract The problem of unsteady MHD free convection flow of nanofluids via a porous medium bounded by a moving vertical semi-infinite permeable flat plate with constant heat source and convective boundary condition in a rotating frame of reference is studied theoretically. The velocity along the plate i.e. slip velocity is assumed to oscillate in time with constant frequency so that the solutions of the boundary layer are the same oscillatory type. The dimensionless governing equations for this investigation are solved analytically using small perturbation approximation. Two types of nanofluids, namely Cu–water and Al_2O_3–water are used. The effects of various parameters on the flow and heat transfer characteristics are discussed through graphs and tables.

1. Introduction

Convective heat transfer in nanofluids is a topic of major contemporary interest both in sciences and in engineering. Heating or cooling fluids such as water, ethylene glycol and engine oil play a crucial role in thermal management of high tech industries but they have poor thermal characteristics, in particular thermal conductivity. Despite the considerable efforts to improve the rate of heat transfer by the usage of extended surfaces, mini-channels and microchannels, further enhancement in heating and cooling rate is always in demand. As solid materials possess higher thermal conductivities many studies have been carried out on thermal properties of suspension of solid particles in conventional heat transfer fluids. Nanotechnology provides means to manufacture solid particles in nanometer scale. Choi [1] was the first to introduce the word nanofluid that represents the fluid in which nanoscale particles (diameter less than 50 nm) are suspended in the base fluid. Nanoparticles are of great scientific interest as they are effectively a bridge between bulk materials and atomic or molecular structures. The common nanoparticles that have been used are aluminum, copper, iron and titanium or their oxides. Experimental studies [2–5] show that even with the small volumetric fraction of nanoparticles (usually less than 5%), the thermal conductivity of the base liquid can be enhanced by 5–20%. The enhanced thermal conductivity of nanofluid together with the thermal conductivity of the base liquid and turbulence induced by their motion contributes to a remarkable improvement in the convective heat transfer coefficient. This feature of nanofluids makes them attractive for the use in application such as advanced nuclear system [6]. Various benefits of the

* Tel.: +91 9748603199.
E-mail address: kd_kgec@rediffmail.com

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application of nanofluids include the following: improved heat transfer, heat transfer system size reduction, minimal clogging, micro-channel cooling and miniaturization of the system. Convective flow in porous media has been widely studied in the recent years due to its wide applications in engineering as post-accidental heat removal in nuclear reactors, solar collectors, drying processes, heat exchangers, geothermal and oil recovery, building construction etc. They are also used in other electronic applications which use microfluidic applications. It should be noticed that there have been published several recent papers [7–12] on the mathematical and numerical modeling of convective heat transfer in nanofluids. These models have some advantages over experimental studies due to many factors that influence nanofluid properties.

The problem on natural convection heat transfer in nanofluids has been investigated numerically by Gilles et al. [13], Jou and Tzeng [14], Ho et al. [15,16], Congedo et al. [17] and Ghasemi and Aminossadati [18]. However, the number of analytical studies on natural convection in nanofluids is relatively small compared with those devoted to forced convection. Khanafer et al. [19] analyzed the two dimensional natural convection flow of a nanofluid in an enclosure and found that for any given Grashof number, the heat transfer rate increased as the volume fraction of nanoparticles increased. Kim et al. [20] introduced a new friction factor to describe the effect of nanoparticles on the convective instability and the heat transfer characteristics of the base fluid. On the other hand, very few works have been done on natural convection flow of rotating fluids. Rotating flows of MHD non-Newtonian fluids have many applications in meteorology, geophysics, turbo machinery and many other fields. Such flows in the presence of a magnetic field are significant because of their geophysical and astrophysical importance. Moreover the present model has applications in biomedical engineering, for instance in the dialysis of blood in artificial kidney, blood flow in the capillaries, flow in blood oxygenation. Engineering applications include the design of filters, the porous pipe design, in transpiration cooling. Bakr [21] and Das [22] discussed free convection flow of micropolar fluid in a rotating frame of reference. Recently, Hamad and Pop [24] studied MHD free convection flow in a rotating frame of reference with constant heat source in a nanofluid. To develop the problem, they used the nanofluid model proposed by Tiwari and Das [23]. It is worth mentioning that while modeling the boundary layer flow and heat transfer, the boundary conditions that are usually applied are either a specified surface temperature or a specified surface heat flux. However, there are boundary layer flow and heat transfer problems in which the surface heat transfer depends on the surface temperature. Perhaps the simplest case of this is when there is a linear relation between the surface heat transfer and surface temperature. This situation arises in conjugate heat transfer problems and when there is Newtonian heating of the convective fluid from the surface. The situation with Newtonian heating arises in what is usually termed as conjugate convective flow, where the heat is supplied to the convective fluid through a bounding surface with a finite heat capacity. This results in the heat transfer rate through the surface being proportional to the local difference in the temperature with the ambient conditions. This configuration of Newtonian heating occurs in many important engineering devices, for example, in heat exchangers, where the conduction in a solid tube wall is greatly influenced by the convection in the fluid flowing over it. On the other hand, most recently, heat transfer problems for boundary layer flow concerning with a convective boundary condition were investigated by Aziz [25], Makinde and Aziz [26], Ishak [27] and Yacob et al. [28]. But so far, no attempt has been made to analyze the boundary layer flow of a nanofluid past a porous vertical moving plate in a rotating frame of reference with convective surface boundary condition.

The objective of the present study is to analyze the development of the unsteady free convection flow of a nanofluid past a moving vertical permeable flat plate in a rotating frame of reference with convective surface boundary condition. It is assumed that the plate is embedded in a uniform porous medium and oscillates in time with a constant frequency in the presence of a transverse magnetic field. The governing equations are solved analytically using perturbation technique. Numerical results are reported for various values of the physical parameters of interest. The organization of the paper is given as follows. The Section 2 deals with the mathematical formulation of the problems. Section 3 contains the closed form solutions of velocity and temperature. Numerical results and discussion are presented in Section 4. The conclusions have been summarized in Section 5.

2. Mathematical formulation of the problem

Consider the unsteady three dimensional free convection flow of an electrically conducting incompressible nanofluid of ambient temperature T_∞ past a semi-infinite vertical permeable moving plate embedded in a uniform porous medium in the presence of thermal buoyancy effect with constant heat source and convective boundary condition. The fluid is a water based nanofluid containing two types of nanoparticles, either Cu (copper) or Al_2O_3 (aluminum oxide). The nanoparticles are assumed to have a uniform shape and size. Moreover, it is assumed that both the fluid phase and nanoparticles are in thermal equilibrium state. Fig. 1 describes the physical model and the co-ordinate system. The flow is assumed to be in the x-direction which is taken along the plate in the upward direction and z-axis is normal to it. Also it is assumed that the whole system is rotate with a constant velocity Ω about z-axis. A uniform external magnetic field B_0 is taken to be acting along the z-axis. It is assumed that there is no applied voltage

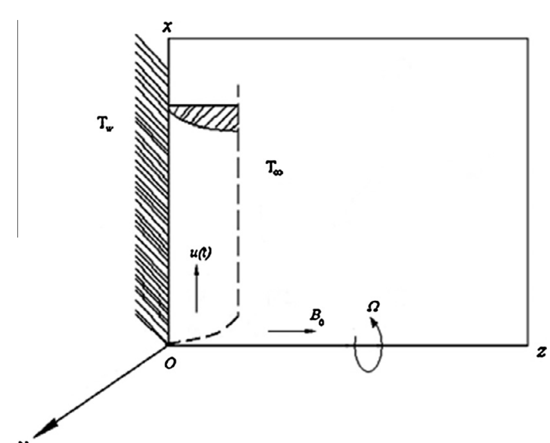

Figure 1 Physical model and coordinate system of the problem.