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ORIGINAL ARTICLE

Thermophoretic MHD slip flow over a permeable surface with variable fluid properties

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Abstract The present paper focuses on the analysis of thermophoretic hydromagnetic slip flow over a permeable flat plate with convective surface heat flux at the boundary and temperature dependent fluid properties in the presence of non-uniform heat source/sink. The transverse magnetic field is assumed to be a function of the distance from the origin. Also it is assumed that the liquid viscosity and the thermal conductivity vary as an inverse function and a linear function of temperature, respectively. The shooting method is employed to yield the numerical solutions for the model. Results show that the thermal boundary layer thickness reduces with increase of surface convection parameter whereas reverse effect occurs for viscosity parameter. It is also observed that the thermophoretic parameter decreases the concentration distribution across the boundary layer.

1. Introduction

Recently, research on aerosol particles deposition has become more and more important for engineering applications. The factors that influence particle deposition include convection, inertial impaction, sedimentation, Brownian diffusion, thermophoresis, electrophoresis, etc. Thermophoresis is an important mechanism of micro-particle transport due to a temperature gradient in the surrounding medium and has found numerous applications, especially in the field of aerosol technology. When a temperature gradient exists in the field surrounding a small particle, a net force is exerted on the particle due to an imbalance of the forces associated with molecular collisions from the hotter and colder region. Due to thermophoresis, small micron sized particles are deposited on cold surfaces. In this process, the repulsion of particles from hot objects also takes place and a particle-free layer is observed around hot bodies (see Goldsmith and May [1]). This phenomenon has many practical applications in removing small particles from gas particle trajectories, from combustion devices, and studying the particulate material deposition turbine blades. Thermophoretic deposition of radioactive particles is considered to be one of the important factors causing accidents in nuclear reactors. Many studies were reported considering the effect of thermophoresis on the boundary layer [2–8]. Partha [9] investigated suction/injection effects on thermophoresis particle deposition in a non-Darcy porous medium. The effects of thermophoresis and radiation on laminar flow were studied

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by Bakier and Gorla [10]. A recent paper by Postelnicu [11] dealt with the effects of thermophoretic particle deposition on the natural convection flow over an inclined porous media.

The magnetohydrodynamic (MHD) boundary layer flow for an electrically conducting fluid in porous medium is of considerable interest in geothermal engineering, energy conservation, modern metallurgical processes, underground disposal of nuclear waste materials and many others. Thermophoresis is also a key mechanism of study in semi-conductor technology especially controlled high quality wafer production as well as MHD energy generation system operations. Since various industrial heat transfer processes involved both the hydromagnetic flows and thermophoresis such as in MHD energy systems, many numerical studies [12–15] on magnetohydrodynamic heat and mass transfer have been reported with buoyancy, Joule heating effects and heat source/sink parameters. Recently, the effects of thermophoresis and internal heat generation/absorption on MHD heat and mass transfer flow over an inclined radiate permeable surface were examined by Noor et al. [16]. All of these studies, however, considered constant fluid properties and no-slip at the boundary. In certain situations, the assumption of no-slip boundary condition does no longer apply. When fluid flows in micro electro mechanical system (MEMS), the no slip condition at the solid-fluid interface is no longer applicable. Slip flow happens if the characteristic size of the flow system is small or the flow pressure is very low. A partial slip may occur on a stationary and moving boundary when the fluid is particulate such as emulsions, suspensions, foams, and polymer solutions. On the other hand most of the MHD applications in microfluidics are in the liquid fields. Thus considering MHD liquid slip flow has promising potential in numerous practical applications such as MHD micro pumps which are a non-mechanical pump. The slip flows under different flow configurations have been studied in recent years [17–21]. Recently, Das [22] have considered the slip effects on heat and mass transfer in MHD micropolar fluid flow over an inclined plate with thermal radiation and chemical reaction.

All of these studies, however, considered constant thermophysical properties such as constant viscosity and thermal conductivity. But, it is well known [23–28] that these physical properties may change with temperature, especially fluid viscosity, thermal conductivity, etc. For lubricating fluids, heat generated by internal friction and the corresponding rise in the temperature affects the physical properties of the fluid and so the properties of the fluid are no longer assumed to be constant. The increase in temperature leads to increase in the transport phenomena by reducing the physical properties across the thermal boundary layer and so the heat transfer at the wall is also affected. Therefore to predict the flow and heat transfer rates, it is necessary to take into account the variable fluid properties. Zueco et al. [29] discussed the effect of thermophoresis particle deposition and of the thermal conductivity in a porous plate with dissipative heat and mass transfer. Recently, Das [30] investigated the impact of thermal radiation on MHD slip flow over a flat plate with variable fluid properties.

To our best knowledge, study on MHD heat and mass transfer slip flow over a radiate permeable surface with thermophoretic particle deposition and variable liquid properties has never been considered till date. Therefore, in this paper, the previous work of Das [30] is extended to include the thermophoretic parameters for both suction and injection. The present objective is to investigate the effects of variable fluid properties with thermophoretic particle deposition for both suction and injection cases.

2. Formulation of the problem

2.1. Governing equations and boundary conditions

Consider a two dimensional steady laminar flow of an incompressible electrically conducting liquid over a radiating permeable flat plate in the presence of a transverse magnetic field $\vec{B}$ (see Fig. 1). The magnetic Reynolds number of the flow is taken to be small enough so that induced magnetic field is assumed to be negligible in comparison with applied magnetic field. Thus $\vec{B} = [0, B(x)]$, where $B(x)$ is the applied magnetic field acting normal to the plate and varies in strength as a function of x. The flow is assumed to be in the x-direction which is taken along the plate and y-axis is normal to it. Suction or injection is imposed on the permeable plate. The viscosity and thermal conductivity of the liquid are assumed to be functions of temperature. The presence of non-uniform heat source/sink and thermophoresis is considered to study the variation of heat transfer and concentration deposition on the flat surface. The pressure gradient, body forces, viscous dissipation and Joule heating effects are neglected in comparison with the effect of heat source/sink. The temperature of the plate surface is held uniform at T_w which is higher than the ambient temperature T_∞. The species concentration at the surface is maintained uniform at C_w while the ambient liquid concentration is assumed to be C_∞.

Under the boundary layer approximations, the conservation equations for the flow regime can be shown to take the following form: (see Ref. [27,30])

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) - \sigma B^2(x)(u - U_\infty), \tag{2}$$

$$\rho c_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \frac{\partial}{\partial y}\left[\left(\kappa + \frac{16T_\infty^3\sigma^*}{3k^*}\right)\frac{\partial T}{\partial y}\right] + q''', \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - \frac{\partial (V_T C)}{\partial y}, \tag{4}$$

where u, v are velocity components along x, y-axis respectively, U_∞ is the free stream velocity, σ is the electrical conductivity of the liquid, T is the temperature of the liquid within the boundary layer, κ is the thermal conductivity of the liquid, c_p is the specific heat at constant pressure p, μ is the dynamic viscosity, ρ is the constant liquid density, σ^* is the Stefan–Boltzmann constant and k^* is the mean absorption coefficient, C is the concentration of the liquid within the boundary layer and D is the molecular diffusivity of the species concentration. The thermophoretic velocity V_T can be written as (see Ref. Talbot et al. [3])

$$V_T = kv\frac{\nabla T}{T_r} = -\frac{kv}{T_r}\frac{\partial T}{\partial y} \tag{5}$$

where T_r is a reference temperature and k is the thermophoretic coefficient which ranges in value from 0.2 to 1.2 as indicated by Batchelor and Shen [4] and is defined from the theory of Talbot et al. [3] by