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ORIGINAL ARTICLE

MHD flow of Boungiorno model nanofluid over a vertical plate with internal heat generation/absorption

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Abstract A mathematical analysis has been carried out to investigate the effect of internal heat generation/absorption on steady two-dimensional radiative magnetohydrodynamics (MHD) boundary-layer flow of a viscous, incompressible nanofluid over a vertical plate. A system of governing nonlinear PDEs is converted into a set of nonlinear ODEs by suitable similarity transformations and then solved analytically using HAM and numerically by the fourth order Runge–Kutta integration scheme with shooting method. The effects of different controlling parameters on the dimensionless velocity, temperature and nanoparticle volume fraction profiles are discussed graphically. The reduced Nusslet number and the local Sherwood number are tabulated. It is found that the nanosolid volume fraction profile decreases in the presence of heat generation and increases in the case of heat absorption and a reverse trend is observed in velocity profile. An excellent agreement is observed between present analytical and numerical results. Furthermore, comparisons have been made with bench mark solutions for a special case and obtained a very good agreement.

1. Introduction

Nanofluids are suspensions of nanoparticles in fluids which was introduced by Choi [1] that show significant

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enhancement of their properties at modest nanoparticle concentrations. Many of the publications on nanofluids are about understanding their behavior so that they can be utilized where straight heat transfer enhancement is paramount as in many industrial applications such as nuclear reactors, transportation, electronics as well as biomedicine and food. This concept attracted various researchers towards nanofluids, and various theoretical and experimental studies have been done to find the thermal properties of nanofluids. Boungiorno et al. [2] studied the thermal conductivity of nanofluids experimentally. The same author proposed an analytical model for convective transport in nanofluids taking into the account of Brownian diffusion and thermophoresis [3].

In recent year, the natural convection flow of nanofluid has been studied in the following publications [4–16]. Kuznetsov and Nield [17] investigated the natural convective boundary-layer flow of a nanofluid past a vertical plate using Boungiorno model. Gorla and Chamkha [18] studied the natural convective boundary layer flow of nanofluid in a porous medium. Khan and Pop [19] studied the boundary layer flow of a nanofluid past a stretching sheet by considering the Brownian diffusion and thermophoresis effects. Khan and Aziz [20] investigated the boundary layer flow of a nanofluid past a vertical surface with a constant heat flux. Aziz and Khan [21] studied natural convective flow of a nanofluid over a convectively heated vertical plate. Recently, Rashad et al. [22] analyzed the natural convection flow of nanofluid over a vertical plate with stream wise temperature variation.

The interaction of natural convection with thermal radiation has increased greatly during the last decade due to its importance in many practical involvements. When free convection flows occur at high temperature, radiation effects on the flow become significant. Radiation effects on the free convection flow are important in context of space technology, processes in engineering areas occur at high temperature. Based on these applications, Olanrewaju et al. [23] investigated the boundary layer flow of nanofluids over a moving surface in a flowing fluid in the presence of radiation past a moving semi-infinite flat plate in a uniform free stream. Poornima et al. [24] analyzed the simultaneous effects of thermal radiation and magnetic on heat and mass transfer flow of nanofluids over a non-linear stretching sheet. Recently, Turkyilmazoglu and Pop [25] studied the thermal radiation effects on the flow of single phase nanofluid over a infinite vertical plate.

The study of heat generation or absorption effects is very important in cooling processes. Although, exact modeling of internal heat generation or absorption is quite difficult, some simple mathematical models can express its average behavior for most physical situations [26,27]. Ahmed et al. [28] investigated the effects of heat source/sink on the boundary layer flow of single phase nanofluid over a stretching tube. Very recently, Akilu and Narahari [29] studied the effects of internal heat generation/absorption on natural convection flow of a nanofluid over an inclined plate numerically.

The main goal of this paper is to analyze the effect of internal heat generation/absorption on steady radiative magnetohydrodynamic free convective boundary layer flow of an incompressible nanofluid over a vertical flat plate both analytically and numerically. The analytical solutions are obtained using HAM and the fourth order Runge–Kutta method along with shooting technique is used to find the numerical solutions for the physical problem.

2. Formulation of the problem

We consider the steady two-dimensional boundary layer flow of a nanofluid over vertical plate in the presence of magnetic field intensity, thermal radiation and volumetric rate of heat generation/absorption. We select a coordinate frame in which the x-axis is aligned vertically upwards. We consider a vertical plate at $y=0$. At this boundary, the temperature T and the nanoparticle volume fraction ϕ take constant values T_w and ϕ_w respectively. The temperature T and the nanoparticle volume fraction of the nanofluid ϕ take values T_∞ and ϕ_∞ respectively as $y\to\infty$. We also consider influence of a constant magnetic field strength B_0 which is applied normally to the plate. It is further assumed that the induced magnetic field is negligible in comparison to the applied magnetic field. Under the above assumptions, the boundary layer equations governing the flow, thermal and concentration fields can be written in dimensional form as Ref. [17].

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

$$\frac{\partial p}{\partial x}=\mu\frac{\partial^2 u}{\partial y^2}-\rho_f\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)-\sigma B_0^2 u +\left[(1-\phi_\infty)\rho_{f\infty}\beta g(T-T_\infty)-(\rho_p-\rho_{f\infty})g(\phi-\phi_\infty)\right] \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\nabla^2 T+\frac{Q}{(\rho c)_f}(T-T_\infty) +\tau\left[D_B\frac{\partial\phi}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right]-\frac{1}{(\rho c)_f}\left(\frac{\partial q_r}{\partial y}\right) \tag{3}$$

$$u\frac{\partial\phi}{\partial x}+v\frac{\partial\phi}{\partial y}=D_B\left(\frac{\partial^2\phi}{\partial y^2}\right)+\frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where u and v are the velocity components along the x and y directions respectively. p is the fluid pressure, ρ_f is the density of base fluid, ρ_p is the nanoparticle density, μ is the absolute viscosity of the base fluid, $\alpha=\frac{k}{(\rho c)_f}$ is the thermal diffusivity of the base fluid, $\tau=\frac{(\rho c)_p}{(\rho c)_f}$ is the ratio of nanoparticle heat capacity and the base fluid heat capacity, ϕ is the local solid volume fraction of the nanofluid, β is volumetric thermal expansion coefficient of the base fluid, D_B is the Brownian diffusion coefficient, D_T is the