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ORIGINAL ARTICLE

Q1 A study of heat and mass transfer on magnetohydrodynamic (MHD) flow Q2 of nanoparticles

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Received 31 March 2016; accepted 29 August 2016

KEYWORDS

Nanofluid;
Brownian motion;
Thermophoresis;
Nusselt number;
Sherwood number

Abstract Investigation of the flow, heat and mass transfer of a nanofluid over a suddenly moved flat plate is presented using Buongiorno's model. This study is different from some of the previous studies as the effects of Brownian motion and thermophoresis on nanoparticles volume fraction are passively controlled on the boundary rather than actively. The partial differential equations governing the flow are reduced to a system of nonlinear ordinary differential equations. Viable similarity transforms are used for this purpose. A well-known numerical scheme called Runge-Kutta-Fehlberg method coupled with shooting procedure has been used to find the solution of resulting system of equations. Discussions on the effects of different emerging parameters is provided using graphical aid. A table is also given that provides the results of different parameters on local Nusselt and Sherwood numbers. The passive control model can be used to control the boundary layer thickness as well as the rate of mass transfer at the wall.

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Peer review under responsibility of National Laboratory for Aeronautics and Astronautics, China.

http://dx.doi.org/10.1016/j.jppr.2018.02.001
2212-540X

Please cite this article as: Syed Tauseef Mohyud-Din, et al., A study of heat and mass transfer on magnetohydrodynamic (MHD) flow of nanoparticles, Propulsion and Power Research (2018), http://dx.doi.org/10.1016/j.jppr.2018.02.001

1. Introduction

In many practical situations nowadays, there are situations in which we have to work out with different types of nanoparticles. These nano sized particles play a crucial role in controlling the different thermo physical properties of different fluids involved. Most of the fluids in practice such as water, ethylene, glycol, kerosene oil, engine oil are the poor conductors of heat. Lower values of thermal conductivity and other thermal properties is a major factor for this. To cope with this problem and to enhance the thermal properties of these fluids, nanoparticles are added to the base fluids. Many researchers studied and proposed various models to get a concrete analysis of these nanoparticles based nanofluids. Choi [1], Choi et al. [2], Buongiorno [3], Nield and Kuznetsov [4] and Kuznetsov and Nield [5], presented various models to study various properties of nanofluids. They presented both Brownian motion and thermophoresis effects on transport equations by reducing them to the nonlinear boundary value problems. Many researchers used these models to study various problems involving nanofluids that can be seen in Refs. [6–13].

The classical Stokes' problem is the investigation of diffusion of vorticity over a suddenly moved flat surface [14]. Rajagopal and Na [15] extended the traditional problem for the case of non-Newtonian fluid. Over the years, many researchers studied several properties of velocity field in Stokes' problem. Many studies can be seen in literature on Stokes' problem [16–31]. Recently, after the pioneering works in nanofluids, Naseem Uddin et al. [32] presented a study of nanofluids due to a suddenly moved plate. Rosali et al. [33] used the Buongiorno model to study the effects of Brownian motion and thermophoresis on heat and mass transfer in nanofluids.

In a recent study, Nield and Kuznetsov [34–36] presented a new revised model that in cooperated the zero flux boundary condition for concentration profile at the wall. This boundary condition includes the effects of Brownian motion and thermophoresis so that the nanofluid particle fraction can be passively controlled at the wall. They also commented that this model is more realistic physically as compared to earlier models.

In present study, the model presented by Nield and Kuznetsov [34–36] is used to investigate the flow behavior of a nanofluid over a suddenly moved flat plate. Effects of Brownian motion and thermophoresis are incorporated in the zero flux boundary condition. Equations governing the flow are solved using a well-known numerical procedure Runge-Kutta-Fehlberg method after converting the partial differential equations to a set of ordinary differential equations. A comprehensive discussion on the effects of emerging parameters is provided supported by graphical aid.

2. Governing equations

Consider the flow of a Newtonian nanofluid lying over an impulsively started heated plate. Cartesian coordinate system is taken to describe the flow behavior. x and y respectively are the coordinates along and normal to the plate. Initially (at time $t=0$), the plate is starts moving with a constant velocity U_∞. The plate is kept at a constant temperature T_w, and the nanoparticle volume fraction C_w. At a large distance from the plate, the temperature and the nanoparticle volume fraction are represented by T_∞ and C_∞, respectively. A uniform time dependent transverse magnetic field is applied in y-direction. Strength of magnetic field is taken to be $B=B_0$. Induced magnetic field is assumed to be very small as compared to the applied magnetic field and is neglected. Figure 1 shows the schematic diagram for the flow problem.

Fluid phase and the nanoparticles are assumed to be in a thermal equilibrium and there is no slip between them. Under the assumptions mentioned above, the equations governing the flow are [18]:

$$\frac{\partial u}{\partial t}=\upsilon\left(\frac{\partial^2 u}{\partial y^2}\right)-\frac{\sigma B_0^2}{\rho_f}u, \tag{1}$$

$$\frac{\partial T}{\partial t}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\tau\left[D_B\left(\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}\right)+\left(\frac{D_T}{T_\infty}\right)\left(\frac{\partial T}{\partial y}\right)^2\right], \tag{2}$$

$$\frac{\partial C}{\partial t}=D_B\left(\frac{\partial^2 C}{\partial y^2}\right)+\frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial y^2}\right), \tag{3}$$

where, u is the velocity component along the y-axis, U_∞ is the free stream velocity, ρ_f is the density of base fluid, $\upsilon=\frac{\mu_f}{\rho_f}$ is kinematic viscosity, σ is electrical conductivity, B_0 magnetic field flux density, α thermal diffusivity, D_B is Brownian motion diffusion coefficient, D_T thermophoresis diffusion coefficient, T and C are fluid temperature and nanoparticle volume fraction, respectively, τ is the parameter defined by $\frac{(\rho c)_f}{(\rho c)_p}$, where $(\rho c)_f$ is the heat capacity of the nanofluid and $(\rho c)_p$ is the effective heat capacity of the nanoparticle material.

For active control model, the initial and boundary conditions are:

$$\begin{aligned} t<0:&\ u=0,\ T=T_w,\ C=C_w, && \text{for all } x,y\\ t\geq 0:&\ u=U_\infty,\ T=T_w,\ C=C_w, && \text{at } y=0\\ &\ u\to 0,\ T\to T_\infty,\ C\to C_\infty, && \text{as } y\to\infty \end{aligned} \tag{4}$$

The initial and boundary conditions for passive control model are:

$$\begin{aligned} t<0:&\ u=0,\ T=T_w,\ C=C_w, && \text{for all } x,y\\ t\geq 0:&\ u=U_\infty,\ T=T_w,\ D_B\frac{\partial C}{\partial y}+\frac{D_T}{T_\infty}\frac{\partial T}{\partial y}=0, && \text{at } y=0\\ &\ u\to 0,\ T\to T_\infty,\ C\to C_\infty, && \text{as } y\to\infty \end{aligned} \tag{5}$$

It is pertinent to mention that the last part of the boundary condition takes the thermosphoresis into account and normal flux of the nanofluid at the boundary is taken to be zero [21–23]. The major purpose of this condition is the passive control of nanoparticle volume fraction at the boundary. This condition is different from the earlier studies

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