Particuology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

Effect of a chemical reaction on magnetohydrodynamic boundary layer flow of a Maxwell fluid over a stretching sheet with nanoparticles

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ARTICLE INFO

Article history:
Received 28 February 2015
Received in revised form 19 April 2016
Accepted 9 May 2016
Available online xxx

Keywords:
Magnetohydrodynamics
Nanoparticle
Maxwell fluid
Boundary layer flow
Chemical reaction

ABSTRACT

The influences of the convective boundary condition and heat generation/absorption on magnetohydrodynamic boundary layer flow of a Maxwell fluid over a stretching surface in the presence of nanoparticles have been numerically investigated. In the model, the physical mechanisms responsible for Brownian motion and thermophoresis with a chemical reaction are considered. Similarity equations are derived and then solved using the shooting method with the fourth-order Runge–Kutta integration scheme. The rates of heat and mass transfer are enhanced with a destructive chemical reaction and Biot number. The opposite influence is found with a generative chemical reaction in the presence of Brownian motion and the thermophoretic property.

Introduction

Non-Newtonian fluids over a stretching surface have received great attention owing to their wide applications in engineering and industry, such as for chemicals, petrochemicals, molten plastics, electronic chips, bioengineering, and pharmaceuticals. The vast majority of non-Newtonian fluid models are simple models, such as the power laws with grades two or three. Reviews of non-Newtonian fluid flow problems have been presented (Abel, Sanjayan, & Nandeppanavar, 2008; Abel, Datti, & Mahesha, 2009; Afify, 2009; Ahmad & Asghar, 2011; Hayat, Shafiq, Alsaedi, & Awais, 2013; Megahed, 2015; Sahoo & Do, 2010; Vajravelu, Prasad, & Rao, 2011).

The Maxwell fluid model is the simplest subclass of rate type fluids. This fluid model predicts relaxation time effects. The Maxwell model is a model of non-Newtonian fluids predicting the shear thinning liquid. The classical Maxwell model was proposed by Maxwell (1867). Numerous researchers have examined the flow and heat transfer of non-Newtonian upper-convected Maxwell (UCM) fluids over a stretching sheet with various regimes. Sadeghy, Najafi, and Saffaripour (2005) investigated hydrodynamic flow of the UCM model over a steadily moving plate. They found that the friction factor decreases with increasing Deborah number for Sakiadis flow of a UCM fluid. Aliakbar, Alizadeh-Pahlavan, and Sadeghy (2009) studied magnetohydrodynamic (MHD) flow of a UCM fluid above a semi-infinite stretching sheet with the influence of viscous dissipation and thermal radiation. The results showed that heat transfer from the sheet to the fluid increases with increasing elasticity number. The unsteady flow of a Maxwell fluid between two side walls owing to a suddenly moved plate was investigated by Hayat, Fetecau, Abbas, and Ali (2008). They used the Fourier sine transform for presentation of closed form solutions. Mukhopadhyay, Ranjan De, and Layek (2013) investigated the thermal radiation effect on two-dimensional boundary layer flow of a Maxwell fluid and heat transfer over an unsteady stretching permeable surface. The results indicated that the friction factor decreases with an increase in the unsteadiness parameter and the Maxwell parameter.

Nanofluids are useful in several engineering and industrial applications because of their special thermal conductivity. Choi (1995) was the first person to use the term "nanofluid" to describe a fluid-containing nanoparticle. Buongiorno (2006) modified the reasons behind the enhancement of heat transfer of nanofluids. More recently, numerous researchers have effectively applied Buongiorno's model. Nield and Kuznetsov (2009) used the Buongiorno model to study the Cheng–Minkowycz problem for natural convection flow of a nanofluid past a vertical plate immersed in a porous medium. Kuznetsov and Nield (2010) numerically investigated Brownian motion and thermophoresis effects on natural

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http://dx.doi.org/10.1016/j.partic.2016.05.003

Nomenclature

a	positive constant (s^{-1})
B_0	constant magnetic field ($kg/(s^2 A)$)
Bi	Biot number
C	nanoparticle concentration (kg/m^3)
C_∞, C_w	free stream and surface particle concentrations (kg/m^3)
C_f	skin friction coefficient
C_p	specific heat (J/(kg K))
D_B	Brownian diffusion coefficient (m^2/s)
D_T	thermophoretic diffusion coefficient (m^2/s)
$f(\eta)$	dimensionless free stream function
k	thermal conductivity of the fluid (W/(m K))
Le	Lewis number
M	magnetic parameter
Nb	Brownian motion parameter
Nt	thermophoresis parameter
Nu_x	local Nusselt number
Sh_x	local Sherwood number
Pr	Prandtl number
T	fluid temperature (K)
T_∞, T_f	free stream and surface fluid temperatures (K)
u, v	velocity components along the x and y axes (m/s)
x, y	Cartesian coordinates (m)

Greek symbols

α	thermal diffusivity of the base fluid (m^2/s)
γ	chemical reaction parameter
δ	heat generation/absorption parameter
η	similarity independent variable
θ	dimensionless temperature
λ	elastic parameter
μ	dynamic viscosity of the fluid (kg/(m s))
ν	kinematic viscosity capacity of the nanoparticle material (m^2/s)
ρ_f	fluid density (kg/m^3)
$(\rho C)_f$	heat capacity of the fluid ($J/(m^3 K)$)
$(\rho C)_p$	effective heat capacity of the nanoparticle material ($J/(m^3 K)$)
σ	electrical conductivity (S/m)
τ	nanoparticle to base fluid heat capacity ratio
φ	dimensionless nanoparticle concentration
ψ	dimensionless stream function

Subscripts

w	surface condition
∞	condition far away from the surface

convective boundary layer flow of a nanofluid past a vertical plate. They found that the decrease in the strengths of Brownian motion and thermophoresis leads to reduction in the cooling rate from the plate. Khan and Pop (2010) introduced nanofluids over a stretching sheet with the effects of Brownian motion and thermophoresis forms. They used the Keller-box method to simulate the governing non-linear differential system. Makinde and Aziz (2011) investigated the effect of a convective boundary condition on boundary layer flow of nanofluids past a linear stretching sheet. They found that the local concentration of nanoparticles increases as the convection Biot number increases. Afify and Bazid (2014) numerically analyzed the influence of Brownian motion and thermophoresis with variable fluid properties of a nanofluid over a vertical plate. They concluded that the influences of variable fluid properties with Brownian motion and the thermophoretic property play a crucial role in the heat transfer characteristics. Recently, Kuznetsov and Nield (2014) proposed a revised model of natural convective boundary-layer flow of a nanofluid past a vertical plate.

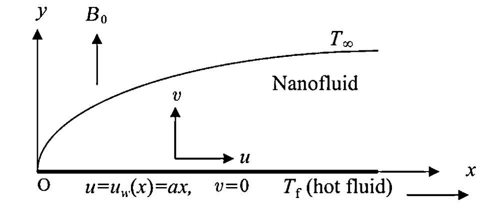

Fig. 1. Physical model and coordinate system.

A chemical reaction may either regularly occur throughout a given phase (homogeneous reaction) or in an enclosed region (boundary) of the phase (heterogeneous reaction). Das, Duari, and Kundu (2015) investigated hydromagnetic heat and mass transfer in a nanofluid over a heated stretching sheet with the influences of chemical reaction and thermal radiation. To the best of our knowledge, the influences of chemical reaction, convective boundary condition, and heat generation/absorption on MHD flow and the heat transfer characteristics of Maxwell nanofluids over a stretching surface have not been investigated. In this study, numerical results of the velocity, temperature, and nanoparticle concentration distributions are presented. The skin friction coefficient, local Nusselt number, and local Sherwood number are also presented and discussed.

Mathematical formulation

We consider a steady, laminar boundary layer of a non-Newtonian nanofluid past a stretching surface coinciding with the plane $y=0$. The flow is confined to the region $y>0$, where y is the coordinate measured normal to the stretching surface, as shown in Fig. 1. It is also assumed that the bottom surface of the stretching plate is heated by convection from a hot fluid with temperature T_f, which provides a heat transfer coefficient h_f. In this study, a first-order homogeneous chemical reaction of species is considered. The plate is stretched along the x axis with linear velocity $u_w=ax$, where a is a positive constant. A magnetic field with uniform strength B_0 is applied in the y direction (i.e., normal to the flow direction). The magnetic Reynolds number is assumed to be small. Hence, the induced magnetic field is small compared with the externally applied magnetic field. Under the above assumptions, the boundary layer equations of a Maxwell nanofluid can be written as (Buongiorno, 2006; Motsa, Hayat, & Aldossary, 2012)

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+k_0\left(u^2\frac{\partial^2 u}{\partial x^2}+v^2\frac{\partial^2 u}{\partial y^2}+2uv\frac{\partial^2 u}{\partial x\partial y}\right) = \nu\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^2}{\rho_f}\left(u+k_0 v\frac{\partial u}{\partial y}\right), \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\tau\left\{D_B\left(\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}\right)+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\} + \frac{Q_0}{\rho C_p}(T-T_\infty), \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2}-k_1(C-C_\infty), \tag{4}$$

Please cite this article in press as: Afify, A. A., & Elgazery, N.S. Effect of a chemical reaction on magnetohydrodynamic boundary layer flow of a Maxwell fluid over a stretching sheet with nanoparticles. *Particuology* (2016), http://dx.doi.org/10.1016/j.partic.2016.05.003