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Three dimensional radiative flow of magnetite-nanofluid with homogeneous-heterogeneous reactions

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A B S T R A C T

Present communication deals with the effects of homogeneous-heterogeneous reactions in flow of nanofluid by non-linear stretching sheet. Water based nanofluid containing magnetite nanoparticles is considered. Non-linear radiation and non-uniform heat sink/source effects are examined. Non-linear differential systems are computed by Optimal homotopy analysis method (OHAM). Convergent solutions of nonlinear systems are established. The optimal data of auxiliary variables is obtained. Impact of several nondimensional parameters for velocity components, temperature and concentration fields are examined. Graphs are plotted for analysis of surface drag force and heat transfer rate.

Introduction

Nanofluids are relatively new materials with suspension of nano-sized metallic or nonmetallic particles (1–100 nm). Nanofluids are dilute suspensions of functionalized nanomaterials with base fluids such as water, ethylene glycol etc. The nanofluid are considered useful in application such as engine cooling, drag reductions, domestic refrigerator chillers, electronic cooling, transformer cooling, nuclear systems cooling, oil engine transfer, boiler exhaust flue gas recovery, microwave tubes, diesel electric generator as jacket water coolant, high-power lasers, drilling, lubrications, cooling of welding, cooling and heating of buildings, thermal storage and solar water heating. Choi and Eastman [1] used metallic oxides nanoparticles for an enhancement of thermal conductivity. Heat transfer enhancement of nanofluids is studied by Xuan and Li [2]. Saidur et al. [3] presented a review about challenges and applications of nanofluids. Slip effects for silver and aluminium oxide nanofluid flow in a microchannel is presented by Karimipour et al. [4]. Hayat et al. [5] described flow of nanofluid past an exponential stretching with effects of thermal and solutal stratification. Zhang et al. [6] elaborated slip effects in time dependent power-law flow of nanofluid past a stretched sheet. Few more recent studies on nanofluids may include the (Refs. [7–15]).

Flow past a stretching surface in view of its significance related to industry and engineering fields. Such applications include condensation process of liquid films, glass fiber, paper production, crystal growing, plastic films and wires, polymer extrusion drawings and food manufacturing. Studies about linear stretching velocity has been widely discussed. Pioneer work on flow past a stretching surface was done by Crane [16]. Khan et al. [17] studied the three-dimensional flow of nanofluid over a nonlinear stretching sheet: An application to solar energy. Three-dimensional flow of nanofluid due to slendering stretching sheet with slip effect is discussed by Babu and Sandeep [18]. Mahanthesh et al. [19] presented a nonlinear radiative heat transfer in MHD three-dimensional flow of water based nanofluid over a non-linearly stretching sheet with convective boundary condition. MHD flow and nonlinear radiative heat transfer of Sisko nanofluid over a nonlinear stretching sheet is elaborated by Prasannakumara et al. [20].

Convective heat problems are significant in physical science within heat sources among the field. Applications related to energy problems including solidification of costing and cooling of underground electric cables are of great significance. Unsteady stretched flow with heat source/sink and thermal radiation is presented by Pal [21]. Ramandevi et al. [22] considered combined influence of viscous dissipation and non-uniform heat source/sink on MHD non-Newtonian fluid flow with non-Fourier heat flux model. Heat transfer control is important for final product of desired quality. Modern system of astrophysical flow, space vehicles, cooling of nuclear reactors, plasmas and electric power generation are

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governed by applications of linear and nonlinear thermal radiation. Khan et al. [23] examined behavior of gyrotactic microorganisms and non-linear thermal radiation in flow of magneto-Burgers nanofluid. Peristaltic flow of nonconstant viscosity fluid with nonlinear thermal radiation is presented by Latif et al. [24]. Here impact of thermal radiation on electrical MHD flow of nanofluid over nonlinear stretching sheet with variable thickness discussed by Daniel et al. [25].

Homogeneous-heterogeneous reactions are natural processes of chemically reacting structures such as combustion, biochemical processes and catalysis. At different rates the relation among homogeneous-heterogeneous reactions along with consumption and production of reactant species within liquid and on catalytic surface is quite complicated. Some reactions have capacity to move slowly or not at all except in the existence of a catalyst. Applications of chemical reactions include manufacturing of food, formation and dispersion of fog, manufacturing of ceramics, production of polymer, crops damage via freezing, hydrometallurgical industry. Merkin [26] analyzed homogeneous-heterogeneous reactions in viscous fluid flow on a catalytic surface. Stagnation-point flow past a stretchable sheet in the presence of homogeneous-heterogeneous reactions are studied by Bachok et al. [27]. Gireesha et al. [28] describes three dimensional nonlinear flow of Casson-Carreau fluids with homogeneous and heterogeneous reactions. Nanofluid flow past a rotating disk of variable thickness and homogeneous-heterogeneous reactions is addressed by Hayat et al. [29]. Sajid et al. [30] presented influence of magnetohydrodynamics on Fe_3O_4-nanofluid with thermal radiation and homogeneous-heterogeneous reactions. Numerical study of silver and copper-water nanofluids with non-linear thermal radiation and homogeneous-heterogeneous reactions is due to Qayyum et al. [31].

Object of present communication is to analyze nonlinear radiative flow of magnetite nanofluid past a nonlinear stretching sheet. Effects of homogeneous-heterogeneous reactions are analyzed. Optimal homotopy analysis technique (OHAM) [32–40] is initialized for convergent series solutions of physical quantities. The residual errors are shown through numerical data. Graphical results are used to elaborate the impacts of involved parameters.

Mathematical modeling

Three-dimensional flow of viscous nanofluid is examined. Flow caused by nonlinearly stretching sheet with velocities $\breve{u}_w = c(x+y)^n$ and $\breve{v}_w = d(x+y)^n$ (n being the power-law index) (see Fig. 1). Contribution due to non-uniform heat source/sink

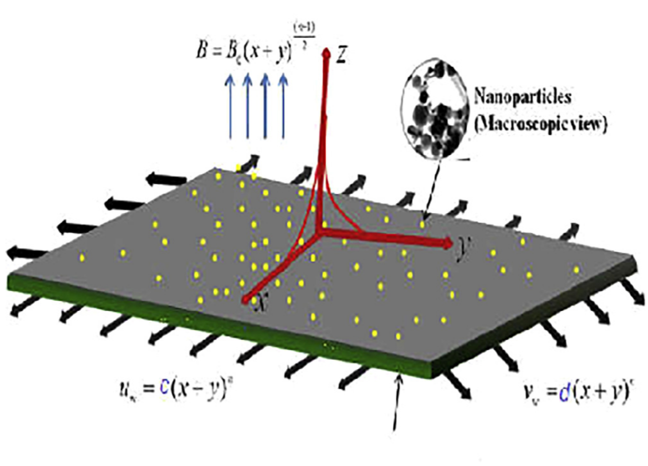

Fig. 1. Flow geometry.

and non-linear radiation are studied. Applied magnetic field of strength $\widetilde{B}_0$ acts transversely to flow. Omission of electric and induced magneticfield is ensured. Homogeneous-heterogeneous reactions of two typical chemical species A and B have been analyzed. Homogeneous reactions for cubic autocatalysis are

$$A + 2B \rightarrow 3B, \quad \text{rate} = \kappa_c \breve{a}\breve{b}^2, \tag{1}$$

while on catalyst surface the required heterogenous reactions is

$$A \rightarrow B, \quad \text{rate} = \kappa_e \breve{a}, \tag{2}$$

where rate constants are κ_c and κ_e and A and B are rate of chemical species having concentrations $\breve{a}$ and $\breve{b}$.

The problem statements are

$$\frac{\partial \breve{u}}{\partial x} + \frac{\partial \breve{v}}{\partial y} + \frac{\partial \breve{w}}{\partial z} = 0, \tag{3}$$

$$\rho_{nf}\left(\breve{u}\frac{\partial \breve{u}}{\partial x} + \breve{v}\frac{\partial \breve{u}}{\partial y} + \breve{w}\frac{\partial \breve{u}}{\partial z}\right) = \mu_{nf}\left(\frac{\partial^2 \breve{u}}{\partial z^2}\right) - \sigma_{nf}\widetilde{B}_0^2 \breve{u}, \tag{4}$$

$$\rho_{nf}\left(\breve{u}\frac{\partial \breve{v}}{\partial x} + \breve{v}\frac{\partial \breve{v}}{\partial y} + \breve{w}\frac{\partial \breve{v}}{\partial z}\right) = \mu_{nf}\left(\frac{\partial^2 \breve{v}}{\partial z^2}\right) - \sigma_{nf}\widetilde{B}_0^2 \breve{v}, \tag{5}$$

$$(\rho Cp)_{nf}\left(\breve{u}\frac{\partial \breve{T}}{\partial x} + \breve{v}\frac{\partial \breve{T}}{\partial y} + \breve{w}\frac{\partial \breve{T}}{\partial z}\right) = k_{nf}\frac{\partial^2 \breve{T}}{\partial z^2} - \frac{1}{(\rho C_p)_{nf}}\frac{\partial q_{\breve{h}}}{\partial z} + Q''', \tag{6}$$

$$\breve{u}\frac{\partial \breve{a}}{\partial x} + \breve{v}\frac{\partial \breve{a}}{\partial y} + \breve{w}\frac{\partial \breve{a}}{\partial z} = D_A\frac{\partial^2 \breve{a}}{\partial z^2} - \kappa_c \breve{a}\breve{b}^2, \tag{7}$$

$$\breve{u}\frac{\partial \breve{b}}{\partial x} + \breve{v}\frac{\partial \breve{b}}{\partial y} + \breve{w}\frac{\partial \breve{b}}{\partial z} = D_B\frac{\partial^2 \breve{b}}{\partial z^2} + \kappa_c \breve{a}\breve{b}^2, \tag{8}$$

$$\begin{gathered}\breve{u} = \breve{u}_w = c(x+y)^n,\ \breve{v} = \breve{v}_w = d(x+y)^n,\ \breve{w} = 0,\ \breve{T} = \breve{T}_w,\\ D_A\frac{\partial \breve{a}}{\partial z} = k_e\breve{a},\ D_B\frac{\partial \breve{b}}{\partial z} = -k_e\breve{a} \text{ at } z = 0,\\ \breve{u} \rightarrow 0,\ \breve{v} \rightarrow 0,\ \breve{a} \rightarrow \breve{a}_0,\ \breve{T} \rightarrow \breve{T}_\infty,\ \breve{b} \rightarrow 0, \text{ as } z \rightarrow \infty,\end{gathered} \tag{9}$$

where (x,y,z) components of velocity are $(\breve{u}, \breve{v}, \breve{w})$, $\breve{T}$ temperature, ρ the fluid density, σ fluid electrical conductivity and D_A and D_B the diffusion coefficients respectively.

Here effective dynamic viscosity of nanofluid is

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}}. \tag{10}$$

Heat capacitance $(\rho C_p)_{nf}$, the effective density ρ_{nf}, effective thermal conductivity k_{nf} and thermal diffusivity α_{nf} of nanofluid are

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}},\ \rho_{nf} = (1-\phi)\rho_f + \phi\rho_s,\ (\rho C_p)_{nf} = (1-\phi)(\rho C_p)_f + \phi(\rho C_p)_s, \tag{11}$$

where ϕ the solid and spherical volume fraction of nanoparticles magnetite (Fe_3O_4), C_p the specific heat, k_f the thermal conductivity, k_{nf} the effective thermal conductivity and s and f in subscript are for

Table 1
Thermophysical properties of magnetite (Fe_3O_4) and water.

	$k(W/mk)$	$\rho(kg/m^3)$	$\sigma(Um)^{-1}$	$C_p(J/kgk)$
(Fe_3O_4)	9.7	5180	25000	670
Water (H_2O)	0.613	997.1	0.05	4179