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SHORT COMMUNICATION

Irregular response of nanofluid flow subject to chemical reaction and shape parameter in the presence of variable stream conditions

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Heat source/sink

Abstract The problem of boundary layer of nanofluid flow which results from the stretching of a flat surface has been investigated numerically. The model includes the effects of Brownian motion, magnetic effect, non-linear velocity, variable thickness, thermophoresis, chemical reaction, porous medium, shape, thickness and heat source. The Partial differential equations are converted to ordinary deferential equations to solve analytically using shooting technique. The velocity, temperature and concentration profiles are discussed in detail for all parameters.

1. Introduction

Nanofluids are described as fluid in which solid nanoparticles with length 1–100 nm suspended in conventional heat transfer basic fluid. These nanoparticles enhance many properties of the fluid. For example, to use water to cool electronic equipment and by adding nanoparticles and creating a nanofluid, it improves the water's capability to conduct heat by 30–40%. Therefore, numerous methods have been taken to improve the thermal conductivity of fluids using nanoparticles [2]. The term nanofluids have been invented by Choi [1–3]. There are considerable researches explained the enhanced heat transfer characteristics using nanofluids. Nanofluid features were adapted by many researchers by identifying the parameters influence on it, and some researches investigated the parameters affecting overall [4–17] while some researches focused on single or more parameters.

Porous medium is defined as a material volume consisting of solid matrix with an interconnected void. It is mainly characterized by its porosity, and ratio of the void space to the total volume of the medium. Earlier studies in flow in porous media have revealed the Darcy law [18] which relates linearly the flow velocity to the pressure gradient across the porous medium. The porous medium is also characterized by its permeability which is a measure of the flow conductivity in the porous medium. An important characteristic for the combination of the fluid and the porous medium is the tortuosity which represents the hindrance to flow diffusion imposed by local boundaries or local viscosity. The development of transport models in porous media had a bearing in the progress of several applications such as geology, chemical reactors, drying and liquid composite molding, combustion and biological applications. In this review, the impact of the theory of trans-

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port in porous media on medical and biological sciences is discussed for different applications. Researches [19–21] investigated the effect of porous medium parameter in nanofluid behavior, while studies [22–25] focused on effects of magnetic parameter.

Energy flux can be generated not only by the temperature gradients but also by the composition gradients. Mass fluxes can be created by the temperature gradients that result in Soret (thermo-diffusion) effect. On the other hand, the energy fluxes caused by the composition gradients are termed as Dufour (diffusion-thermo) effect. When there is a density difference in the flow regime, such fluxes play a significant role. Thermo-diffusion and diffusion-thermo phenomena occur quite often. So, we hope that our study shall cast some light on different aspects of these effects. By understanding the flow of nanofluids around the surface of the planes, scientists and engineers would be able to enhance the performance of the aircrafts furthermore. Literature survey reveals that no study is available discussing thermo-diffusion effects on a permeable stretching sheet saturated by a porous medium with convective boundary condition. To fill out this gap, a concrete analysis is provided in current study. Main objective of this study was to extend the work of Abdel-wahed et al. [26] for a permeable sheet incorporating the porous medium. Convective boundary condition is considered instead of isothermal condition. Mathematical formulation of the problem is carried out to study the combined effects of thermophoresis, Brownian motion and thermo-diffusion. Thickness parameter was studied by researches [27,28], while the radiation parameter was investigated by studies [29–32]. The effect of chemical reaction in nanofluids was investigated by [33–37], while thermophoresis parameter included in researches [38,39], Brownian motion parameter [40,41], heat source parameter [42–45] and convective parameter which studied by researches [46–48].

This study makes combination of several parameters all together to figure out the effect of this parameter in nanofluids in addition to its effect on other parameters.

2. Formulation of the problem

Consider a steady, laminar, two dimensional flow of an incompressible conduction nanofluid over flat in the presence of magnetic field, heat generation and chemical reaction γ and assume that the electrically conducting fluid and external electric field are negligible, if we have small magnetic Reynolds number.

Fig. 1 illustrates the components of velocity of nanofluid flowing where x-axis runs along the center of the surface which

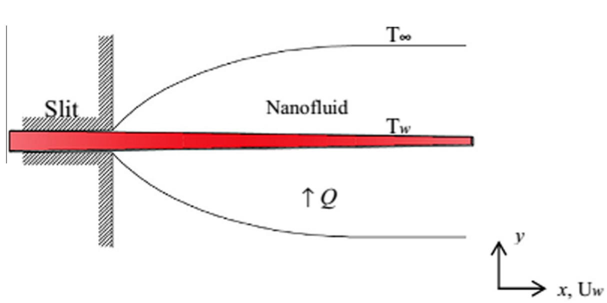

Figure 1 Physical model and coordinate system.

is described as $y = \delta(x+b)^{\frac{1-n}{2}}$ which means that the surface is not flat and thin by making δ small.

The governing boundary layer equations for the steady two-dimensional hydro-magnetic nanofluid flow over a moving surface and subjected to heat source and chemical reaction can be written as

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

$$u \cdot \frac{\partial u}{\partial x} + v \cdot \frac{\partial v}{\partial y} = \upsilon . \frac{\partial^2 u}{\partial y^2} - \frac{\sigma \cdot B^2(x)}{\rho} \cdot u - \frac{\upsilon}{K} \tag{2}$$

$$u \cdot \frac{\partial T}{\partial x} + v \cdot \frac{\partial T}{\partial y} = \alpha . \frac{\partial^2 T}{\partial y^2} + \tau \left[D_B . \frac{\partial C}{\partial y} . \frac{\partial T}{\partial y} + \frac{D_T}{T_\infty} \left(\frac{\partial T}{\partial y} \right)^2 \right] + \frac{Q(x)}{\rho \cdot c_p} (T - T_\infty) \tag{3}$$

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

Subject to the boundary conditions

$$u = U_w, \quad v = 0, \quad T = T_w, \quad C = C_w, \quad \text{at } y = \delta(x+b)^{\frac{1-n}{2}} \tag{5}$$

$$u = 0, \quad v = 0, \quad T = T_\infty, \quad C = C_\infty, \quad \text{as } y \to \infty$$

where u and v are the components of velocity in the directions x, y respectively, v is the kinematic viscosity, ρ is the density of base fluid σ is the electrical conductivity, K is the permeability of surface, α is the thermal diffusion, D_B is the Brownian diffusion coefficient, D_T is the thermophoretic diffusion coefficient, τ is the ratio between the effective heat capacity of nanoparticle and heat capacity of the fluid, k_1 is the rate of chemical reaction(Generative chemical reaction), $B(x)$ is the magnetic field force, where $B(x) = B_0(x+b)^{\frac{n-1}{2}}$ and heat source $Q(x) = Q_0(x+b)^{n-1}$.

Both B and Q are chosen to obtain a similarity solution. The velocity, temperature, and concentration are assumed in the form of

$$U_w(x) = a(x+b)^n, \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \quad \emptyset(x) = \frac{C - C_\infty}{C_w - C_\infty} \tag{6}$$

where a, b are constant, n is the shape parameter and $n > -1$ for validity of this study.

For Eqs. (2)–(4) we look for a similarity solution subject to Eq. (5) boundary condition of the form of

$$\eta = y \cdot \sqrt{\left(\frac{n+1}{2} \right) \cdot \left(\frac{a(x+b)^{n-1}}{v} \right)},$$

$$\psi = \sqrt{\left(\frac{2}{n+1} \right) \cdot (x+b)^{n+1} \cdot a\upsilon} \cdot F(\eta) \tag{7}$$

where η is the similarity variable, ψ is the stream function which is defined as $u = \frac{\partial \psi}{\partial x}$ and $v = \frac{\partial \psi}{\partial x}$.

This satisfies Eq. (1) and substituting Eq. (7) into Eqs. (2)–(4) we obtain the following ordinary differential equations: