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ORIGINAL ARTICLE

MHD flow over a permeable stretching/shrinking sheet of a nanofluid with suction/injection

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Abstract In this study we analyzed the influence of thermal radiation and chemical reaction on two dimensional steady magnetohydrodynamic flow of a nanofluid past a permeable stretching/shrinking sheet in the presence of suction/injection. We considered nanofluid volume fraction on the boundary is submissive controlled, which makes the present study entirely different from earlier studies and physically more realistic. The equations governing the flow are solved numerically. Effects of non-dimensional governing parameters on velocity, temperature and concentration profiles are discussed and presented through graphs. Also, coefficient of skin friction and local Nusselt number is investigated for stretching/shrinking and suction/injection cases separately and presented through tables. Comparisons with existed results are presented. Present results have an excellent agreement with the existed studies under some special assumptions. Results indicate that the enhancement in Brownian motion and thermophoresis parameters depreciates the nanoparticle concentration and increases the mass transfer rate. Dual solutions exist only for certain range of stretching/shrinking and suction/injection parameters.

1. Introduction

The development of nanotechnology is going to bring an unimaginable and multidimensional changes in our way of life, in the coming years. Recently many researchers focused on this topic due to it prominent importance in engineering and its allied areas. Choi [1] was the first person who introduced the term "nanofluid". The detailed discussion, importance and future scope of nanofluids were pioneered by Das et al. [2]. Uddin et al. [3] proposed a mathematical model for radiative MHD flow with slip effects. Heat transfer in second order fluid over a stretching sheet with constant surface temperature was discussed by Bujurke et al. [4]. Ece [5] proposed the similarity analysis for the laminar free convection boundary layer flow in the presence of a transverse magnetic field. Mohankrishna et al. [6] and Sandeep et al. [7] discussed the heat transfer characteristics of nanofluids by immersing the high conductivity nanomaterials in base fluids and they concluded that the effective thermal conductivity of the fluid increases appreciably and consequently enhances the heat transfer characteristics by suspending the high thermal conductivity of nanomaterials into the base fluids. Zaimi et al. [8] analyzed steady two dimensional flow of a nanofluid over a stretching/shrinking sheet. Wang and Mujumdar [9] gave good literature on heat transfer characteristics of nanofluids. Rana and Bhargava [10] used

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finite element and finite difference methods for nonlinear stretching sheet problem. Zaimi et al. [11] extended the work of Rana and Bhargava and studied heat transfer and boundary layer flow of a nanofluid over a stretching/shrinking sheet.

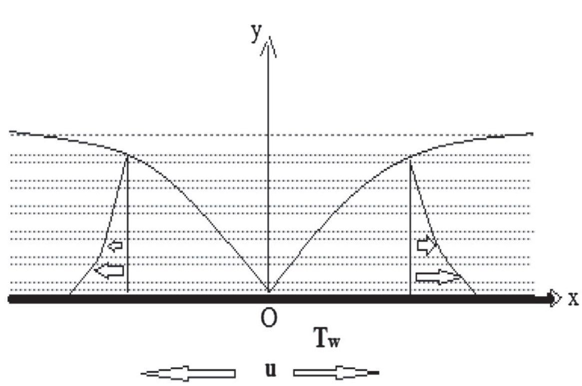
Radiation effect on MHD viscous fluid over exponentially stretching sheet with porous medium was analyzed by Ahmad et al. [12]. They used homotopy analysis method to solve the boundary layer approximations. Heat and mass transfer for stagnation point flow over a stretching sheet in a porous medium by considering heat source was studied by Hamad and Ferdows [13]. The importance of heat, mass and momentum transfer over a stretching surface was explained by Atlatn et al. [14]. Ellahi et al. [15] discussed about the influence of nanoparticles shape by considering Cu–water nanofluid. Sheikholeslami et al. [16] analyzed the effect of thermal radiation on MHD nanofluid flow and heat transfer by using two phase model. Rashidi et al. [17] illustrated the stream wise transverse magnetic fluid flow with heat transfer around an obstacle embedded in a porous medium. Heat generation and heat flux effects on the peristaltic flow with interacting nanoparticles were presented by Akbar et al. [18]. A study of natural convection heat transfer in a nanofluid filled with elliptic inner cylinder was analyzed by Sheikholeslami et al. [19]. The influence of heat transfer on the nanofluid flow over a permeable stretching wall in a porous medium was studied by Sheikholeslami et al. [20]. Interaction of nanoparticles for the peristaltic flow in an asymmetric channel by considering the induced magnetic field was analyzed by Akbar et al. [21].

Ramesh et al. [22] explored their research on stretching sheet and they analyzed the heat transfer characteristics of a nanofluid. Many researchers like [23–25] have studied and given valuable contribution in the field of nanofluid flows over a permeable stretching sheet. Simulation of magnetohydrodynamic CuO–water nanofluid flow and heat transfer in the presence of Lorentz forces was discussed by Sheikholeslami et al. [26]. Ellahi et al. [27] illustrated non-Newtonian nanofluids flow through a porous medium between two coaxial cylinders by considering variable viscosity. Nanofluid flow in tapering stenosed arteries with permeable walls was presented by Akbar et al. [28]. Ellahi [29] presented the analytical solution to analyze the effects of MHD and temperature dependent viscosity on the flow of non-Newtonian nanofluid in a pipe. MHD flow of water/ethylene glycol based nanofluids by considering porous medium was discussed by Zeeshan et al. [30]. Ellahi et al. [31] presented series solutions for non-Newtonian nanofluids by considering Reynolds' and Vogel's models by using homotopy analysis method.

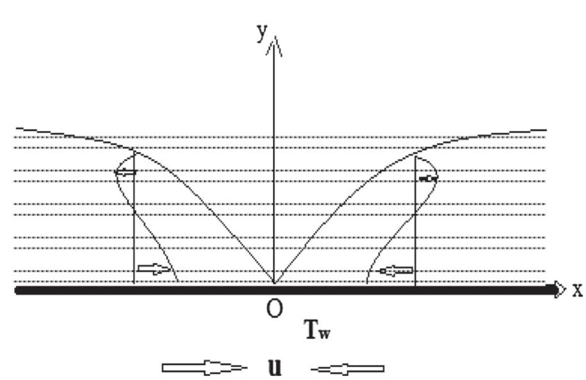
All the above investigations limited their study on either stretching or shrinking case by considering suction or injection effects. In this study we are focusing on two dimensional steady magnetohydrodynamic flow of a nanofluid past a permeable stretching/shrinking sheet in a porous medium with suction/injection effects. Here we considered nanofluid volume fraction on the boundary is submissive controlled rather than active controlled [32,33], which makes the present study entirely different from the past studies and it is physically more realistic. The governing partial differential equations are reduced into ordinary differential equations by similarity transformation and then solved numerically by using bvp4c with MATLAB package. Effects of thermal radiation parameter, chemical reaction parameter, magnetic field parameter, Brownian motion parameter, thermophoresis parameter and porosity parameter on velocity, temperature, concentration, skin friction and local Nusselt number are thoroughly investigated for stretching/shrinking and suction/injection cases separately and presented through graphs and tables. Comparisons with existed results are presented.

2. Mathematical formulation

Consider a steady, incompressible, two dimensional MHD flow of a nanofluid past a permeable stretching/shrinking sheet in porous medium coinciding with the plane $y = 0$ and the flow is assumed to be confined to $y > 0$. The flow is along the x-axis where x is the coordinate measured along the stretching/shrinking sheet and y-axis is normal to the surface. A transverse magnetic field B_0 is applied in the y-direction and the stretching/shrinking sheet velocity is assumed as $u_w(x) = cx$, where $c > 0$ is a constant. The uniform temperature near the sheet is assumed as T_w and the temperature, concentration far away from sheet is assumed as T_∞, C_∞ respectively.



(a) Stretching Case ($\lambda > 0$)



(a) Shrinking Case ($\lambda < 0$)