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Unsteady flow of Maxwell fluid in the presence of nanoparticles toward a permeable shrinking surface with Navier slip

Samir Kumar Nandy*

Department of Mathematics, A.K.P.C. Mahavidyalaya, Bengai, Hooghly 712 611, India

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ABSTRACT

A detailed study on the problem of unsteady boundary layer flow and heat transfer of an upper-convected Maxwell fluid in the presence of nanoparticles over a permeable shrinking sheet with wall mass transfer is presented. In contrast to the conventional no-slip condition at the surface, Navier's slip condition is applied at the surface. By use of a similarity transformation, the partial differential equations are reduced to a system of ordinary differential equations which is then solved numerically with shooting technique. The numerical results pertaining to the present study indicate that dual solutions exist for negative values of the unsteadiness parameter (A). It results in from the stability analysis that the upper branch solutions are stable and physically realizable, while the lower branch solutions are not stable and, therefore, not physically realizable. It is also found that as the Maxwell parameter (β) and velocity slip parameter (δ) increase, the range of the unsteadiness parameter (A) for which the solution exists gradually increases. The local Nusselt number and the local Sherwood number increase with the increase in the values of Maxwell parameter (β) and velocity slip parameter (δ). Furthermore, the effects of different physical parameters on the flow, temperature and concentration profiles are shown graphically and discussed in details.

1. Introduction

Ultra high-performance cooling is one of the most vital needs of many industrial technologies. However, low thermal conductivity is a limitation in developing energy-efficient heat transfer fluids that is required for ultra high-performance cooling. The cooling applications of nanofluids include silicon mirror cooling, electronics cooling, vehicle cooling, transformer cooling and so on. Nanofluid technology can help to develop better oils and lubricants. Nanofluids are now being developed for medical applications, including cancer therapy and safe surgery, by cooling. To all the numerous applications must be added that, nanofluids can be used in major process industries, including materials and chemicals, food and drink, oil and gas, paper and printing etc.

The enhancement of thermal conductivity of conventional fluids via suspensions of solid particles is a modern development in engineering technology aimed for increasing the heat transfer coefficient. The thermal conductivity of solid metal is higher than the base fluid, so the suspended particles are able to increase the thermal conductivity and heat transfer performance. Choi [1] was the first who experimentally verified that addition of nanoparticles in conventional base fluids appreciably enhanced the thermal conductivity. Experimental results [2,3] have illustrated that the thermal conductivity of the nanofluid can be increased considerably via introduction of a small volume fraction of nanoparticles. Hwang et al. [4] measured the thermal conductivity of several nanofluids and showed that the volume fraction of suspended particles is the effective parameter to enhance the thermal conductivity.

Recently, the flow of non-Newtonian fluids has attracted the attention of many authors due to its numerous applications in engineering and several technical purposes particularly in metallurgy and polymer industries. Many materials in real field like melts, printing ink, slurries and food stuff show properties which differ from those of Newtonian fluids. The governing equations of non-Newtonian fluids are highly non-linear and much more complicated than those of Newtonian fluids. There are different models to study non-Newtonian fluids which accommodate all the features of non-Newtonian materials. These models are classified into three categories – differential, rate and integral type models. Maxwell fluid model is a subclass of rate type models where the relaxation phenomena are taken into consideration. This fluid model is especially useful for polymers of low molecular weight. The proposed size-dependent thermal conductivity models, based on aggregation theory, become insensitive to the nanoparticle size for a well-dispersed system, since these models revert back to the Maxwell model for no aggregation. Also the models that consider liquid layering on the nanoparticle surface are

* Tel.: +91 943 4667 221; fax: +91 3211 246772.
E-mail address: nandysamir@yahoo.com

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Nomenclature

A	Unsteadiness parameter
a	Constant proportional to the stretching/shrinking velocity
C_f	Skin friction coefficient
c_p	Specific heat at constant pressure
C	Nanoparticle volume fraction
C_w	Nanoparticle volume fraction at the surface
C_∞	Nanoparticle volume fraction in the free stream
D_B	Brownian diffusion coefficient
D_T	Thermophoresis diffusion coefficient
$f(\eta)$	Dimensionless stream function
k	Relaxation time of the UCM fluid
Le	Lewis number
N_1	Slip velocity factor
Nb	Dimensionless Brownian motion parameter
Nt	Dimensionless Thermophoresis motion parameter
Nu_x	Local Nusselt number
Pr	Prandtl number
q_m	Wall mass flux
q_w	Wall heat flux
Re_x	Local Reynolds number
s	Wall mass transfer parameter
Sh_x	Local Sherwood number
T	Temperature of the fluid
T_w	Temperature of the fluid at the surface
T_∞	Temperature of the fluid in the free stream
u, v	Velocity components along x and y axes, respectively
u_{slip}	Slip velocity at the boundary
u_w	Velocity at the sheet
U	Free stream velocity
v_w	Velocity of mass transfer
Greek symbols	
α	Thermal diffusivity
β	Maxwell parameter
γ	Eigenvalue parameter
λ	Dimensional unsteadiness parameter
$\phi(\eta)$	Rescaled nanoparticle volume fraction
η	Similarity variable
θ	Dimensionless temperature of the fluid
ν	Kinematic viscosity of the fluid
δ	Dimensionless velocity slip parameter
ρ_f	Density of the base fluid
τ	Ratio of the effective heat capacity of the nanoparticle material and the ordinary fluid
ψ	Stream function

able to predict a particle-size-dependent thermal conductivity for a well-dispersed nanofluid. The increased order of the interfacial liquid molecules surrounding nanoparticles increases the effective phonon mean free path, which causes the heat transport through the interfacial nanolayer to be ballistic and non-local and increases the effective thermal conductivity of that layer. Some important aspects of Maxwell fluid under different physical conditions can be found in some recent published articles [5–10].

Shrinking sheet boundary layer flow problem has attracted many researchers due to its applications such as the shrinking film which is used in packaging of bulk product. The boundary layer flow caused by a shrinking sheet is quite different from the stretching case. From a physical point of view, vorticity generated at the shrinking sheet is not confined within a boundary layer and a steady flow is not possible unless adequate suction is applied at the sheet. Wang [11] was the first to study the shrinking sheet problem by considering the case of stretching deceleration surface. Later Miklavcic and Wang [12] proved the existence and uniqueness for steady viscous flow due to a shrinking sheet. Wang [13] also studied the stagnation-point flow toward a shrinking sheet, considering both two-dimensional and axisymmetric cases. Note that with an added stagnation flow to contain the vorticity, similarity solution is possible even in the absence of suction at the sheet. Other published papers related to the boundary layer flows induced by shrinking sheets in various aspects can be found in [14–18].

The non-adherence of the fluid to a solid boundary, known as velocity slip, is a phenomenon that has been observed under certain circumstances. The technological application of the hydrodynamic slip flow has become the center of attraction of scientists, engineers and researchers. Beavers and Joseph [19] proposed a slip flow condition at the boundary. Of late, there has been a revival of interest in the flow problems with partial slip. Andersson [20] analyzed the slip flow past a stretching surface. Wang [21] investigated the stagnation-point slip flow and heat transfer over a moving plate. Later, Fang et al. [22] gave an exact solution of the MHD viscous flow over a stretching sheet with partial slip at the boundary. In another paper, Fang et al. [23] investigated the viscous flow over a shrinking sheet with a second order slip at the boundary. On the other hand, the steady mixed convection boundary layer flow and heat transfer of a viscous incompressible fluid near the stagnation-point on a vertical surface with partial slip at the boundary was analyzed by Aman et al. [24]. Recently, in another paper, Aman et al. [25] investigated the steady two-dimensional stagnation point flow over a linearly stretching/shrinking sheet in a viscous fluid in the presence of an external magnetic field.

Aforementioned studies were primarily concerned with the boundary layer flow of viscous fluid. Buongiorno [26] developed a model in which he considers seven slip mechanisms, including inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus, fluid drainage, gravity and claimed that, of these seven, only Brownian diffusion and thermophoresis are important slip mechanisms in nanofluids. Above mentioned model was used by Kuznetsov and Nield [27] to study the influence of nanoparticles on natural convection boundary layer flow past a vertical plate. Khan and Pop [28] first time studied the problem of laminar fluid flow resulting from the stretching of a flat surface in a nanofluid. After this pioneering work, different surveys were conducted for effective viscosity, effective conductivity and the total heat transfer enhancement of nanofluids (see [29–35]).

The problem of unsteady shrinking surface with wall mass suction in a nanofluid was studied numerically by Rohni et al. [36]. On the other hand, Makinde [37] studied the combined effects of buoyancy force, convecting heating, Brownian motion and thermophoresis on the stagnation point flow and heat transfer of an electrically conducting nanofluid toward a stretching sheet. Effect of magnetic field on stagnation point flow and heat transfer due to nanofluid toward a stretching surface was investigated by Ibrahim et al. [38]. On the other hand, Nandy and Mahapatra [39] analyzed the effects of velocity slip and heat generation/absorption on MHD stagnation point flow and heat transfer over a stretching/shrinking sheet. Different from stretching sheet, it was found that the solutions for a shrinking sheet are non-unique. Recently, Malvandi et al. [40] investigated the problem of unsteady two-dimensional stagnation-point flow and heat transfer of a nanofluid over a stretching surface with Navier's slip condition at the boundary. Very recently, the steady two dimensional MHD boundary layer flow and heat transfer of a Maxwell fluid past a stretching sheet in the presence of nanoparticles was analyzed by Nadeem et al. [41].

To the present knowledge of the author, no study is reported in the literature, which investigate the unsteady boundary layer flow of Maxwell fluid over a permeable shrinking sheet in a nanofluid using the Buongiorno [26] model. The employed model for Maxwell fluid in

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