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Original Research Paper

Unsteady convective heat and mass transfer in pseudoplastic nanofluid over a stretching wall

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ABSTRACT

In this article, unsteady boundary layer flow of a power-law nanofluid over a stretching surface with a convective boundary condition is investigated numerically. A power-law model that incorporates the effects of Brownian motion and thermophoresis is used for non-Newtonian nanofluids. A set of similarity transformation is used to reduce Navier–Stokes, energy and nanoparticles concentration equations to a set of nonlinear ordinary differential equations which are then solved numerically by using a fourth order Runge–Kutta scheme coupled with a conventional shooting procedure. The effects of unsteadiness, suction/injection parameters, the generalized Prandtl and Lewis numbers and convective parameter on skin friction coefficient and reduced Nusselt number are investigated. Comparison with previously published work is performed and excellent agreement is observed for the limited case of existing literature. Numerical results show that dimensionless nanofluid concentration increases with the unsteadiness parameter whereas the values of dimensionless velocity and temperature decrease with it. Also, it is found that the effects of the unsteadiness parameter on the velocity boundary layer thickness are more pronounced compared to the concentration and temperature boundary layer thicknesses.

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1. Introduction

Boundary-layer behavior on a moving continuous solid surface plays an important role in a number of engineering processes. A number of technical processes employing polymers involve the cooling of continuous strips or filaments by drawing them through a quiescent or moving fluid. In these cases, the mechanical properties of the final product highly depend on the rate of heat transfer from the product and the surface stretching rate, which can be controlled by engineers. Boundary layer flow of nanofluid is gaining interest in industries due to the higher thermal conductivity of nanofluids. A comprehensive survey of convective transport in nanofluids was made by Buongiorno [1] and Kakaç and Pramuanjaroenkij [2]. Kuznetsov and Nield [3] have examined the influence of nanoparticles on natural convection boundary layer flow past a vertical plate, using a model in which Brownian motion and thermophoresis are accounted for. Khan and Pop [4] extended their work for the flow over a stretching surface in a nanofluid. They have assumed the simplest possible boundary conditions, namely those in which both the temperature and the nanoparticle fraction are constant along the wall. Hajmohammadi et al. [5] studied the effects of presence Cu and Ag nano-particles on flow and heat transfer. Khalili et al. [6] investigated mixed convection on a permeable stretching cylinder in porous medium with heat generation or absorption. Further, Sheremet et al. [7] studied the natural convection of a nanofluid in a porous enclosure using Buongiorno's mathematical model. EL-Kabeir et al. [8] discussed the effects of the nonlinear Forchheimer terms and thermal radiation and on nanofluid flow and heat transfer by non-Darcy natural convection from a vertical cylinder embedded in a porous media. Malvandi and Ganji [9] studied the force convection flow of a nanofluid in a parallel-plate channel. Recently, Rashidi et al. [10] investigated the effects of buoyancy on magnetohydrodynamic (MHD) flow over a stretching sheet in the presence of the thermal radiation. Their results showed that the presence of magnetic field leads to decrease the nanofluid velocity and increase the nanofluid temperature while, the rising of buoyancy has opposite trends. Also, in

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Nomenclature

A	unsteadiness parameter
B, D	constants
C	nanoparticles volume fraction
c_p	specific heat, kJ/kg K
C_f	skin friction coefficient
D_B	Brownian diffusion coefficient, kg/m s
D_T	thermophoretic diffusion coefficient, kg/m s K
$f(\eta)$	dimensionless stream function
h	heat transfer coefficient, W/m^2 K
h_m	mass transfer coefficient, kg/m^2 s
k	thermal conductivity, W/m K
Le	Lewis number
n	Power-law index
N_b	generalized Brownian motion parameter
N_t	generalized thermophoresis parameter
Nu_x	local Nusselt number
Pr	Prandtl number
q_m	wall mass flux, kg/m^2 s
R	suction/injection parameter
Re_x	local Reynolds number
Sh_x	local Sherwood number
T	temperature, K
u, v	velocity components
x, y	Cartesian coordinates, m

Greek symbols

α	thermal diffusivity, m^2/s
γ	time constant
η	similarity variable
$\theta(\eta)$	dimensionless temperature
μ	dynamic viscosity, kg/m s
υ	kinematic viscosity, m^2/s
ρ	fluid density, kg/m^3
τ	shear stress, kg/m s^2
$\phi(\eta)$	rescaled nanoparticle volume fraction
ψ	stream function

Subscripts

w	condition at the surface of the plate
∞	ambient condition
f	fluid
nf	nanofluid
s	solid

Superscripts

$'$	differentiation with respect to η

recent works the nanoparticles diameter and the Brownian motion effects on nanofluid flows were studied by Ghalambaz et al. [12] and Fani et al. [12], respectively.

Makinde and Aziz [13] studied the boundary layer flow induced in a nanofluid due to a linearly stretching sheet by using a convective heating boundary condition. The above literature review reveals that in most of the previous investigations, Newtonian fluids were used as the base fluid. The first question to be asked with respect to the viscosity of nanofluids is whether nanofluids are Newtonian fluids or a shear thinning or thickening process is important to them. Pak and Cho [14] found that the suspensions are Newtonian at very low particle volume fractions and start showing shear thinning behavior with increasing particle volume fraction. Also, Chen et al. [15] found that there is obvious shear-thinning behavior in the semi-concentrated nanofluids (nanofluids with 5–10% volume concentration). Ding et al. [16,17] discussed how the nanoparticle structuring affects the thermal conductivity and viscosity of nanofluids. Chen et al. [18] found that the shear viscosity is much higher than that predicted by the conventional viscosity models for dilute suspensions. Hassanien et al. [19] studied the flow and heat transfer in a power-law fluid over a non-isothermal stretching sheet. Khan and Gorla [20] extended the work by Hassanien et al. [19] to analyze the behavior of power-law nanofluids over a stretching surface in a nanofluid with uniform surface nanoparticle concentration. The same problem was studied by Khan and Gorla [21], for prescribed wall temperature and surface nanoparticle concentration. Also, the effects of using non-Newtonian power-law fluid on the steady flow characteristics have been studied by Erfanian et al. [22] and Rashidi et al. [23]. Recently, Nadeem et al. [24] analyzed the steady non-orthogonal stagnation point flow and heat transfer of a second grade nanofluid toward a stretching surface. They found that the velocity at a point increases with the increase in the elasticity of the fluid. Also, a comprehensive study of a third grade non-Newtonian fluid flow between parallel plates was done by Keimanesh et al. [25]. They have used a multi-step differential transform method to find the analytical solution of the governing equations. Recently, some researchers have considered the fundamental concepts of nanofluids. For example, Zerradi et al. [26] presented a new correlation of Nusselt number which developed from the experimental data of nanofluids. After that, Loulijat et al. [27] studied the effect of solid–solid inter-atomic potential type on the thermal conductivity of nanofluids. They have showed that the thermal conductivity of

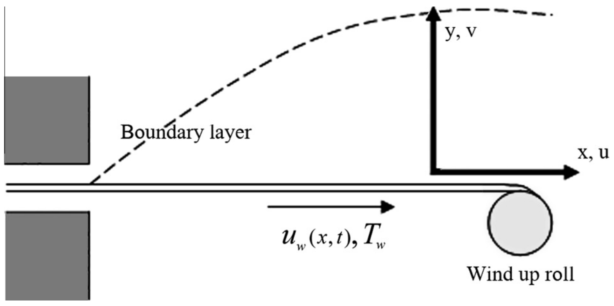

Fig. 1. Physical model of two-dimensional flow with coordinate system.

Table 1
Comparison of dimensionless wall shear stress $|f''(0)|$ for different power-law fluids with $N_b = N_t = 10^{-5}$.

R	$n = 0.5$			$n = 1$		
	Khan and Gorla [20]	Hassanien et al. [19]	Present study	Khan and Gorla [20]	Hassanien et al. [19]	Present study
−1	0.759	0.759826	**0.7594**	0.61803	0.618042	**0.6180**
−0.5	0.92924	0.931104	**0.9292**	0.78078	0.780781	**0.7808**
0	1.16136	1.165235	**1.1614**	1	1	**1**
0.5	1.47815	1.485498	**1.4782**	1.28078	1.280777	**1.2808**
1	1.90665	1.919345	**1.9067**	1.61803	1.618034	**1.6181**

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