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Original Research Article

Slip effects on unsteady stagnation point flow of a nanofluid over a stretching sheet

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ABSTRACT

Unsteady two-dimensional stagnation point flow of a nanofluid over a stretching sheet is investigated numerically. In contrast to the conventional no-slip condition at the surface, Navier's slip condition has been applied. The behavior of the nanofluid was investigated for three different nanoparticles in the water-base fluid, namely copper, alumina and titania. Employing the similarity variables, the governing partial differential equations including continuity, momentum and energy have been reduced to ordinary ones and solved via Runge–Kutta–Fehlberg scheme. It was shown that a dual solution exists for negative values of the unsteadiness parameter A and, as it increases, the skin friction Cfr grows but the heat transfer rate Nur takes a decreasing trend. The results also indicated that, unlike the stretching parameter ε, increasing in the values of the slip parameter λ widen the ranges of the unsteadiness parameter A for which the solution exists. Furthermore, it was found that an increase in both ε and λ intensifies the heat transfer rate.

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1. Introduction

For years, many researchers have paid a lot of attention to viscous fluid motion near the stagnation region of a solid body, where "body" corresponds to either fix or moving surfaces in a fluid. This multidisciplinary concept has frequent applications in high speed flows, thrust bearings and thermal oil recovery. Hiemenz [1] developed the first investigation in this field. He applied similarity transformation to collapse two-dimensional Navier–Stokes equations to a nonlinear ordinary differential one and then presented its exact solution. Extension of this study was carried out with the similarity solution by Homann and Angew [2] to the case of axisymmetric three dimensional stagnation point flow. After these original studies, many researchers have put their attention to this subject. Attia [3] considered the effects of an external magnetic field in the presence of suction/blowing parameter simultaneously for this problem. Later Massoudi and Ramezan [4] applied a perturbation technique to solve the stagnation point flow and heat transfer equation of a non-Newtonian second grade fluid. They perused their previous study for the case of non-isothermal surface later [5]. Garg [6] enhanced Massoudi's results numerically for any value of the non-Newtonian parameters. Some excellent literature in this field can be found in Refs. [7–12].

Beside stagnation point flow, stretching surfaces has a wide range of applications in engineering and several technical purposes particularly in metallurgy and polymer industry. For instance, gradual cooling of continuous stretching metal or plastic strips which have multiple applications in mass production. Needless to say, the final quality of the product strongly depends on the rate of heat transfer from the stretching surface. Crane [13] is the first to present a self-similar solution in the closed analytical form for steady two-dimensional incompressible boundary layer flow caused by the stretching plate whose velocity varies linearly with the distance from a fixed point on the sheet. Following Crane's study, the thermal approach to this problem was investigated by Carragher and Crane [14]. They assumed that temperature difference between the sheets and the ambient is proportional to a power of the distance from the fixed point. Subjecting uniform heat flux boundary condition, Dutta et al. [15] presented the temperature distribution for a stretching surface in an ambient with different temperatures. The combination of stretching surface and stagnation point flow was analyzed by Mahapatra and Gupta [16]. Different types of fluids such as viscoelastic [17] and micropolar [18] ones past a stretching sheet have been studied later. The popularity of boundary layer flow and stretching surfaces can be gauged from the researches done by scientists for its frequent applications and can be found in the recent literature e.g. [19–26].

Improving the technology, it was realized that the energy consumption of the industrial devices and their volumes have to be optimized both [27]. So the idea of adding particles to a conventional fluid in order to enhance its heat transfer characteristics was emerged. Among all dimensions of particles such as macro, micro and nano, due to

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Nomenclature

a,b	Constants
A	Unsteadiness parameter
Pr	Prandtl number
q_w	Surface heat flux (W/m^2)
T	Temperature (K)
$U_e(x)$	Free stream velocity (m/s)
N_1	Slip velocity factor
Nu_x	Nusselt number
Re_x	Reynolds number
S	Blowing/suction parameter

Greek symbols

α	Thermal diffusivity (m^2/s)
$(\rho c_p)_f$	Heat capacity of the fluid (kg/m.s^2)
$(\rho c_p)_p$	heat capacity of the nanoparticles (kg/m.s^2)
μ	Dynamic viscosity (kg/m.s)
ρ	Density (kg/m^3)
ψ	Stream function
η	Similarity variable
ϕ	Solid volume fraction
θ	Dimensionless temperature
ε	Stretching parameter
λ	Slip parameter

Subscripts

w	Condition on the sheet
∞	Ambient conditions
nf	Nanofluid
f	Fluid

some obstacles in pressure drop of the system [28] or keeping the mixture homogeneous [29–31], nano-scaled particles have attracted more attention. These tiny particles have high thermal conductivity, so the mixed fluids have better thermal properties [32]. In order to define the conductivity of the mixture, different simulating models were developed such as Maxwell [33], Hamilton and Crosser [34], Wang et al. [35] which are strongly depended on the size and shape of the nanoparticles. Later, Tiwari and Das [36] proposed a model to analyze the nanofluid behavior taking into account the effects of the solid volume fraction. After these seminal studies, different surveys were conducted for effective viscosity, effective conductivity and the total heat transfer enhancement of nanofluids [37–46]. Afterwards, boundary-layer flow of a nanofluid past a stretching sheet was studied by Khan and Pop [47]. They have reported that the reduced Nusselt number decreases with Reynolds and Prandtl numbers; on the other hand, the reduced Sherwood number is an increasing function of higher Prandtl numbers and a decreasing function of lower ones. Later on, three dimensional stagnation point flow of a nanofluid was studied by Bachok et al. [48]. In a different study, stagnation-point flow over a stretching/shrinking sheet in a nanofluid has been considered by Bachok et al. [49]. They have concluded that skin friction and heat transfer coefficients increase as nano-particle volume climbs up.

This paper deals with the effects of slip velocity and stretching parameter on the unsteady stagnation point flow of a nanofluid over a stretching sheet where velocity of the sheet and free stream vary continuously with time. The employed model for nanofluid incorporates the effects of unsteadiness parameter, slip parameter, stretching parameter and solid volume fraction simultaneously. The basic boundary layer equations have been reduced into a two-point boundary value problem via similarity variables, and solved numerically. As far as the authors' knowledge, there is no study on the current subject that has thus far been communicated and they have not been published before.

2. Governing equations

Consider an incompressible unsteady viscous flow of nanofluids being confined to $y > 0$ toward a stretching sheet coinciding with the plane $y = 0$ with a fixed stagnation point at $x = 0$ as shown in Fig. 1. We have assumed that the free stream and sheet's velocity vary with time from a fixed stagnation point in the form of $U_e(x,t) = ax(1 - ct)^{-1}$ and $U_w(x,t) = bx(1 - ct)^{-1}$ respectively where a, b and c are positive constants. Current assumptions are necessary in order to provide a similarity solution. It is also assumed that the temperature at the surface has a constant value of T_w while the ambient temperature beyond the boundary layer has a constant value of T_∞. The basic unsteady conservation equations of mass, momentum, and thermal energy can be expressed as, see Bachok et al. [50]

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

$$\frac{\partial u}{\partial t} + \left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \frac{\partial U_e}{\partial t} + U_e\frac{dU_e}{dx} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial T}{\partial t} + \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right). \tag{3}$$

Subject to the boundary conditions

$$\begin{aligned} &v = 0, \quad u = U_w(x,t) + U_{Slip}(x,t), \quad T = T_w \quad \text{at} \quad y = 0 \\ &u = U_e(x,t) = ax(1-ct)^{-1}, \quad T = T_\infty \quad \text{as} \quad y \to \infty. \end{aligned} \tag{4}$$

Here u and v are the velocity components along the x and y directions respectively, $U_{Slip}(x,t) = N_1 \nu \frac{\partial u}{\partial y}$ where $N_1 = N\sqrt{t}$ is the slip velocity factor and t is the time. T is the temperature, μ_{nf} is the viscosity of nanofluid, ρ_{nf} is the density of nanofluid and α_{nf} is the thermal

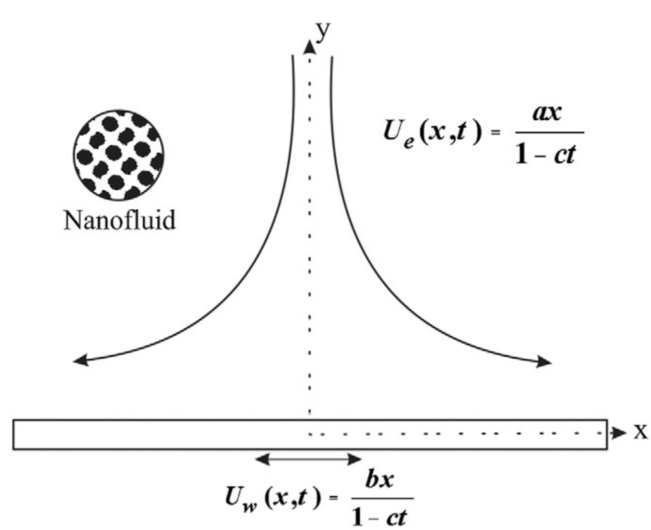

Fig. 1. Physical model and coordinate system.

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