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An analytical study on entropy generation of nanofluids over a flat plate

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Abstract The steady two-dimensional boundary layer flow of nanofluids over a flat plate is studied analytically to analyze the generated entropy inside the boundary layer at a constant wall temperature. Applying the transformation of the PDE equations of continuity, momentum and energy to ODE ones by similarity variables, a dimensionless equation for entropy generation inside the boundary layer is presented. The most accurate series solution was found by coupling the homotopy-perturbation method (HPM) and the variational iteration method (VIM), which provides an effective technique for solving strongly nonlinear ordinary differential equations. The analytical results indicated that the generated entropy strongly depends on the nanoparticle volume fraction (ϕ), Prandtl, Eckert and Reynolds numbers. Based on the series solution, the effects of ϕ on velocity, temperature and entropy generation were explained in details and the related figures are plotted.

1. Introduction

The classical concept of boundary layer corresponds to a thin region next to the wall in a flow where viscous forces are important which may affect the engineering process of producing. For example viscous forces play essential roles in glass fiber drawing, crystal growing and plastic extrusion. Blasius [1] studied the simplest boundary layer over a flat plate. He employed a similarity transformation which reduces the partial differential boundary layer equations to a nonlinear third-order ordinary differential one before solving it analytically. In contrast to the Blasius problem, Sakiadis [2] introduced the boundary layer flow induced by a moving plate in a quiescent ambient fluid. A large amount of literatures of this problem has been cited in the books by Schlichting and Gersten [3], Bejan [4] and White [5] and also in research papers such as [6,7].

As technology improves, it was realized that the industrial devices have to be cooled in more effective ways [8] and the

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Nomenclature

c_f	skin friction coefficient
f	dimensionless stream function
c_p	specific heat at constant pressure
k	thermal conductivity
Nu	local Nusselt number
Pr	Prandtl number
q_w	surface heat flux
Re	local Reynolds number
T	fluid temperature
S	total entropy generation
S'''_{gen}	volumetric entropy generation rate
u,v	velocity components along the x- and y-directions, respectively
Ec	Eckert number
Be	Bejan number
x,y	cartesian coordinates along the surface and normal to it, respectively
S_h	entropy generation due to heat transfer
S_f	entropy generation due to fluid friction

Greek symbols

α	thermal diffusivity
θ	dimensionless temperature
ν	kinematic viscosity
μ	dynamic viscosity
ρ	fluid density
τ	shear stress
ψ	stream function
η	similarity variable
ϕ	dissipation term in energy equation
Φ	volume fraction of nano-particle

Subscripts

w	condition at the surface of the wedge
∞	ambient conditions
nf	nanofluid
f	fluid
p	particle

Superscript

$'$	derivative with respect to η

conventional fluids such as water are not appropriate anymore, so the idea of adding particles to a fluid was presented. Adding nano-particles to a base fluid affects the homogeneity of the fluid and the randomness motion of the molecules increases. These tiny particles have high thermal conductivity, so the mixed fluids have better thermal properties [9–11]. The materials of these nano-scale particles are aluminum oxide (Al_2O_3), copper (Cu), copper-oxide (CuO), gold (Au), silver (Ag), etc., which are suspended in base fluids such as water, oil, acetone and ethylene glycol. Al_2O_3 and CuO are the most well-known nano-particles used by many researchers in their studies [11–15]. They claimed different results due to the size and shape and so the contact surface of the particles. The popularity of nanofluids can be gauged from the researches done by scientists for its frequent applications and can be found in the literature, for example, [16–22].

Adding these nano-particles to a fluid makes the base fluid inhomogeneous, as a result, thermodynamic irreversibility in the flow increases which causes more energy and power losses in the system. Conserving useful energy depends on how to design an efficient heat transfer process from a thermodynamic point of view. Energy conversion processes are led to an irreversible increase in entropy. Thus, even though energy is conserved, the quality of the energy decreases by converting it into a different form of energy at which less work can be obtained. Reducing the generated entropy will result in more efficient designs of energy systems. In 1996, Bejan [4,23] presented a method named Entropy Generation Minimization (EGM) to measure and optimizes the disorder or disorganization generated during a process specifically in the fields of refrigeration (cryogenics), heat transfer, storage and solar thermal power conversion. There is no question that by "optimize" we mean the stabled process in which the system loses the least energy while still performing its fundamental engineering function. The method is also known as second law analysis and thermodynamic optimization. This field has been developed astoundingly during the 1990s, in both engineering and physics.

Recently, second-law analysis of fluid flow and heat transfer across a flat plate has been conducted by Malvandi et al. [24]. They considered the effects of Reynolds, Eckert and Prandtl numbers on entropy generation in a wide range of parameters. In another study, Malvandi et al. [25] considered the effects of velocity ratio – which represents the ratio of the wall velocity to the free stream fluid velocity – on a moving plate. Their outcomes reveal that focusing on the velocity ratio as a pivotal parameter, entropy generation can be minimized. In all of the mentioned studies, physical conditions such as geometry, viscosity of the fluids, free stream velocity and temperature on entropy generation minimization are investigated in details. Recently a lot of attention has been attracted to entropy generation of nanofluids for different geometries. Sohel et al. [26] conducted a study about entropy generation of nanofluids in circular micro/mini channels. In another study, focusing on Reynolds number, Moghaddami et al. [27] studied the effects of flow regime on entropy generation and they obtained an optimum Reynolds number at which the entropy generation is minimized. Entropy generation due to natural convection of cooling nanofluids has been studied by Shahi et al. [28]. Flow of nanofluids between co-rotating cylinders has been analyzed by Mahian et al. [29,30]. Later the mixture of TiO_2 and water in vertical annulus in the presence of magnetic effects has been studied from thermodynamical point of view by Mahian et al. [31]. Studying recently-published reviews about entropy generation in nanofluids can be beneficial for rigorous readers [32,33].

The novelty of this study is considering *the effects of nanoparticle inclusion in the classical Blasius problem*. For doing so, we have employed the similarity variables introduced