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Original Research Paper

Stagnation-point heat transfer of nanofluids toward stretching sheets with variable thermo-physical properties

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ABSTRACT

The objective of this study is to investigate stagnation-point flow of nanofluids over an isothermal stretching sheet. The volume fraction of nanoparticles at the sheet is assumed to be passively controlled. Furthermore, due to low volume fraction of nanoparticles and dilute nanofluid, the thermal conductivity and dynamic viscosity of the nanofluid are assumed to be linear functions of the volume fraction of nanoparticles. In order to study the effects of a plethora of parameters on the boundary layer flow and heat and mass transfer, a practical range of these parameters have been utilized. An accurate numerical solution of the governing equations based on the finite difference method is obtained and the effect of various physical parameters such as the Prandtl number, Lewis number, thermophoresis parameter, and the Brownian motion parameter on the thermal, hydrodynamic, and concentration boundary layers is evaluated. In order to examine the alteration of the thermal convective coefficient, a dimensionless heat transfer enhancement ratio parameter is introduced. The results show that the variation of different thermodynamic parameters induces substantial impression on the behavior of the nanoparticles distribution. For example, it is found that an increase in the value of the Lewis number leads to a decrease in the value of the non-dimensional nanoparticles volume fraction at the sheet, but it does not have any influence on the thermal and hydrodynamic boundary layers. Increasing the Prandtl number is predicted to decrease the thermal boundary layer thickness and the volume fraction of nanoparticles at the surface. In most instances, the heat transfer augments in the presence of nanoparticles.

1. Introduction

The stagnation flow over a stretching sheet has attracted considerable pursuit of many researchers due to its broad range of applications in technology and industry. Some of these applications include polymer extrusion in a melt-spinning process, glass fiber, wire drawing, and cooling of metallic sheets or electronic chips. Depending on the rate of cooling in the process, the specified features would be produced. Sakiadis [1] was one of the first researchers who worked on the boundary layer on solid surfaces, after that many studies have been conducted on flow of Newtonian and non-Newtonian fluids over linear and non-linear stretching sheets [2–5]. Due to the importance of heat transfer in some fluids such as water, grease, oil, which are poor conductors with respect to others, researchers have endeavored to enhance the thermal conductivity of such fluids. For this purpose, they manufactured nanofluids intelligently. In fact, a nanofluid is a new engineered fluid which is synthesized of solid nanoparticles in a conventional heat transfer liquid (base fluid). The experimental measurements of the thermo-physical properties of nanofluids reveal that incorporation of the nanoparticles leads to augmentation of the thermal conductivity and the dynamic viscosity of the mixture [6–9]. Currently, there are several excellent reviews on the practical and potential industrial applications of nanofluids [10–12].

As mentioned above, the dispersion of nanoparticles in a base fluid would augment the thermal conductivity of the nanofluid. Therefore, it is expected that the presence of nanoparticles increases the convective heat transfer. However, the nanoparticles in the base fluid also alter the other thermo-physical properties such as the dynamic viscosity, density, and the heat capacity. Accordingly, the addition of nanoparticles may cause an increase or a decrease of the heat transfer coefficient of a nanofluid with respect to the base fluid. In addition, there are several slip

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Nomenclature

(x, y)	Cartesian coordinates
D_B	Brownian diffusion coefficient (m^2/s)
D_T	thermophoretic diffusion coefficient (m^2/s)
f	rescaled nanoparticles volume fraction, nanoparticles concentration
h	convective heat transfer coefficient (J/m^2)
k	thermal conductivity (W/m K)
Le	Lewis number
N_b	Brownian motion parameter
N_c	variable thermal conductivity parameter
N_t	thermophoresis parameter
N_v	variable viscosity parameter
P	pressure (Pa)
Pr	Prandtl number
Re_x	local Reynolds number
S	dimensionless stream function
T	temperature (K)
u, v	x and y velocity components (m/s)

Greek symbols

(ρc)	heat capacity (J/m^3 K)
μ	viscosity (Pa s)
α	thermal diffusivity (m^2/s)
η	dimensionless distance
θ	dimensionless temperature
ν	kinematic viscosity
ρ	density (kg/m^3)
φ	nanoparticles volume fraction
ψ	stream function

Subscripts

∞	free stream
bf	the base fluid
drift-flux	the drift flux model
nf	nanofluid
p	nanoparticles
w	sheet, wall, surface

mechanisms, including Brownian motion and thermophoresis effects, which tend to move the nanoparticles in the base fluid. The slip velocity of nanoparticles would affect the concentration and the heat transfer in the boundary layer. Hence, a special attention to the fundamental analysis of convective boundary layer heat transfer of nanofluids is highly demanded.

Due to the fact that the concentration of nanofluids would not remain constant and nanoparticles may have a slip velocity relative to the base fluid [13–15], some researchers showed that the migration of nanoparticles could transfer energy and also influence the thermo-physical properties [14,16]. Buongiorno [14] investigated the forces which affect the nanoparticles in the nanofluid. Buongiorno [14] found that the Brownian motion and the thermophoretic effects are two considerable forces which cause the drift-flux (slip velocity) of nanoparticles in the base fluid. Buongiorno [14] proposed a model to evaluate the concentration gradient of nanoparticles in the convective heat transfer flows.

Utilizing Buongiorno's model [14], different aspects of the convective boundary layers of nanofluids over a flat plate have been analyzed. For example, Khan and Pop [17] have evaluated the boundary layer flow and heat transfer of nanofluids over a linear stretching sheet. Moreover, different aspects of a boundary layer flow and heat transfer of nanofluids over a stretching sheet have been analyzed by previous researchers. Noghrehabadi et al. [15] considered a partial slip velocity for the nanofluid at the sheet. Rana and Bhargava [18] studied the effect of a non-linear velocity of the sheet. Makinde and Aziz [19] as well as Noghrehabadi et al. [20] examined the effect of a convective boundary condition below the sheet. Noghrehabadi et al. [21] analyzed the magnetohydrodynamic (MHD) effects for the same problem. Mustafa et al. [22] studied the flow of a nanofluid near the stagnation point toward an isothermal stretching surface. Hamad and Ferdows [23] analyzed the effect of a porous medium on the stagnation-point toward an isothermal stretching surface.

In all of the mentioned studies [13–15,17,18–23,24], it was assumed that the concentration of nanoparticles at the surface is controlled actively. Therefore, there is a mass flux of nanoparticles through the surface, and hence, the Sherwood number is non-zero there. However, there is not any justification for how the concentration of nanoparticles can be controlled actively at the surface.

In the mentioned studies [13–15,17,18–23,24], it was assumed that the migration of nanoparticles in the boundary layer would carry significant amount of energy. However, in a very recent study by Behseresht et al. [24], it has been reported that the energy transfer because of the migration of nanoparticles in natural convection flows is not significant. They have reported that the range of non-dimensional parameters corresponding to nanofluids, adopted in the literature, is not in agreement with the practical range of these parameters. The same conclusion is applicable in the case of a boundary layer flow over stretching sheets. In all of the mentioned studies [13–15,17,18–23], the Brownian motion parameter and thermophoresis parameter are assumed much larger than their practical values. In the most of the previous studies, these parameters are adopted in the order of 10^{-1}; however, they should be in the order of 10^{-6} and lower. Such low values of these parameters diminish the contribution of nanoparticles in the heat transfer equation. However, the concentration boundary layer is related to the ratio of thermophoresis to the Brownian motion parameter and may remain significant. In addition, the previous studies [13–15,17,18–23,24] assumed that the thermal conductivity and the dynamic viscosity of nanofluids are solely functions of the ambient volume fraction of nanoparticles and that they can be assumed constant in the governing equations. Hence, the effect of the local volume fraction of nanoparticles on the thermal conductivity and the dynamic viscosity was completely neglected. This assumption in the case of nanofluids could be an inadequate assumption. Because the experiments show that even a very low volume fraction of nanoparticles can significantly affect the thermo-physical properties of nanofluid [25,26]. In fact, since a nanofluid is a dilute mixture of a base fluid and nanoparticles, any variation of the concentration of nanoparticles in the base fluid could be significant.

The aim of the present study is to evaluate a stagnation-point flow and boundary layer heat and mass transfer of nanofluids over a stretching sheet. A practical boundary condition, the zero mass flux of nanoparticles through the sheet, is adopted. The dynamic viscosity and the thermal conductivity of the nanofluid are considered as functions of the local volume fraction of nanoparticles. The governing partial differential equations are transformed into a set of ordinary differential equations using similarity variables. Adopting the practical range of non-dimensional parameters, the effect of the nanofluids parameters on the boundary layer flow, heat and mass transfer is theoretically analyzed.