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Analyze of fluid flow and heat transfer of nanofluids over a stretching sheet near the extrusion slit

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ABSTRACT

The objective of the present study is to analyze the boundary layer flow and heat transfer of nanofluids over a stretching sheet near the extrusion slit in the presence of variable thermal conductivity. The effects of Brownian motion and thermophoresis are taken into account. The governing partial differential equations are reduced to dimensionless form and solved numerically using finite difference scheme and Point Successive Over Relaxation algorithm. The critical Reynolds number is introduced to distinguish the non-similar region from the self-similar region of velocity and temperature profiles. Furthermore, the effects of dimensionless parameters such as Prandlt number, Schmidt number, variable thermal conductivity parameter, Brownian motion and thermophoresis parameters on the velocity and temperature profiles and also on reduced Nusselt number, reduced Sherwood number and critical Reynolds number are investigated. It is found that the critical Reynolds number for the temperature profile is significantly affected by Prandtl number. In addition, the reduced Nusselt and Sherwood numbers found to be much higher in non-similar regions near the extrusion slit than that of self-similar region.

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1. Introduction

Fluid flow and heat transfer in a boundary layer flow over a stretching sheet has been studied by many researchers; because it has significant applications in many industries such as extrusion of plastic, paper production, metal spinning, wire drawing, glass blowing, hot rolling, manufacture of rubber sheet, polymer engineering, cooling of metallic sheets and crystal growing [1,2].

Sakiadis [3,4] examined viscous flow over a continuous solid surface with application of boundary layer theory. Crane [5] was the first one who extended the work of Sakiadis [3,4] and studied the viscous flow and heat transfer caused by a linearly stretching sheet. After pioneer work by Crane [5], Al-Sanea and Ali [6] studied flow and heat-transfer over a continuously moving horizontal material in the presence of suction or injection very close and far away downstream from the extrusion slit. They are considered the effects of extrusion slit by solving the governing partial differential equations used finite volume method and carried out the solutions in the non-similar and similar regions. Further, Kiwan and Ali [7] did the same case for the flow and heat transfer over a stretching surface in a porous medium with internal heat generation or absorption and suction and injection. They considered full governing equations for mapping out the solution near the slit and far away downstream from the extrusion slit.

The heat transfer rate from the sheet is very important in such application because it induces a direct impact on the quality of the products. However, the common heat transfer fluids such as water, ethylene glycol, and engine oil have limited heat transfer capabilities owing to their low thermal conductivity whereas metals have much higher thermal conductivities than these fluids. Therefore, dispersing high thermal conductive solid particles in a conventional heat transfer fluid may enhance the thermal conductivity of the resulting fluid.

Nanofluid is a fluid containing nanometer-sized particles. The term “Nanofluid” was proposed by Choi [8] to indicate engineered colloids consist of nanoparticles dispersed in a base fluid. The base fluid is usually a conductive fluid, such as water or ethylene glycol. Other base fluids include bio-fluids, polymer solutions, oils and other lubricants. The nanoparticles used in synthesis of nanofluids are typically metallic (Al, Cu), metallic oxides (Al_2O_3, TiO_2), carbides (SiC), nitrides (AlN, SiN) or carbon nanotubes with the diameter which ranges between 1 and 100 nm. One of the outstanding characteristic of nanofluids is their enhanced thermal conductivity [9]. Comprehensive references on this subject can be found in the recently published book by Das et al. [10] and in the papers by

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Nomenclature

a	constant
C	nanoparticle volume fraction
C_w	nanoparticle volume fraction at the stretching sheet
C_∞	ambient nanoparticle volume fraction
C_f	skin friction coefficient
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
H	height normal to the sheet
k	thermal conductivity
$k_{m,\infty}$	the effective thermal conductivity of the nanofluid outside the boundary layer
L	length of the sheet
m_w	wall mass flux
Nb	Brownian motion parameter
Nc	variable thermal conductivity parameter
Nt	thermophoresis parameter
Nu	Nusselt number
P	pressure
Pr	Prandtl number
q_w	wall Heat flux
Re_L	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	fluid temperature
T_∞	ambient temperature
T_w	temperature at the stretching sheet
u,v	velocity components along x and y-axes
u_w	velocity of the stretching sheet
x, y	physical coordinates (x-axis is aligned along the stretching sheet and y-axis is normal to it)

Greek

α	thermal diffusivity
β	clustering parameter
$\varphi(\eta)$	dimensionless nanoparticle volume fraction
η	similarity variable
$\theta(\eta)$	dimensionless temperature
υ	kinematic viscosity of nanofluid
$(\rho c)_{nf}$	heat capacity of the nanofluid
$(\rho c)_p$	effective heat capacity of the nanoparticle material
ρ	nanofluid density
ρ_p	nanoparticle mass density
ψ	stream function
ω	vorticity function
ξ, ζ	computational coordinates (ξ-axis is aligned along the stretching sheet and ζ-axis is normal to it)

Superscript

*	dimensional parameters

Subscript

C	critical value
CFD	PSOR result
nf	nanofluid
p	nanoparticles
sim	similarity result
∞	ambient value

Wang and Mujumdar [11], Kakaç and Pramuanjaroenkij [12], Chandrasekar et al. [13] and Wu and Zhao [14].

The effects of nanofluids could be considering in different ways such as dynamic effects which include the effects of Brownian motion and thermophoresis diffusion [15–17], and the static part of Maxwell's theory [18–21].

Recently, many researchers, using similarity solution, have examined the boundary layer flow, heat and mass transfer of nanofluids over stretching sheets. Khan and Pop [22] have analyzed the boundary-layer flow of a nanofluid past a stretching sheet using a model in which the Brownian motion and thermophoresis effects were taken into account. They reduced the whole governing partial differential equations into a set of nonlinear ordinary differential equations and solved them numerically. In addition, the set of ordinary differential equations which was obtained by Khan and Pop [22] has been solved by Hassani et al. [23] using homotopy analysis method. After that, many researchers, using similarity solution approach, have extended the heat transfer of nanofluids over stretching sheets and examined the other effects such as the chemical reaction and heat radiation [24], convective boundary condition [25], nonlinear stretching velocity [26], partial slip boundary condition [27],magnetic nanofluid [28], partial slip and convective boundary condition [29], heat generation/absorption [30], thermal and solutal slip [31], nano non-Newtonian fluid [32], and Oldroyd-B Nanofluid [33]. In all of the mentioned studies [22–33], it was assumed that the values of the Reynolds number are high and the effects of extrusion slit could be neglected, because of that, the similarity solution were used to carried out the results. However, the analysis of the boundary layer of regular fluids over stretching sheets reveals that for the low values of the Reynolds number, the boundary layer approximations are not valid in the vicinity of the slit; hence, the extrusion slit significantly affects the boundary layer flow and heat transfer [6,7]. In addition, the stretching velocity of the sheet is very low in many practical applications; and hence, the practical Reynolds number is also very low. At the present time, it is not clear when the boundary layer approximations are adequate for analysis of flow and heat transfer of nanofluids over a stretching sheet in the case of flow and heat transfer of nanofluids.

As mentioned, the enhancement of the thermal conductivity of nanofluids is the most outstanding thermo-physical properties of nanofluids. In all of the previous studies [22–33], the effect of local volume fraction of nanoparticles on the thermal conductivity of the nanofluid was neglected [34,35]. However, in the work of Buongiorno [36], it has been reported that the local concentration of nanoparticles may significantly affect the local thermal conductivity of the nanofluids.

The objective of the present study is to analyze the flow and heat transfer of nanofluids near the extrusion slit and where the Reynolds number of the flow is low. The effect of local volume fraction of nanoparticles on the thermal conductivity of nanofluid is taken into account. A critical Reynolds number, $Re_{L,C}$, is introduced to distinguish between the self-similar and non-similar regions of the velocity and temperature profiles. The results of present study also provide practical guidelines for the adequately of the available similarity solutions.

2. Formulation of the problem

Consider the two dimensional laminar steady flow of an incompressible nanofluid caused by stretching of the sheet, where the x^*-axis is measured along the sheet and the y^*-axis is measured normal to the sheet (see Fig. 1). It is assumed that the temperature (T^*) and the nanoparticles volume fraction (C^*) are constant at the

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