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Boundary layer flow and heat transfer over a stretching sheet with Newtonian heating

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ABSTRACT

The steady boundary layer flow and heat transfer over a stretching sheet with Newtonian heating in which the heat transfer from the surface is proportional to the local surface temperature, is considered in this study. The transformed governing nonlinear boundary layer equations are solved numerically by a finite-difference method. Numerical solutions are obtained for the heat transfer from the stretching sheet and the wall temperature for a large range of values of the Prandtl number *Pr*. The Newtonian heating is controlled by a dimensionless conjugate parameter, which varies between zero (insulated wall) and infinity (wall temperature remains constant). The important findings in this study are the variation of the surface temperature and heat flux from the stretching surface with the conjugate parameter and Prandtl number. It is found that these parameters have essential effects on the heat transfer characteristics.
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1. Introduction

The fluid dynamics due to a stretching sheet is important in extrusion processes. The production of sheeting material arises in a number of industrial manufacturing processes and includes both metal and polymer sheets like the cooling of an infinite metallic plate in a cooling bath, paper production, glass blowing, etc. The quality of the final product depends on the rate of heat transfer at the stretching surface. In view of these applications, Sakiadis (1961) first investigated the boundary layer flow on a continuous solid surface moving at constant speed. Due to the entrainment of the ambient fluid, this boundary layer flow is quite different from the Blasius flow past a flat plate. Sakiadis's theoretical predictions for Newtonian fluids were later corroborated experimentally by Tsou *et al.* (1967). Flow of a viscous fluid past a stretching sheet is a classical problem in fluid dynamics. Crane (1970) was the first who has studied the forced convection boundary layer flow over a stretching sheet. The heat and mass transfer on a stretching sheet with suction or blowing was investigated by Gupta and Gupta (1977). They considered the isothermal moving plate and obtained the temperature and concentration distribution. Chen and Char (1988) studied the laminar boundary layer flow and heat transfer from a linearly stretching, continuous sheet subjected to suction or blowing. Two cases are considered; moving plate with prescribed wall temperature and heat flux. This problem has been then extended to viscous fluids, viscoelastic fluids or micropolar fluids by many investigators (Elbashbeshy, 1988; Elbashbeshy and Bazid, 2004; Fan *et al.*, 1999; Hassanien *et al.*, 1998; Ishak *et al.*, 2007, 2008a,b; Mahapatra and Gupta, 2002; Na and Pop, 1997; Rollins and Vajravelu, 1991; Sahoo, 2010a,b) considering the boundary conditions that are usually applied are either constant wall temperature (CWT) or constant wall heat flux (CHF).

Merkin (1994) has shown that, in general, there are four common heating processes specifying the wall-to-ambient temperature distributions, namely, (i) constant or prescribed wall temperature; (ii) constant or prescribed surface heat flux; (iii) conjugate conditions, where heat is supplied through a bounding surface of finite thickness and finite heat capacity. The interface temperature is not known a priori but depends on the intrinsic properties of the system, namely the thermal conductivity of the fluid and solid; and (iv) Newtonian heating, where the heat transfer rate from the bounding surface with a finite heat capacity is proportional to the local surface temperature and which is usually termed conjugate convective flow.

Generally, in modelling the convection boundary layer flow problems, the boundary conditions that were usually applied are

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Nomenclature

a	positive constant
C_f	skin friction coefficient
f	dimensionless stream function
h_s	heat transfer parameter for Newtonian heating
k	thermal conductivity
Nu_x	local Nusselt number
Pr	Prandtl number
q_w	surface heat flux
Re_x	local Reynolds number
T	fluid temperature
T_w	surface temperature
T_∞	ambient temperature
u, v	velocity components along the x and y directions, respectively
$u_w(x)$	velocity of the stretching surface
x, y	Cartesian coordinates along the surface and normal to it, respectively

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
η	similarity variable
γ	conjugate parameter for Newtonian heating
μ	dynamic viscosity
ν	kinematic viscosity
ρ	fluid density
τ_w	surface shear stress
ψ	stream function
θ	dimensionless temperature

(i) and (ii). However, the Newtonian heating conditions (iv) have been used only quite recently by Lesnic *et al.* (1999, 2000, 2004) and Pop *et al.* (2000) to study the free convection boundary layer over vertical and horizontal surfaces as well as over a small inclined flat plate from the horizontal surface embedded in a porous medium. The asymptotic solution near the leading edge and the full numerical solution along the whole plate domain have been obtained numerically, whilst the asymptotic solution far downstream along the plate has been obtained analytically. Chaudhary and Jain (2006, 2007) studied the unsteady free convection boundary layer flow past an impulsively started vertical infinite flat plate with Newtonian heating. Recently, Salleh and Nazar (2010); Salleh *et al.* (2009); Salleh *et al.* (in press) studied the forced convection boundary layer flow at a forward stagnation point with Newtonian heating as well as the free and mixed convection boundary layer flow over a horizontal circular cylinder with Newtonian heating, respectively.

The situation with Newtonian heating arises in what are usually termed conjugate convective flows, where the heat is supplied to the convective fluid through a bounding surface with a finite heat capacity. This configuration occurs in many important engineering devices, for example in heat exchanger where the conduction in solid tube wall is greatly influenced by the convection in the fluid flowing over it. Further, for conjugate heat transfer around fins where the conduction within the fin and the convection in the fluid surrounding it must be simultaneously analyzed in order to obtain the vital design information and also in convection flows set up when the bounding surfaces absorb heat by solar radiation (Chaudhary and Jain, 2006, 2007). This results in the heat transfer rate through the surface being proportional to the local difference in the temperature with the ambient conditions. Recent demands in heat transfer engineering have requested researchers to develop various new types of heat transfer equipments with superior performance, especially compact and light-weight ones. Increasing the need for small-size units, focuses have been cast on the effects of the interaction between developments of the thermal boundary layers in both fluid streams, and of axial wall conduction, which usually affects the heat exchangers performance. Therefore, we conclude that the conventional assumption of the absence of interrelation between coupled conduction-convection effects is not always realistic, and this interrelation must be considered when evaluating the conjugate heat transfer processes in many practical engineering applications (Chaudhary and Jain, 2006, 2007). Since the early paper by Luikov *et al.* (1971) many contributions to the topic of conjugate heat transfer have been studied. Excellent reviews of the topics of conjugate heat transfer problems can be found in the books by Kimura *et al.* (1997) and Martynenko and Khramtsov (2005).

The aim of the present paper is to study the boundary layer flow and heat transfer over a stretching sheet with Newtonian heating (NH). The governing nonlinear partial differential equations are first transformed into ordinary differential equations and they are then solved numerically using the Keller-box method, an implicit finite-difference scheme. To the best of our knowledge, this problem has not been considered before, so that the reported results are new.

2. Problem formulation and equations

Consider the steady, laminar boundary layer flow and heat transfer of a viscous and incompressible fluid over a stretching sheet. In this two-dimensional model, rectangular Cartesian coordinates (x, y) are used, in which the x- and y-axes are taken as the coordinates parallel to the plate and normal to it, respectively, and the fluid occupies the region $y \geq 0$. Further, u and v are the velocity components along the x- and y- directions, respectively. The physical model and coordinate system of this problem is shown in Fig. 1. We assume that the wall is subjected to a Newtonian heating of the form proposed by Merkin (1994). Under the boundary layer approximations and neglecting the viscous dissipation in the energy equation, the basic equations are

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (1)$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2}, \quad (2)$$

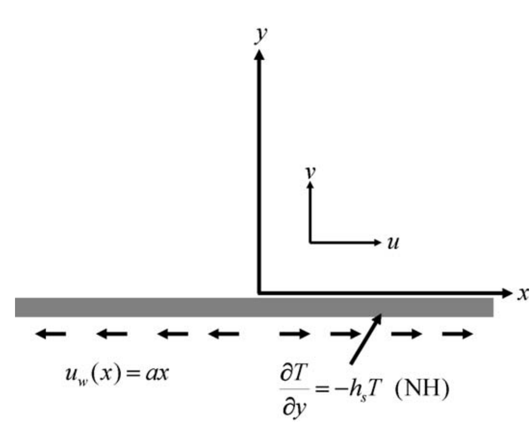

Fig. 1. Physical model and coordinate system.

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