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Effect of non-uniform slot injection (suction) on a forced flow over a slender cylinder

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Abstract

An analysis is performed to obtain the non-similar solution of a steady laminar forced convection boundary layer flow over a horizontal slender cylinder including the effect of non-uniform slot injection (suction). The effects of transverse curvature and viscous dissipation are also included in the analysis. The governing boundary layer equations along with the boundary conditions are first cast into a dimensionless form using suitable transformations and the resulting system of nonlinear coupled partial differential equations is then solved by an implicit finite difference scheme in combination with the quasilinearization technique. Numerical results for the effect of non-uniform slot injection (suction) on skin friction coefficient and heat transfer rate are presented. The effects of transverse curvature, viscous dissipation and Prandtl number on velocity and temperature profiles and skin friction and heat transfer coefficients are also reported.

1. Introduction

Flows over cylinder are usually consider to be two dimensional as long as the body radius is large compared to the boundary layer thickness. On the other hand for slender cylinder, the radius of the cylinder may be of the same order as that of the boundary layer thickness. Therefore, the flow may be consider as axisymmetric instead of two dimensional. In such a case, the governing equations contain the transverse curvature term which strongly influences the velocity and temperature fields and correspondingly the skin friction coefficient and heat transfer rate at the wall. Among the earlier studies, the magnitude of the transverse curvature effect has been investigated for isothermal laminar flows by Cebeci [1] and the results show that the local skin friction can be altered by an order of magnitude due to an appropriate change in the ratio of boundary layer thickness to cylinder radius. Further, Chen and Mucoglu [2] and Mucoglu and Chen [3] have investigated buoyancy effects on forced convection flow along vertical cylinder for uniform wall temperature and uniform heat flux conditions, respectively. Subsequently Bui and Cebeci [4], Wang and Kleinstreuer [5], and recently, Takhar et al. [6] have studied the combined effect of free and forced convection flows over vertical slender cylinder. It is therefore evident that the calculations of momentum and heat transfer on slender cylinders should consider the transverse curvature effect, especially in applications such as wire and fiber drawing, where accurate predictions are required and thick boundary layers can exist on slender or near-slender bodies.

In many cases of interest, mass transfer from a wall slot (i.e., mass transfer occurs in a small porus section of the body surface while there is no mass transfer in the remaining part of the body surface) into the boundary layer is of interest for various potential applications including thermal protection, energizing of the inner portion of boundary layer in adverse pressure gradient, and skin friction reduction on control

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Nomenclature

A	surface mass transfer parameter
C_f	local skin friction coefficient
C_p	specific heat at constant pressure
Ec	Eckert number
f, F	dimensionless stream function, velocity component
G	dimensionless temperature
k	thermal conductivity
Nu	local Nusselt number
Pr	Prandtl number
r	radial coordinate
Re_x	Reynolds number
r_0	radius of cylinder
T	temperature
u	axial velocity component
U	free stream velocity component
v	radial velocity component
x	axial coordinate
w^*	slot length parameter

Greek symbols

η	similarity variable
μ	dynamic viscosity
ν	kinematic viscosity
ξ	transverse curvature
ρ	density

Subscripts

w, ∞	conditions at the wall and infinity, respectively
ξ, η	denote the partial derivatives w.r.t. these variables, respectively

surfaces. In fact, mass transfer through a slot strongly influences the development of a boundary layer along a surface and different studies [7–9] show the effect of slot injection (suction) into a laminar compressible boundary layer over a flat plate by considering the interaction between the boundary layer and oncoming stream. Uniform mass transfer in a slot causes finite discontinuity at the leading and the trailing edges of the slot. The discontinuities can be avoided by choosing a non-uniform mass transfer distribution along a streamwise slot as has been discussed in Minkowycz et al. [10] and also in recent investigations by Roy [11] and Roy and Saikrishnan [12,13].

In the present analysis, the influence of non-uniform slot injection (suction) on a flow over a horizontal slender cylinder including the effects of transverse curvature, viscous dissipation and Prandtl number are considered. The present analysis may be useful in understanding many boundary layer flow problems of practical importance because the use of a slender body reduces the drag and even produces sufficient lift to support the body in certain situations. Further several transport processes with surface mass transfer i.e., injection (or suction) in industry where thermal diffusion caused by the temperature gradient such as polymer fiber coating or the coating of wires, etc. may have useful applications of the present study. In this investigation, the non-similar solutions have been obtained starting from the origin of streamwise coordinate using the quasi-linearization technique with an implicit finite difference scheme. There are two free parameters in this problem, one measures the length of the slot (i.e., the part of the body surface in which there is a mass transfer) and another parameter fixes the position of the slot. Thus, these two parameters help to vary the slot length and to move the slot location. It may be also noted that the finite discontinuities at the leading and trailing edges of the slot have been avoided following [10–13]. Thus, the present analysis differs from those in [7–9] with finite discontinuities.

2. Analysis

We consider the steady laminar forced convection flow over a horizontal slender cylinder of radius r_0 with non-uniform slot injection/suction. The flow is taken to be axisymmetric and Fig. 1 shows the coordinate system and the physical model. The blowing rate is assumed to be small and it does not affect the inviscid flow at the edge of the boundary layer. The effects of transverse curvature and viscous dissipation are also included in the analysis. The fluid at the edge of the boundary layer is maintained at a constant temperature T_∞ and the body has a uniform temperature T_w ($T_w >$ or $< T_\infty$, i.e., the cylinder is either heated or

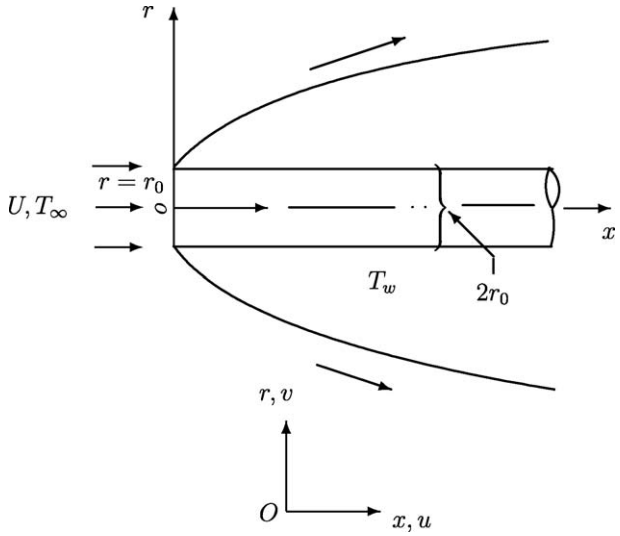

Fig. 1. Physical model and coordinate system.