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REVIEW

Free convection boundary layer flow of a viscous fluid above a hot horizontal semi-infinite flat plate with prescribed surface temperature

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Abstract The problem of steady two-dimensional free convection boundary layer flow of an incompressible viscous fluid above a hot horizontal semi-infinite flat plate is investigated for the case of power-law variation in the surface temperature. The analysis is extended to cover the whole range of the Prandtl number Pr values, and means of the values of Pr are taken from $Pr \to 0$ to $Pr \to \infty$. Further the analysis reveals a definite range of the wall temperature parameter s ($-0.5 < s < 2.0$) for which this flow problem will be valid. The asymptotic values of heat transfer and skin-friction coefficients are determined as a function of Pr for different values of s.

Contents

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1. Introduction

One of the most basic flows in fluid mechanics is the free convection boundary layer flow. This is observed in many heat transfer processes in nature. Flow and heat transfer aspects of this flow are of considerable interest in many engineering applications such as cooling of electronic equipments, heat transfer from refrigeration coils, heat loss from power transmission lines, heat transfer from human and animal bodies (see [1,2]). Following the pioneering work of Stewartson [3], various aspects of this flow problem have been investigated widely in theoretical, experimental and numerical grounds by the research community. Stewartson [3] studied the theoretical work on free convective heat transfer from a horizontal plate, and reported the existence of similarity solutions for a semi-infinite isothermal horizontal flat plate that is immersed in air. However, this analysis was affected by a sign mistake that led the author to an erroneous conclusion regarding the conditions for the existence of free convection boundary layer flow on a horizontal flat plate. Gill et al. [4] reconsidered the same problem and pointed out the Stewartson's conclusion that boundary solution exists only when the heated plate faces downwards is erroneous. They showed that boundary solution exists only when the heated plate faces upwards and constituted the correct solution to the problem. Theoretical work on a heated plate facing upwards (or a cooled one facing downwards) has been carried out by Rotem and Claassen [5] for free convective flows above an isothermal semi-infinite plate. They also presented the numerical results for some specific values of the Prandtl number and included the asymptotic cases for sufficiently large and small values of the Prandtl number. On the other hand, Kuiken [6] presented an analysis of free convection boundary layer by the method of matched asymptotic expansion for fluids with low Prandtl number.

Similarity theory for an isothermal horizontal plate is the most ready solution in the existing literature and is included in the book by Schlichting and Gersten [7]. Heat transfer solution was obtained by Ackroyd [8], who considered the flow paths, near a horizontal rectangular plate, to be parallel. Bandrowski and Rybski [9] investigated the analytical solutions of free convection mass transfer from horizontal plates. Numerical solutions of the governing mass, momentum and energy equations were obtained by Wei et al. [10], who considered the free convection from isothermal plates heated at both sides. Numerical and experimental works on heat transfer in laminar free convection above an upward facing heated horizontal plate which is placed in a semi-infinite medium were investigated by Pretot et al. [11]. A thermal boundary layer in which there is a mutual coupling between velocity and temperature via buoyancy, flows along the isothermal horizontal plate was investigated by Daniels [12]. Experimental work on free convection from horizontal heated surface has been investigated by many researchers. For the sake of brevity here we mention only a few works by Husar and Sparrow [13], Rotem and Claassen [5], Goldstein et al. [14], Kitamura and Kimura [15], Martorell et al. [16] and Kozanoglu and Lopez [17].

All the above investigations were carried out for an isothermal horizontal plate. But a large number of important practical and experimental free convection flows correspond to the cases where the surface dissipates heat non-uniformly rather than maintaining at constant temperature. Gebhart et al. [18] presented the generalized similarity equations for free convection boundary layer flow above a semi-infinite horizontal flat plate with power law variation in temperature. They presented the numerical results of dimensionless velocity and temperature profiles only for the case of an isothermal horizontal plate. These results are, however, the same with the corresponding results reported by Schlichting and Gersten [7]. Chen et al. [19] studied the effect of natural convection on horizontal, inclined and vertical plates for the cases where the plate is subjected to a variable surface temperature or heat flux. Wickern [20] investigated the natural convection flow above a horizontal plate subjected to uniform heat flux. On the other hand, the mass transfer effects on the free convection flow for an incompressible polar fluid under several physical conditions were analyzed by Patil [21], Patil and Hiremath [22], and Patil and Kulkarni [23,24].

It is worth remarking at this point that Samanta and Guha [25] have very recently represented the similarity solution for natural convection from a horizontal plate with variable heat flux or variable wall temperature. They showed the effect of the wall temperature parameter (starting from the value 0 to 100) on the skin friction and heat transfer coefficients. The results of their study are, however, of doubtful validity for the following reasons. For moderate values of s, $x^{*s} \to 0$ (in the limit) since $0 < x^* \leqslant 1$ and the temperature boundary condition viz. $T = T_w = T_\infty + Ax^{*s}$ at $\eta = 0$ tends to $T = T_w = T_\infty$, which is same as the boundary condition on temperature at $\eta \to \infty$. This phenomenon strongly suggests that the wall temperature parameter has a definite range, which is discussed in the respective section of the present analysis, for the validation of the present problem. Moreover, a sign mistake is found in the governing boundary layer Eq. (46) of their analysis.

The present paper is devoted to study the effects of the Prandtl number (starting from small to large values of Prandtl number) over a definite range of values of the wall temperature parameter on the velocity and temperature profiles as well as the skin friction and heat transfer coefficients of this flow dynamics. The concerning issue of constant surface temperature has been considered and compared our results with the corresponding results reported by Gill et al. [4], and Rotem and Claassen [5]. In this paper we would like to focus on the determination of the range of the wall temperature parameter and the asymptotic values of heat transfer and skin-friction coefficients as a function of Pr for different values of the wall temperature parameter within the prescribed range.

2. Mathematical formulation

We consider a semi-infinite horizontal flat plate in a viscous and incompressible fluid of ambient temperature T_∞. It is