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PERIODICALLY HEATED TURBULENT FLOW OVER A ROUGH SURFACE: CHARACTERISTICS OF THE ERROR IN ORIGIN

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INTRODUCTION

A classical means to enhance the transfer of heat at a wall is to use surfaces that are not smooth but rough. Then, depending on the geometry of the roughness elements, the transfer of heat can be altered at will. In fact, the problem of selecting surfaces that will furnish a determined heat transfer coefficient to a particular application is not a trivial one.

Most of the studies on flows over rough heated surfaces have dealt so far with steady conditions. The complexities caused by the roughness on the proper assessment of the flow properties are of such an order that inputting an extra condition of temperature unsteadiness redeems the problem solution formidable. That is one of the reasons why not many works on time dependent temperature boundary conditions are available in literature. The result is that, for the evaluation of properties related to the thermal boundary layer, the standard approach is to resort to some analogy between the momentum and the heat transfer processes defined by steady formulations of the problem. For example, the classical result Cf/2 = St, where Cf is the skin-friction coefficient and St is the Stanton number, is a very good working expression which has been used extensively in the past.

The purpose of this work is to investigate both the velocity and the temperature fields in boundary layers that develop over rough surfaces with periodic heating conditions. In this situation, it is not clear that a straight Reynolds analogy will work. Here we are especially interested in studying the validity of two universal relations, the law of the wall and the law of the wake, for both, the velocity and the temperature fields.

For flows over a rough surface, we know that Cf and St cannot be evaluated directly through methods that resort to the gradient of the log-law because the effective origin of the boundary layer is not known a priori. This prompted some authors to develop detailed procedures for the determination of this effective origin that could be used to evaluate Cf directly from the angular coefficient of a “corrected” law of the wall. In the present work, the behavior of the error in origin for the velocity and the temperature fields will be investigated for two types of rough surface: 1) a “K” type rough surfaces and, 2) a “D” type rough surfaces. Then, any analogy between the velocity and the temperature fields will be assessed.

EXPERIMENTAL PROCEDURE

The experiments were carried out in the high-turbulence wind tunnel located in the Laboratory of Turbulence Mechanics of PEM/COPPE/UFRJ. The tunnel is an open circuit tunnel with a test section of dimensions 67cm x 67cm x 10m. The test section can be fitted with surfaces having different types of roughness and of wall heating. Two types of rough surface were considered where the roughness elements consisted of equally spaced transversal rectangular slats. The wall surface was heated over periods ranging from 30 minutes to 1 hour, having its temperature raised to a maximum of 75 ^{o}C. The temperature was controlled by an electric circuit that provided a sine-like profile, 15 thermocouples set at five stream-wise stations at three span-wise positions were used to monitor the wall temperature. The measurements were performed for values of the free-stream velocity of 3.12 m/s; the free stream-level of turbulence was about 2%.

Mean velocity profiles and turbulence intensity levels were obtained using a DANTEC hot-wire system series 56N. The probes were of the type 55P15, 55P51, 55P76. A Pitot tube, an electronic manometer, and a computer controlled traverse gear were also used. The mean temperature profiles were obtained through a chromel-constantan micro-thermocouple. The uncertainty associated with the velocity and temperature measurements were: U = 0.064 m/s precision, 0 bias (P=0.95); T = 0.214 ^{o}C precision, 0 bias (P=0.99).

THEORY

To extend the classical formulation of the law of the wall and the law of the wake to the temperature turbulent boundary layer we used the theory of Avelino and Silva Freire[1]. Alternatively, we could have used dimensional arguments. The details of the theory will be omitted; here, it suffices to say that, from an asymptotic point of view, the important factor in the determination of the flow structure is the correct assessment of the order of magnitude of the fluctuating quantities. Then, analogies between the transfer of momentum and the transfer of heat can be constructed.

For flows over rough surfaces, the characteristic length scale for the near wall region must be the displacement in origin. Indeed, in this situation, the viscosity becomes irrelevant for the determination of the inner wall scale because the stress is transmitted by pressure forces in the wakes formed by the crests of the roughness elements. It is also clear that, if the roughness elements penetrate well into the fully turbulent region, then the displaced origin for both the velocity and the temperature profiles will always be located in the overlap fully turbulent region. The similarity in transfer processes for turbulent flows then suggests that expressions with the form of the classical expressions of the law of the wall and the law of the wake can be written for the temperature field.

RESULTS

The velocity error in origin was estimated according to the procedures of Perry and Joubert[2], of Perry et al.[3], of Thompson[4] and of Bandyopadhyay[5]. A straightforward extension of the method of Perry and Joubert[2] to the temperature profiles was made to evaluate the temperature error in origin. Twenty points were used to characterize the velocity and temperature inner layer profiles. That procedure allowed for a good determination of the error in origin in a span of time short enough to characterize an “instantaneous” measurement. At least three profiles were taken for every period.

For surfaces of type “D”, the error in origin for the temperature profiles were systematically found to attain much higher values than the error in origin for the velocity profiles. For surface “K”, however the calculated errors in origin are seen to approach asymptotically the same value.

Thus, it appears that for surfaces with a small aspect ratio roughness the error in origin for the velocity and the temperature profiles follow a different behaviour with the latter growing at a much faster rate. The conclusion is that a Reynolds analogy under this flow condition seems to fail. Indeed, an evaluation of Cf and of St through the turbulent fluxes at the wall shows that we can only use the gradient of the log-laws to determine St. The straightforward analogy (½ Cf) = St does not work anymore.

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