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EXPERIMENTAL DETERMINATION OF VELOCITY AND TEMPERATURE ROUGHNESS FUNCTIONS IN TURBULENT BOUNDARY LAYER FLOWS

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Abstract. *In the present work, turbulent transfer of momentum and heat over rough surfaces are described in terms of the roughness geometry using functions of the law of the wall for the velocity and for the temperature fields. The effects of sudden changes are predicted in the case of a turbulent flow around surface-mounted two-dimensional ribs when subjected to a sudden change in surface roughness. A particular interest of this study is to investigate temperature distributions in terms of velocity distributions. Three different surface roughness geometries were considered to simulate velocity and thermal boundary layer flows. The behavior of the displacement in origin for the velocity and the temperature fields is investigated. Wall functions that take into account characteristic parameters of the surface roughness are used to describe the behavior of the velocity and temperature profiles over different types of rough surfaces. Four configurations are simulated here, namely one extensive uniformly smooth surface, that is taken as a reference case, and three characteristic types of rough surfaces. In all the cases, the velocity boundary layer reaches a hot surface, where the thermal boundary layer flow initiates. Experimental measurements are presented for velocity and temperature profiles, for the different surfaces considered. The results show that for the roughness function, an analogy between the velocity and the thermal fields can be obtained.*

Keywords*experimental methods, boundary layer, turbulence, roughness, law of the wall*

1. Introduction

Turbulent flows are an effective mean of heat removal in engineering applications, however, the current level of knowledge in this field and the complexity of the process make it impossible to create a rigorous theory of turbulent heat transfer. Fluids with a low Prandtl number have relatively good heat transfer properties. Fluids with a mean or high Pr-number frequently require technical measures to improve the heat transfer. One method frequently used for this purpose, consists in artificially roughening the heat-transferring surface. Depending on the geometry of the rough elements, the transfer of heat can be controlled. In fact, the problem of selecting surfaces that will provide a required heat transfer coefficient is extremely important. This is precisely the reason why the number of studies concerned with this problem has increased during the recent years.

In the case of fluids with low thermal conductivity, most of the resistance to heat transfer is concentrated in a thin layer near to the wall, where it is difficult to conduct experimental measurements. The slightest errors in determining the transport mechanisms within the viscous layer and the fully turbulent region result in disagreement between analytical and experimental results. A complete understanding of the effects of a step change in surface roughness on the properties of a turbulent boundary layer has been the object of several experimental and theoretical investigations in recent years, particularly in cooling of electronics. Most electronic device configurations present sudden changes in roughness and temperature on the surface. When these conditions occur simultaneously, giving rise to complex flow configurations, a large number of parameters to describe the roughness is required.

In previous studies of flows over rough surfaces, different methods have been used to compose the roughness. The early studies have used sand grains glued onto a surface. The more recent studies have preferred to machine protrusions with a well-defined geometry. In the latter case, authors (see, e.g., Antonia and Krogstad(2000), Antonia and Luxton(1971), Wood and Antonia(1975), Perry and Joubert(1963)) have classified the rough surfaces into two distinct types of surfaces: 1) 'K' type rough surfaces and 2) 'D' type rough surfaces.

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In the cases where the nature of the roughness can be expressed with the help of a single length scale, the height of the protrusions, 'K', the surface is termed of 'K' type. Flows that are apparently insensitive to the characteristic scale 'K', but dependent on other global parameters of the flow are termed 'D' type roughness. This is the case when the roughness is geometrically characterized by closely spaced grooves where the flow generates stable vortical configurations within the grooves.

An important parameter in the velocity boundary layer, which determines the properties of the flow over rough surfaces, is the roughness function for the velocity, $\Delta u/u_\tau$, which can be determined from isothermal pressure drop measurements or from measurements of the velocity distribution, as we shall investigate in more detail in the next sections. Besides, an analogy with the temperature profile will be assessed, for the determination of the roughness function for the temperature, $\Delta t/t_\tau$, for the rectangular roughness.

Thus, the prop osal of this work is to investigate both the velocity and temperature fields of boundary layer flows that develop over surfaces with a sudden change in roughness, and particularly, obtain a characterization of the roughness function for both the velocity and temperature distributions.

One feature of the flows that develop over rough surfaces is the displacement in origin, also known in literature as error in origin. The displacement in origin behavior is also presented for the velocity and thermal boundary layers. In the problem to be studied here, a flow over a smooth surface is made to pass over a hot, rough surface. Therefore, for a certain length after the change in surface nature, the velocity and the thermal boundary layers will be in a different state of development. Here, turbulent transfer of momentum and heat over rough surfaces are described in terms of parameters of the roughness geometry using functions of the law of the wall.

For flows over rough surfaces, skin-friction coefficient C_f and Stanton number St cannot be evaluated directly through methods that assume the validity of a log-law for the effective origin at the wall is not known a priori. This prompted some authors (e.g., Perry and Joubert(1963), Perry et al.(1987) to develop detailed procedures for the determination of this effective origin, which could be used to evaluate C_f directly from the angular coefficient of a "corrected" law of the wall.

In this work, the behavior of the displacement in origin for the velocity and the temperature fields will be investigated for three types of rough surfaces. Then, an analogy between the velocity and the temperature fields will be obtained. To achieve this objective, the present work will investigate experimentally the characteristics of turbulent boundary layers that are subjected to a step change in surface roughness and temperature, with emphasis on the characterization of the velocity and temperature profiles in the fully turbulent region of the boundary layer.

2. Experimental Apparatus and Proceadure

Over the years, several studies on the behavior of boundary layers having a non-uniform distribution of temperature or heat flux at the wall were carried out. For flows over smooth walls, the works of Hartnett(1956), Johnson(1957, 1959), Reynolds(1958) and Spalding(1961) are classical. Johnson(1957) reports that for a thermal boundary layer with 4.27m of unheated starting length and a free stream velocity of 7.62m/s, measurements taken 1.83m downstream of the step point reveal that the normalized temperature profiles have shapes different from the normalized velocity profile. Also, the temperature intermittency profile has a different form than the velocity intermittency profile. Antonia et al.(1977) considered 1.83m of an unheated length, after which a constant surface heat flux was applied. He observed that after 1.8m of development the face heat flux was applied, the temperature profiles had not yet reached a fully development form.

For flows over rough surfaces, the number of studies is limited. Studies on flows over rough surfaces with changes in the thermal boundary conditions were made by Coleman et al.(1976) and by Ligrani et al.(1979, 1983,1985). With the help of a kernel function and the superposition of a heat transfer theory, expressions were advanced for the evaluation of Stanton number. This was supposed to hold for such different conditions as variable wall temperature, wall blowing, free-stream velocity, and steps in wall temperature and blowing.

The experiments were carried out in the high-turbulence wind tunnel which is an open circuit tunnel with a test section of dimensions 67cm x 67cm x 3m. The test section is divided into three sections of equal length, which can be fitted with surfaces having different types of roughness and of wall heating. The first section, which is normally kept at ambient temperature, consists of a smooth glass wall. The second and third parts of the test section are equipped with independent electric heaters.

The flow was subjected to a step change in roughness after travelling over a smooth surface. The roughness elements are consisted of equally spaced transversal rectangular slots. The dimensions of roughness elements are shown in Table 1 and Fig. 1, together with the definition of the coordinate system. For the roughness elements, K denotes the height, S the length, W the gap, and λ the pitch. In constructing the surface, extreme care was taken to keep the first roughness element always depressed below the smooth surface, its crest kept aligned with the smooth glass wall surface.

The glass surface was also followed by a sudden change in temperature. The test section had its wall temperature raised to 75 ± 5^oC. The wall temperature was controlled by 15 thermocouples, set at five stream wise stations at three span wise positions. Because the wind tunnel was an open circuit tunnel, the external environment affected controlling the temperature in the final of 0.2 meter.

Mean velocity profiles and turbulence intensity levels were obtained using a DANTEC hot-wire system series 56N. The boundary layer probe was of the type 55P15. A static pitot tube, an electronic manometer, and a computer controlled transverse gear were also used. In getting the data, 10,000 samples were considered. The profiles were constructed from about 100 points. The mean temperature profiles were obtained through a chromel-constantan thermocouples mounted on the same traverse gear system used for the hot-wire probe. An uncertainty analysis of the data was performed according to the procedure described in Kline(1985). Typically the uncertainty associated with the velocity and temperature measurements were: U=U±0.0391m/s precision, T=T±0.0058°C precision.

To obtain accurate measurements, the mean and fluctuating components of the analogical signal given by the anemometer were used. The mean velocity profiles were calculated directly from the untreated signal of channel one. The signal given by channel two was 1Hz high-pass filtered leaving, therefore, only the fluctuating velocity.

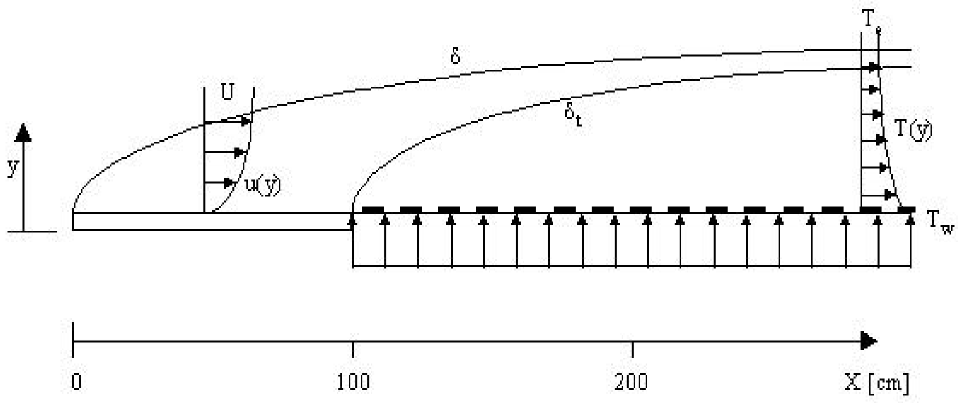

Figure 1. Figure of the test section.

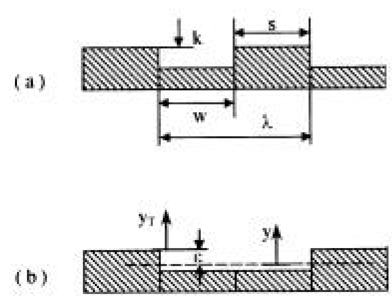

Figure 2. Geometry of the roughness elements and coordinate system.

Table 1. Geometry of the roughness elements.

	Surface Type I	Surface Type II	Surface Type III
K [mm]	4.77	4.77	6.35
W [mm]	15.88	31.76	15.88
S [mm]	15.88	15.88	4.76
λ[mm]	31.76	47.64	20.64
W / K	3.33	6.66	2.5

3. Theory

Before considering the experimental data, let us first introduce a short review of the theory of turbulent flow over rough surfaces. For this type of flow, Moore(1951) has shown that a universal expression can be written for the wall region by setting the origin for measuring the velocity profile some distance below the crest of the roughness elements. The displacement in origin is also referred to in literature as error in origin, $\in$. A detailed method to determine the displacement in origin can be found originally in Perry and Joubert(1963), and Perry et al.(1987). Thus, for any kind of rough surface, it is possible to write

$$\frac{u}{u_t} = \frac{1}{k} \ln \frac{(y_T + \in) u_t}{n} + A - \frac{\Delta u}{u_t} \tag{1}$$

where,

$$\frac{\Delta u}{u_t} = \frac{1}{k} \ln \frac{\in u_t}{n} + C_i \qquad (2)$$

and $\kappa = 0.4$, $A = 5.0$, and C_i, i=K,D; is a parameter characteristic of the roughness (see, e.g., Perry and Joubert(1963)).

Equations (1) and (2), although of universal character, have the inconvenience of needing two unknown parameters for their definition, namely the skin-friction velocity, u , and the displacement in origin, $\in$. A main concern of many works on the subject is, therefore, to characterize these two parameters. In fact, the fundamental concepts and ideas on the problem of a fluid flowing over a rough surface were first established by Nikuradse(1933), who investigated the flow in sand-roughened pipes. Even at that early age, Nikuradse was capable to establish that, at high Reynolds number, the near wall flow becomes independent of viscosity, being a function of the roughness scale, the pipe diameter and Reynolds number. He also found out that, for the defect layer, the universal laws apply to the bulk of the flow irrespective of the condition at the wall. The roughness effects are, therefore, restricted to a thin layer.

To extend Eqs. (1) and (2) to the temperature turbulent boundary layer, the theory of Silva Freire and Hirata(1990) is adopted. 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 the 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 crest 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 buffer layer. The similarity in transfer processes for turbulent flows then suggests that, Avelino(2000),

$$\frac{T_w - t}{t_t} = \frac{1}{k_t} \ln \left[\Pr \frac{(y_T + \in_t) u_t}{n} \right] + B - \frac{\Delta t}{t_t} \qquad (3)$$

where,

$$\frac{\Delta t}{t_t} = \frac{1}{k_t} \ln \left[\Pr \frac{\in_t u_t}{n} \right] + D_i \qquad (4)$$

and D_i, i=K,D; is a parameter characteristic of the roughness. Equations (3) and (4) are the law of the wall formulation for flows over rough surfaces with heat transfer. In the above equations all symbols have their classical meaning; C_i, i=K, D is a constant characteristic of the type of roughness; the coordinate y_T is the distance measured from the crest of the roughness elements ($y=y_T+\in$); $\in$ is the displacement in origin.

4. Experimental Results and Discussion

4.1. Velocity Profile Data

The measured velocity profiles for the three different flow configurations are shown in Figs.(3) to (5), in comparison with measured profiles for flow developing over smooth surface, which is adopted as the reference flow case. In Figs.(3) to (5), the dashed line is the classical law of the wall, with κ=0.4, and A=5.0, or the particular case of the Eq.(1) when $\Delta u/u_\tau=0$. It is seen that the experimental data agree with this analytical result for the smooth surface. The comparison between the profiles developed over the rough surfaces and the reference case furnishes the mathematical value of the velocity roughness functions, $\Delta u/u_\tau$.

It is known that for turbulent boundary layers developing over rough surfaces, the logarithmic regions of the flow suffer a slight deformation to the left side. In fact, as we shall see, a very popular method to find $\in$ is based on a procedure to restore the lower portion of the velocity profile to a logarithmic profile.

The displacement in origin, $\in$, was estimated by four different procedures. In fact, the procedures of Perry and Joubert(1963) and Perry et al.(1987) are the most rigorous that can be found in literature so that the data resulting from them must be seen as reliable. The procedures of Thompson(1978) and Bandyopadhyay(1987) are more simplified so that the values of $\in$ obtained through them must be seen just as a first approximation.

In Perry and Joubert(1963) method, arbitrary values of $\in$ are added to the wall distance measured from the top of the roughness elements and a straight line is fitted to the log-law region. The value of $\in$ that furnishes the logarithmic region is then considered to be the correct value for the displacement in origin. The method of Perry et al.(1987) is more sophisticated, resorting to a cross plot of $\in$ vs. $2\prod/\kappa$, where $\prod$ stands for Cole's wake profile.

Therefore, to determine the displacement in origin, the velocity profiles were plotted in semi-log form, in dimensional coordinates. Next, the normal distance from the wall was incremented by 0.1mm and a straight line fit was applied to the resulting points. Searching for the maximum coefficient of determination, the best fit was determined. Other statistical parameters were also observed, as the residual sum of squares and the residual mean square.

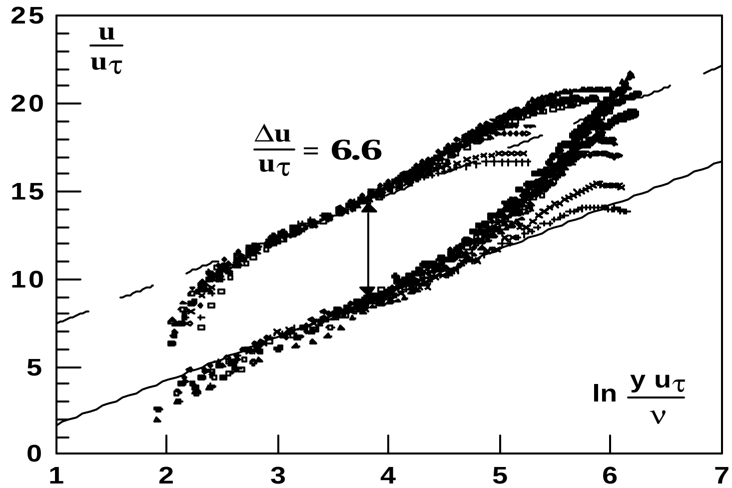

Figure 3. Velocity profiles for the flows over smooth and Type I rough surfaces.

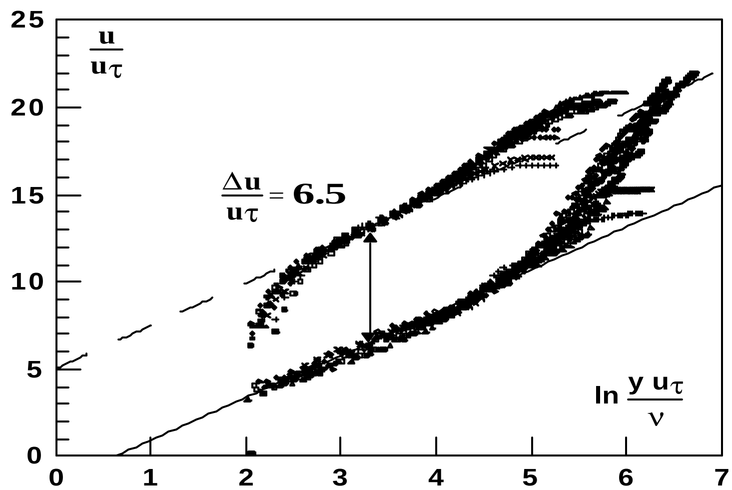

Figure 4. Velocity profiles for the flows over smooth and Type II rough surfaces.

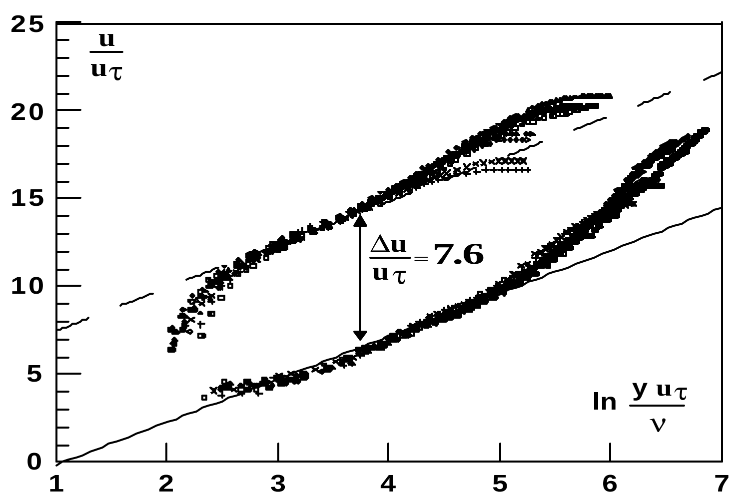

Figure 5. Velocity profiles for the flows over smooth and Type III rough surfaces.

Having found $\in$, the gradient of the log-law is used to determine u_τ. Another method to determine u_τ is the momentum-integral equation. The latter method, however, is very sensitive to any three-dimensionality of the flow and the determination of the derivatives of the various mean flow parameters is less accurate. The difficulty with the cited methods is that they depend on the evaluation of the derivatives. For flows subjected to step changes in surface roughness, the momentum-integral method further suffers from the ill definition of the boundary layer origin. The process of finding adequate parameters for the curve fitting is, therefore, increased.

The results for $\in$ in the rough surfaces types I, II and III, are presented in Figs. 8 to 10. Considering the high degree of difficulty involved in finding these results, and the good agreement between the predictions based on the two alternative procedures, the results of $\in$ and consequently for C_f are expected to be representative of the flow.

Figures 8 to 10 clearly show that $\in$ represents a relatively quick streamwise evolution for surfaces Types I and II, a fact that has been previously observed in 'K' type rough surfaces. The evolution of $\in$ on surface type III is observed to be rather slower and representative of a 'D' type surface. In Fig. 9, the value of $\in$ calculated through procedure suggested in Thompson(1978) furnishes $\in$=2.44.

4.2. Temperature Profile Data

Convective transfer of heat always involves transfer of momentum; therefore it is convenient to analyze temperature distributions on the basis of velocity distributions. Initially the temperature profiles were measured over a smooth surface in order to obtain a reference case, and to determine the temperature distributions in the law of the wall region. These results were then used to separately determine the displacement in origin and the temperature roughness function were investigated. Data from the original measurements of temperature profiles for the three different flow configurations are shown in Figs.(6) to (8).

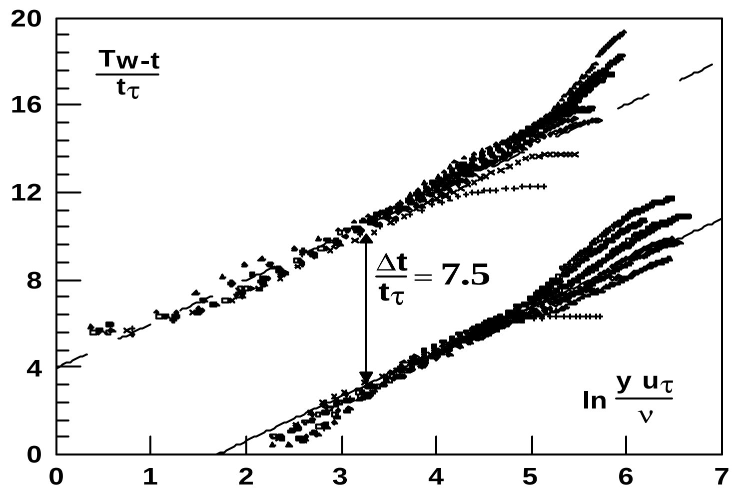

Figure 6. Temperature profiles for the flows over smooth and Type I rough surfaces.

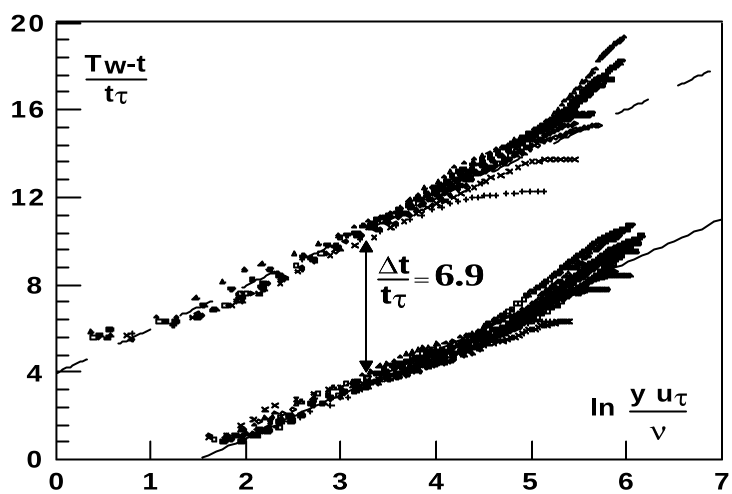

Figure 7. Temperature profiles for the flows over smooth and Type II rough surfaces.

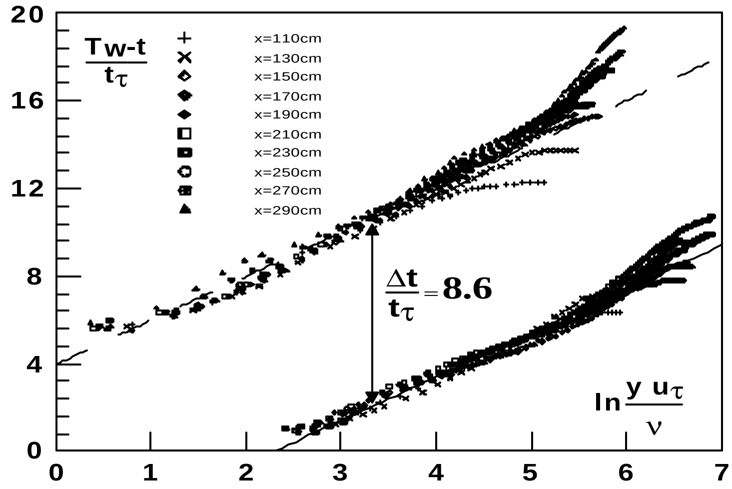

Figure 8. Temperature profiles for the flows over smooth and Type III rough surfaces.

According to similarity considerations with the velocity profiles, the temperature profiles are also observed to exhibit a shift to the left when compared with data for flows over smooth surface, Avelino and Silva Freire(2002). Since close to the point of change in surface nature the thermal boundary layer is still in its initial state of development, a logarithmic region cannot be clearly identified in the first stations. Concerning the shape of the temperature profiles at he edge of the boundary layer, in the majority of the measurements the thickness of the velocity and the thermal boundary layers coincide. Indeed, at low turbulence intensity this effect may be insignificant.

Figures (6) to (8) suggest that all the procedures advanced for the evaluation of $\in$ can be extended to the temperature profiles for the evaluation of $\in_t$. Thus, a straightforward extension of the method of Perry and Joubert(1963) to the temperature profiles can be made to evaluate $\in_t$. In the same way as for the velocity profiles, in Figs.(6) to (8), the dashed line is the temperature law of the wall according to Persius and Slanciauskas(1990).

It is seen the experimental data agree with this analytical result for the smooth surface. The comparison between the profiles developed over the rough surfaces and the reference case furnishes the mathematical value of temperature roughness functions, $\Delta t/t_\tau$. Figures (12) to (14) present the evaluated temperature error in origin for all types of surfaces considered.

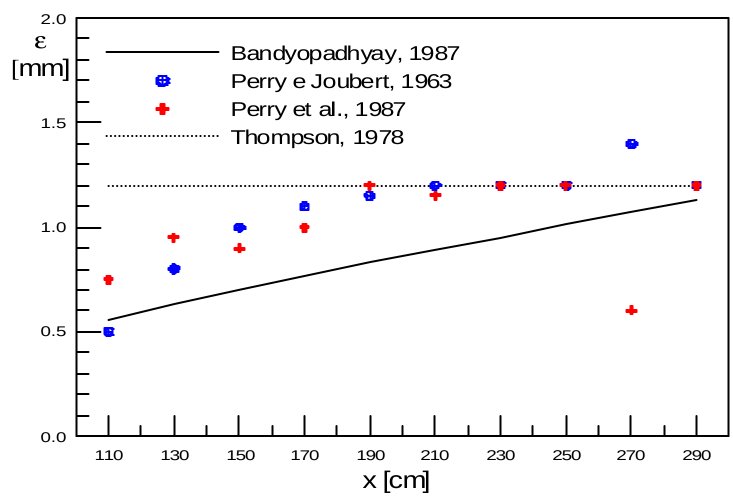

Figure 9. Displacement in origin for velocity profiles - Type I rough surface.

According to similarity considerations with the velocity profiles, the temperature profiles are also observed to exhibit a shift to the left when compared with data for flows over smooth surface. Since close to the point of change in surface nature the thermal boundary layer is still in its initial state of development, a logarithmic region cannot be clearly identified in the first stations. Concerning the shape of the temperature profiles at he edge of the boundary layer, in the majority of the measurements the thickness of the velocity and the thermal boundary layers coincide. Indeed, at low turbulence intensity this effect may be insignificant.

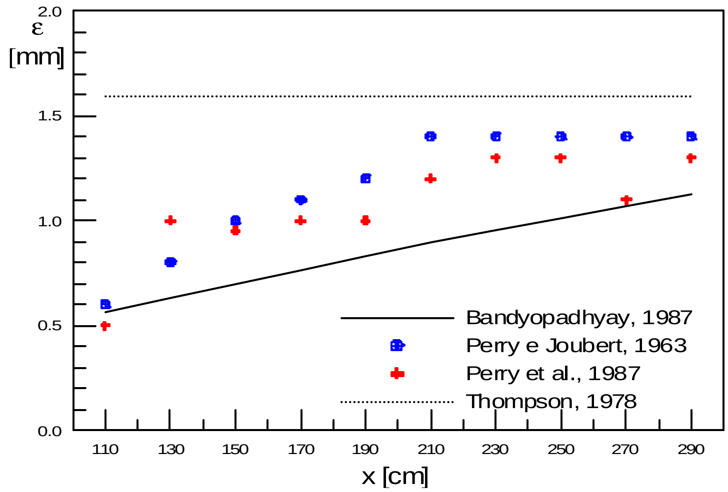

Figure 10. Displacement in origin for velocity profiles - Type II rough surface.

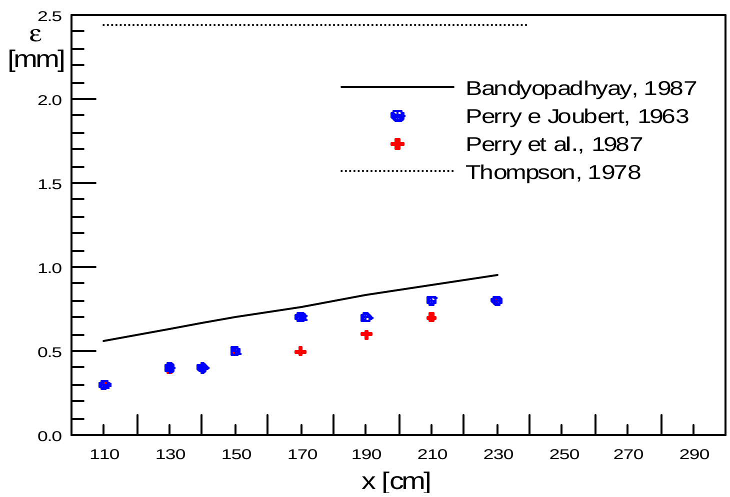

Figure 11. Displacement in origin for velocity profiles - Type III rough surface.

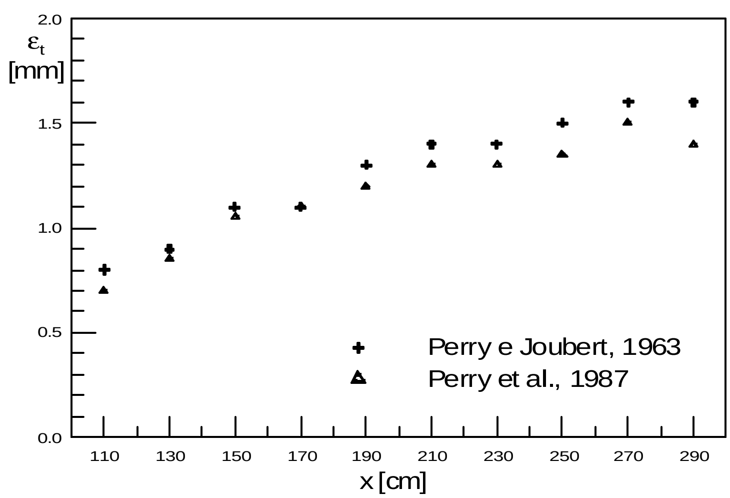

Figure 12. Displacement in origin for temperature profiles - Type I rough surface.

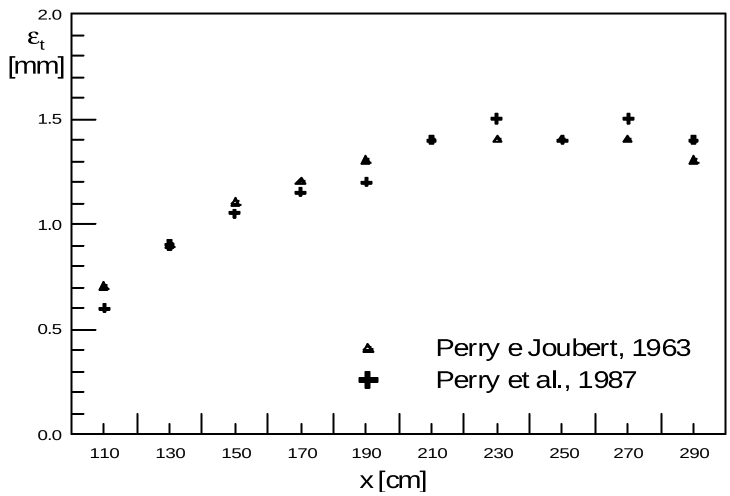

Figure 13. Displacement in origin for temperature profiles - Type II rough surface.

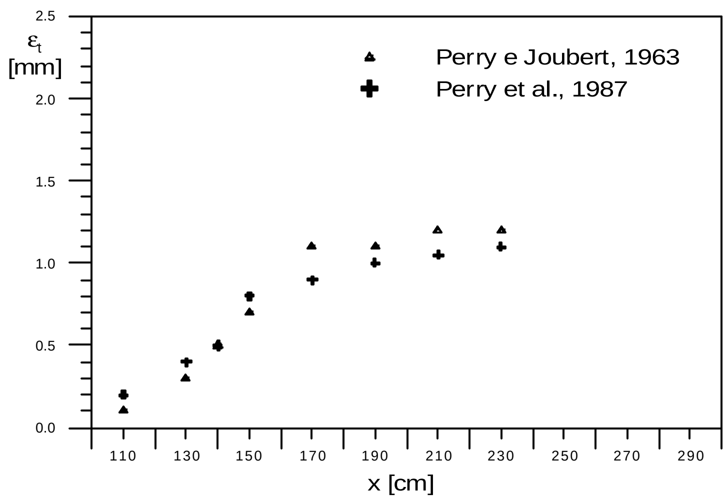

Figure 14. Displacement in origin for temperature profiles- Type III rough surface.

Figures (6) to (8) suggest that all the procedures advanced for the evaluation of $\in$ can be extended to the temperature profiles for the evaluation of $\in_t$. Thus, a straightforward extension of the method of Perry and Joubert(1963) to the temperature profiles can be made to evaluate $\in_t$. For temperature profiles, in the same way as for the velocity profiles, in Figs.(6) to (8), the dashed line is the temperature law of the wall according to Persius and Slanciauskas(1990).

It is seen the experimental data agree with this analytical result for the smooth surface. The comparison between the profiles developed over the rough surfaces and the reference case furnishes the mathematical value of temperature roughness functions, $\Delta t/t_\tau$. Figures (12) to (14) present the evaluated temperature error in origin for all types of surfaces considered.

Table 2. Behavior of displacement in origin and the roughness functions.

Type of Surface	$\in$ (mm)	$\in_t$(mm)	$\Delta u/u_\tau$	$\Delta t/t_\tau$
I	1.2	1.5	7.4	7.5
II	1.4	1.4	6.7	6.8
III	0.8	1.2	7.9	8.4

3. Concluding Remarks

It should be pointed out that a consistency between the wideness and highness ratio of the roughness element and the behavior of the roughness functions both for velocity and temperature distributions was found. The numerical values of $\Delta u/u_\tau$ and $\Delta t/t_\tau$ are summarized in TABLE 2 for the three types of roughness. Thus, as expected, the closer the rough elements are, lager is the numerical value of the roughness functions. Temperature roughness functions reached larger values at the temperature profiles.

For surfaces of type I and III, the displacement in origin for the temperature profiles were systematically found to attain much higher values than the displacement in origin for the velocity profiles. In fact, for the total length of the heated surface considered in this work, $\in$ and $\in_t$ approached different limiting values at the end of the test section. This is illustrated in TABLE 2.

For surface type II, however, where relation W/K>>3.0 holds, the calculated $\in$ and $\in_t$ are seen to approach asymptotically a same value; $\in \approx \in_t \approx 1.4$. Moreover, the experiments show that $\in_t$ grows at about the same rate of $\in$. Thus, the error in origin for the velocity and the temperature profiles follow a different behavior with $\in_t$ growing much faster rate. It must be pointed out that the velocity boundary layer is in a more advanced state of development then the thermal boundary layer in the first fetches of the rough-hot surface, which strongly influences the growth of the thermally developing flow, as observed in Ligrani(1985) and Avelino(2000).

The nature of the variation of the temperature profile that is a function of Pr is quite important. The effect of property variations on the velocity profiles for opposite directions of heat flux is different. This is also related to the nature of variation in the temperature profile. If air is heated by the plate, its viscosity and thus the Pr at the wall will increase. This results is a temperature variation that is more distributed over the entire boundary layer, more specifically, when Pr in the wall increases, the velocity profile, which is a function of Pr, extends…

The calculated values of $\in$ and $\in_t$ were obtained through the methods of Perry and Joubert(1963) and Perry et al.(1987). In the first method, by systematically adding an arbitrary value to the distance from the top of the roughness elements, a least square procedure was built to furnish the best-discriminated straight-line fit. The second method uses the universal wake profile of Coles and to a cross plot of $\in$ vs. $2\Pi/ê$.

In previous works, some authors (see, e.g., Guimaraes et al.(1999)) have expected, on asymptotic grounds, that the values of $\in$ and $\in_t$ would be very close. Here, we have shown that this appears to be the case for surfaces where W/K>>3.0, surfaces of type 'K'; for surfaces of type 'D' the results differ appreciably.

Determining of the displacement in origin has always been a difficult problem that has been focused by many authors. Here we have made a comparison between $\in$ and $\in_t$ for three different types of surfaces. Since the main objective of the work has been to assess the usefulness of equations 1 to 6, we have presented only mean velocity and temperature data.

In completion to the work of Guimaraes et al.(1999), this work has shown that a working relationship between the rates of growth for the displacement in origin for the velocity and the temperature profiles can be established. Evidence suggests that for surfaces of type 'K' both $\in$ and $\in_t$ growth at the same rate. For surfaces of type 'D' this does not seem to be the case.

3. Acknowledgement

The present work was financially supported by National Science Foundation of USA (NSF) and by Brazilian National Research Council (CNPq).

4. Nomenclature

- A Parameter in velocity law of the wall
- B Parameter in temperature law of the wall
- C_i Parameter in velocity law of the wall
- D_i Parameter in temperature law of the wall
- C_f Skin-friction coefficient
- Pr Prandtl number
- Re Reynolds number
- S Lenght of the roughness element
- u Axial velocity
- u_τ Friction velocity
- t Temperature
- t_τ Friction temperature
- T_w Wall temperature
- x Axial coordinate
- y_T Transverse coordinate with origin at the top of the roughness element.
- W Gap of the roughness element

Greek Letters

- $\in$ displacement in origin for the velocity profiles
- $\in_t$ displacement in origin for the temperature profiles
- ρ Fluid density
- λ Distance between leading edge of roughness elements
- ν Kinematic viscosity
- μ Dynamic viscosity
- κ von Kármán constant used in Eqs.
- κ_t von Kármán constant used in Eqs.
- t_w Wall shear stress

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