DETERMINATION OF SKIN FRICTION ON A ROUGH SURFACE

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Abstract: *The problem of the skin friction determination in a rough wall boundary layer under external turbulent flow is discussed in the paper.*

Introduction

The skin friction distribution is one of the most important characteristics of boundary layers. Its determination is a difficult task even if the surface is the smooth plane and only time mean values are required. The authors are investigating the joint effect of external turbulence and surface roughness on a flat-plate boundary layer development from the laminar state up to fully turbulent structure. They ascertained some gaps in the knowledge of the skin friction measuring methods in such complex conditions.

Analysis of mean velocity profiles

Generally, skin friction τ_w can be evaluated from the mean velocity profile $U(y)$ if a sufficiently large number of experimental points are available in the region attached to the surface $y = 0$, where the Newton's friction law can be applied

$$\tau_w = \mu \left(\frac{\partial U}{\partial y} \right)_w \qquad (1)$$

The linear interpolation allows determine not only skin friction, but also simultaneously the position of the "zero level" y'_0 (where $U(y'_0) = 0$). However in many applications this region (viscous sub-layer in a turbulent boundary layer) is too thin. Then the evaluation of skin friction can proceed with the interpolation of the measured profile or its segments with some universal/similarity profiles known for the investigated type of boundary layer; e.g. Blasius solution for a laminar flat plate boundary layer, logarithmic law and law of the wake in turbulent boundary layers. Generally different consequences are known on the individual action of the surface roughness and turbulence of the external flow on a boundary layer.

The surface roughness causes the shift of the position of the "zero level" y'_0 towards the level of roughness grains $y' = 0$ and simultaneously a downward shift the velocity profile. It is not difficult derive (e.g. Rotta, 1962) the validity of log-law also in the case with the surface roughness. Clauser (1954) and Hama (1954) found that the effect of surface roughness is restricted to the inner layer. The surface roughness causes a downward shift in the log law characterized by the roughness function Δu^+. It is customary write the log-law in the case of the so-called transient roughness in the form

$$u^+ = \frac{1}{\kappa} \ln y^+ + B - \Delta u^+; \quad u^+ = \frac{U}{u_\tau}; \quad y^+ = \frac{\rho y u_\tau}{\mu}; \quad y = y' - y'_0; \quad u_\tau = \sqrt{\frac{\tau_w}{\rho}} \qquad (2)$$

where $\kappa = 0.41$ and $B = 5$ are the von Kármán constant and the smooth wall log-law intercept. The function of the roughness, Δu^+, expresses the shift of the velocity semi-logarithmic plot below the shape in case of aerodynamically smooth surface. Once the roughness function was determined for the given surface it can be used for the friction loses calculations of any surface with the same roughness, Rotta (1972). The log-law deviates from the actual velocity profile for large values of y^+. Then the formula (2) does not hold above the inertial sub-layer. So the velocity defect is more appropriate

$$\frac{U_e - U(y)}{u_\tau} = -\frac{1}{\kappa} ln(\eta) + B_2\left(\frac{u_\tau}{U_e}\right); \quad \eta = \frac{y}{\delta} \tag{3}$$

Many experimental studies support outer layer similarity and universal velocity defect profile for smooth and rough surfaces. After Coles (1956), introducing the wake function $w(\eta)$ it is possible interpolate the profile in both the overlap region and the outer region by the formulae

$$u^+ = \frac{1}{\kappa}\ln y^+ + B - \Delta u^+ + \frac{\Pi}{\kappa} w(\eta) \tag{4}$$

where Π is the wake strength. The wake function, proposed by Coles (1956), has the form $w(\eta) = 2\sin^2\left(\frac{\pi}{2}\eta\right)$ (5)

Introducing the wake function the velocity defect law reads

$$u_e^+ - u^+ = -\frac{1}{\kappa} ln(\eta) + B' - \frac{\Pi}{\kappa} w(\eta) \tag{6}$$

From Clauser (1954) investigations results, that the approximation

$$u_e^+ - u^+ = -\frac{1}{\kappa} ln(\eta) + 2.5 \tag{7}$$

holds at $y/\delta > 0.15$ with a small scattering (e.g. Hinze, 1975 and Rotta, 1962). The formulaes (2) and (6) make possible the evaluation of the three unknowns $y_0', u_\tau, \Delta u^+$ in case of a turbulent boundary layer on rough surface under an external flow with very low turbulence level. According to Schultz and Flack (2007) many studies support a universal velocity defect profile for smooth and rough surfaces but some have reported that the wake strength Π is significantly higher for rough-wall case. It should be mentioned an uncertainty following from some papers reported that the wake strength Π significantly increases for rough-wall case (see e.g. Schultz and Flack, 2007).

The perturbation of a boundary layer on the hydraulically smooth surface by external turbulence depends on the state of the layer development. In brief, the mean velocity profiles remain unchanged beyond the indifference Reynolds number even though turbulent velocity fluctuations are presented (some times the layer is called *pseudo-laminar* layer). External turbulence accelerates the start of laminar-turbulent transition, shortens the transitional region and considerably influences the turbulent boundary layer. There the external turbulence does not affect the universal features of the mean flow in the inner region (e.g. Hancock, 1980) and its effect appears namely in thickening the layer and altering the velocity defect law in the outer layer. Hancock (1980) proved that the wake function depends on the external turbulence characteristics. He tested the Coles (1956) wake function and some other formulations but he did not found a satisfactory universal formulation for a wake function in an external turbulent flow.On the basis of presented knowledge the procedure has been developed that allowed to evaluate the skin friction coefficient distributions from the mean velocity profiles measured in flat plate (zero pressure gradient) boundary layers affected by the joint effect of the surface roughness and external turbulence. Details on the procedure and examples of results presented Jonáš (2008), Jonáš et al. (2009a, b, c).

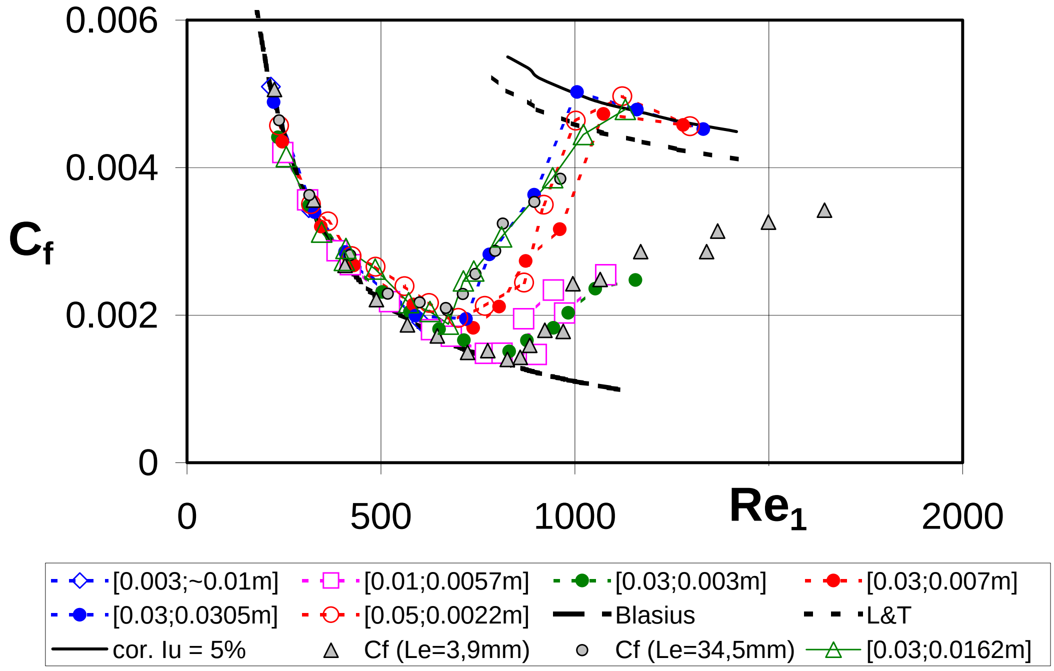

Figure 1 Distributions of skin friction coefficient in boundary layers on smooth surface under external turbulent flow

The lengthy measurement of velocity profiles can be shorten applying methods using devices e.g. Stanton tube, Preston tube, boundary layer fence, floating element balances, heated wall sensor, sublimation technique, liquid tracers etc. These measuring techniques are generally known with their advantages and deficiencies for the skin friction measurement on a smooth surface. An exhaustive review of them was made by Winter (1977). It is important to note that each of these methods must be calibrated and they are mostly derived for the use in well-developed turbulent layers. Next, their use is generally limited to single points on the surface and for time averaged measurements. It is evident, that apply the mentioned devices for the measurements on a rough surface is not promising in particular that a method producing instantaneous values of a signal proportional to skin friction is also desirable. Several examples demonstrate the contribution to understanding the flow physics on the bases of various analyses of the skin friction time series e.g. Jonáš et al. (1999, 2006 and 2009).

Figures 1 and 2 illustrate results of the skin friction evaluation from the mean velocity profiles measured by a miniature flattened Pitot tube. The values of turbulence intensity and dissipation length parameter are presented in square brackets [Iu_e, L_e].

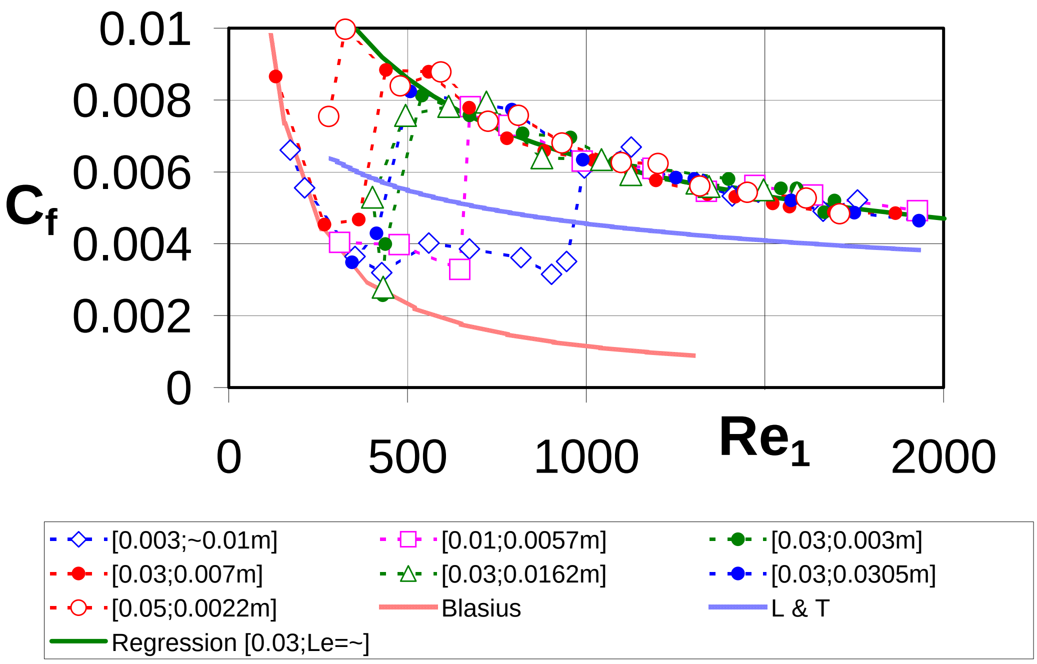

Figure 2 Distributions of skin friction coefficient in boundary layers on rough surface (grids 80) under external turbulent flow

Device with wall proximity wires

Heated wall sensors have a fast dynamical response and they can be readily adapted to moving along the smooth surface. Good experiences in the IT CAS are with a set up composed of a hot film/wire glued to a thin steel foil that is dragged in the stream wise direction on a smooth surface. Repeated friction sliding would disrupt the distribution of grains on the rough surface. Hence a device with wheels has been developed incorporated with the x-y traversing system (Figure 3).

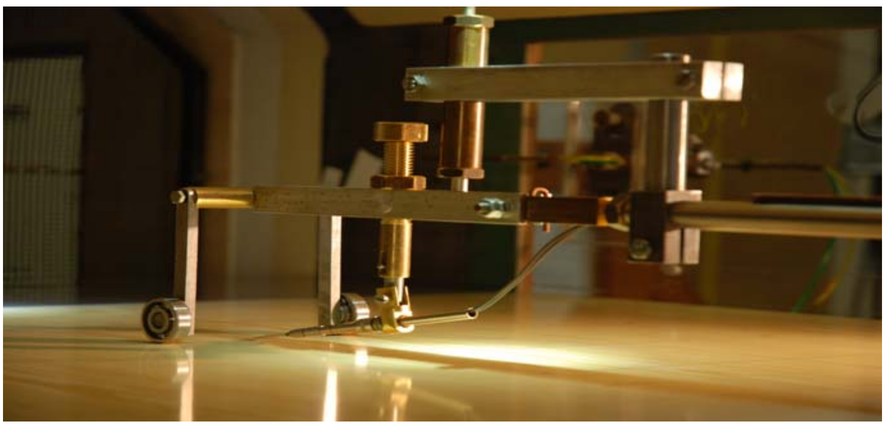

Figure 3 HW probe moving in wall proximity

This device is carrying the probe with two heated wires parallel mutually and as has been expected parallel with the surface (DANTEC t. 55P71). The distance between wires is $\Delta y = 0.36\ \mathrm{mm}$ and the wire close to the surface is in the distance y_1 that can be adjusted from $y_1 \approx 0.10\ \mathrm{mm}$ up to few millimetres.

Calibration of both heated wires was made in the velocity region from about 0.5 m/s up to 14 m/s and in the interval of the working temperature from 373 K up to 473 K in an external low turbulence flow. The equal working temperatures of wires were adjusted in the course of calibration and during the actual measurements (T_w = 423 K). It is believed that thus the interactions between both wires were included into calibration. The calibration and measurements were evaluated using the well known generalised Collis and Williams hot-wire cooling law (the customary nomenclature is introduced)

$$Nu\left(T_m/T\right)^{M_i} = A_i + B_i\, Re_w^{N_i} \tag{8}$$

with empirical parameters A_i, B_i, M_i and N_i ; $i = 1,2$. the subscript 1 belongs to the wire closer to the surface. The wall proximity corrections must be applied on the HW readings, as the probe is moving in a close proximity along the surface. This correction was done by means of the modified procedure proposed by Wills (1962)

$$U_i = U_i'\left(1 - N_i \Delta_i\left(y, Re_w\right)/\,0.45\right)^{1/N_i}\ ;\ \Delta_i = G_i\left(Re_w\right)_i^{-0.45} exp\left(-0.217\left(\frac{2y_i}{d_w}\right)^{0.63}\right) \tag{9}$$

here U_i' represents the mean flow velocity evaluated from the cooling law and U_i denotes the corrected mean flow velocity. The local differences in the heat convection into wall are considered by means of parameters G_1 and G_2. The values $G_i = 1 \pm 0.2$ were estimated at experiments described in papers e.g. Jonáš et al. (1999) and (2000). Reynolds number is defined with the fluid physical features taken at the film temperature $T_m = \left(T_w + T\right)/2$

$$Re_w = \frac{d_w \rho\left(P, T_m\right) U'}{\mu\left(T_m\right)} \tag{10}$$

In principle, the implementation of the assumptions, i.e. coordinates of the wires, y_i, are sufficiently low, the wires spacing, $\Delta y = y_2 - y_1$, is determined with a high accuracy and the wall proximity correction (9) works perfectly, allows directly calculate skin friction τ_w and a possible shift of the zero level y_0

$$\tau_w = \mu\left(T\right)\left(\frac{\partial U}{\partial y}\right)_w = \mu\left(T\right)\frac{U_2 - U_1}{\Delta y};\quad y_0 = \frac{\Delta y U_1}{U_2 - U_1} - y_1 \tag{11}$$

In reality, an additional calibration of skin friction is necessary as the correction (9) is not exactly known ($G_i = ?$) and the shift y_0 was changed with moving the probe stream wise, in x direction, as has been observed.

So far the calibration was made at boundary conditions corresponding to one of COST/ERCOFTAC Test Case T3A+ namely the boundary layer on a smooth plate in grid turbulence with characteristics in the leading edge plane: the intensity Iu_e = 3% and the dissipation length parameter L_e = 5.9 mm. Details on original measurements and the determined C_f – distribution are presented in Jonáš et al (2000). The C_f – distribution was interpolated in parts as the function of the local Reynolds number

$$Re_x = \frac{\rho x U_e}{\mu} \tag{12}$$

The comparison of Test Case measurement and interpolation is shown in Figure 4. The green circles were determined at boundary conditions identical to conditions during the calibration.

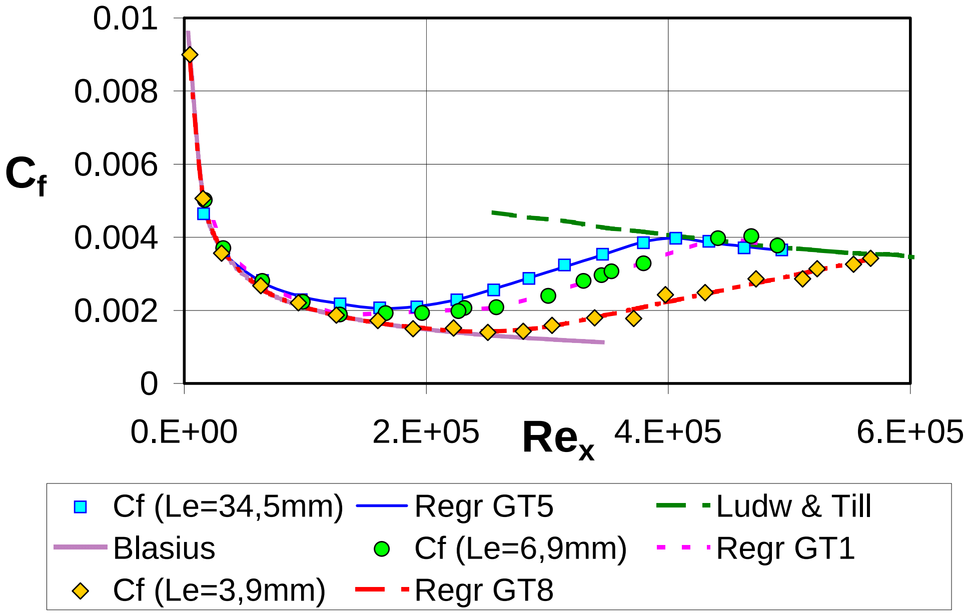

Figure 4 Distributions of skin friction coefficient in boundary layers (grad P = 0) under external grid turbulence flows with the intensity of velocity fluctuations Iu_e = 3% at the onset of the layer x=0

The calibration of the device in development proceeded by calculation of

$$Re_x \rightarrow C_f\left(x\right) \rightarrow \tau_w\left(x\right) = 0.5\rho U_e^2 C_f \tag{13}$$

at all locations x where the velocities U_1' and U_2' were measured. Then the values of G_i and y_0 must be found necessary to accomplish the relations (11).

So far it was found that the distance from the surface y_0 of the couple of probes is changing during the movement with the coordinate x. The alterations of y_0 are between the limits about 0.15 mm up to 0.35 mm and they depend on the position of the manipulator. Owing to this a reconstruction of the described device is in the development. However it must be mentioned, that regardless of varying distance y_0 some signal statistic e.g. intermittency can be evaluated (Hladík et al., 2009).

Conclusions

So far, under the joint effect of external turbulence and surface roughness, we are able determine skin friction distribution only from carefully made measurement of the mean velocity profiles in a flat-plate boundary layer developing from the laminar state up to fully turbulent structure.

With the aim make more effective this experimental investigations a device with wheels has been developed incorporated with the x-y traversing systém. The first experiences were received with the probe calibration and evaluation of quantitative results. Time series of the output signal recorded at various boundary conditions (surface roughness and external turbulence) are preliminary indicating the good applicability of this device for qualitative analyses. An improvement of the device is in the development.

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