By-passe transition of flat plate boundary layers on
the surfaces near the limit of admissible roughness

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Abstract.
Results of the experimental investigation on the development of boundary layers on flat plates with the smooth surface and with the surfaces covered by sandpapers 60-grit, 80-grit and 100-grit under external turbulent flows of various grid turbulence scales are presented. The displacement thickness Reynolds number was at the most 2000 during experiments. The investigated boundary layers belong to the class of layers close to the lower limit of admissible roughness region, $k^+ = 4.6, 5.7$ and 8.7 respectively. It was certified that both the wall roughness and the free stream turbulence accelerate individually the boundary layer development from the laminar state of boundary layer to turbulence. Next it was ascertained that their joint effect amplifies the development of boundary layers so, that the surface roughness impact is predominating but the actions of intensity and length scale of the free stream turbulence disturbances are also significant. With the increasing roughness number the initial region with a pseudo-laminar flow structure and the transitional region become shorter.

1. Introduction

The flows over rough surfaces occur very often in engineering applications, environmental studies and geophysics. The incoming flow is frequently disturbed by turbulence and/or by some vortical structures. Therefore a deeper understanding of the individual effects and the joint impact of the wall roughness (WR) and the free stream turbulence (FST) on boundary layer may be important in natural science and technical areas.

The effect of surface roughness on the flow behavior and its action on bodies was closely investigated already by Nikuradse (1933) and the rough-wall boundary layers are still interesting for the researchers e.g. Antonia & Krogstad (2000), Bergstrom, Kotey & Tachie (2002), Bernard & Wallace (2002), Jimnez (2004), Pope (2000), Raupach, Antonia & Rajagopalan (2000), Schultz & Myers (2003) and Schultz & Flack (2007). Mainly the properties of turbulent boundary layer are examined. Problem of a laminar boundary layer on a rough surface drew minor attention e.g. Kendall (1990), who mentioned that the flow over rough surface is merely displaced outward from the plane to which the roughness grains are pasted. Gibbins & Al-Shukri (1996) and Gibbins & Al-Shukri (1997) published an experimental study of the combined influence of a sandpaper rough surface and FST to the laminar boundary layer. A notion on the flow structure at a rough surface assumes local flow separations - wakes composed of counter-rotating vortex pairs arising on roughness grains attached to the basic surface. These separations cause local pressure distributions, resulting on the one hand in local form drags which act as a part of
tangential forces exerted on the surface together with the viscous wall shear stress and on the other hand they produce roughness sublayer. Vortices with a length scale proportional to the roughness length scale \( k \) are shed into the flow above the crests of the grains. Further away from the crests, the roughness sublayer structure blends smoothly into the flow. Apparently these vortices are suppressed by viscosity at very low local Reynolds number \( Re_x \) and they accelerate laminar-turbulent transition process with the increasing \( Re_x \). The sole action of the effect of WR appears in an acceleration of the laminar turbulent transition i.e. under otherwise equal conditions, the transition occurs at smaller distance from the onset of boundary layer for a rough surface than for a smooth one. A great ratio of the wall roughness to the boundary layer thickness can suppress the value of the critical Reynolds number up to one tenth of that for a smooth wall (e.g. Schlichting & Gersten (2000)) and thus dramatically shorten the piece of laminar boundary layer occurrence.

Usually two types of roughness are distinguished namely the \( k \)-type and the \( d \)-type of roughness. This classification judges the impacts of different shapes of roughness on turbulent boundary layer. The \( k \)-type corresponds with concept of Nikuradse (1933) and Clauser (1954) explained by Rotta (1962). They introduced broadly accepted classification of surfaces: hydraulically smooth, transient rough and fully rough that are distinguish by the ratio of roughness grains dimension to the viscous length scale. Numerous experiments confirm the validity of the velocity similarity laws (the law of the wall and the velocity defect law) also in rough wall layers. The WR causes a shift \( \varepsilon \) of the mean velocity zero level below the plane of the crests of the roughness elements. Next WR produce a downward shift in the log-law valid in canonical turbulent boundary layers on smooth surface. The roughness function \( \Delta u^+ \) was introduced into the log-law as to describe this shift. Once the function of the roughness \( \Delta u^+ \) is known for the given surface it can be used for the friction loses calculations of any surface with the same sort of roughness. Further certain experimental evidence indicates departures of the velocity defect law with the wake function proposed by Coles (1956), when applied in a rough wall boundary layer e.g. Perry, Lim & Henbest (1987) and Krogstad, Antonia. & Browne (1992). Bradshaw (1985) attributed the observed overestimates of the friction velocity to the underestimated value of the strength of the wake implied in Coles approximation.

The effect of free stream turbulence (FST) on boundary layer namely on laminar-turbulent transition is continuously studied since the Second World War time e.g. Schubauer & Skramstad (1943-48), Schubauer & Klebanoff (1955). Plenty of contributions deal with this problem up to now, e.g. Brandt, Schlatter & Henningson (2004), Fransson, Matsubara & Alfredsson (2005), Hernon, Walsh & McEligot (2007), Johnson & Fashifar (1994), Jonáš, Mazur & Uruba (2000), Morkovin (1969), Morkovin (1993), Savill (1995). The effect of turbulent velocity fluctuations intensity is investigated predominantly. Subsequent research also clearly proved the effect of the turbulence length scale \( L \) on by-pass transition, e.g. Jonáš, Mazur & Uruba (2000), Roach & Brierley (2000) and Brandt, Schlatter & Henningson (2004). It has been shown that the same location of by-pass-transition start can be induced by a proper adjustment of turbulence intensity keeping the given length scale and vice versa.

Investigations of the effect of FST on turbulent boundary layer were very favoured in seventies and eighties of 20th century, e.g. Castro (1984), Charnay, Mathieu & Comte-Bellot (1976), Dyban & Epik (1985), Hancock (1980), Hancock & Bradshaw (1983), Hancock & Bradshaw (1989), Huffman, Zimmerman & Bennet (1972), Jonáš (1992), Meier & Kreplin (1980). This problem is still investigated with meaningful results, e.g. Thole & Bogard (1996), Volino (1998). Current investigations question the notion that turbulent diffusion is the primary mechanism and suggest a direct link between FST and boundary layer fluctuations.

The effect of the FST on any boundary layer is significant. It induces both the beneficial and undesirable actions e.g. postpone of flow separation, increase of the wall friction, intensification of heat exchange, acceleration of transition of the laminar boundary layer to turbulence etc. The
main mechanisms by whose FST influences turbulent boundary layer are turbulent diffusion, the entrainment of fluid particles from the external stream and penetrating of turbulent disturbances in the layer. Jonáš (1992) presented a broader discussion of this effect. Numerous experiments confirm the validity of the velocity similarity laws (the law of the wall and the velocity defect law) also in boundary layers under FST. Similarly as in the case of rough wall boundary layers the velocity defect law with the Coles wake function is not well appropriate. The wake function in boundary layers on smooth surfaces in FST display a strong dependence on the FST scales, e.g. Hancock (1980).

As follows from the introductory considerations, the problem of joint action of surface roughness and external turbulence on the boundary layer development is very extensive. The effect on laminar turbulent transition deserves a special attention. The particular relevance of the transition problem is in changes of skin friction and heat transfer caused by increased momentum and scalar diffusion after the transition. The mechanism of how originally laminar boundary layer is forced by disturbances penetrating into the layer from environment and of the corresponding routes to turbulent layer were described elsewhere (e.g. Jonáš (1997). The opinion generally accepted is that the final phase of boundary layer laminar/turbulent transition starts with the occurrence of first turbulent spots regardless of the initial conditions. The turbulent spots followed by calmed regions are defined structures that dominate the last stage of transition. Spots production affects the length of transition region, e.g. Narasimha (1985). The turbulent spots creation rate, growth characteristics and their merging lead to fully developed turbulent flow. Boundary layer transition has many faces (e.g. Morkovin (1969)) that are why turbulent spots with associated calmed regions somewhat change with the initial and boundary conditions. Causal connections of the FST intensity, length scale, surface roughness and by-pass transition are not yet formulated. The preliminary investigation of turbulent spots during by-pass transition on smooth wall (Jonáš, Elsner, Mazur, Uruba & Wysocki, 2009), was an attempt to contribute to physical insight into the role of FST scales.

The paper concerns only the narrow part of the complex effects cause by FST and WR. The aim of this study is to compare consequences of the individual and joint actions of the sandpaper roughness and grid turbulence on the development, particularly by-pass transition, of the zero pressure gradient boundary layer at weak k-type transient roughness and at low Reynolds number.

2. Experimental facility

Experiments were performed in the close circuit wind tunnel of the Institute of Thermomechanics, Academy of Sciences of the Czech Republic in Prague. The working section is 2.69m in length, 0.9m in width and 0.5m high. The investigated boundary layers were developing either on an aerodynamically smooth plate (2.75m long and 0.9m wide) or on plates covered by sandpaper. In the Fig. 1, the scheme of the test section is shown and the orthogonal co-ordinate system \((x, y, z)\) is introduced.

![Figure 1. Working section of the close circuit wind tunnel of the Institute of Thermomechanics AS CR, Praha.](image-url)
The smooth plate was made from a laminated wood-chip board 25\textit{mm} thick but with very thin (2\textit{mm}) duralumin leading edge with the shape developed for stability and transition studies by Kosorygin, Levchenko & Polyakov (1982). The circulation around the plate is removed by means of the full span deflected flap and a screen across the flow far downstream the leading edge. Owing to this and due to fine adjusting the angle of attack of the plate, the free stream velocity is constant and equal to the value \( U_e \) in the leading edge plane \( x = 0 \) (within the measuring accuracy \( \sim 0.5\% \)) until \( x = 1.6m \); farther downstream (the part is located in diffuser) the free stream velocity decreases to 0.96\( U_e \) at \( x \approx 2m \).

Sand papers of different roughness, grits 60, 80 and 100 respectively, cover three rough plates made from thin plywood (7\textit{mm} thick), which are individually placed on the smooth plate. The leading edges of every rough plate are of the same elliptic shape (\( a \times b = 60\text{mm} \times 20\text{mm} \)) and they cover the primary leading edge. The narrow adhesive belt (10\textit{mm} width) makes stronger the adhesive attachment to the leading edge, so the boundary layer starts on the short piece of smooth surface. The maximum size of grains on sandpaper was chosen as the representative length of the sand paper roughness \( s \). (The label \( k \) reserved for the corresponding length of the sand grain type of roughness.) It was repeatedly measured by means of a micrometer and then averaged with the results:

- grits 60: \( s = (0.435 \pm 0.014)\text{mm} \);
- grits 80: \( s = (0.343 \pm 0.009)\text{mm} \);
- grits 100: \( s = (0.215 \pm 0.007)\text{mm} \).

Boundary conditions for the investigated boundary layers on the smooth surface were set up experimentally to fulfill the requirements: the constant mean velocity of external flow \( U_e \) in the stream wise direction (complied within the measuring accuracy \( \pm 0.5\% \)) and the two-dimensionality of the incoming flow (checked near the leading edge in the region \( z = \pm 0.25m \)). The mean velocity of external flow \( U_e \) was between 5.1\textit{m/s} up to 5.3\textit{m/s} during the whole period of the presented experiments. But the value of \( U_e \) was constant within the measuring accuracy (\( \sim 0.5\% \)) during every mean velocity profile measurement.

Free stream turbulence (FST) was either natural (indicated as No GT) or produced by means of square mesh (\( M \)) plane grids/screens with cylindrical rods (\( d \)). Grid placed in the plane \( x = x_{GT} \) generates homogeneous and close to isotropy turbulence. The intensity \( I_{u_e} \) and the dissipation length parameter \( L_e \) (Hancock & Bradshaw, 1989) characterize the fundamental features of the grid turbulence

\[ I_{u_e} = \sqrt{\left( \frac{\langle u^2 \rangle_e}{U_e} \right)}; \quad L_e = \frac{-\left( \langle u^2 \rangle_e \right)^{3/2}}{U_e \left( \frac{d(u^2)}{dx} \right)_e}, \]  

where \( U_e \) and \( u \) are the mean velocity of external stream and the longitudinal component of velocity fluctuations. Subscript \( e \) attached to any quantity denotes value valid in the leading edge plane \( x = 0 \). The decay law with empirically determined parameters describes the evolution of the velocity turbulent fluctuations

\[ I_{u_e}^{-2} = C \left( \frac{x}{M} - x_{GT} \frac{x_{GT}}{M} - x_0 \frac{x_0}{M} \right)^m, \]  

where \( x = 0 \) and \( x = x_{GT} < 0 \) are the plane of the plate’s leading edge and the plane with the inserted grid. Important characteristics of FST in the course of experiments are shown in Table 1. For more details of the experimental set up and turbulence generators see e.g. Jonaš (1989) and Jonaš, Mazur & Uruba (2000).

A part of experiments with the smooth surface was executed within the scope of the COST/ERCOFTAC Test Case T3A+ already before 2000 (Jonaš, Mazur & Uruba, 2000). The CTA measuring technique was employed for measurement of the mean velocity and its
fluctuations profiles in boundary layers on smooth surface. Two single wire probes working simultaneously were applied in the following way. The first probe, placed in a fixed reference position in the free stream \(x_r\), indicates the signal corresponding to the reference velocity \(U(t, x_r) \approx U_e\) proportional to the mean velocity \(U_e \approx 5m/s\) of external stream. The second probe, the profile probe, is put into position \([x, y, z = 0]\) by the traversing system. The distance \(y\) from the wall of the profile HW-probe is determined from the distance between the wire and its image in the smooth surface. This distance is measured by the cathetometer with the precision 0.01\(mm\). Digital records of the output signals (25kHZ, 750000 samples, 16 bit) are acquired simultaneously and then records of the relevant instantaneous velocities are evaluated using data from the calibration measurements performed prior to the experiment. Finally, the correction of the wall proximity effect on hot-wire cooling has to apply. The linear regression of the mean velocity close to the wall was received within this correction. The instantaneous wall friction time series records are the conclusion of the evaluation. The records are to be subjected to the relevant statistical analyzes. Detailed description of the procedure was presented e.g. Jonáš, Mazur & Uruba (1999) and Jonáš, Mazur & Uruba (2009).

The pressure measurements took priority over CTA method during the rough wall layer measurements of mean velocity profiles \(U(x, y, 0)\) in the plane \(z = 0\). The reason for this decision are the regard to the surface roughness and to the easy breakability of hot-wire probes by the spikes of roughness grains. The couple of the flattened Pitot probe (0.18 \(\times 2.95mm^2\) and round nosed static pressure probe (diameter = 1.8\(mm\)) connected with the pressure transducer BARATRON (on high accuracy special order; max 1\(kPa\); error \(\pm 0.02\%) of reading above 20\(Pa\)) is used for the measurement of the local dynamic pressure \(q(x, y, 0) = P_t - P_s\). The probes are shown in Fig. 2. Pitot-static tube (diameter = 6\(mm\)) connected with the pressure transducer OMEGA Techn. Ltd., (max 120\(Pa\); \(\pm 0.25\%) FS) is used for the measurement of the representative pressure \(q_r\) in the fixed position \([x_r, y_r, z_r] = [0.23m, 0.13m, 0.36m]\). At the same time the probe serves as the static pressure intake \(P_s[Pa]\) (the pressure transducer Druck DPI 145; max 100\(kPa\); 0.005% FS). The flow temperature \(t\) [\(^\circ\)C] is measurement by means of a thermometer Pt 100 connected to the Data Acquisition/Switch Unit HP 34970A.

Output signals proportional to the mean values of \(P, q_r\) and \(t\) are read by means of the unit HP 34970A just after start of measurement-observation in the point \([x, y, 0]\) (\(z = 0\) is the plane of vertical symmetry of flow). Afterwards, they follow the simultaneous reading and 30s averaging of signals proportional to \(q_r\) and \(q'(x, y)\). After the end of the reading the data are recorded in a personal computer. As to improve the measuring accuracy all pressure transducers were calibrated against the transducer BARATRON (till 1\(kPa\)) and if necessary against the micro-manometer AVA Gottingen (Betz type) for the pressure differences till 4\(kPa\) and the zero-readings before any observation were recorded.

The effect of wall proximity on the total pressure \(P_t\) measurement by means of a flattened Pitot tube is rectified after the procedure proposed by MacMillan (see Tropea, Yarin & Foss

Table 1. Free stream turbulence characteristics downstream individual grid generators.

| Grid | \(d[mm]\) | \(M[mm]\) | \(C[1]\) | \(x/M[1]\) | \(m[1]\) | \(z/M[1]\) | \(I_{u=x=0}[1]\) | \(L_{x=0}[mm]\) |
|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| GT1  | 3         | 20        | 72.68     | 10.31     | 1.0835    | -22.7     | 0.03      | 6.9       |
| GT5  | 10        | 35        | 0.3406    | -29.36    | 1.945     | -34.6     | 0.03      | 34.5      |
| GT8A | 1.65      | 5.75      | 19.016    | 6.035     | 1.229     | -171.7    | 0.01      | 7.7       |
| GT8B | 1.65      | 5.75      | 19.016    | 6.035     | 1.229     | -33.7     | 0.03      | 3.9       |
| GT8C | 1.65      | 5.75      | 19.016    | 6.035     | 1.229     | -18.1     | 0.05      | 2.8       |
The length of the consecutive displacements of Pitot tube is measured by means of the cathetometer (±0.01 mm).

Errors caused by small and slow variations of the external flow velocity and the air temperature during measurement of any profile were reduced by the simultaneous measurement of the local dynamic pressure \( q(x, y, z = 0) \) [Pa] and the representative dynamic pressure \( q_r \) [Pa]

\[
q(x, y) = 0.5 \varrho U^2(x, y) = \frac{q'(x, y) \bar{q}_r}{q_r}; \quad \bar{q}_r = \text{mean}(q_r).
\]

The instantaneous wall friction in a rough wall boundary layer is measured by means of a hot-wire probe working in CTA mode but the measurements procedure in the smooth wall boundary layer and in the rough one are different. The problem with the determination of the wire distance \( y \) from the rough wall (the wire reflection is lacking) was bypassed using a probe support with 3 wheels made from bearings (Fig. 3).

The support connected to the traversing system is moving along the rough surface in the streamwise direction \( x \). A probe with two heated parallel wires (DANTEC t:55P71) oriented parallel to the surface is attached to the support. The distance between wires is 0.49 mm. The calibration of both heated wires is done outside the action of wall proximity effect. Then the distance from the surface of the wire near the wall \( y_w < 0.3 \text{mm} \) is adjusted on a mirrored plate and the support is placed on rough wall and moved in predetermined locations \( x, y_w, 0 \). The CTA output signals processing follows assuming the adjusted \( y_w \) like that in the smooth wall case with one important difference. Initially it was assumed that this wire distance \( y_w = \text{const} \) would remain constant. Unfortunately irregular variations of the distance \( y_w \) in hundredth millimeters with the location \( x \) occur and we did not succeeded remove them. Thus an auxiliary local correction of \( y_w \) must be made. The correction equals in the given location \( x_j \) the time averaged skin friction coefficient determined from the mean velocity profile with the mean value of skin friction coefficient calculated from the CTA measurement. The instantaneous
wall friction is evaluated in the vicinity of \( x_j \) using the corrected distance \( y_w \). Finally the digital records (25kHz, 750000 samples, 16 bit) of the instantaneous wall friction are collected in every investigated location. The records were utilized in a statistical analysis of the wall friction. In the paper only the transitional intermittency factor \( \gamma(x) \) evaluated from the wall friction records acquired at different \( \text{FST and WR} \) is presented.

### 3. Evaluation of boundary layer characteristics

The aim of the analysis of the mean velocity profile is the determination of the customary boundary layer thickness \( \delta \) \( (U(\delta) = 0.99U_w) \), the displacement thickness and the momentum one \( \delta_1 \) and \( \delta_2 \) respectively, the wall shear stress \( \tau_w(x) \) and the related characteristics as the shape factor \( H_{12} \) and skin friction coefficient \( C_f \). Besides this, the values of the roughness function \( \Delta u^+ \) and the shift of the mean velocity zero level into the layer of roughness elements must be determined in the case of rough wall boundary layer. The definitions of the mentioned characteristics are generally known and need not duplicate e.g. Schlichting & Gersten (2000).

The wall shear stress \( \tau_w(x) \) can be evaluated from the slope of mean velocity profiles \( U(x,y) \) interpolated very near the surface. It requires a high accuracy of determination of the probe displacements from the starting position i.e. traverser’s reading \( y' = 0 \) with the probe in contact with the surface. This requirement was fulfilled every time during HW-measurements of the mean velocity profile and during Pitot tube measurements in the rough wall layers with pseudolaminar structure or in the early stage of intermittently turbulent flow. Then the interpolation of several points of the mean velocity profile allow determining the statistical estimates of the mean velocity derivative at the wall together with the shift \( \varepsilon \) of the velocity zero level:

\[
U = a + by' = b\left(y' + \frac{a}{b}\right); \quad y = y' + \varepsilon; \quad \tau_w = \mu \left( \frac{dU}{dy} \right)_{y=0} = \mu b. \tag{4}
\]

The interpolation is performed in the region of the coordinates \( y' \) from 0.1mm up at most 1mm. The observed displacements of the probe nose from the surface \( y'_{i+1} - y'_i \) were measured with the cathetometer. Unfortunately the dead travel of the traversing unit and the elastic deflection of the probe nose are reasons of uncertainty in ideal touch with the wall. Owing to this the estimate of the shift \( \varepsilon \) includes also the error \( y_1 \) caused from these actions. The average value of the error \( y_1 \) is \((0.18 \pm 0.05)mm\). It was determined from measurements on smooth surface; this value includes also the effective shift of the centerline 0.09mm. Obviously the estimates \( y_1 \) and \( \varepsilon \) affect the determinations of boundary layer thicknesses and shape factor but with the increasing thickness this effect becomes less important. The estimated error of calculated \( \tau_w \) is between two and three percent (better accuracy with a smooth surface).

Further unknowns join the previous one after finishing the transition process, in turbulent boundary layer on a rough surface. Namely they need to be determined the shift of the mean velocity profile \( \Delta u^+ \) (the roughness function) in the overlap region and the wake function \( \omega(y/\delta) \) with the strength of the wake \( \Pi \) (Coles, 1956) when the surface is rough. The effect of roughness on the outer layer appears in the formulae for the dimensionless mean velocity profile

\[
u^+ = \frac{1}{\kappa} \ln(y^+) + B - \Delta u^+ + \frac{2\Pi}{\kappa} \omega(\eta), \tag{5}
\]

where the dimensionless distances from the wall are \( y^+ \) and \( \eta \) and following relations are introduced

\[
y^+ = \frac{y u_r}{\nu}; \quad \eta = \frac{y}{\delta}; \quad y = y' + \varepsilon; \quad \delta = y'_\delta + \varepsilon; \quad u_r = \sqrt{\frac{\tau_w}{\rho}}. \tag{6}
\]
The boundary layer thickness \( \delta \) is measured in the distance from the wall where \( U(x, \delta) = 0.99U_e \), the real normal distance from the surface of the velocity zero level is \( y \) and \( y' \) denotes the traverse reading.

Representation of the mean velocity profile in terms of the velocity defect law is more suitable for fitting the measurements than the log law

\[
\frac{u^+}{u^+} - 2\Pi\frac{\omega(1) - \omega(\eta)}{\kappa} - \frac{1}{\kappa}\ln(\eta). \tag{7}
\]

Certain experimental evidence indicates departures from the Coles wake function in the boundary conditions characterized: by a smooth wall and external turbulent flow (e.g. Hancock (1980)) and by a rough wall and low turbulence external flow (e.g. Perry, Lim & Henbest (1987)). It was observed that using the Coles wake function and the Hama (1954) approximation (proposed farther from the wall) the estimates of the friction velocity were higher than calculations from the momentum balance or by the estimate of the velocity profile derivative on the wall. Bradshaw (1985) attributed this effect to the underestimated value of the strength of the wake implied in Hama’s approximation.

This problem Krogstad, Antonia. & Browne (1992) analyzed in detail and concluded that a formulation allowing to optimise also the strength of the wake \( \Pi \) in the wake function is necessary. Numerous authors recommend the use of the wake function already proposed by Finley, Khoo & Chin (1966) and Granville (1976)

\[
\omega(\eta) = \frac{\eta^2}{2\Pi}[(1 + 6\Pi) - (1 + 4\Pi)\eta]. \tag{8}
\]

Introducing formula (8) into the equation (7), we obtain after some formal adaptations

\[
\frac{U(\eta)}{U_e} = \frac{1}{\kappa}u_\tau\frac{[-2\Pi + \ln(\eta + (1 + 6\Pi)\eta^2 - (1 + 4\Pi)\eta^3]]}{u_e}. \tag{9}
\]

This is a non-linear equation in three unknowns \( u_\tau \), \( \varepsilon \) and \( \Pi \). The method of least squares was applied for the computation of the statistical estimates of the unknowns. Details on this procedure are given in Jonáš (2010). It should be mentioned that the first results dealing with boundary layer on sandpaper roughness 80-grits were evaluated by procedures after Rotta (1962) using the Clauser and Hama approximations Jonáš, Mazur & Uruba (2008a) and Jonáš, Mazur & Uruba (2009). This explains some differences in results.

4. Measurement uncertainties

The experimental uncertainties are estimated based on knowledge of instrumentation, calculated root mean square errors of interpolations and taking into account the spread of repeated observations. The upper limits of relative measurement errors are estimated of the representative dynamic pressure and the local one:

\[
\frac{\Delta q_r}{q_r} \leq \pm 0.02atU_r \approx 5m/s; \quad \frac{\Delta q}{q} \leq \pm 0.02atU(x, y) \geq 0.6m/s; \quad \Delta P = \pm 5Pa. \tag{10}
\]

The absolute error of the local time averaged velocity \( U(x, y, 0) \) is roughly constant, less than \( \pm 0.1m/s \). Estimates of relative probable errors of the displacement thickness \( \delta_1 (\sim 1.5\%) \) and the momentum one \( \delta_2 (\sim 1.5\%) \), the shape factor \( H_{12} (\sim 3\%) \) and the wall friction \( \tau_w (\sim 2\%) \) follow essentially from the performed error analysis in the case of a smooth surface. The dead travels of the probe traversing unit and the shift of the velocity zero level in boundary layer on a rough surface introduce some additional errors. The measurement errors are estimated higher than errors usual in the investigation of boundary layers on smooth surfaces e.g. the
probable error of the wall friction is about $3 - 4\%$. The considerable scatter, between 0.04\textit{mm} and 0.09\textit{mm} was found in the estimates of the shift of the velocity zero level.

5. Results of mean flow investigations

The distributions of the fundamental boundary layer characteristics have been established on the basis of detailed mean velocity measurements. For the purpose of the presentation’s transparency, the main results following from the analysis of sixteen investigated boundary layers are further illustrated by examples only. The distributions of the thickness $\delta$ are similar to the distribution following from the Blasius solution (e.g. Schlichting & Gersten (2000)) upstream from the start of the laminar/turbulent transition ($x \sim 0.1\text{m}$) regardless of the WR and FST; both increase the process of the layer broadening farther downstream.

Examples of the dimensionless mean velocity profiles measured in the locations with different flow structure are shown in Fig. 4. Turbulence of the external flow was on the natural level with the intensity $I_u = 0.003$ and four different types of the flat plate surface were tested. Profiles are very similar/identical to Blasius solution in the region upstream transition ($x = 0.05\text{m}$). Boundary layer remains pseudo-laminar on the smooth surface but at the same time becomes transient character on the rough wall in the vicinity of the cross section $x = 0.3\text{m}$. The surface roughness, however small it is, is exciting the transitional flow structure with very similar profiles of a transitional type. The rough wall turbulent boundary layers occur farther downstream near $x = 1.2\text{m}$. Only the beginning of the transition process appears in the layer on the smooth surface in the same cross section.

![Figure 4. Mean velocity profiles for different wall roughness under the low turbulence free stream.](image-url)

The mean velocity profiles shown in Fig. 5 indicate the effect of the free stream turbulence intensity on the acceleration of boundary layer development. A less distinct effect of the
turbulence length scale is also appreciable. It will be later demonstrated more clearly.

![Figure 5](image1.png)
**Figure 5.** Examples of the effect of the free stream turbulence on the mean velocity profiles.

![Figure 6](image2.png)
**Figure 6.** Examples of the velocity defect profiles using outer scales at distinct boundary conditions.

Examples of the interpolation of measured profiles with the velocity defect formulae (9) in the outer region of the rough wall turbulent boundary layers are shown in Fig. 6. Obviously introducing the wake function (8) into the velocity defect law (7), the difference between the actual velocity profiles in the outer region and the logarithmic law is interpolated with a quite satisfactory accuracy (error less than 2%). Small systematic departures occur at the edge of boundary layer only. Modifications of the strength of the wake do not reduce these departures. Possible reasons are in the expression of the velocity defect law. It should be mentioned, that the estimates of the strength appear very low in comparison with the Coles representation of the velocity defect law and as well with data published in e.g. Bergstrom, Kotey & Tachie (2002). Also the absolute member in the Log-law is reaching higher value $B = 5.2$ than usual 5. A possible reason (Finley, Khoo & Chin, 1966) may be in quite low values of the momentum thickness Reynolds number $Re_2$ during the presented experiments as shown in Fig. 7. The achieved values of $Re_2$ are about of order lower than those presented e.g. by Bergstrom, Kotey & Tachie (2002).

The wall friction is one of the most important boundary layer characteristics being the grounds for determination of the inner scales in a boundary layer and for the calculation of the friction losses. Five examples of the skin friction coefficient $C_f$ distributions are shown in Fig. 8. The green marks denote the results received in the low turbulence external flow ($Iu = 0.003$) and the red/blue marks denote the distributions valid under increased turbulence level ($Iu = 0.03$). (Let us remind that the level $Iu$ is describing the intensity of grid turbulence fluctuations in...
the leading edge of the plate, \( x = 0 \), with the attached boundary layer.) Results referring to boundary layers on smooth surface are marked with triangles while circles denote the results with the surface covered by the sandpaper-grits 60. From these distributions follows that the regions with pseudo-laminar flow and velocity profiles similar to Blasius solution occur near the leading edge of the plate. They follow the shape of the Blasius solution (solid line). Also, other boundary layer characteristics, e.g. the distributions of the shape factor \( H_{12} \), confirm the similarity with the laminar boundary layer in the zero pressure gradient. Further from the skin friction distributions is obvious that both the surface roughness and the free stream turbulence are accelerating the boundary layer transition and shorten the transition region. Their joint action enhances this acceleration. The effect of the surface roughness is more significant than the free stream turbulence.

The effect of the outer stream turbulence length scale on by pass transition in a layer on smooth surface was proved formerly (Jonáš, Mazur & Uruba, 2000). The results plotted in Fig. 8 confirm that this effect is not negligible also in the case of boundary layer on a rough surface, but it is less distinct. This is evident from the comparison of the distributions marked with blue and red circles in Fig. 8.

Statistical estimates of the friction velocity \( u_\tau \), the strength of the wake \( \Pi \) and the velocity zero level \( \varepsilon \) are the result of the interpolation of velocity profiles with the velocity defect law in the formulation (9). Every measured mean velocity profile was individually interpolated. It must be emphasized that only data calculated at the displacement thickness Reynolds number \( Re_1 \) higher than thousand were derived from the interpolation because the formulation (9) is valid in a rough wall turbulent boundary layer only. Examples of the evaluated velocity zero levels are shown in Fig. 9. Considerable scatter up to \( \pm 0.04 \text{mm} \) was found in the calculated values \( \varepsilon \). The averaged size of the shifts \( \varepsilon \) from the top plane of roughness grains toward the roughness bottom were 0.17\text{mm}, 0.18\text{mm} and 0.18\text{mm} for sand-papers with grits 100, 80 and 60.
respectively. The probable error of these estimates is about ±0.03 mm. No significant effect of the free stream turbulence was ascertained on the size of $\varepsilon$. The evaluated values of the strength of the wake $\Pi$ differ moderately with the grits number and the effect of turbulence level $I_u$ appears small. As an example the strength of the wake evaluated from the investigations of boundary layers on sand-paper grits 60 is shown in Fig. 10. Similar scatter of data and a soft tendency of the strength to grow with the increasing Reynolds number $Re_1$ were found with surface covered by other types of the sand-paper. The arithmetic averages of the strength of the wake $\Pi$ calculated in the region $Re_1 > 10^3$ are as follows: grits 100: $(0.44 \pm 0.04)$; grits 80: $(0.46 \pm 0.06)$ and grits 60: $(0.34 \pm 0.06)$; here the probable errors are presented.

Figure 9. Examples of the velocity zero level estimates; $y_0[mm] = 0.19 \pm 0.01$.

Figure 10. Examples of the strength of the wake.

Figure 11. Examples of the roughness function distributions.

The estimate of the roughness function $\Delta u^+$ is calculated subsequently substituting in the Log Law (5). Distributions of the roughness function shown in Fig. 11 exhibit general trends namely the rise with the increasing Reynolds number and the increase with the amplification of turbulence intensity. It should be mentioned that the example of experiments with the sand paper roughness grits 60, shown in Fig. 11, looks more arranged that the results received with the other types of surface roughness. Most likely the reasons consist in the fact that the sand-papers with grits 80 and 100 are not ”enough rough”. The comparison of the roughness Reynolds number $s^+$, defined with the length of the largest roughness grains and with the corresponding length of the sand-grain type of roughness $k^+$ supports this opinion. This is shown in Fig. 12. Corresponding roughness lengths $s$ and $k$ produce the same shift of the Log Law. Thus the mapping of $k^+$ and $s^+$ is made using the relation borrowed from Raupach, Antonia & Rajagopalan (2000)

$$\Delta u^+ = \frac{1}{\kappa} \ln k^+ - 3.2. \quad (11)$$

Obviously, the investigated rough wall boundary layers were developing on surfaces with the roughness around the interface ($k^+ = 5$) between ”hydraulically smooth” and ”transitionally rough” surface.
6. Results on transitional intermittency investigations

Valuable information on turbulent spots role in transition process can be deduced with regard to Emmons (1951) ideas and Narasimha (1985) concept of intermittency from the measured distributions of $\gamma(x)$. The transitional intermittency factor $\gamma(x)$ was evaluated from the wall friction records.

The applied method of the transitional intermittency analysis is so called TERA-method (Turbulent Energy Recognition Algorithm-Method), e.g. Zhang, Chew & Winoto (1996) and the procedure of is very similar to that described in Hendley & Keffer (1974) and Elsner & Kubacki (2000). The method consists of several consecutive steps. At the first, the obtained records of the instantaneous values of wall friction fluctuations $\tau'_w$ are filtered by Butterworth filter with low pass frequency $1\text{kHz}$ to eliminate noise from the signal. At the second step, the detector function $D(t)$ is derived as to emphasize the differences of the signal time behavior during turbulent and non-turbulent periods. The detector function is computed after the formula:

$$D(t) = |\tau'_w \cdot \partial^2 \tau'_w / \partial t^2|.$$  \hspace{1cm} (12)

Then the detector function is smoothed to eliminate the scales much smaller than those to be recognized, thus the criterion function $K(t)$ is created. The criterion function, the threshold and the indicator function $I(t)$ are evaluated successively. The indicator function allows sort the whole record in the time intervals with turbulent structure ($I = 1$) and those with laminar/nonturbulent structure ($I = 0$). Finally the transitional intermittency factor $\gamma(x)$ is calculated. Details are presented in Hladík & Uruba (2009) and Jonáš, Mazur & Uruba (2009).

The authors applied the method in a cooperation with Elsner, Wysocki & Drobniak (2006) within the investigation of the smooth flat plate boundary layer developing in the FST with turbulence intensity $Iu = 0.03$ and different values of the FST length parameter Jonáš, Mazur & Uruba (2009). The records of measured data have been made already during the experiments performed within the COST Action F5 and the thematic network TRANSPRETURB (e.g. Jonáš, Mazur & Uruba (2000)). The rough wall boundary layer records of the instantaneous wall friction are a follow up of the mean flow investigation (the prior section). The dramatic effect of WR and FST on laminar turbulent transition is illustrated by the distributions $\gamma(x)$ versus $Re_x$ shown in Fig. 13. Results related to smooth wall layers are marked with triangles, circles mark results related to rough wall layers and various colours differentiate free stream after the intensity $Iu$ and the length parameter $Le$. Data on FST and WR are given in square brackets in captions. The shape of the factor $\gamma(x)$ can be described after Narasimha (1985) as the function of the local Reynolds number $Re_x$ and with the dimensionless spot production parameter $n^*\sigma$

$$\gamma(Re_x) = 1 - \exp[-(Re_x - Re_t)^2 n^*\sigma], \quad Re_x = xU_e/\nu, \quad n^*\sigma = n\sigma\nu^2/U_e^3.$$ \hspace{1cm} (13)
Following Narasimha the formulae can be derived that is suitable for the statistical estimates of the transition start $x_s$ and the value of parameter $n^*\sigma$

$$F'(\gamma) = \sqrt{-\ln(1-\gamma)} = \sqrt{n^*\sigma(Re_x - Re_{xs})} = a_0 + a_1 Re_x.$$  \hspace{1cm} (14)

The linear interpolations of the discussed examples are shown in Fig. 14. The local Reynolds number of transition boundaries $Re_{xs}$ and the dimensionless turbulent spot production rate $n^*\sigma$ can be evaluated from the statistical estimates of the parameters $a_0$ and $a_1$.

Figure 13. Distributions of transitional intermittency factor $\gamma$.

Figure 14. Linear interpolations of the function $F'(\gamma)$.

A comparison was made between the estimates of the transition region boundaries made from the analysis of skin friction coefficient distributions, $Re_x(C_f)$, and the estimates calculated from the interpolation (14) $Re_x(\gamma)$. The start and the end of transition were defined in the locations where the intermittency factor assume values $\gamma = 0.1$ and $\gamma = 0.9$. From this comparisons result that the estimates correspond mutually within 20% in all investigated regimes except that: 1) the estimate of transition start in boundary layer on the smooth plate-wall under the FST with the large length parameter ($Iu_e = 0.03$ and $Le = 33.4 mm$); 2) two estimates of transition termination in boundary layers on the rough plate-wall under the FST ($Iu_e = 0.03$ and $Le = 3.8 mm$ or $33.4 mm$). The possible explanation of the first exception is a bad estimate of transition start as the course of the measured $C_f(Re_x)$ diverges very slowly from the course of Blasius solution. The other mentioned exceptions possibly result from too sparse net of skin friction measurement in quickly developing boundary layers. Then it is difficult determine the extreme in the measured course of skin friction. The priority of delimitation the transition region from the transitional intermittency factor is obvious.

The authors Jonáš, Elsner, Mazur, Uruba & Wysocki (2009) evaluated dimensionless turbulent spot production rates $n^*\sigma$ from experiments on the smooth flat plate boundary layer using both the intermittency analysis and the wavelet analysis Elsner, Wysocki & Drobniak (2006). The authors demonstrated that both methods are in accordance mutually and also with the published results received by Fransson, Matsubara & Alfredsson (2005) at different FST. The value $n^*\sigma$ relates to the length of transition region $\Delta Re_t$ also in case of the rough wall boundary layer as shown in Fig. 15, where the straight line represents the Fransson et al results

$$n^*\sigma = 1.52\Delta Re_t^{-2}.$$  \hspace{1cm} (15)

Next triangles denote the results received in the smooth surface layers, circles represent results evaluated from the rough wall boundary layers and colors distinguish various pairs of the intensity and length parameter of free stream turbulence. Apparently turbulent spot production
starts sooner and with higher intensity in the rough wall boundary layer than in the smooth one at otherwise equal conditions.

Figure 15. Dimensionless spot production rate as function of transition length $Re$-number.

7. Conclusions

Investigated boundary layers on surfaces covered with sand-papers grits 100, 80 and 60 belong to the class of layers close to the lower limit, $k^+ \approx 5$, of the admissible roughness region. Corresponding values of the sand-grain type of roughness $k^+$ are 4.6; 5.7 and 8.7 respectively.

The external flow turbulence accelerates the development of boundary layer on a rough surface so that the initial region with pseudo-laminar flow preserves but shortens and as well the transitional region becomes shorter.

Effect of the surface roughness on the boundary layer development is predominating but the impact of the free stream turbulence intensity is also significant and as well the effect of turbulence length scale is not negligible.

The shift of the velocity zero level from the top-plane of roughness grains into the roughness layer equals about 20 percent, 48 percent and 58 percent of the representative roughness length for sandpapers with grids 100, 80 and 60 respectively.

The statistical estimates of the wake factor $\Pi$ in boundary layers after completing the transition process have a considerable scatter. They are smaller than 0.55 (the Coles value), which is contrary to the published data. The assumed reasons are small values of the Reynolds number $Re_1$ and the type of investigated surface roughness.

The measurements of transitional intermittency factor are very suitable tool to make exact determination of the start and the end of laminar-turbulent boundary layer transition region.

The dimensionless spot production rates $n^*\sigma$ depend on Reynolds number, defined with the length of the transition region, regardless on the FST length parameter $Le$, like the results received by Fransson, Matsubara & Alfredsson (2005) at different FST structure ($Iu, Le$) at the onset of the boundary layer $x = 0$.

Turbulent spot production starts sooner and with higher intensity in the rough wall boundary layer than in the smooth one at otherwise equal conditions and the increase of the free stream turbulence intensity amplifies this process.

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