ON TURBULENT SPOTS DURING BOUNDARY LAYER BY-PASS TRANSITION

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Introduction

The transition from laminar to turbulent flow structure depends on the specific type of flow and on the type of the acting disturbances that influence the process. Regardless to this fact, the final phase of laminar boundary layer transition starts with the occurrence of first turbulent spots. Emmons [1] first reported spots as isolated regions of strong fluctuations that are stream-wise carried, growing in size and coalescing with neighbours. Spots appear irregularly in time and at arbitrary locations of the boundary layer. Spots are an essential feature of transition to turbulence; they appear as the building blocks of boundary layer turbulence, they control the length of the transition region etc. 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 [2]. The spot creation rate, growth characteristics and the merger of turbulent spots lead to fully developed turbulent flow. A brief summary on turbulent spot and calmed region was compiled in [3].
The effect of the free stream turbulence (FST) level Tu on the location of transition onset is known as very important since forties of 20th century e.g. Schubauer and Skramstad [4]. The authors clearly proved (Jonáš et al. [5, 6]) that the length scale L_e of the FST also influences the start of boundary layer by-pass transition. Later also Roach and Brierley [7] and Brandt et al. [8] emphasized the importance of both FST scales, of the velocity scale and the length one, on the laminar boundary layer receptivity and transition onset. But a clear physical notion on the role of the FST length scale in transition process is not elaborated yet. The authors believe that the investigation of the spots behaviour during transition at various FST scales can contribute to the problem explanation. They linked up the experiences of instantaneous wall-friction, τ_w(t) measurement and conditional analysis (Jonáš et al. [9, 10],) with the experience of the spot detection procedure by using the wavelet transform (Elsner et al. [11]) to perform a preliminary study. The initial results are presented in this contribution.

Experimental set up, measurement method and evaluation procedures

The experiment was made in the close circuit wind tunnel of the Institute of Thermomechanics at Prague (test section: 0.5 x 0.9 x 2.7 m^3). The investigated boundary layer develops itself on a smooth wooden plate (zero pressure gradient). The FST is controlled by plane grids of different geometry with cylindrical rods and square holes placed across the flow in a proper distance upstream from the plate as to produce homogeneous nearly isotropic turbulence of the assigned value of *Tu*-level and various L_e in the leading edge plane, x = 0. The employed CTA measuring method, with refined hot wire calibration and measurement corrections allow determine statistical characteristics of the instantaneous velocity and wall-friction. Details are given in [6 and 9, 10]. Boundary conditions correspond to the ERCOFTAC Test Case T3A+, Savill [12]. Mean velocity of the free stream was U_e = 5 m/s . Grids are generating turbulence of the same FST level *Tu* = 0.03 but with different dissipation length parameters L_e = 3.8, 5.9 and 33.4 mm respectively in the leading edge of the plate, in the plane x = 0

$$Tu = \sqrt{\overline{u_i u_i} / 3U_e^2} \cong Iu_e = \sqrt{\overline{u_e^2}} \Big/ U_e \; ; \quad Le = -\left(\overline{u_e^2}\right)^{3/2} \Big/ U_e \frac{d\overline{u_e^2}}{dx} \; ; \quad i = 1,2,3 \qquad (1)$$

Valuable information on turbulent spots role in transition process can be deduced with regard to Emmons ideas and Narasimha concept of intermittency. The flow intermittency analysis was based on digital records of $\tau_w(t)$. The procedure is very similar to that one described by Hedley and Keffer [13] and Elsner and Kubacki [14]. The detector function *D*(t), threshold *Th* and indicator function *I(t)* are evaluated. The digital records of $\tau_w(t,x)$ allow us, e.g. [15], derive finally the indicator function *I(t)* that allows sorting of the time intervals in those with turbulent flow structure (*I* = 1) and those with laminar/non-turbulent structure (*I* = 0), next the transitional intermittency factor $\gamma(x)$ is calculated

$$\gamma(x) = \sum_{j=1}^{N} \frac{I(x, t_j)}{N}; \quad N = 750000 \qquad (2)$$

Finaly the conditionally averaged distributions of the wall friction during periods with turbulent character and the laminar can be determined as was demonstrated in e.g. [16].

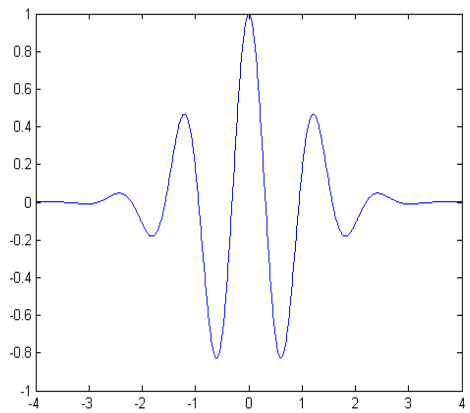

Figure 1 Morlet wavelet.

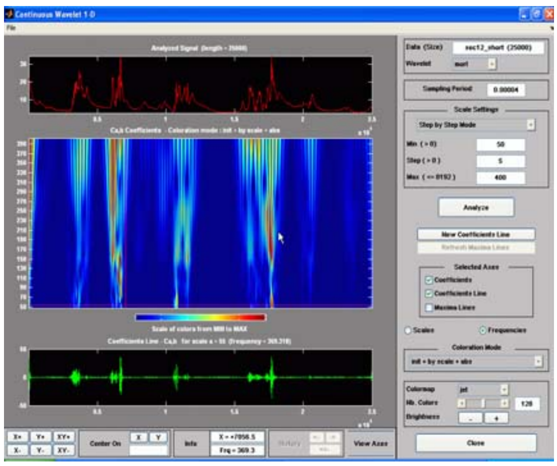

Figure 2 Example of the spot detection.

Other approach to the investigation of turbulent spots during boundary layer transition represents the application of wavelet transform of digital records $\tau_w(t,x)$. The advantage of the wavelet analysis is the clearness of observation of particular spot passages through the location of observation. Elsner et al. [11] derived an original detection procedure employing the wavelet analysis. From time series of wall friction (or velocity) record, the spot passage may be confirmed by the time of occurrence, magnitude and shape of the signal. The spot interior is characterized by much finer turbulence scales than the flow further from the wall, so it could be identified based on the frequency contents additionally. The wavelet transform is able detect particular frequency components and localize the investigated event in time. The Morlet wavelet (Figure 1) transform was selected with view to experiences of Elsner et al. [11] and all calculations were performed with the Wavelet Toolbox of Matlab software [17]. Figure 2 is giving a general view of the spot detection method. A piece of velocity record (upper picture) and the corresponding results of the wavelet analysis, the Morlet wavelet transform (middle picture) and corresponding cross section for the selected value of scale number a = 55, corresponding with the frequency 369 Hz (bottom picture) are shown in the Figure 2. Obviously a relatively good correspondence is between local maxima of signal and maxima on the contour map.

The consecutive steps of the detection procedure are presented in Figure 3. Record of the original CTA output voltage corrected for the wall proximity effect and next converted to the signal proportional to the instantaneous wall friction is displayed in Figure 3a. Its wavelet transform with the use of the Morlet function is then calculated (similarly to Figure 2) and the isolines of wavelet coefficients *C(t)* for selected scales/frequencies are determined. The isoline of time signal *C(t)* for a scale a = 4 is shown in Figure 3b. Next the absolute value of time derivative $\left|dC/dt\right|$ i.e. the raw base function is calculated. Absolute value of the time derivative, Figure 3c is very irregular shaped thus it is necessary apply a moving average smoothing procedure to derive the smoothed base function (Figure 3d). Finally the raw base function is calculated and spots are distinguished by applying a threshold window *Th*. A threshold has to be selected as to derive the detection function *D(t)*, i.e. to assort turbulent spots occurrence (*D(t)* = 1) from random disturbances and quiet shape of the base function (*D(t)* = 0) (see Fig. 3e). Finding a proper value of *Th* is a delicate problem. It is suitable proceed from calculating number of spots at a row of values *Th* from measurement in a section near the start of transition, where spots are not yet merged and are separated by flow with low level of fluctuations. The proper *Th* corresponds to maximum in plot of number of spots as a function of threshold level. Details on the whole detection procedure are explained in Elsner et al. [11].

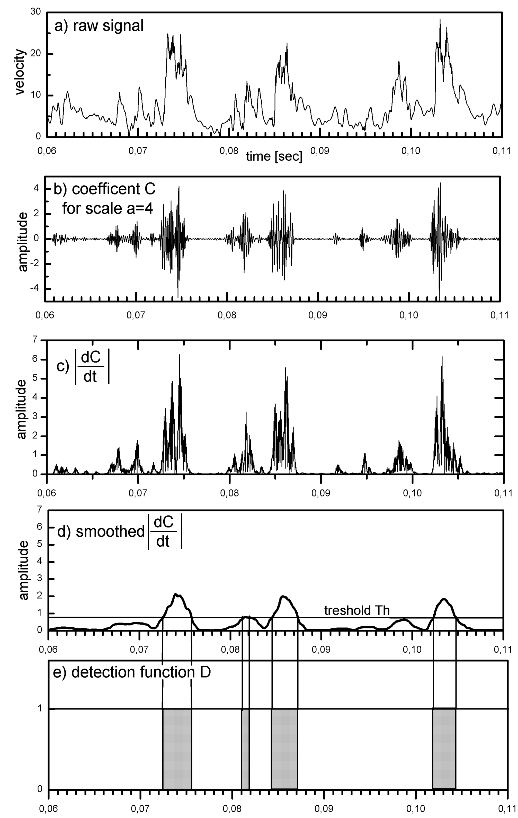

Figure 3 Brief summary of spot detection.

With regard to the Elsner's experiences, the resolution of temporal time localization is increasing for the lower scales (higher frequencies) as it is indicated by much finer spacing of isolines at the bottom of the contour map. This is graphically demonstrated in the Figure 4 (right). Clear differences are shown in Figure 4 between signals and their transform in an ordinary turbulent flow (left) before receiving the value of the indifference Reynolds number (Re_1 = 520, defined with the displacement thickness of boundary layer) and transitional boundary layer flow (right) with occurring turbulent spots at about critical value of Re_1. All records of the skin friction at different sections *x* downstream from the turbulence generators GT1 (Le = 5.9 mm) and GT5 (Le = 33.4 mm) were first of all transformed similarly to the Figure 4 and next evaluated.

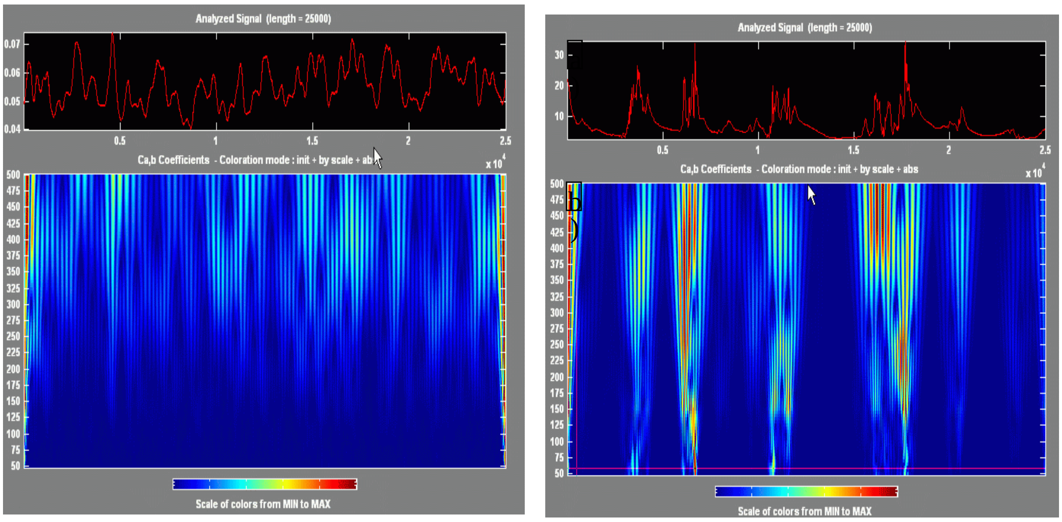

Figure 4 Morlet wavelet transforms of skin friction signal Tu = 0.03, Le = 5.9 mm: left: x = 0.1 m, Re_1 = 318, γ = 0: right: x = 1.0 m, Re_1 = 921, γ = 0.52.

Results

The transitional intermittency factor $\gamma(x)$ was determined from the digital records of the instantaneous wall friction $\tau(t,x)$ at different values of the free stream turbulence length scale *Le*. The distributions γ versus Re_x shown in Figure 5 confirm the effect of *Le*. Even though always *Tu* = 0.03 at *x* = 0, the start of transition is moving upstream and the termination of transition region is moving downstream with the increasing FST length scale *Le*.

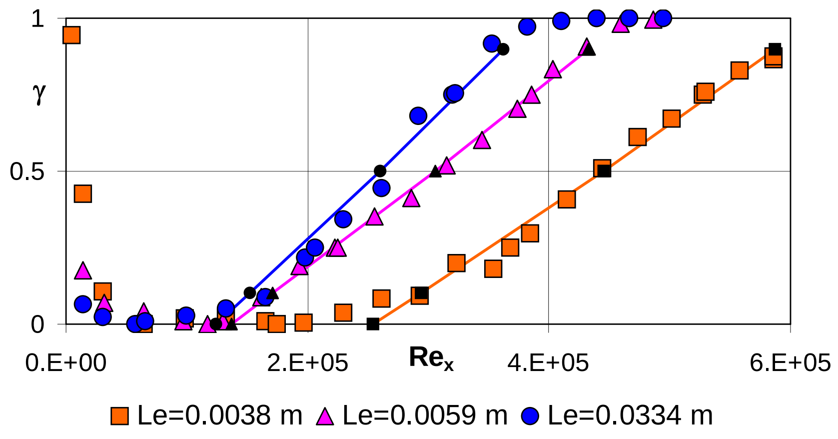

Figure 5 Transitional intermittency factor as function of the local Reynolds number.

In compliance with Narasimha [2] the transitional intermittency factor *γ(*x*)* can be expressed in form involving the spot production rate *n* and Emmons non/dimensional parameter σ

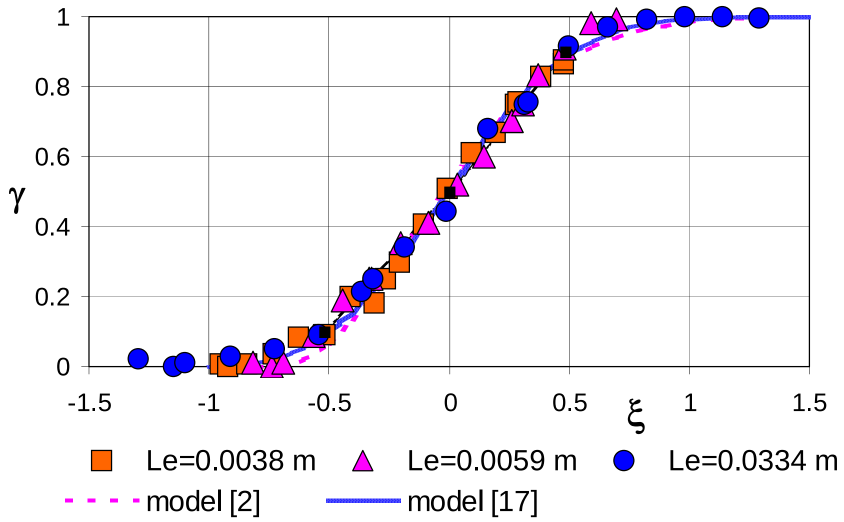

Figure 6 Universal intermittency function: models according to [2] and [17] and experimental data.

$$\gamma(x) = 0\,, x \le x_t\,; \gamma(x) = 1 - exp\left[-(x - x_t)^2\, n\sigma / U_e\right];\ x \ge x_t \qquad (3)$$

where the term $n\sigma / U_e$ is assumed constant. Introducing local Reynolds number Re_x into formulae (3) we receive

$$\gamma(Re_x) = 1 - exp\left[-(Re_x - Re_{tr})^2\, n^*\sigma\right];\quad Re_x = xU_e/\upsilon\,;\quad n^*\sigma = n\sigma\upsilon^2/U_e^3 \qquad (4)$$

here the parameter $n^*\sigma$ stands for the dimensionless spot production rate. Now it is possible introduce a new variable ξ

$$\xi = \left(Re_x - Re_{tr}\right) / \Delta Re_{tr} ; \Delta Re_{tr} = Re_x(\gamma = 0.9) - Re_x(\gamma = 0.1); Re_{tr} = Re_x(\gamma = 0.5) \quad (5)$$

and follow up Narasimha to express the formulae (3) in a universal form (Figure 6)

$$\gamma\left(x\right) \doteq 1 - exp\left[-a\left(\xi + b\right)^2\right] \doteq 1 - exp\left[-c\left(\xi + d\right)^3\right] \quad (6)$$

Constant parameters *a*, *b*, *c* and *d* are as follows: *a* = 1.42 and *b*= 0.72 (Narasimha model [2]); c = 0.6 and d = 1.05 (Johnson and Fashifar model [17]). The comparison of presented results with models proposed in [2] and [17] demonstrates their compatibility with universal form and a somewhat better correspondence with Johnson and Fashifar model [17].

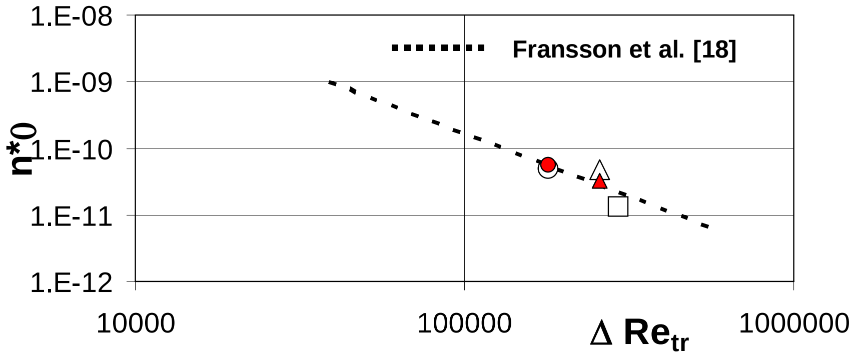

Figure 7 Dimensionless spot production rate as function of the transitional region length Re (marks as in Fig. 6, filled marks are calculated from the wavelet analysis).

The dimensionless spot production rates $n^*\sigma$ were evaluated for different dissipation length parameter values L_e from the equation (4). Results are plotted versus Reynolds number ΔRe_{tr}, defined with the length of the transition region in Figure 7 (symbols as in Figure 6, red filled marks denote wavelet analysis results) together with the line segment interpolating results presented in the paper Fransson et al. [18].

Interesting comparison is drawn in Figure 8, where the evaluated dimensionless spot production rates are plotted versus turbulence level Tu either in the leading edge plane (x = 0, Tu = 0.03, empty black marks) or in sections of the transition start ($x = x_{tr}$, Tu < 0.03, filled marks). Together with measurement results are plotted interpolations proposed by Fransson et al. [18] and Mayle [19].

It is possible make a preliminary conclusion from the analysis of Figures 7 and 8. The dimensionless spot production rates, $n^*\sigma$ evaluated from both the intermittency analysis and using wavelet analysis are in accordance mutually and also with the results of Fransson [18] (Figure 7). The model proposed by Mayle [19] is giving a quite true picture (Figure 8) of the dependency $n^*\sigma$ versus *Tu* if the turbulence level *Tu* is considered at the location of transition start, $x = x_{tr}$. It appears that the incoming flow turbulence length scale *Le* express itself by way of decelerating of turbulent motions decay with the increasing *Le* i.e. local increase of *Tu* (x).

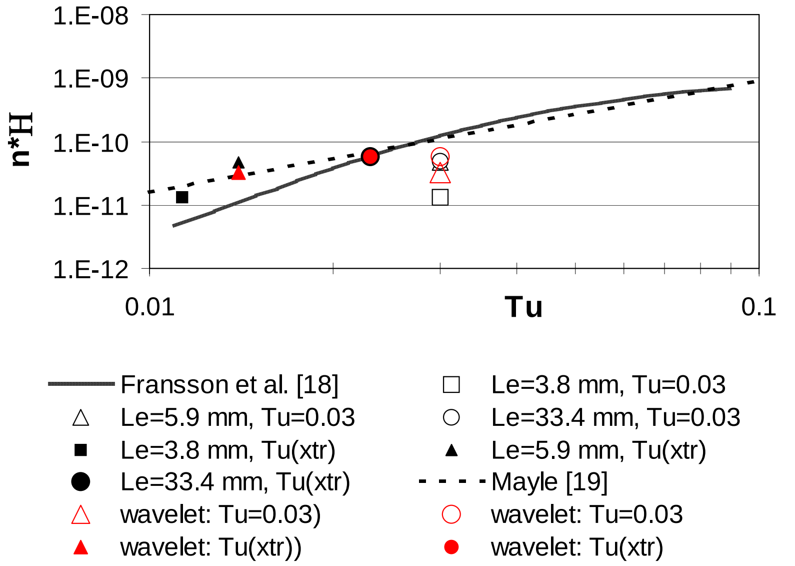

Figure 8 The dimensionless spot production rates plotted versus turbulence level Tu (in the leading edge plane x = 0, Tu = 0.03, empty black marks and in sections of the transition start x = x_{tr}, Tu < 0.03, filled marks).

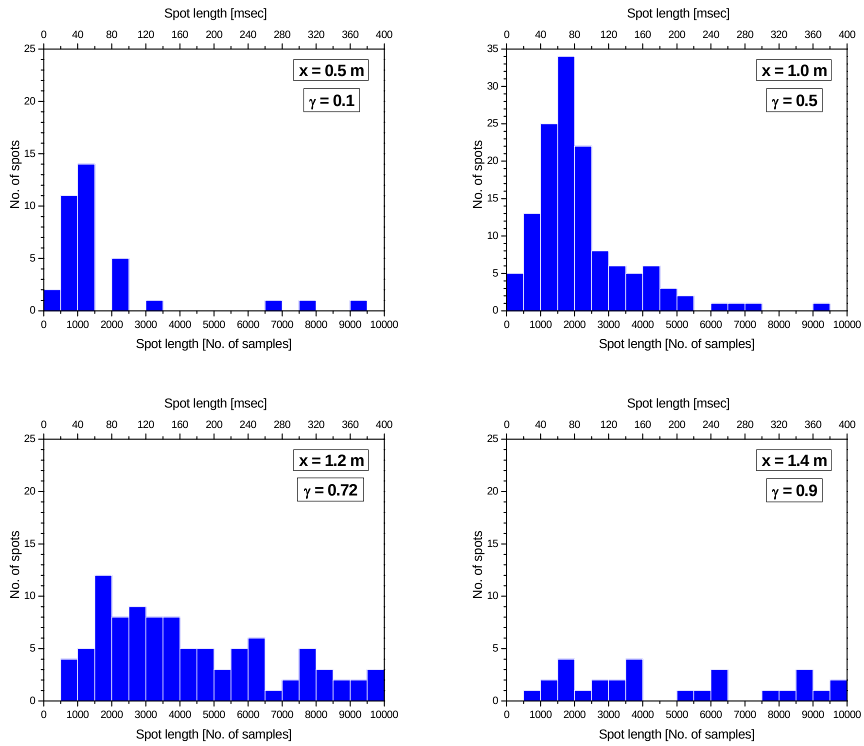

Fig. 9. Number of spots as a function of spot length (for the coordinates x = 0.5, 1.0, 1.2 and 1.4 m), GT1, Le = 5.9 mm.

The advantage of the wavelet analysis in the observation of particular spot passages through the location of observation was mentioned earlier. Histograms of detected number of spots for different configurations and locations were determined from the relevant Morlet wavelet transforms. For example, numbers of turbulent spots at selected sections are shown as functions of the spot length in Figure 9 (incoming flow Ue = 5 m/s, Tu = 0.03 and Le = 5.9 mm) and Figure 10 (incoming flow Ue = 5 m/s, Tu = 0.03 and Le = 33.4 mm). The particular cross sections are located along the transition zones with regard to comparable developed transition process at both length parameters Le = 5.9 mm and 33.4 mm.
Full scales of Figures 9 and 10 are horizontally 0.4 s or 10^4 samples (25 kHz) and vertically 25 spots. Obviously, namely at the beginning of transition (γ = 0.1), the spot occurrence is more numerous at larger length scale. Probably some spots excited by large turbulent disturbances upstream the section of indifference Re survive the viscous damping and join those generating at the transition start. The merging of turbulent spots near the end of transition regions appears itself in a distinct elongation of events and therefore more opportune is call these events turbulent regions than spots.

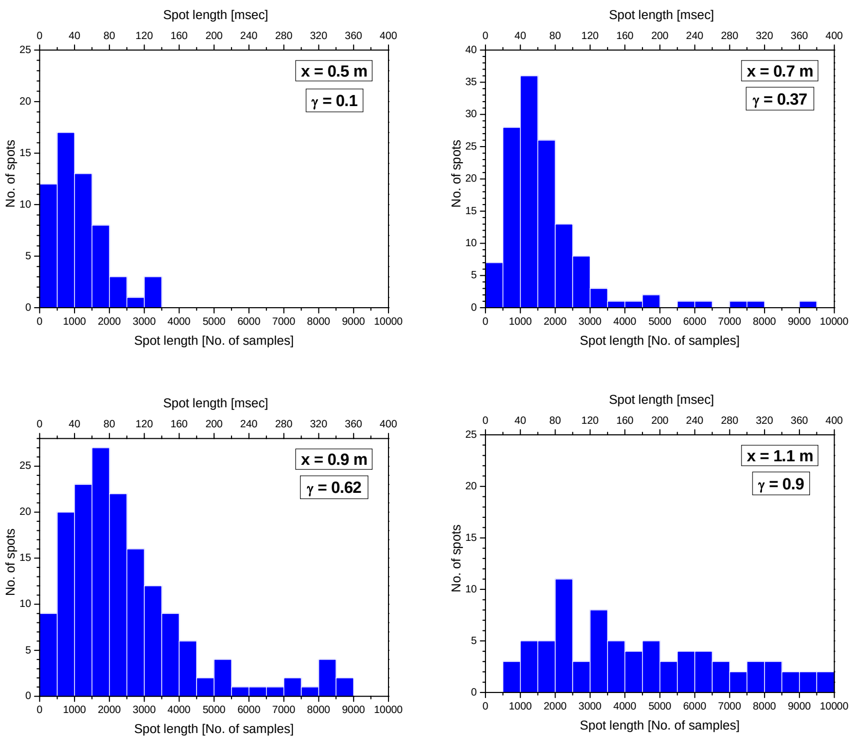

Figure 10 Number of spots as a function of spot length (for the coordinates x = 0.5, 0.7, 0.9 and 1.1 m), GT-5, Le =33.4 mm.

Taking in account the growth and the propagation of turbulent spot the normalized - reduced number of spots must be determined (procedure see Elsner et al. [11]) and next the non/dimensional spot production rate n*σ (Fig. 7 and 8). The reduced number of spots and mean length of identified turbulent regions arising from turbulent spots are plotted versus the distance x and versus the local intermittency γ in Fig. 11 and 12. They suggest that the spot generation starts more intensively at the larger *Le* but this difference disappears farther downstream (γ > 0.1). Maximum of the spot occurrence is near γ = 0.25 because then the spot production is effectively inhibited due to calming (see Ramesh and Hodson [20]). Mean length of identified turbulent regions arising from turbulent spots (Fig. 12) initially slowly grows regardless the L_e up to the location where γ > 0.7. This corresponds probably to identification of the individual spots and does not indicate an effect of the *Le*. Probably the merging of spots causes a dramatic increase of the mean length of turbulent regions farther downstream (Fig. 12).

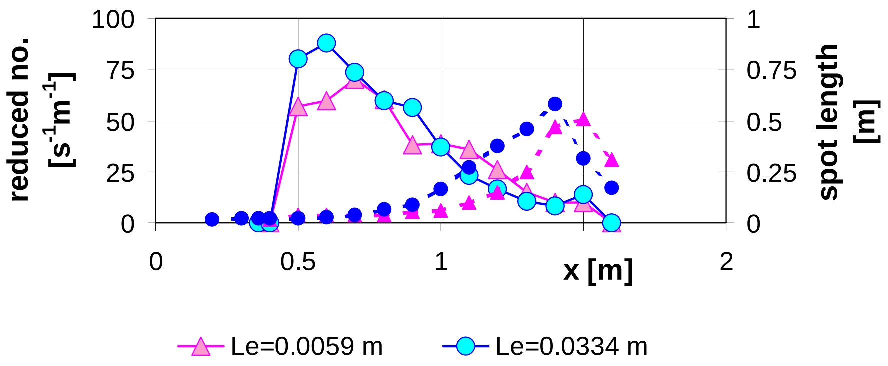

Figure 11 Distribution of reduced number (light colour) and mean length of the identified turbulent regions (bright colour) versus the distance x.

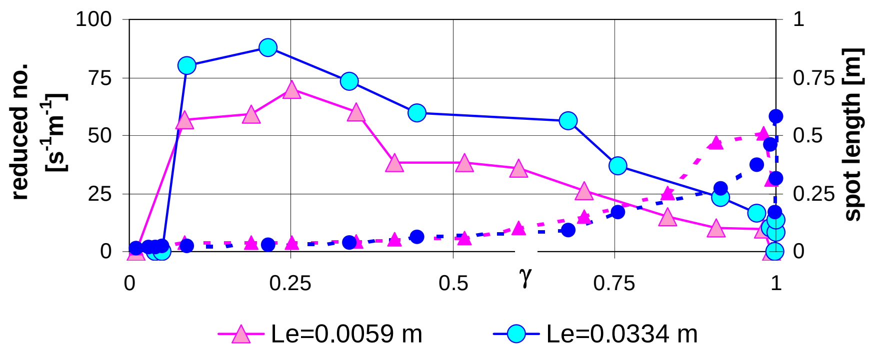

Figure 12 Reduced number and mean length of the identified turbulent regions versus intermittency factor (marks as in Figure 11)

Conclusions

Transitional intermittency factor distributions in boundary layer under turbulent flows with different length scales are compatible (Fig. 6) with the Narasimha [2] universal form but somewhat better correspond with intermittency model proposed by Fashifar [17]

The dimensionless spot production rates, $n^*\sigma$ evaluated from both the intermittency analysis and using wavelet analysis are in accordance mutually and also with the results of Fransson [18] (Fig. 7). The determined spot production rates, $n^*\sigma$ depend on the Reynolds number ΔRe_{tr}, defined with the length of the transition region, regardless on the Le like results received by Fransson et al. [18] at different free stream turbulence structure.

The dependence of spot production rates on turbulence level Tu (Fig.8) compared with models proposed by Fransson et al. [18] and Mayle [19] documents, that presented measurements support Mayle model if the local turbulence level, at the location of transition start, $x = x_{tr}$ is considered. It appears that the incoming flow turbulence length scale *Le* express itself by way of decelerating of turbulent motions decay with the increasing *Le* i.e. local increase of *Tu* (x).

The spot occurrence (Fig. 9, 10) is more numerous at larger length scale namely at the beginning of transition ($\gamma = 0.1$). Probably some spots excited by larger turbulent disturbances upstream the section of indifference Reynolds number survive the viscous damping and join those generating at the transition start. Difference disappears farther downstream ($\gamma > 0.1$). Maximum of the spot occurrence is near $\gamma = 0.25$ at different length scales because then the spot production is effectively inhibited due to calming effect. Mean length of identified turbulent regions arising from turbulent spots initially slowly grows regardless the L_e up to the location where $\gamma \approx 0.7$. This corresponds probably to identification of the individual spots and does not indicate an effect of the *Le*. Farther downstream $\gamma > 0.7$ a dramatic increase of the mean length of turbulent regions arises. Probably the merging of turbulent spots is the reason.

Acknowledgement

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