BY-PASS TRANSITION EXPERIMENTAL STUDY WITH A CONTROL OF OUTER STREAM TURBULENCE SCALES

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ABSTRACT

This paper aims at an experimental demonstration of the free stream turbulence velocity and length scales role in the by-pass boundary layer transition. The start/end of transition region was achieved at the same interval of locations by two ways. The first way was controlling of turbulence level at very small turbulence length scale changes and the second way was controlling of the turbulence length scale at constant turbulence level (COST/ERCOFTAC Test Case T3A+). The collected data can serve for searching of a proper turbulence parameter as a function of the free-stream turbulence scales applicable for universal description of the by-pass transition. Some attempts to find such a parameter have been done but without success since now.

1. MOTIVATION

The effect of the intensity of the outer stream turbulence fluctuations on the position of the transition region is well known since the forties. Recently, the effect of the outer stream turbulence length scale on the course of the flat plate boundary layer transition has been also shown, e.g. Jonas et al. (2000) and Roach and Brierley (2000). This effect was clearly demonstrated (Figure 1) in the framework of experiments carried out for the COST/ERCOFTAC Test Case T3A+, characterized by the parameters: flat-plate boundary layer; mean velocity U_e of 5 m/s; outer stream turbulence with the intensity Iu = 3% and different length scales, L_e at the origin of the layer, ($x = 0$).

$$Iu = \left(\sqrt{\overline{u^2}}\right)_e \Big/ \overline{U}_e \; ;$$

$$L_e = -\left(\overline{u^2}\right)_e^{3/2} \Big/ \left(\overline{U}\, d\left(\overline{u^2}\right)\big/ dx\right)_e \; ;$$

$$\mathrm{Re}_2 = \delta_2 \overline{U}_e / \nu \qquad (1)$$

where index “e” denotes values outside the boundary layer.

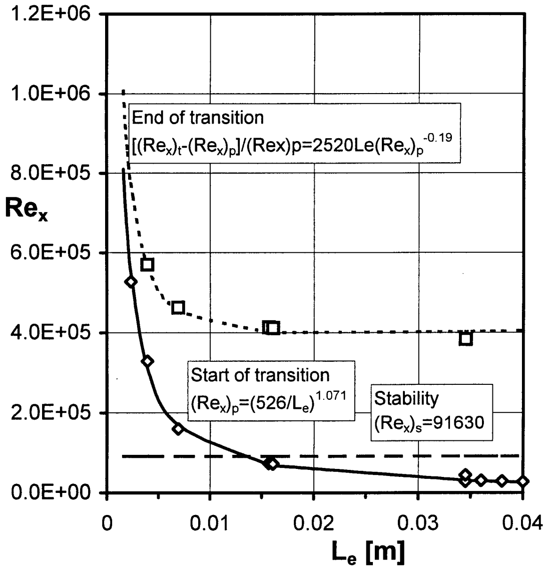

Figure 1: Influence of outer stream turbulence length scale on start/end of transition

Apparently, there are two ways how to move, in certain limits, the onset of by-pass transition. Either by controlling turbulence velocity scale of the outer stream maintaining the length scale broadly constant or making it conversely. The second way was undertaken in the framework of Test Case T3A+ study. Derived correlation of Reynolds numbers corresponding to the onset and termination of by-pass transition with the dissipation length parameter L_e (Figure 1) are valid at boundary conditions relating to the COST/ERCOFTAC Test Case T3A+

only. To receive correlation of more general validity, further experiments are necessary.

2. EXPERIMENTAL FACILITY AND MEASUREMENT TECHNIQUE

A series of experiments linked to experiments within the scope of the COST/ERCOFTAC Test Case T3A+ was executed at the Institute of Thermomechanics AS CR (IT). Experimental facility, the plate with the investigated boundary layer, measuring technique and boundary conditions were carefully maintained the same as during the measurements dedicated to Test Case T3A+. They are described by e.g. Jonas et al. (2000). The only dissimilarity from the prior measurements was the properties of the incoming turbulence. The turbulence was generated by a grid (mesh M = 5.75 mm, porosity 51%) perpendicular to the flow direction. This wire-screen turbulence generator is marked as GT8 in Jonas et al. (2000). Moving the grid towards the plate-leading edge (x = 0) caused increase in the intensity Iu (from 2.8 up to 16%) and decrease in the dissipation length parameter L_e (from 4 down to 1mm) at the leading edge plane.

The grid was placed across the flow at several distances $x = x_G < 0$ upstream of the plate to initiate the onset of transition close to the chosen sections $x = x_p$.

The turbulence intensity I_u as a function of the nondimensional distance from the screen x'/M is shown in Figure 2. The true distance downstream from the plane of the screen is

$$x' = x - x_G . \qquad (2)$$

Vertical lines denote the position of the leading edge at different sets of measurement.

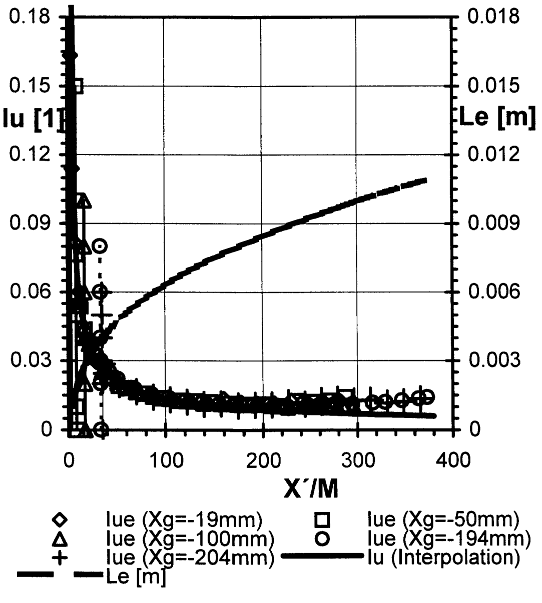

Figure 2:Decay of the outer stream turbulence

Taking the magnitude of the distance x'/M into consideration, in words of Batchelor and Townsend, the turbulence at the leading edge of the plate can be classified as in the building-up period of evolution in the configuration with the screen very near to the leading edge. The other generated kinds of turbulence can be classified as an initial and transition period of the grid turbulence development. The dashed line denotes the distribution of the dissipation length parameter L_e in Figure 2. The dissipation length parameter L_e may lose its physical meaning at the nondimensional distance of about 200 because farther downstream the turbulence intensity weakly increases. Owing to this the distributions of the lateral Taylor microscale λ_2 were evaluated. The determined ratios of the dissipation length parameter L_e and the microscale λ_2 are of order one. Thus, it was possible to derive the length scale also at more distant locations.

3. RESULTS

The changes of turbulence in the leading edge plane evoke a dramatic shift of position and extent of the transition region.

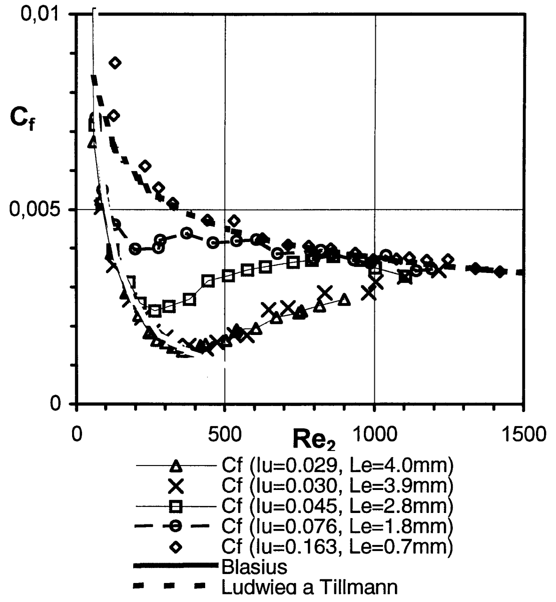

Figure 3: Skin friction coefficient distribution ($L_e \approx$ const, $Iu \sim$ var)

Figure 3 shows the distribution of the skin friction coefficient C_f along the plate as a function of the momentum thickness Reynolds number Re_2. The skin friction coefficient distribution as well as the distributions of other fundamental boundary layer characteristics, thicknesses of various kinds, shape factor H_{12} and intermittency factor γ, were evaluated from the mean velocity profiles.

We understand the start of transition as the beginning of turbulent spot formation accompanied with a departure of the mean flow parameter distributions from their laminar boundary layer counterparts (intermittency is still equal to zero). After the end of transition the mean velocity profiles and the mean flow parameter distributions approach the shape typical for a turbulent boundary layer – usually at a low value of the local momentum thickness Reynolds number Re_2 (intermittency factor attains the value equal one). Thus we determine the start of transition and the termination of the transition process on the bases of the courses of fundamental boundary layer characteristics, particularly from the C_f distribution.

From the distributions shown in Figure 3 it is evident that the turbulent boundary layer originates very near the leading edge if the screen is in the minimum distance upstream the leading edge. Maybe, a small separation region occurs at the origin of the layer in this case. However a well-developed logarithmic mean velocity profile was observed already in the section $x = 0.025$m in this case.

As has been awaited, with the increasing distance upstream from the leading edge the turbulence intensity decreases and the start of transition is moving downstream. With the largest distance between the screen-turbulence generator and the flat plate leading edge, the transition did not finished in the working section of the closed circuit wind tunnel (0.5 x 0.9 m^2).

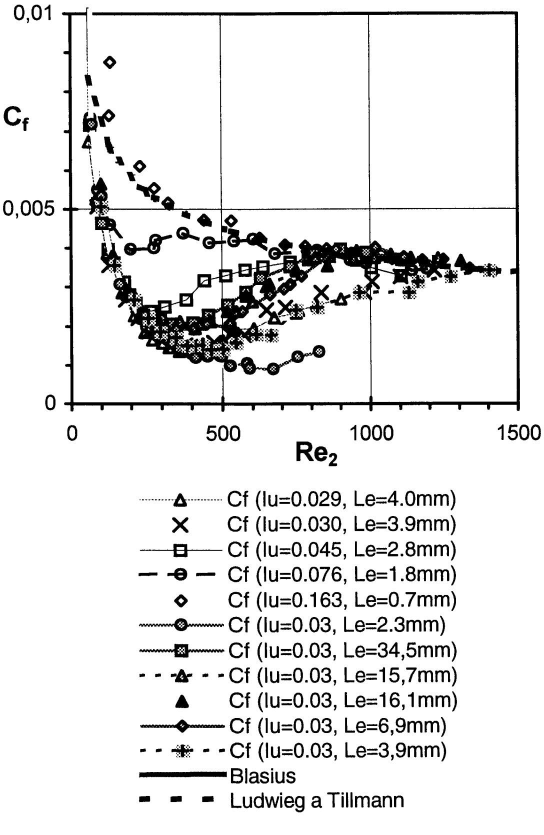

Figure 4: Skin friction coefficient distribution (L_e, Iu ~ var)

The distributions of these results and those from the Test Case T3A+ (Test Case) investigation are plotted as functions of the momentum thickness Reynolds number Re_2 in the Figure 4. The values of the intensity Iu and the dissipation length parameter L_e at the leading edge plane ($x = 0$) are introduced in the legend. It is obvious that we succeeded to overlap the regions of the transition start at both investigated kinds of boundary conditions. Apparently, there are two ways how to move, in certain limits, the onset of by-pass transition. Either to maintain the length scale constant controlling the velocity scale of outer stream turbulence, or to make it conversely. The analysis of the distributions of the shape factor and the intermittency leads to the same conclusion.

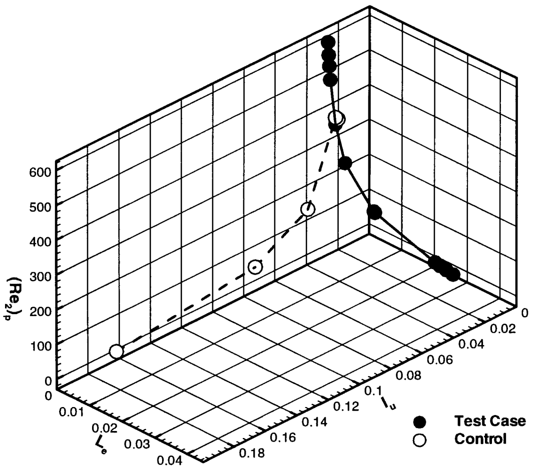

Figure 5: Onset Reynolds number against Iu and L_e

A clear vision of effect of both the velocity and the length scales of turbulence follows from the Figure 5. The derived values of the momentum thickness Reynolds number at the start of transition $(Re_2)_p$ are plotted as function of two variables I_u and L_e. It is not difficult to conclude that it would be a great task to determine the surface of the onset Reynolds number with a sufficient accuracy.

Neglecting influence of the turbulence length scale is one of the important reasons of the disparity of the published observations and of the unsatisfactory accuracy of prediction methods of the start and the end of by-pass transition.

This is apparent from the Figure 6, where the momentum thickness Reynolds number $(Re_2)_p$ corresponding to the transition start is plotted as a function of the outer stream turbulence intensity. Predictions according to Abu Ghannam & Shaw (1980), Fasihfar & Johnson (1992) and Mayle (1991) are compared with results obtained from our experiments. It should be mentioned that each of these predictions is consistent with the set of original experiments from which it has been derived.

The measured values of $(Re_2)_p$ are plotted as function of turbulence intensity at the origin of the boundary layer $I_u(0)=0.03$ (right marks) and along with this as a function of the local intensity $I_u(x_p)$ at the location x_p where the transition process begins (left marks). Obviously, the transition prediction based on turbulence intensity $I_u(0)$ fails.

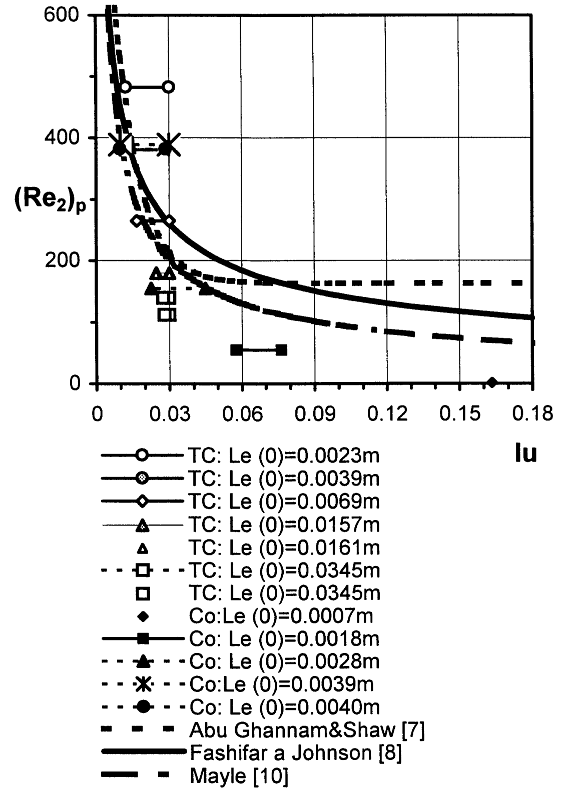

Figure 6: Reynolds number at the start of transition as function of the turbulence intensity.

However, as it is apparent from Figure 6, also the local turbulence intensity $Iu(x_p)$ alone is not sufficient for transition description by an one variable universal function.

Similarly, it is possible to demonstrate that the turbulence length scale is not applicable as a variable for description of the start and the end of the transitional boundary layer. The values of the momentum thickness Reynolds number at the start (circles) and at the end (squares) of transition as functions of the Reynolds number Re_L are shown in Figure 7. The Reynolds number Re_L is defined with the dissipation length parameter L_e as the length scale and with the outer stream mean velocity U_e as the velocity scale.

Obviously, the intervals of values $(Re_2)_p$ and $(Re_2)_t$ with the control of turbulence level (Control - marks without color)) overlap the corresponding intervals of Reynolds numbers with the control of the dissipation length parameter (Test Case – grey marks). However the courses Control and Test Case, of distributions $(Re_2)_p$ and $(Re_2)_t$, against Re_L differ from each other.

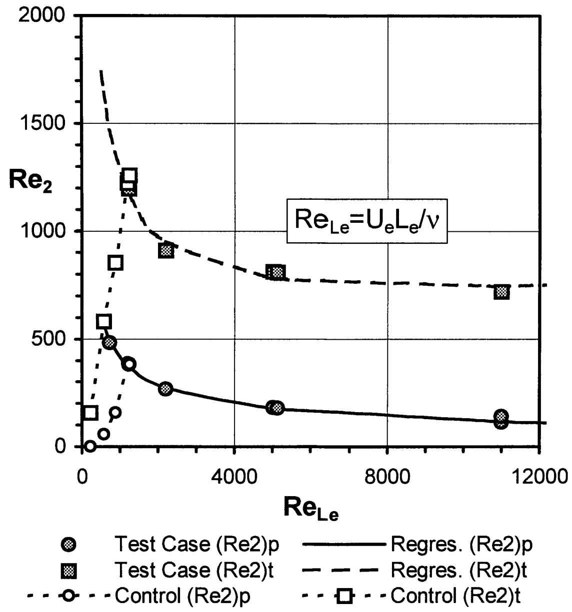

Figure 7: Momentum thickness Reynolds number at the start $(Re_2)_p$ and the end $(Re_2)_t$ of transition.

Similar differences between the distributions of $(Re_2)_p$ and $(Re_2)_t$ coming from two sets of experiments are observed with the other independent variables. E.g. with the turbulence Reynolds number Re_T as variable (Figure 8)

$$\mathrm{Re}_T = \sqrt{\overline{u^2}}\, L_e / \upsilon \; (at \quad x = 0) \tag{3}$$

and with the parameter $F(HAN)$ (Figure 8), proposed by Hancock & Bradshaw (1983)

$$F(HAN) = Iu / (L_e / \delta + 2) \tag{4}$$

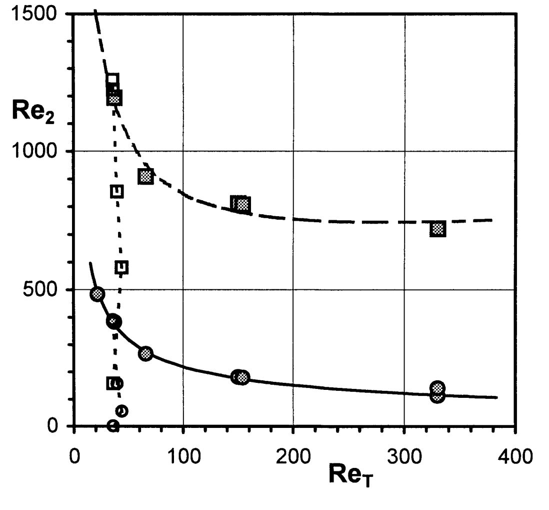

Figure 8: Momentum thickness Reynolds number at

It should be mentioned that the Hancock parameter $F(HAN)$ or its modification for low Re-numbers $F(CAS)$, proposed by Castro (1984) works well at

the description of the effect of the outer stream turbulence on a turbulent boundary layer. So we could expect that it would work at the end of transition. Unfortunately, it is not true.
the start $(Re_2)_p$ and the end $(Re_2)_t$ of transition.

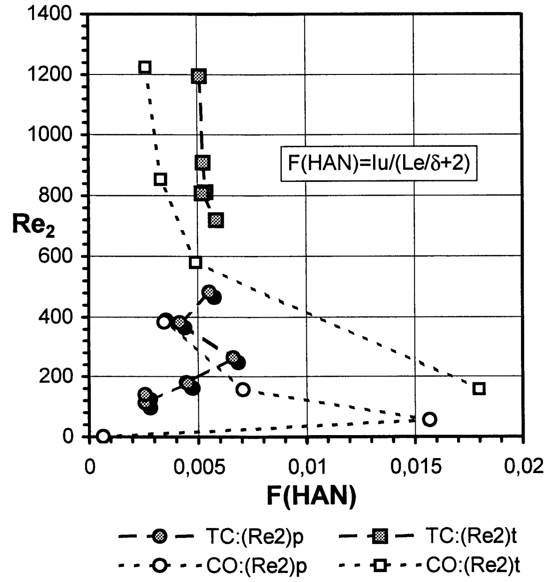

Figure 9: Momentum thickness Reynolds number at the start $(Re_2)_p$ and the end $(Re_2)_t$ of transition.

4. CONCLUSION

The experiments with the control of the turbulence velocity scale together with those referring to the control of the turbulence length scale (COST/ERCOFTAC Test Case T3A+) show that both scales of the incoming flow influence remarkably the position of the start and end of by-pass transition.

For the need of prediction methods development it is necessary to derive a proper turbulence parameter, function of *Iu* and L_e, applicable for universal description of the by-pass transition. The collected data can serve for the searching of such a parameter.

As it is apparent from the presented analyse, the intensities Iu at the origin of boundary layer, $x = 0$ or at the start of transition, $x = x_p$, the tested Reynolds numbers and the parameter proposed by Hancock are not the proper parameters for universal description of the by-pass transition.

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