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A BOUNDARY LAYER SEPARATION DYNAMICS

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***Summary**: Dynamics of separation process of a turbulent boundary layer subjected to adverse pressure gradient is studied experimentally. The Time Resolved PIV method is used to acquire spatiotemporal data of the flow field in the separation region. The flow-field in the vicinity of the separation zone is found to be extremely complex.*

Introduction

A boundary layer separation from the plane wall could occur in so called adverse pressure gradient condition, this mean its positive value along the wall. It is known (see e.g. Chang, 1970) the flow downstream the separation is highly dynamical in nature. The reason is that the separation point is not stable in location on the wall, forming zone of separation. Next, the separated free shear layer is unstable tending to transition to turbulence. Finally, the flow between the separated boundary layer and the wall (recirculation zone) is highly turbulent, thus dynamical in nature.

The details of the dynamical behavior of the flow in vicinity of the separation zone are still unknown. This study could contribute in this field.

Experimental setup

The blow-down aerodynamic rig of IT has been used for the experiment. The new test section for generation of adverse pressure gradient in channel was designed and manufactured.

In Fig. 1 the schema of experimental setup is shown. The section **A** represents the starting point of adverse pressure gradient region as well as the origin of the streamwise position coordinate **x**, The cross-section in **A** position is 100 x 100 mm^2. Downstream of this section, the upper wall is inclined with angle $\alpha = 16°$, while the bottom plane wall is used to study the boundary layer separation. To prevent separation from the upper wall, this is permeable and sucked out. The section **B** is the "mean" position of a boundary layer separation (please note, that the separation point is not stable).

The mean flow velocity in section **A** was 12.4 m/s, while the suction velocity could be estimated to 5 m/s.

From the point **C**, located 350 mm upstream the **A** section, the seeding for the PIV method was inserted. The spray 10 % solution of glycerol forming droplets 3 μm diameter in average was used. The turbulent boundary layer, approx. 3 mm thickness was detected in **A** section.

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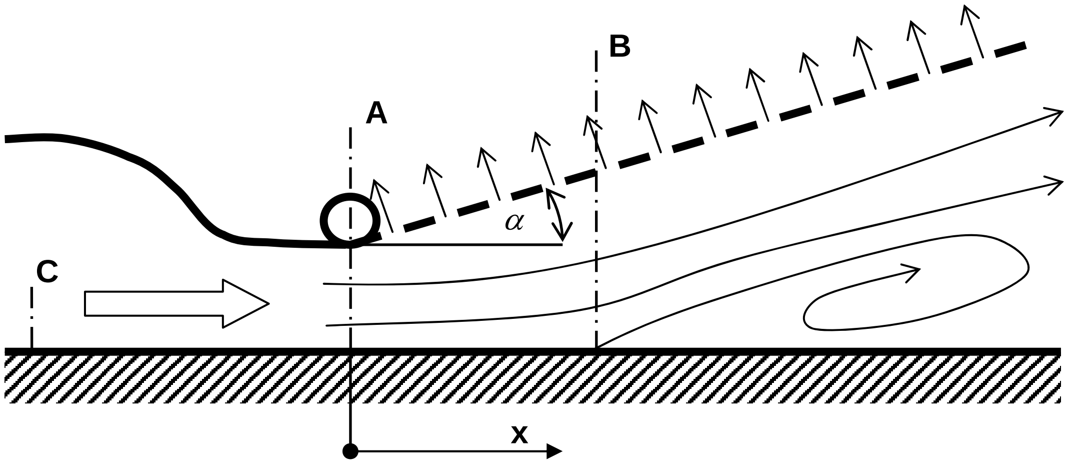

Fig. 1 – Schema of the experimental setup

In the paper the results obtained time-resolved PIV method are to be presented. The measuring system DANTEC consists of laser with cylindrical optics and CCD camera. The software FlowMap 3 was used for velocity-fields evaluation.

Laser New Wave Pegasus Nd:YLF, double head, wavelength 527 nm, maximal frequency 10 kHz, a shot energy is 10 mJ for 1 kHz (corresponding power 2 x 10 W). Camera NanoSense MkIII, maximal resolution 1280 x 1024 pixels and corresponding maximal frequency 512 double-snaps per second. The camera internal memory 4 GB represents 1635 full resolution double-snaps. From each double-snap the instantaneous vector-map of 63 x 79 vectors in the measuring plane has been evaluated using the adaptive evaluation method. So, we obtained 512 samples of instantaneous vector-maps per second, the total acquisition time was 3.2 s.

Static pressure as function of streamwise coordinate **x** is shown in Fig. 2. The value of the

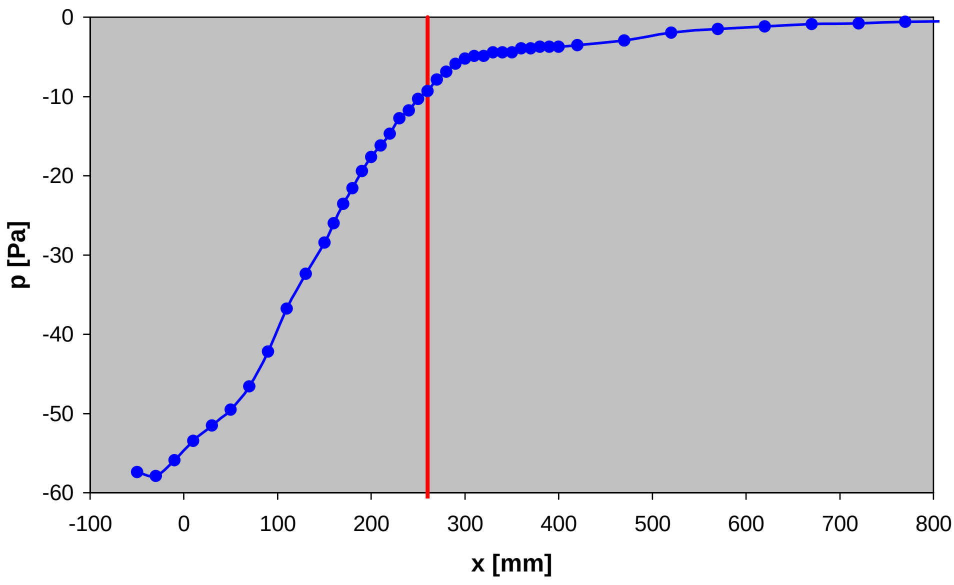

Fig. 2 – Wall static pressure distribution

wall static pressure gradient between sections **A** and **B** has been estimated on the basis of measured data about 0.2 Pa/mm. The mean separation position evaluated using the forward-flow-fraction coefficient (see next paragraph) is shown as a red line. This position could be considered as **B** section.

Results

The flow has been explored in the plane of symmetry in the boundary layer separation region.

To study the separation point dynamics, the forward-flow-fraction coefficient was evaluated. This coefficient was defined in Uruba et al. (2005), it evaluates the time fraction in which the parallel-wall velocity component is positive:

$$\mathbf{FFF} = \mathbf{T_F/T}$$

where **FFF** is forward-flow-fraction coefficient, $\mathbf{T_F}$ is additive time of forward flow and **T** is total time of observation. The value 1 corresponds to pure forward-flow, while 0 corresponds to pure back-flow. Obviously, the forward flow direction corresponds to positive value of streamwise velocity component U, while the backward direction corresponds to its negative value. It is natural to consider its value 0.5 in “mean” reattachment point position.

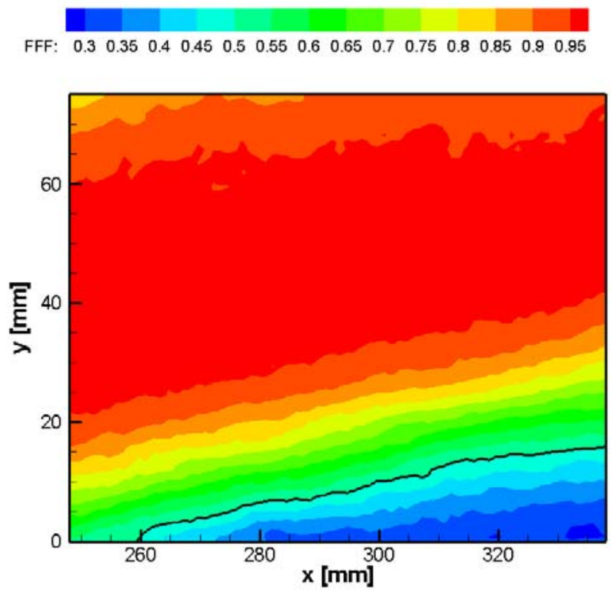

Fig. 3 – Distribution of forward-flow-fraction coefficient **FFF**

In Fig. 3 the forward-flow-fraction coefficient distribution is shown. The typical value of **FFF** in mean flow is about 0.95, indicating predominant forward flow direction. In the separated zone the **FFF** value falls down to 0.3 demonstrating highly perturbed predominantly backward oriented flow. The black line represents the value 0.5 satisfying the mean reattachment point definition at the wall.

To evaluate position mean reattachment point exactly, the evolution of **FFF** near the wall (**y** = 1 mm) is plotted in Fig. 4. The linear regression could be applied on data near the expected position of the mean reattachment point. This procedure indicates the mean reattachment point position, using the definition given above, the value **x** = 257.6 mm.

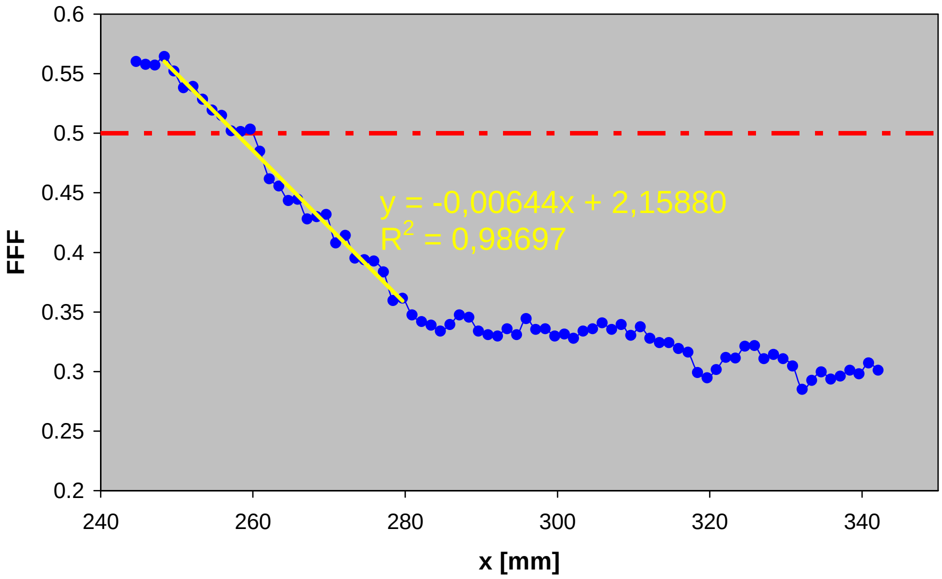

Fig. 4 –forward-flow-fraction coefficient **FFF** 1 mm above the wall

The mean velocity vector flow-field was studied in the reattachment region. In Fig. 5 distribution of the mean streamwise velocity component U is shown. The values of streamwise velocity are given in [m/s] in legend, the black line corresponds to zero value. The zero level line is clearly visible showing the position of the mean reattachment point on the wall. Its position coincides with this evaluated from the forward-flow-fraction analysis shown above.

The mean velocity vector modulus distribution is shown in Fig. 6. The low-velocity separation zone is clearly visible. The character of modulus distribution is very similar to this of mean streamwise velocity component, indicating that the transversal mean velocity components are insignificant.

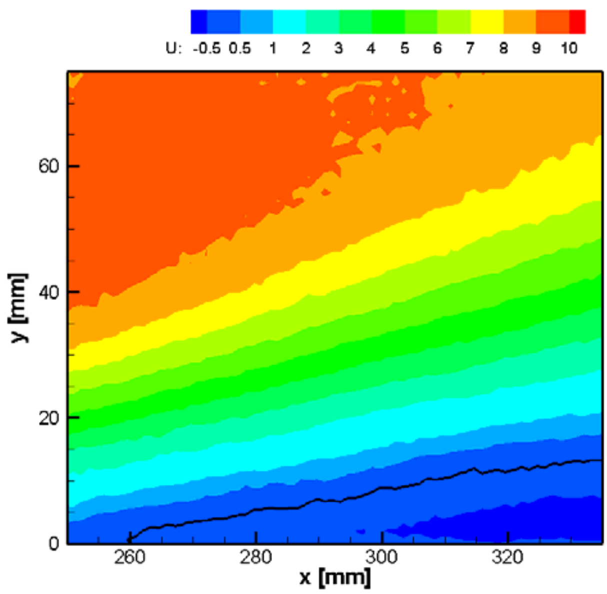

Fig. 5 – Mean streamwise velocity component **U** distribution

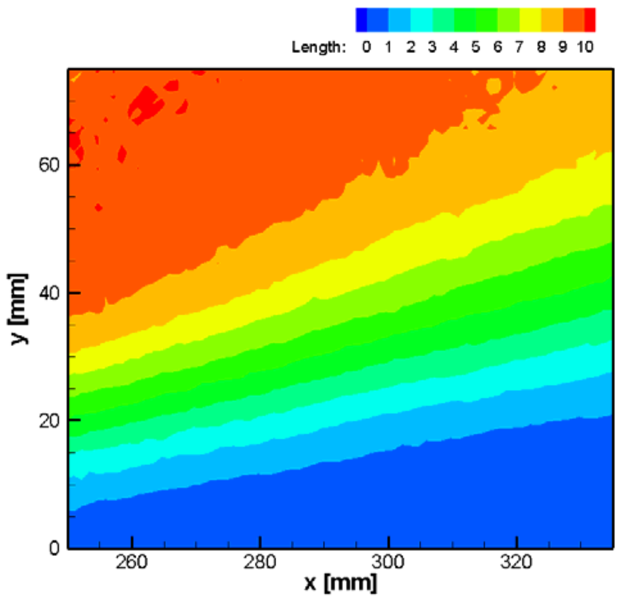

Fig. 6 – Distribution of mean velocity vector modulus

The local flow dynamics could be characterized with help of velocity fluctuation standard deviation. In Fig. 7 distribution of variance of mean velocity vector modulus is shown. The higher velocity modulus, the higher value of its variance. It is surprising, that relatively low fluctuation activity is indicated in the zone of recirculation, however, also velocity vector modulus is very small in this region (see Fig. 6).

To study the turbulence production, correlation coefficient of streamwise and spanwise velocity components was evaluated. The result is given in Fig. 8. High positive value was detected in the separation zone of recirculation, while negative values are in separated shear

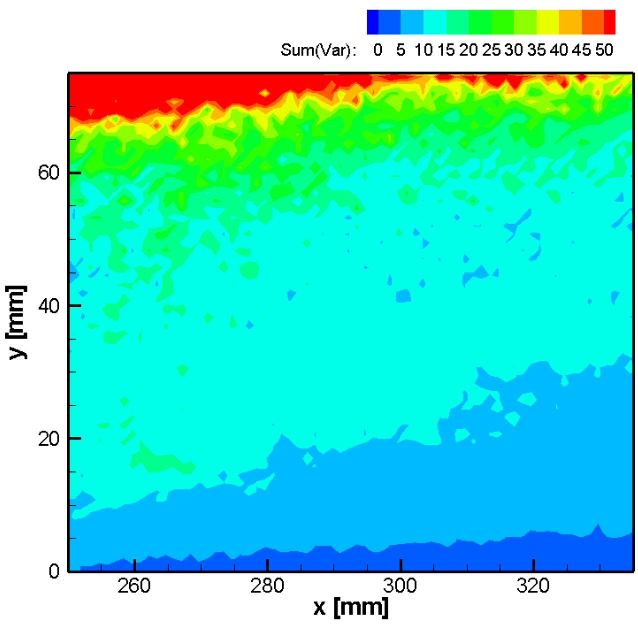

Fig. 7 – Distribution of mean velocity vector modulus variance

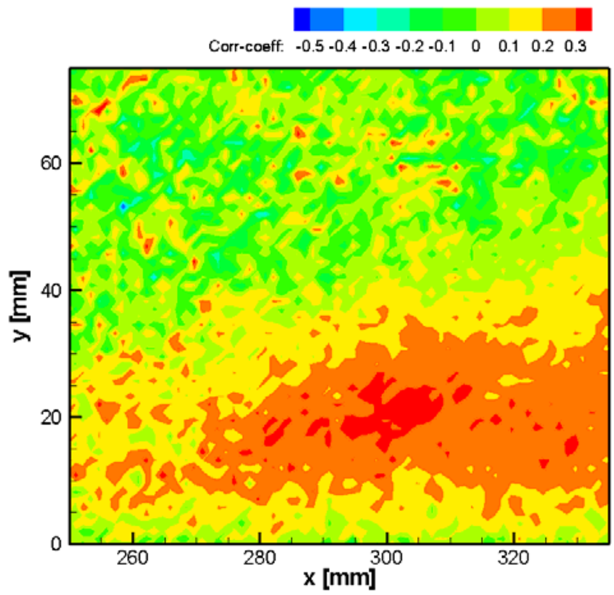

Fig. 8 – Distribution of correlation coefficient

layer.

Conclusion

The presented results have shown that dynamics of a boundary layer separation region is very complex and complicated process. The particular details of this process could provide valuable information for control of this process.

The systematic study of this process will continue in future in our laboratory. The lot of vortical structures was detected, especially in the zone of recirculation. The detailed study of their dynamics will be given next.

The main result of the presented experiments is experimental proof, that the new experimental device works satisfactory and it is ready for systematic research.

References

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