

# EXPERIMENTAL INVESTIGATION OF TURBULENT FLOW IN A CHANNEL WITH THE BACKWARD-FACING INCLINED STEP

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**Abstract:** *The work deals with the experimental investigation of turbulent flow in a closed channel with the backward-facing inclined step. Experiments were carried by means of the PIV optical measuring method in the channel of the rectangular cross-section in the inlet part and with inclined steps of the constant height  $H$  mm and various inclination angles for a wide range of the Reynolds number. The attention was paid especially to the separation region behind the step and to the relaxation of the shear layer after the reattachment in the outlet part of the channel. The dependence of the length of the separation region on the Reynolds number was obtained for various step angles. Optical measurements were completed by the measurement of static pressure distribution in the inlet and outlet part of the channel to estimate energy losses.*

## 1. INTRODUCTION

Channels with various types of expansion occur often in many technical applications, especially divergent channels with rectangular cross-section. Turbulent flow in one-sided plane diffuser is often used as the test case for evaluating of turbulence models (see e.g. Iaccarino [1] and results of ERCOFTAC workshop [2]). Flow over an inclined step is a link between a one-sided plane diffuser without flow separation and a channel with perpendicular backward-facing step with separation on the step edge. There are many publications dealing with flow in plane diffusers including their optimization, but equivalent results for turbulent flow over backward-facing inclined steps with angles higher than  $10^\circ$  are very rare. While data for energy losses in channels with plane diffusers and with an abrupt expansion can be found in literature, such data for flow over inclined steps with distinct separation are practically missing. The only extensive experiment was carried out by Makiola [3] and Ruck and Makiola [4, 5].

The presented paper deals with experimental investigation of turbulent flow in a channel of the rectangular cross-section with the inclined step with various inclination angles for various Reynolds numbers. Similar investigations of turbulent flow in the open water channel with an inclined step were carried out by Příhoda et al. [6, 7].

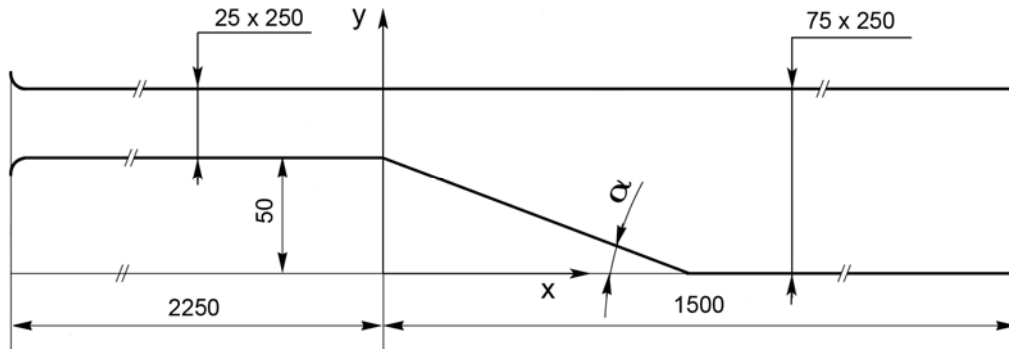
## 2. EXPERIMENTAL ARRANGEMENT AND MEASURING TECHNIQUES

Experiments were carried out in the blown-down wind tunnel equipped with the settling chamber, screens and the contraction nozzle. The test section was formed by the inlet

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part, the backward-facing step and by the outlet part. The inlet part has the rectangular cross-section  $25 \times 250$  mm and is 2250 mm long. The high aspect ratio 1:10 should secure the two-dimensional character flow in the middle part of the channel and the relative length  $L_1/H_1 = 90$  ensures the developed channel flow at the step. The inclined step with various angles of inclination  $\alpha = 20^\circ; 30^\circ$  and  $45^\circ$  was  $H = 50$  mm high and so the expansion ratio was  $ER = H_2/H_1 = 3$ . The outlet part of the cross-section  $75 \times 250$  mm was 1500 mm long including the step length. The test section was made of transparent plastic material allowing the use of contactless optical measuring techniques. The sketch of the test section is given in Fig.1.



**Figure 1: Sketch of the geometrical arrangement**

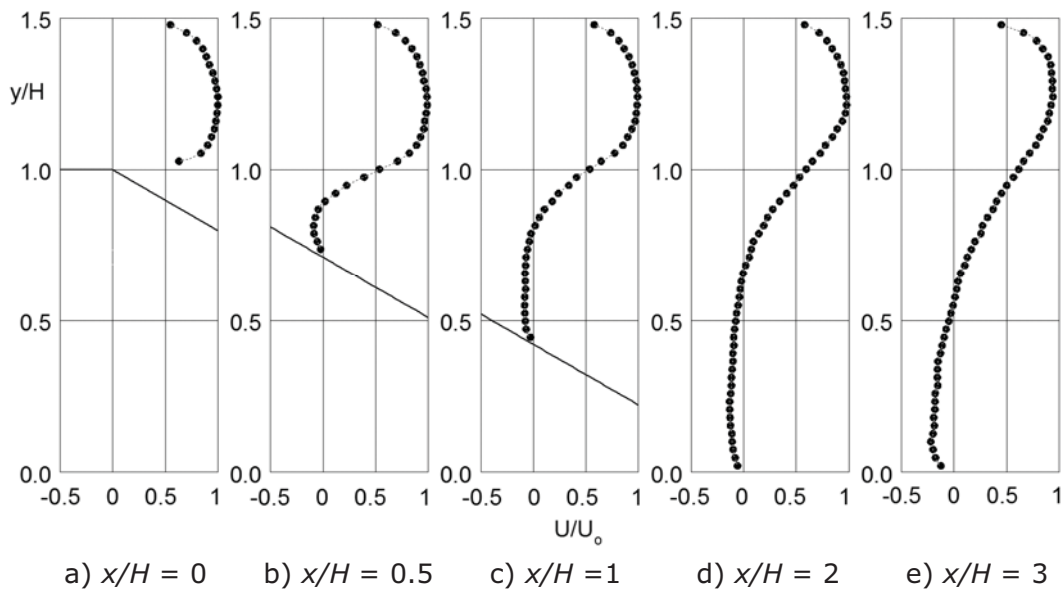
The flow field in the channel was measured with the Particle Image Velocimetry (PIV) system of Dantec Dynamics. The investigated area was illuminated by double pulse laser New Wave Gemini emitting a vertical laser sheet. The Safex F2010 seeded the flow with  $5\mu\text{m}$  tracking particles. The HighSense camera with the spatial resolution  $1280 \times 1024$  pixels recorded the area of dimensions  $120 \times 90$  mm. The camera was positioned on a traversing portal. This assembling was selected because of the length of investigated area. Sequential traversing improved the resulting spatial resolution of the velocity profiles in the channel. The PIV method is limited with the dynamical range of velocity. In the inlet part velocities reached up to  $45$  m/s, elsewhere they also came down to zero. Using sequential traversing and recording with appropriate parameter's values (double image delay, interrogation areas dimensions etc.) significantly better accuracy of measurement was obtained. Sequential vector maps were put together into one completed flow field. For each place, 100 records were captured for statistical evaluation of mean velocity and fluctuations. Due to PIV limits higher values of fluctuations are expected close to the walls. These fluctuations (respectively standard deviation) are caused also by errors of cross correlation algorithm (image noise and light reflections on walls). Measurement error beyond  $1.5$  mm from the wall does not exceed 3%.

Besides the optical measurements, the flat Pitot tube  $2 \times 0.3$  mm were used for measurements of mean velocity profiles in the plane  $x = -135$  mm. The static pressure was measured by the pressure probe  $\phi 1.5$  mm. The Pitot tube was traversed using the traversing system consisting of the DISA traversing unit and the stepping motor powered by the Microcon controller M1486. Expected error of the probe position was about  $0.02$  mm. The flow symmetry was checked by the measurement of velocity in the transversal direction. Further, the pressure distribution on the wall in the channel middle plane was measured to establish energy losses due to the enlargement of the cross-section by the inclined step.

The pressure measurements were carried out using the pressure transducers OMEGA PX653 with voltage output 1-5 V. Three transducers differing with ranges of differential pressure were used with maximal pressure corresponding to 0.1", 0.5" and 1" of water column respectively. The maximal error of the transducers was 0.3 %. The measuring software was created using the LabVIEW software system. The data acquisition has been accomplished using the Agilent 34970A Data Acquisition/Switch Unit. The temperature in the tunnel settling chamber was measured using the sensor AHLBORN Pt100 P444 311 with covered sensor (diameter 3 mm, precision class A). The error of temperature readings was 0.06°C, while error of voltage readings on used range 0-10 V was of order  $10^{-6}$  V. The 5 s records of voltage and temperature data were acquired, computing the mean value. The reference velocity was set using the Schilknecht water manometer with reading precision 0.05 mm H<sub>2</sub>O.

### 3. RESULTS

Experiments were carried out for angles  $\alpha = 20; 30$  and  $45^\circ$  and the Reynolds numbers  $Re_H = U_o H/\nu$  in the range from 70000 to 160000, i.e. for the maximum velocity range  $U_o$  from 22 to 48 m/s. As a reference plane, the cross section  $x = -135$  mm, i.e.  $x/H = -2.7$  was chosen.



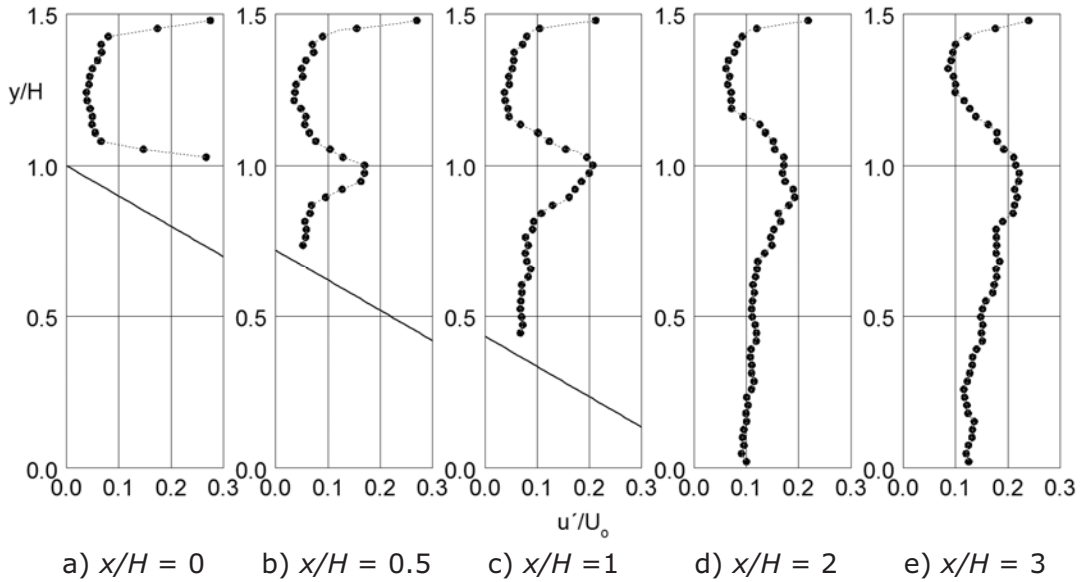
**Figure 2: Profiles of mean longitudinal velocity for  $\alpha = 30^\circ$  and  $Re_H = 7.3 \times 10^4$**

Fig.2 shows mean longitudinal velocity profiles in the symmetry plane over the inclined step and in the outlet channel for  $\alpha = 30^\circ$  and the Reynolds number  $Re_H = 7.3 \times 10^4$ . The mean velocity profile in the upper part of the channel follows the developed channel flow in the inlet part. The separation starts at the inclined step edge and the separation region covers approximately the length  $6.5H$ .

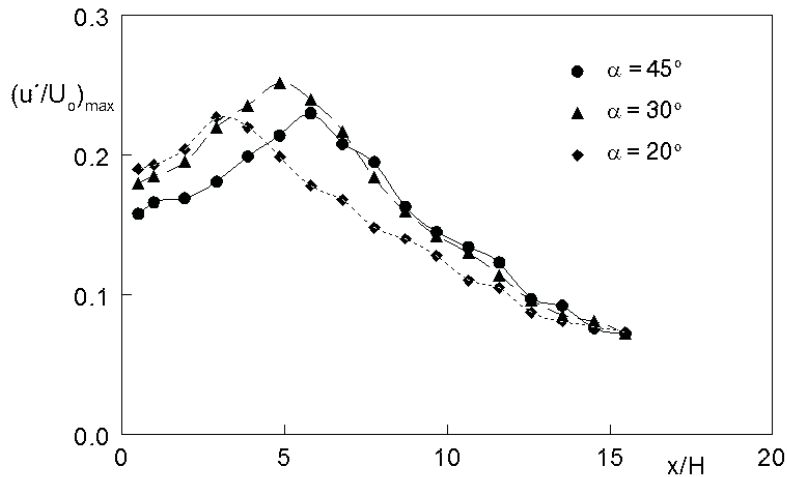
Profiles of longitudinal velocity fluctuation  $Tu = u'/U_o$  are given for the same flow regime in Fig.3. The turbulence level in the middle part of the inlet channel is about  $Tu = 5\%$  and reaches in the reverse flow region values about  $Tu = 10 - 15\%$ . The maximum of longitudinal turbulent fluctuations behind the step is situated in the mixing layer on the boundary of the reversal flow region approximately at the distance  $y/H \approx 1$ . The

maximum value of turbulence level is about  $Tu = 25\%$  and lies at the distance  $x/H = 5$  behind the step edge.

The distribution of the maximum of longitudinal velocity fluctuations behind inclined steps is shown in Fig.4 for the Reynolds number  $Re_H = 7.3 \times 10^4$ . After the reattachment the maximum begins to decrease and reaches values  $(u'/U_o)_{max} \approx 0.07$  at the distance  $x/H = 16$  for all inclined steps.



**Figure 3: Profiles of longitudinal velocity fluctuations for  $\alpha = 30^\circ$  and  $Re_H = 7.3 \times 10^4$**

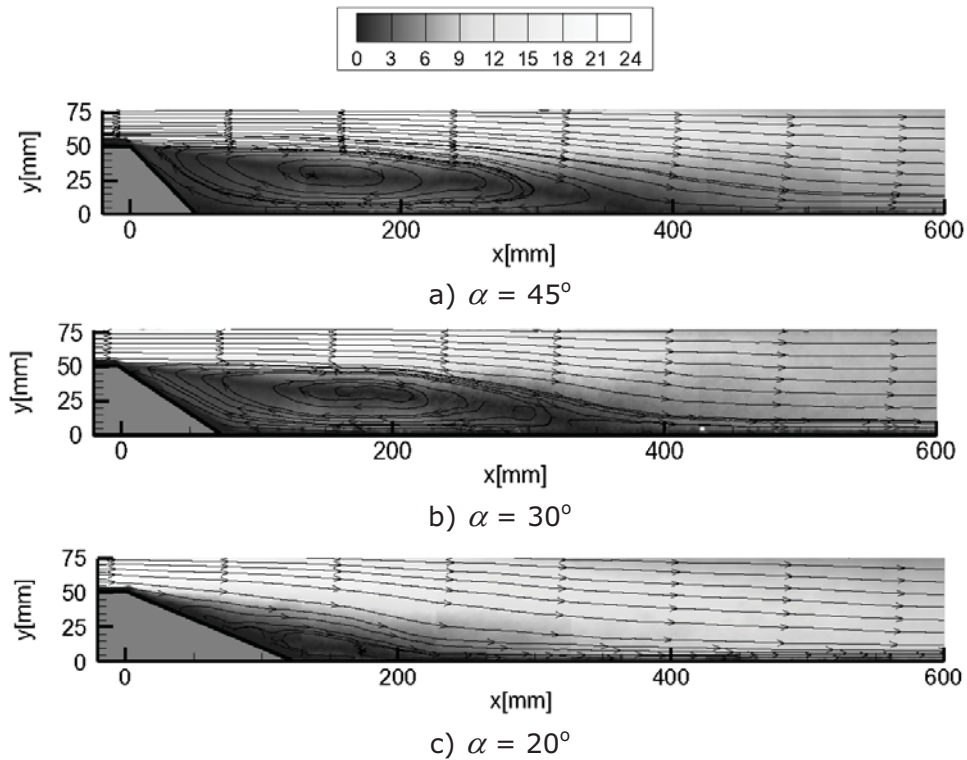


**Figure 4: Distribution of maximum longitudinal velocity fluctuations for  $Re_H = 7.3 \times 10^4$**

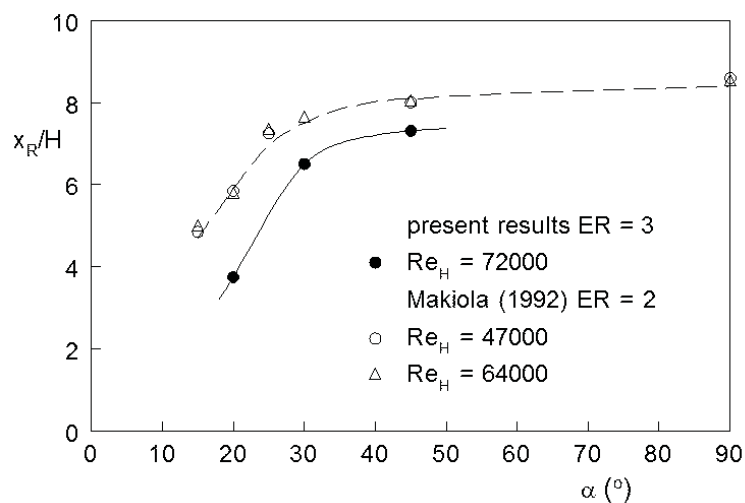
Mean velocity field in the channel with various inclined steps is illustratively shown in Fig.5 for the Reynolds number  $Re_H = 7.3 \times 10^4$ . The recirculating flow with relatively low mean velocities is clearly obvious. It can be seen that the extent of the separation region for angles  $\alpha = 30$  and  $45^\circ$  is roughly same, but it is substantially smaller for  $\alpha = 20^\circ$ .

The variation of the reattachment length  $x_R/H$  with the inclination angle  $\alpha$  is given in Fig.6. Present results obtained for the expansion ratio  $ER = 3$  are compared with data of

Makiola [3] for the backward-facing and inclined steps with the expansion ratio  $ER = 2$ . The reattachment length is dependent as on the geometrical arrangement particularly on the expansion ratio and the inclination angle as on flow conditions. For turbulent flow, the reattachment length  $x_R/H$  is not dependent on the Reynolds number for values  $Re_H$  higher than approx. 15000, but the inlet turbulence level has a significant effect on the length of the separation region, see Příhoda [8]. Changes of the reattachment length with the inclination angle are the same in the both cases, but experimental data obtained for  $ER = 3$  are rather lower due to higher turbulence level.



**Figure 5: Mean velocity field in the channel with various inclined steps for  $Re_H = 7.3 \times 10^4$**



**Figure 6: Variation of the reattachment length with the inclination angle**

#### 4. CONCLUSIONS

The experimental investigation of turbulent flow in a rectangular channel with the inclined step was carried out by means of the PIV technique for inclination angles  $\alpha = 20; 30$  and  $45^\circ$  and Reynolds numbers  $Re_H$  in the range from 70000 to 160000. The analysis of experimental data was concentrated mainly on the development of flow separation behind the inclined step and the relaxation of the shear flow in the outlet part of the channel.

The separation starts at the inclined step edge and the separation region covers approximately the length  $6.5H$  for  $\alpha = 30^\circ$  and  $7.3H$  for  $\alpha = 45^\circ$  respectively. The separation length decreases substantially with the decreasing inclination angle. The maximum of longitudinal turbulent fluctuations behind the step is situated in the mixing layer on the boundary of the reversal flow region and the highest value approximately corresponds to the reattachment position. The reattachment length  $x_R/H$  is independent on the Reynolds number for values of  $Re_H$  higher than approx. 15000, but is dependent on the expansion ratio and especially on the inlet turbulence level.

#### 5. ACKNOWLEDGEMENT

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