Mean Structure of the Flow over Backward Facing Step in a Narrow Channel

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Abstract Flow structure behind the backward facing step in a narrow channel was studied in details. The step height was 25 % of the channel width. The structure of the region just behind the step forming the back-flow region was subjected to experimental investigation using stereo PIV technique. Time-mean 3D structures behind the step are evaluated and shown in the paper.

1 Introduction

The backward facing step flow has been established as a benchmark configuration for separated flow studies in fluid mechanics. The presented paper deals with 3D backward-facing step at high Reynolds numbers (order of $5\ 10^4$ based on hydraulic diameter of the inlet channel and the bulk velocity just upstream the step edge). A back-facing step configuration of a channel occurs in many engineering applications ranging from various fluidic elements, cooling of turbine blades, air-conditioning pipelines to many other devices.

Flow separation on the step edge is a source of pressure loss, vibrations, and noise and affects heat transfer (reattachment region corresponds to maximum heat transfer however low-heat transfer appears in separation region). Turbulent shear flow in channels with sudden expansion of the cross-section could be met very often in many technical applications in mechanical and civil engineering. This flow belongs to the complex-flow family defined in the pioneering paper by BRADSHAW (1971). The flow over a backward-facing step is a very simple as to its geometry but the flow structure is extremely complex.

The flow-field in the recirculation region is described in URUBA et al. (2006). Initially, a couple of nearly stable contra-rotating corner vortices in the channel input near sidewalls are passing towards the plane of symmetry, they are pushed downwards in the same time. Then, they form a kidney-shaped common footprint on the bottom wall behind the step (confirmed by wall visualization). Finally, the vortices rebound from the wall pointing up and turning downstream being pressed to the center of the channel.

2 Experimental setup and methods

The existing blow-down test rig was modified for experiments with the separated flow in a channel with a backward facing step. The tunnel has rectangular cross-section with filled corners (to suppress corner vortices), honeycomb and a system of damping screens followed by contraction with contraction ratio 16. The area of the test section input is 0.25 m in height and 0.1 m in width. The time mean velocity departures from homogeneity in planes perpendicular to the tunnel axis are of order tenth of percent with the exception of corners, where corner vortex starters could be detected. Reynolds number based on the hydraulic diameter of the inlet channel and volume velocity was about $5\ 10^4$, while that based on step height was approximately $3.5\ 10^4$. Conventional thickness of boundary layer at the step tip was approximately 0.003 m. The natural turbulence level was about 0.1% in the working section input. The channel downstream the backward facing step was 1 m in length, and the ratio of the input channel width to the step height was 4.

The time-resolved PIV method was used for the experiments. The measuring system DANTEC consists of laser with cylindrical optics and two CCD cameras with Scheimpflug correction. The software Dynamics Studio 3.2 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 10 W per head). Cameras NanoSense MkIII have maximal resolution 1280 x 1024 pixels and corresponding maximal frequency 512 double-snaps per second. For the presented measurements the frequency 50 Hz and 400 double-snaps in sequence corresponding to 8 s of record for mean evaluation was acquired in each measuring plane (see Fig. 2) to obtain data for time-mean structure evaluation.

3 Results

In Figure 1, the test section is shown. The flow is entering from the left over the step (in grey), the coordinate system has origin on the step edge in the middle of the channel. The *z* axis is oriented in the flow direction, *x* forming the step edge, *y* is perpendicular to the flow and to the step edge. Measurement planes are (*xy*), all 3 velocity components are evaluated in the measuring planes. However, the measuring planes cover only part of the channel close to the bottom, *y* = -25 to 30 mm.

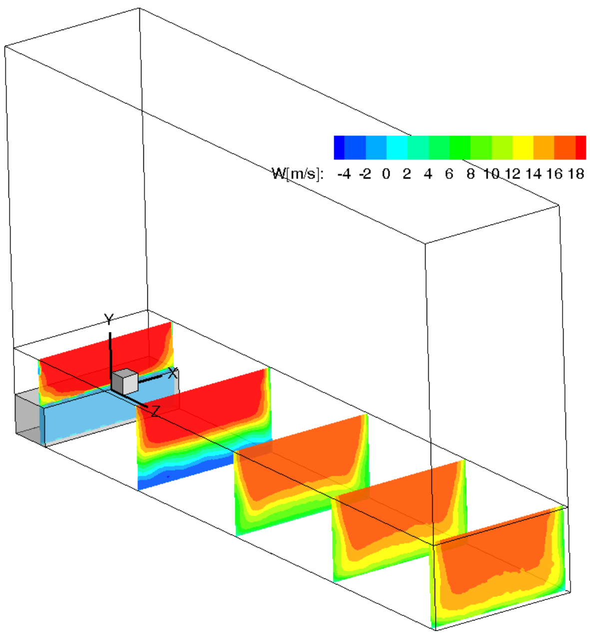

Fig. 1 Channel with step.

In Figure 1 distributions of *W* velocity component are shown in 5 planes along the inspected region. Distribution of all measuring planes is shown in Figure 2.

The velocity field was interpolated within the measuring zone and analyzed in details. Special attention has been paid to the recirculation zone with kidney-shaped footprint coming from the wall visualization, see URUBA et al. (2007), where hypothesis of presence of a counter-rotating vortex pair is presented. Surprisingly, no distinct vortical structures have been detected in the mean velocity field within that region in the obtained velocity data.

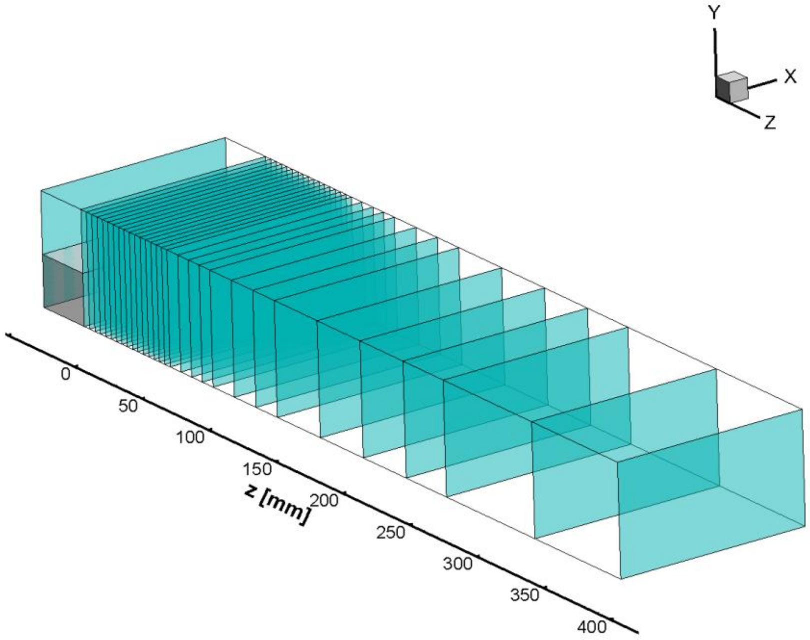

Fig. 2 Measuring planes.

In Figures 3a and 3b the distributions of *V* and *W* mean velocity components are shown in horizontal (*xz*) plane close to the bottom (only 5 mm above, *y* = -20 mm).

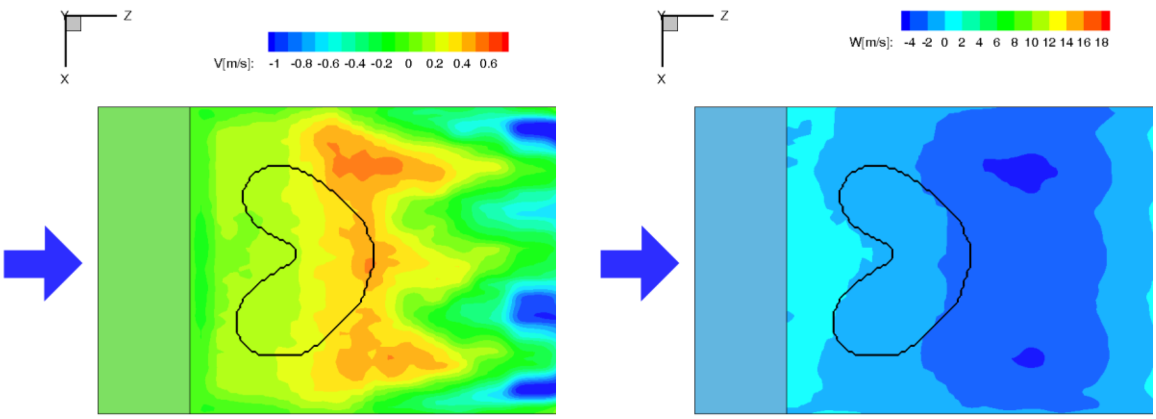

Fig. 3a, b Distributions of *V* and *W* in the plane *y* = -20 mm.

The results reveal intense rising flow downstream the footprint forming trident shape in red in Fig. 3a. In that region maximal negative longitudinal velocity component is seen in Fig. 3b indicating intense back-flow *W* ≈ -2 m/s.

The high positive vertical velocity component region in trident shape was studied in detailes. As the maximal value of the vertical velocity is about 0.6 m/s, the isosurface on *V* = 0.4 m/s was chosen for visualisation – see Figure 4.

The structure originates in corners on the top of the step forming two elongated structures, the thirdth elongated structure arizes in the middle of the channel.

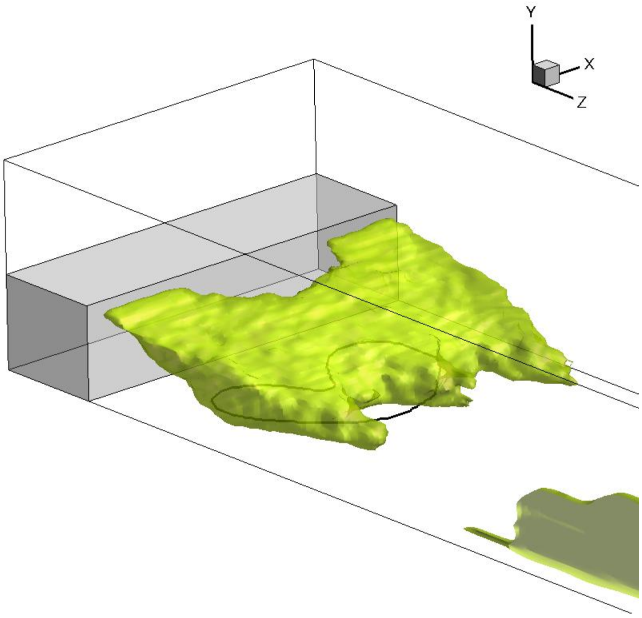

Fig. 4 Isosurface of *V* = 0.4 m/s.

The flow perpendicular to the wall generates a low pressure region close to the wall, resulting in wall shear distribution forming a kidney shape.

4 Conclusion

The time mean structure of the flow behind a step in a narrow channel was shown. The footprint behind the step is not connected with vortical structures, as formulated in older studies, but the low pressure generation close to the channel bottom in the recirculation region seems to be more relevant.

To explain the existence of the kidney footprint, further experiment will be necessary, especially those analyzing the flow dynamics. A few other results are shown in URUBA & JONÁŠ (2012).

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