Validation of SIV measurements of turbulent characteristics in the separation region

N S Dushin¹, N I Mikheev¹,², O A Dushina¹, D I Zaripov¹, A K Aslaev²

¹Kazan Scientific Center of the RAS
Russia, 420111 Kazan, Lobachevskogo str., 2/31
²Kazan National Research Technical University named after A N Tupolev - KAI
Russia, 420111 Kazan, K Marx str., 10

Abstract. Temporally and spatially resolved 2D measurements are important for the studies of complex turbulent flows. The recently developed SIV technique (Smoke Image Velocimetry), which is superior to PIV in some cases, can be used for this purpose. SIV validation results are presented for the steady turbulent backward-facing step flow measurements. Velocity profiles and Reynolds stress profiles are given for the regions of oncoming flow, reverse flow, flow reattachment and relaxation. The Reynolds number based on the step height and oncoming flow velocity at the boundary layer edge was Re₉ = 4834. The obtained data have been compared to LDA measurements and DNS.

1. Introduction
The optical method of PIV is widely used for flow measurements [1]. Non-intrusiveness and ability to measure instantaneous spatial distributions of actual velocity components are among its main advantages. At the same time, hot-wire anemometers are still employed when high spatial and temporal resolution is required. The developers of 2D optical measurement methods are constantly improving the PIV capabilities. Time-resolved PIV with high-frequency high-power lasers have been used for several years [2]. High-speed cameras and continuous-wave lasers have been recently combined in PIV systems [3]. Such an approach allows acquisition of sequences of velocity fields with the time interval equal to a high-speed camera exposure time. At the same time, PIV has a limitation which constrains implementation of characteristics of the above mentioned approach. This is low reflectivity of tracer particles. Therefore further improvement of time-resolved PIV is mainly associated with increase in optical sensitivity of camera sensors and laser power.

Authors [4] submitted a modification of optical measurement methods which is based on digital processing of smoke image visualization videos (SIV technique). Such an approach enables both to significantly increase the reflectivity of measurement area illuminated by the light sheet and level down the requirements to light sheet power. However, in this case the cross-correlation algorithm employed by PIV appeared to be inapplicable to processing of video frames with continuous pixel intensity [5, 6]. For this reason SIV employs not a sloping peak of the cross-correlation function but a sharp minimum of the functional of absolute differences in pixel intensities to estimate the displacement of interrogation windows with the accuracy up to one pixel. It has been shown that the shape of the surface formed by the functional close to the minimum is nearly conical. Thus, subpixel interpolation with a second-order surface is performed in SIV.
SIV testing results obtained so far show that SIV allows the study of high-speed processes with time resolution comparable to constant temperature hot-wire anemometer, high spatial resolution and accuracy not inferior to up-to-date PIV techniques [4, 7]. Thus, SIV is a promising technique but more thorough testing should be performed for different flow cases prior to its extensive application.

The paper estimates applicability of SIV to turbulence measurements in the separation region downstream of a backward-facing step. The backward-facing step flow is a well-known benchmark problem with simple configuration and repeatability of measurements and calculations. This is why this case is often involved in testing of measurement methods and numerical studies of turbulent flows.

Widely acknowledged results from papers [8, 9] were used for validation of measurement results. LDV measurements and DNS performed in these respective papers are in good agreement with each other. The comparison between SIV measurements and the results from [8, 9] are correct because the similarity of geometry and hydrodynamics of the test section was provided.

2. Experimental setup and measurement parameters
The characteristic size of the channel with a backward-facing step is the step height. The latter was chosen allowing for the following factors: velocity gradient over the height of the reference interrogation windows should not exceed 10%; there should be no less than 8 independent reference interrogation windows; the displacement of reference windows should not exceed half of their characteristic size; the flow rate through the suction fan for the given dimensions of the test section should provide self-similarity in the Reynolds number. The step height \( h = 12.5 \text{ mm} \) meets the listed requirements. Thus, the channel cross section was \( 75 \times 150 \text{ mm}^2 \) and the length was 1170 mm (figure 1).

The backward-facing step was mounted 570 mm downstream of the channel inlet. The measurement section and the step were made of transparent material (polycarbonate). A 2D smooth inlet duct was attached to the measurement section inlet. It was shaped according to the Bernoulli lemniscates curve and had a contraction ratio of 5.5:1. To turbulize the flow and fix the point of laminar-turbulent transition, a turbulence generating grid (made of wire with the diameter of 1.4 mm and spacing of 6 mm) was mounted at the measurement section inlet and a P24 abrasive was glued to the channel perimeter.

![Figure 1. Schematic of the experimental setup.](image)

Stability of the air flow rate through the measurement section was provided by the valves, receiver and suction fan characteristics. The volume flow rate was measured by an ultrasonic flow meter IRVIS-RS4-Ultra with the accuracy of no worse than 1%. The flow meter was installed between the receiver and the suction fan.

Smoke was supplied to the flow by a smoke generator Safex (MT-Gravity fluid with medium fog density). The smoke particles size varied from 0.1 to 5 \( \mu \text{m} \). To provide uniform flow seeding, the smoke preparation chamber with the volume of 0.864 \( \text{m}^3 \) was mounted upstream of the measurement
section inlet. The smoke was supplied through the chamber’s sidewall at the distance of 1 m from the inlet.

Smoke visualization was recorded by a monochrome high-speed camera Fastec HiSpec with a high-aperture lens Navitar. Continuous-wave DPSS laser KLM-532/5000-h was used for light sheet generation. The highest laser power was 5 W. The videos were recorded with the frame rate of 12237 fps. For this reason the frame size was reduced. Therefore the measurement region was a narrow band snapped to a given section.

The measurements were conducted in 4 sections: \(x/h = -3; 4; 6; 10\). The origin of the streamwise coordinate \(x\) was counted from the section in which the step was mounted. Thus, the measurements were performed in the oncoming flow region, reverse flow, reattachment region and flow relaxation zone.

The parameters of the considered flow, video recording adjustments and image processing parameters are summarized in tables 1 and 2.

**Table 1.** Flow parameters

| Parameter                                              | Value  |
|--------------------------------------------------------|--------|
| Reynolds number based on the step height, \(Re_h\)     | 4834   |
| Reynolds number based on the channel height in the section \(x/h = -3\), \(Re\) | 25139  |
| Oncoming flow velocity at the boundary layer edge in the section \(x/h = -3\), \(u_0\), m/s | 5.84   |
| Boundary layer thickness in the section \(x/h = -3\), \(\delta\), mm | 13.56  |
| Friction velocity, \(u_\tau\), m/s                      | 0.295  |
| Turbulence intensity, \(Tu\), %                        | 3      |

**Table 2.** Parameters of video recording and image processing

| Parameter                                              | Value  |
|--------------------------------------------------------|--------|
| Frame rate of the recorded video, \(F\), fps           | 12237  |
| Number of frames in one sequence                       | 10000  |
| Exposure time, \(\mu\) s                              | 10     |
| Measurement region, pixel\(^2\) (mm\(^2\))             | 62\times704 (2.4\times28) |
| Scaling factor, \(K_s\), pixel/mm                      | 18.28  |
| Size of the reference interrogation window, pixel\(^2\) | 32\times8 |

3. **Results and discussion**

Figure 2 compares the measured velocity profiles to the data from [8, 9]. The obtained results are in good agreement in all sections. Special attention was paid to the measurement of velocity profile in the section \(x/h = -3\), since the latter determines the validity of comparison between the profiles measured further downstream. Besides, measurements performed in this section yield the flow velocity at the boundary layer edge, the boundary layer thickness and the turbulence intensity of flow. Excellent agreement with the literature in the section \(x/h = -3\) was obtained for the turbulent fluctuations of velocity (figure 4). The behavior of velocity in sections \(x/h = 4\) and 6 and near the wall shows that the flow reattachment point in the present experiments was slightly upstream if compared to the paper [8].
Figure 2. Streamwise velocity component profiles.

Velocity profiles plotted in wall coordinates (figure 3) demonstrate that SIV yields better results and allows valid measurements in the viscous sublayer (the minimal coordinate obtained in the experiments was $Y^+ = 3.2$). The inclination angle of profiles in the logarithmic law region showed that streamwise pressure gradient was negligible.

Disagreement of profiles in $x/h = 10$ section is attributed to the fact that the friction velocity for all cases considered in the present paper was estimated according to Klauser unlike the paper [8] where the skin friction coefficient was measured directly using a laser interferometer. However, SIV results are in better agreement with the theoretical curve.

Figure 3. Velocity profiles in wall coordinates.

The normalized Reynolds stress profiles are plotted in figure 4. The profiles agree well up to the height of $y/h = 2$. Some disagreement is observed for the points located higher. This is attributed to different turbulence intensity in the measurement sections. One can also note that while the disagreement with the literature is within the measurement uncertainty, the profiles of transverse
fluctuations are in better agreement than the streamwise fluctuation profiles. Such behavior is typical of developing flows [10].

![Figure 4](image_url)

**Figure 4.** Streamwise (a), transverse (b) and mixed product (c) of turbulent velocity fluctuations.

**Conclusions**

SIV measurements of velocity profiles and Reynolds stress profiles have been performed in the backward-facing channel flow in the regions of oncoming flow, recirculation, reattachment and relaxation of flow. Steady flow case was considered. It has been shown that the considered flow exhibited slightly higher turbulence intensity compared to the papers taken for reference. Therefore the obtained profiles of streamwise turbulent fluctuations of velocity agree well with LDA measurements and DNS only up to $y/h=2$. Measurements in the near-wall region have been performed down to the coordinate $Y^+ = 3.2$. They agree well with LDA measurements and theoretical velocity profile. Thus, it is possible to conclude that SIV performs well in the considered flows, and it can be used to study the flows with significant velocity gradient, reverse flow and a wide range of vortex dimensions.

**References**

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