3D structure of flow in the near field of the quasi-two-dimensional turbulent jet

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Abstract. The work explores the three-dimensional structure of the near field of a quasi-two-dimensional turbulent jet. The jet stream forms at an outflow from the rectangular channel with aspect ratio B/h equal to 1:2.5 into the channel, formed by two plane-parallel plates. The experiments were carried out for a wide range of Re number from 2 000 to 20 000. The measurements were performed using Tomographic PIV method with high time resolution. It is shown that for the whole investigated range of Re number in the near-field of the quasi-two-dimensional jet, there are formed secondary flows, caused by the presence of longitudinal vortex structures in the flow.

1. Introduction

Bounded turbulent jet flows are widely presented in various technical applications. Initially, the interest in the study of confined jet flows was due to the development of jet logical elements for military and space purposes [1, 2, 3, 4]. These works concerned the study of the effect of the bounding walls on the flow structure in the near field of the jet and aimed at the development of methods for the jet flow control. The studies have shown that the structure of the jet flow, top-bottom bounded by two plates, differs from that of the plane turbulent jets. The difference comes to the presence of secondary flows, formed near the bounding surfaces in the area of mixing layer development. The presence of the secondary flows was found due to the form of isotacs – lines of equal velocities, built in the jet cross sections. The distribution of isotacs in mixing layers had a saddle shape, i.e., a jet near the walls was wider than in the mid-plane. The same character of the confined jet flow was confirmed by visualizing with paint, supplied in different regions of the jet [5]. The isotac form widening is also realized near the wall in the wall jet flow [1]. The formation of the secondary flows is associated with reorientation of vortex filaments. Papers [3, 4] proposed a model of secondary flow forming on the basis of reorientation of the vortex filaments. The work [4] presents a spatial reconstruction of vortex structures, based on visualization of patterns and confirming the model of reorientation of vortex filaments. Authors of [6] experimentally studied the flow of a quasi-two-dimensional turbulent jet in a narrow channel with TomoPIV method [7]. In the near field of the quasi-two-dimensional jet they found longitudinal vortex structures, which according to the authors, make major contribution to the formation of secondary flows.
by [8] the LES technique was used to numerically simulate the flow of the confined turbulent shallow jet. It was shown that in the near, middle and far fields of quasi-two-dimensional jets there are formed longitudinal vortex structures, whose linear size may reach about 10 h. Such longitudinal vortex structures are formed in confined shear flows at longitudinal streamlining of two closely located cylinders [9] and can significantly influence the processes of mass and heat transfer. The process of forming the longitudinal vortex structure is closely associated with the development of Kelvin – Helmholtz (K-H) vortical structures and their interaction with the bounding walls.

To understand the processes of formation of longitudinal vortex structures and to measure their influence on heat and mass transfer there is a need in 3D data on the dynamics of vortex structures in the near field of the jet where the process of their formation and development occur.

This paper presents experimental data on the three-dimensional structure of the near-field of the quasi-two-dimensional jet obtained, with high spatial resolution. The experiments were performed using Time Resolved Tomographic PIV method in a wide range of Re numbers Re = 2*10^3 ÷ 2*10^4.

2. Experimental setup

Photograph of the experimental setup and diagram of the measuring system are shown in Fig. 2a. The experimental setup consists of a hydrodynamic circuit with a constant-level tank, pump, flow meter, and a work area. The work area is a narrow rectangular duct with the size of 307x270 mm², formed by two plane-parallel plates of Plexiglas, spaced 4 mm from each other. The nozzle is formed by two rectangular insets, set in the channel. Geometrical dimensions of the nozzle were as follows: width – 10 mm, length – 70 mm, and depth – 4 mm. The Reynolds number was calculated as Re = h_dU_0/ν, where U_0 is the superficial velocity at the nozzle exit, and h_d is the hydraulic diameter of the nozzle.

![Figure 1](image_url)

**Figure 1.** The photo (left) and the scheme (right) of experimental setup for TomoPIV measurements

The measuring system consisted of a high-speed dual Nd: YAG laser (Photonix DM-532-150 15 MJ, 15 kHz), four high speed CMOS cameras (Photron FASTCAM SA5 with resolution of 1024×1024 pixels, 12 bits with the shooting frequency of 7 kHz) and timing pulse generator Berkeley Nucleonics BNC 575. Laser sheet with 4 mm thickness, which covered the whole measuring volume between the plates, was formed with lens system. In the experiments, polyamide particles with a diameter of 50 microns were used. The optical systems of cameras used lenses SIGMA AF 105 mm f/2.8 EX DG MACRO. The volume of the measuring field was equal to 50×50×4 mm³. The measurements were carried out in the area with dimensions of 8h×10h at the exit of the nozzle. The recording frequency in the experiments was equal to 10 kHz. Instantaneous three-component velocity distributions were calculated based on different successive images with a step
depending on the number of Re. For Re equal to 20 000 the calculation was made on the adjacent images, for Re of 10 000 – in 1 image, for Re of 5 000 – in 2 images, and for Re 2 000 – in 5 images.

3. Calibration and data processing

3.1. Camera placement and calibration
To ensure equal parameters of the optical system of each camera, the cameras were located in the corners of a square in a plane, parallel to the central plane of the measuring volume (figure 1 right). The angles of camera arrangement in vertical and horizontal planes were equal to 30 degrees. In this configuration of the measuring system, cameras were located in four points on the sphere with the center, coinciding with the center of the measuring volume. As a result, identical conditions were provided for each camera, such as: rotation angles of the cameras, correction angles of Scheimpflug and the distance from cameras to the center of the measuring region. To align the focal plane and the matrix plane we used adapters, printed on a 3D printer and allowing one to set the lens at any angle in the range from 0 to 12 degrees in the desired plane. For calibration of the optical system we used a high-precision calibration target from Edmund Optics with dimensions of 50×50 mm² and size of markers of 1 mm, located on a Cartesian grid with a step of 1 mm. As a result of the shallow depth of the channel of 4 mm, the shift of the calibration targets was difficult.

Therefore, to calibrate the measuring space it was necessary to displace the measuring system as a whole. The shift of the measuring system was carried out using a high-precision coordinate system and was controlled with an accuracy of 10 micrometers. The displacement of the measuring system was converted into a target shift, taking into account the difference between the refractive indexes of liquid and air. At that the channel wall was considered as a plane-parallel plate, not changing the direction of the beams. Measurement of markers of the calibration targets was performed in five parallel planes over a depth of the measuring volume.

3.2. Data processing
Data processing was carried out in the “ActualFlow” software. To improve the calibration parameters of the optical model there was self-calibration on pre-processed 500 images [10]. Preprocessing consisted of subtracting the median value, calculated for 21 000 images, applying the filter subtract minimum and a low-pass filter, and normalizing the intensity of particles on the average intensity in the image. As a result of self-calibration, the final average deviation did not exceed 0.05 pixels. The restored volume had dimensions of 506×659×62 voxels. The volumetric particle concentration was 8.5 particles/mm³. Tomographic reconstruction was performed using the SMART algorithm [11]. Correlation analysis was realized using the iterative multigrid algorithm with continuous displacement of the measurement window. In calculating the velocity, four iterations took place: two iterations with a resolution of 64×64×32 voxels and two iterations with a resolution of 32×32×16 voxels. The last iteration was carried out with an overlap of 75%; as a result, the final size of the area for a single velocity vector amounted to 0.52×0.52×0.26 mm³ with a distance of half the size between adjacent vectors.

4. Results and discussion
Figure 2 presents averaged three-dimensional velocity distributions measured in a near field of the quasi two-dimensional jet. Velocity averaging was performed by using 2 000 instantaneous three-dimensional velocity fields for Re = 2 000 and Re = 20 000 and 500 instantaneous three-dimensional velocity fields for Re = 10 000 and Re = 5 000. In the selected planes streamwise vorticity and streamwise velocity isolines are shown for averaged velocity distribution at different Re numbers. Red color corresponds to the clockwise rotation of the fluid while the blue color corresponds to counterclockwise rotation. One can see from the figure that the whole structure of the flow is similar at different Re numbers. There are some pairs of intensive secondary flows in the flow. The first and
the second pairs of secondary flows are presented in the jet shear layer; the third pair is located in the core of the jet. Secondary flows are noticeable at the distance of 2h from the nozzle where Kelvin – Helmholtz vortical structures are larger than h. Secondary flow development comes with intensive fluid entrainment [8] which is also observable in our experiment. Fluid entrainment by K-H vortex structure near the channel walls leads to formation of longitudinal vortex structures which further interact with K-H vortex structures and are carried in the jet core. [12]. The central pair of secondary flows results from complex interaction of vortex structures developed in the nozzle channel and mixing layers. Secondary flows decay results from quasi-two-dimensional turbulent jet meandering and takes place at the distance of 8-9 h from the nozzle.

Figure 2. Streamwise vorticity for averaged velocity field and isolines of streamwise velocity

a) Re 20 000, b) Re 10 000, c) Re 5 000, d) Re 2 000.

5. Conclusion
Tomographic PIV with high temporal resolution is applied for the study of the vortex structure formed in the near field of the quasi-two-dimensional turbulent jet. Experiments were carried out for a wide range of Re from 2 000 to 20 000. It was shown that for the whole range of Re numbers secondary flows form in the near field of the jet which is result of longitudinal vortex structure presence in the flow.

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