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Visualization of Water Toroidal Vortex by Multicolor Particle Image Velocimetry

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Abstract

The work is devoted to the study of the water flow created by a pump in a cuvette by multicolor particle image velocimetry. Multicolor particle image velocimetry method is another modification of the particle image velocimetry. The main difference between this method and other modifications is that not one laser plane is used as probing radiation, but several with different wavelengths. Such modernization makes it possible to obtain velocity vector fields simultaneously in several laser planes. The paper describes an algorithm for carrying out measurements using multicolor particle image velocimetry and processing the recorded data. An experimental setup has been developed and a series of experiments has been carried out, as a result of which the structure of the flow under study has been visualized, vector velocity fields in three laser planes have been obtained.

Keywords: multicolor particle image velocimetry, three-dimensional flow velocity field, 3D flow visualization.

1. Introduction

A great number of theoretical and experimental works have been devoted to the study of gas and liquid flows. Such interest is primarily due to the wide distribution of these phenomena in nature [1]. Besides, much attention to this topic is caused by the widespread use of gas and liquid flows in various fields of modern science and technology. For example, in relation to rocket engineering, swirling flows are realized in centrifugal injectors of liquid rocket engines, rotating rockets, film-cooling systems of nozzle blocks, vortex combustion chambers, thrust module control systems [2, 3]. In particular, highly swirled flows have been widely used in cyclone separators designed for gas and fuel purification, in burner devices in order to stabilize the flame. To optimize the flow mixing process in such devices, it is important to know the flow structure and the mixing mechanism. Various devices with flow twist are used in a number of sectors of the national economy: vortex chamber reactors in chemical technology, centrifugal casting in metallurgy, vortex and turbine flowmeters in measuring technology [4-10].

The particle image velocimetry (PIV) method is currently one of the widely used methods for diagnosing and visualizing flows in gas and liquid media. In contrast to single-point diagnostic methods, PIV allows to register instantaneous spatial velocity distributions in the plane, which is especially necessary in the case of diagnostics of complex structure flows.

The method principle is based on the preliminary seeding of small tracer particles into the medium flow and subsequent observation of their trajectories. For PIV measurements, the area under study is illuminated by a laser plane, in which the displacement of particles is measured for a known time between two consecutive frames. As a rule, a solid-state pulsed

Nd:YAG laser is most often used as a radiation source, a photographic film or a digital camera is used to record the particles position.

The main method advantage is the ability to measure the flow velocity distribution and visualize it in a plane in a certain section of the volume under study. Due to its capabilities, PIV is widely used in conducting a number of diverse studies in various fields of science and technology. However, it is most often used to study the flows of gases and liquids [11, 12].

The currently advanced modifications of the PIV method for flow research, such as the stereo or tomographic PIV method, allow obtaining the most complete information about its structure in comparison with the standard planar PIV research method. The main advantage of these methods is the ability to measure the flow velocity distribution and its three-dimensional visualization [13, 14].

The multicolor particle image velocimetry is another modification of the PIV method. The main difference between the method and other modifications is that not one laser plane is used as probing radiation, but several laser planes with different wavelengths. Such modernization makes it possible to obtain velocity vector fields simultaneously in several planes and visualize the three-dimensional structure of the flow [15-18].

2. Experimental setup and measurement methodology

The operation principle of the experimental setup for determining the flow velocity distribution was based on the multicolor particle image velocimetry method (MPIV).

The MPIV substance is to register the tracer particles positions in scattered light, which are artificially seeded into the stream, at small intervals of time. In this case, the particles must move at the flow velocity and not introduce any disturbances into it. To fulfill these conditions, it is necessary that the particles are small and their density is close to the density of the flow. In the MPIV method, red, green and blue parallel laser planes located at an equal distance from each other are used as probing radiation. The laser modules are selected in such a way that when the experimental image is divided into three colors, the signal from each laser plane is predominantly present in only one of the three color channels. The tracer particles position is recorded using a color digital camera.

As a result of MPIV measurements, resulting images will have three RGB color components. If we apply cross-correlation processing to each pair of images for each color channel in the Pivview program, it is possible to obtain a vector velocity field of the flow in three different planes. In turn, using the results of processing experimental images, it is possible to determine the distribution of the vertical and horizontal components of the particle velocity vectors over specified flow sections. Then, by constructing the distributions of the vertical and horizontal velocity components in space for a set of flow sections in red, green and blue channels and approximating the obtained planes, it becomes possible to visualize the three-dimensional velocity field of the flow under study.

The scheme of the experimental setup for diagnosing the flow velocity by the MPIV method is shown in Figure 1. The source of the probing radiation 1 was the laser planes formation unit, which includes three laser radiation sources of wavelengths 450 nm, 550 nm and 615 nm, and an optical system. As an object of research, the flow created by a pump 2 in a cuvette 3 with liquid was considered. The scattered radiation was recorded using the receiving optical system 4, which is a color digital camera and lens. The recording system was installed on a separate optical bench, so that it was possible to move it freely along a plane parallel to the near wall of the cuvette. Before the experiment, the liquid in the cuvette was previously seeded with tracer particles, which are glass spheres with a radius of up to 100 nm.

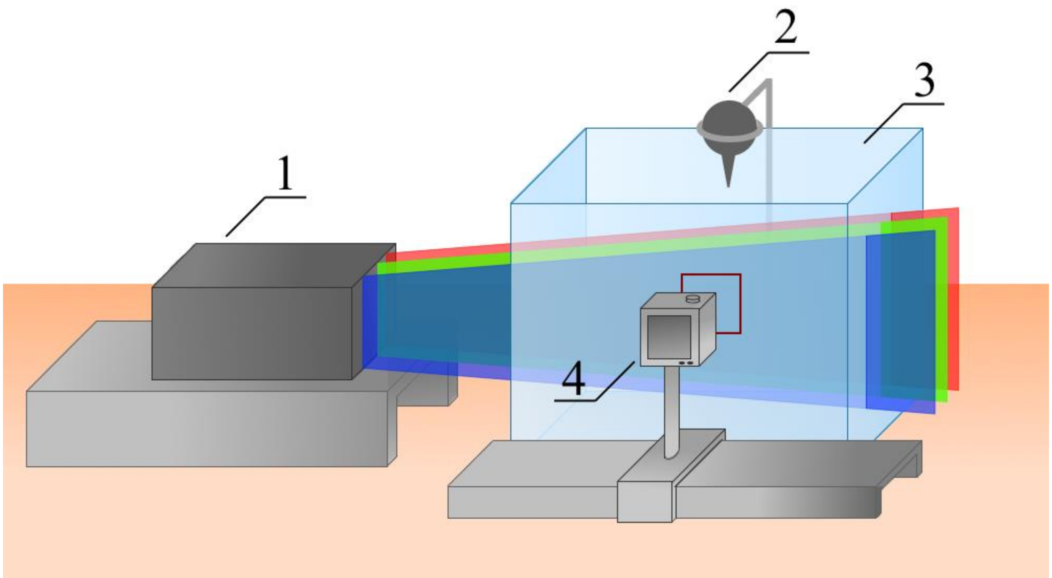


Fig. 1. The experimental setup scheme

The cuvette area, highlighted in Figure 2 with a red square, was taken as the registration area. As a result of measurements, laser radiation scattered by glass spheres from three RGB planes was recorded. The recording was made with a shooting frequency of 60 frames/s. Each recorded image contained information about the distribution of the flow velocities vector field in three planes located at a distance of 3 mm from each other. The thickness of the laser planes was 2 mm.

Figure 2 shows experimental frames obtained at different time intervals. As can be seen from Figure 2, the investigated water flow had a structure similar to a toroidal vortex. Moreover, the size of this structure increased over time in such a way that part of the flow began to fall into the blue and red laser planes.

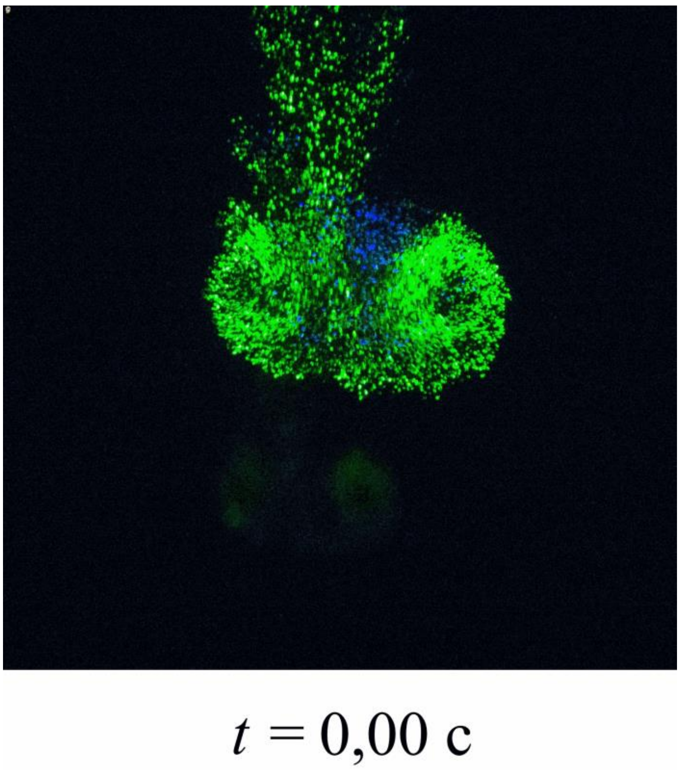
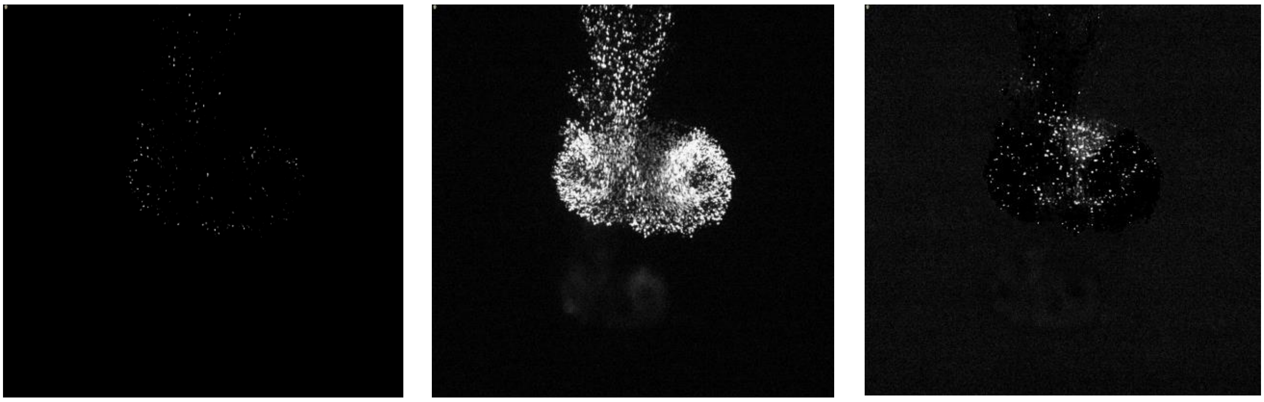


Fig. 2. Visualization of a water toroidal vortex

3. Processing of experimental results

The processing of experimental results was carried out as follows. Each experimental image was previously decomposed into three RGB color channels (fig. 3).



a) b) c)

Fig. 3. Images decomposition into three RGB channels (a) blue color channel (b) green color channel (c) red channel

Next, cross-correlation processing was applied to a pair of images for each color channel. After that, the calculated velocity values were output from the program as a text file, and based on them, a three-dimensional velocity field was constructed.

Figures 4-6 show an example of cross-correlation processing over one of the pairs of experimental images. As can be seen from the images, a change in the displacement velocity of tracer particles is observed in each of the planes.

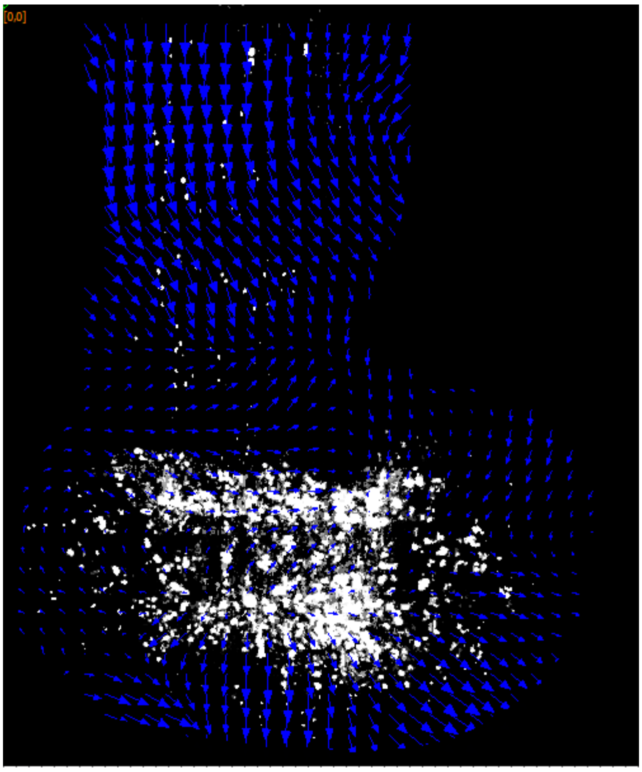


Fig. 4. Blue laser plane

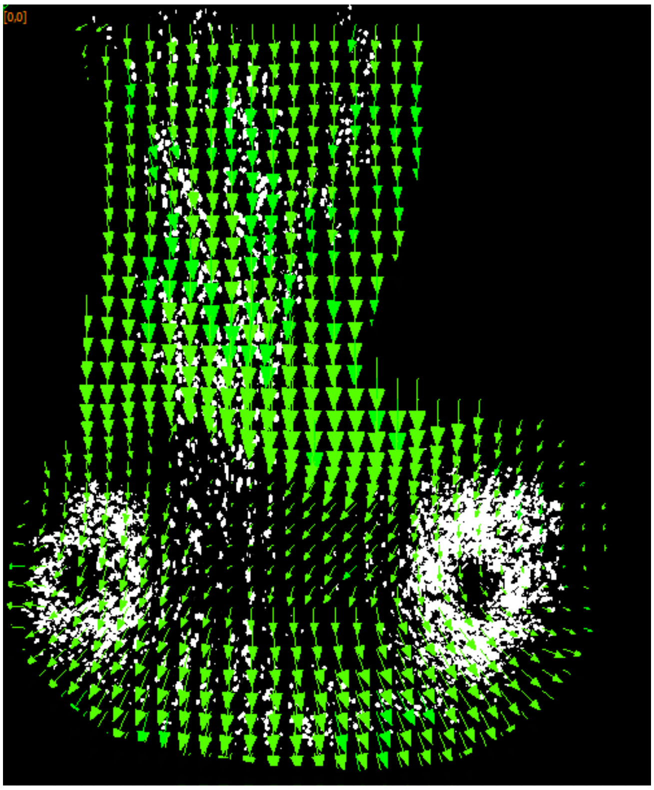


Fig. 5. Green laser plane

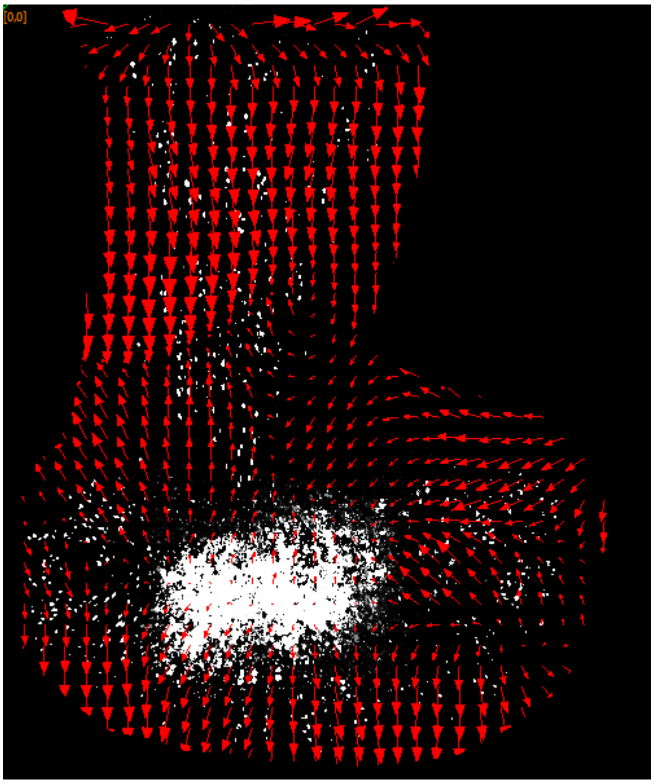


Fig. 6. Red laser plane

To reconstruct the flow three-dimensional structure an appropriate algorithm was developed based on the approximation of data between laser planes. The following types of approximating functions were used for forecasting flow structure: linear, exponential, polynomials from the second to the fifth degree (fig. 7).

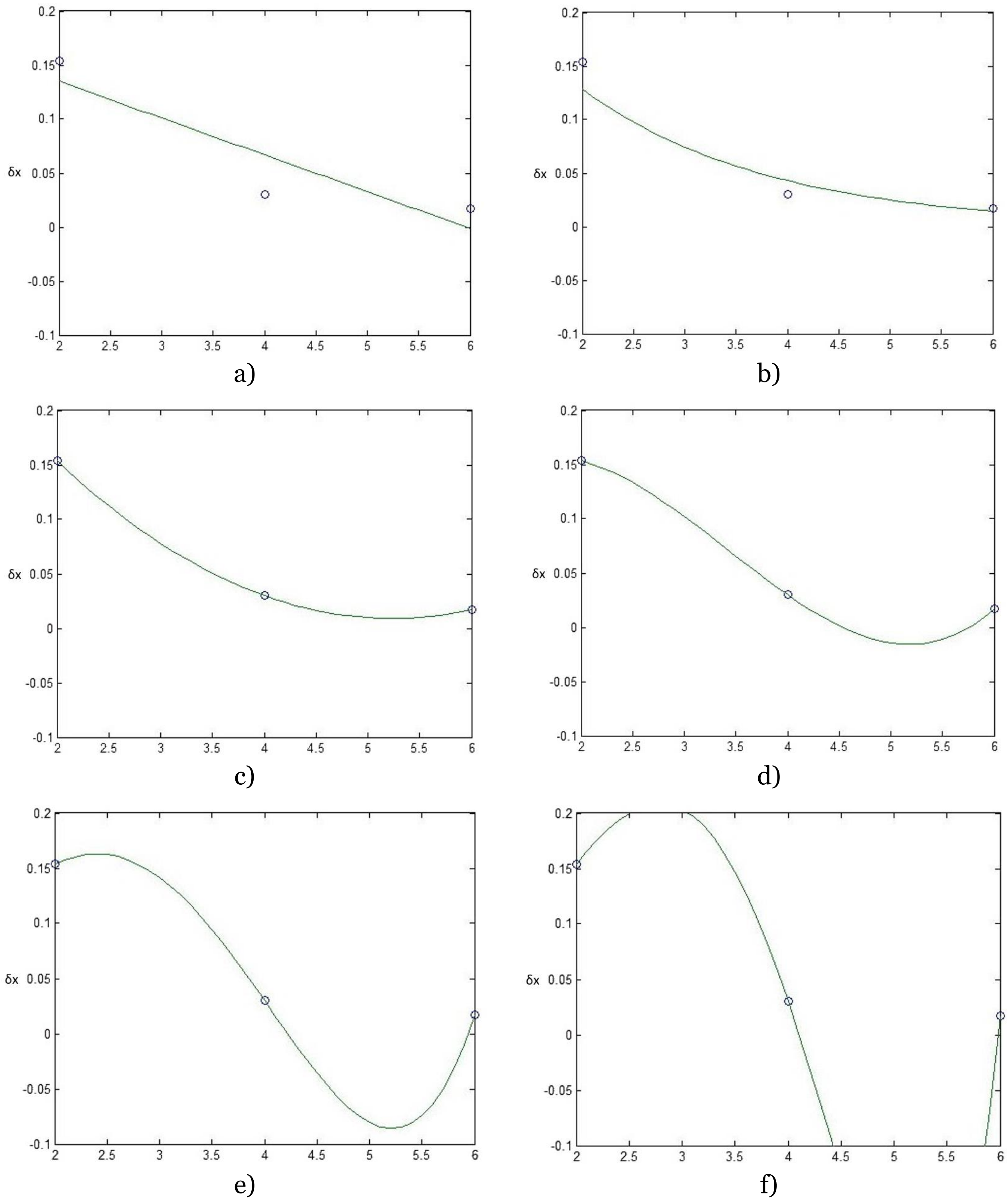


Fig. 7. Approximating functions (a) linear function (b) exponential function (c) second-order polynomial (d) third-order polynomial (e) fourth-order polynomial (f) fifth-order polynomial

To predict the structure of the studied flow in the space between the laser planes, an approximation by a polynomial of the second degree has been chosen, since it has showed the best result (fig. 8).

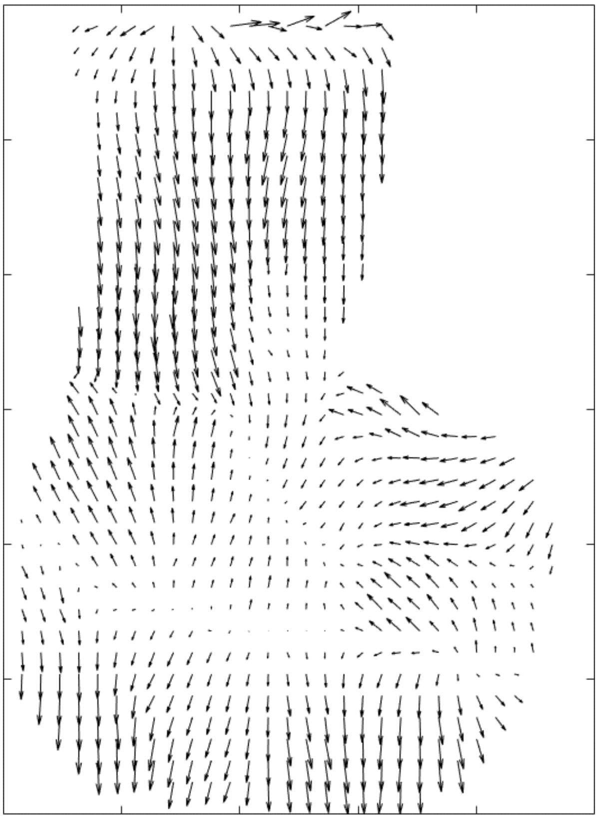


Fig. 8. Visualization of the three-dimensional flow structure

Conclusion

The experimental setup has been assembled, the operation principle of which is based on the multicolor particle image velocimetry. It should be noted that for the correct operation of the method, it is necessary to select the sources of blue, green and red laser radiation in such a way that when the image is decomposed into three color channels, the signal from each of the planes is predominantly present only in one of the channels. Based on the developed experimental setup, the flow created by a pump in a cuvette with water has been investigated. As a result, the flow three dimensional structure has been visualized. The flow had a toroidal structure. Moreover, the size of this structure increased over time in such a way that part of the flow began to fall into the blue and red laser planes.

Gratitude

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