Determining the parameters of vortex structures in a hydrodynamic vortex chamber

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Abstract. This study focused on the large-scale vortex structures. The working section was a tangential vortex chamber with a cylindrical cross-section. The flow was swirled by tangential supply of fluid into the chamber, using 12 direct-flow rectangular nozzles. The design swirl parameter was equal to 6.6 and was determined based on the vortex chamber geometry. The Reynolds number was maintained equal to 30000. Quantitative measurements were realized with the use of the optical technique of laser Doppler anemometry. The results of optical measurements allowed determining main parameters of the vortex core for two basic modes of the vortex flow, including the central direct-flow vortex and the spiral vortex.

1. Introduction

Studies of large-scale vortex structures are of great importance and interest, as these structures regularly occur in nature in a wide range of scales, from quantum vortices to astrophysical objects, such as rotating galaxies [1]. Vortex structures are run across many technical applications, for example, in vortex furnaces, combustion chambers, cyclonic separators and various chemical and biological reactors [2]. Special attention should be paid to the vortex structures, generated behind turbine impellers. Despite numerous studies of swirling flows, there are many effects, for example, the vortex core precession, which require further research. The same is also relevant for new effects and new flow regimes arising with time. In addition to the practical interest, investigation of vortex structures is also of great scientific interest.

The aim of this work is an experimental study of large-scale vortex structures with different helical symmetry in the tangential vortex chamber.

2. Experimental installation

The experiment was conducted in a closed hydrodynamic circuit with fixed values of input parameters. The working fluid (distilled water) was supplied from the tank into the vortex chamber, using a centrifugal pump. The liquid flow rate was maintained in the range from 3 to 25 m\textsuperscript{3}/h and measured by ultrasound flowmeter with a relative error of less than 1.5%. The chamber, where a vortex structure formed, was a cylindrical channel with a diameter $D=190$ mm and a height of 600 mm. The working section was made of transparent plexiglass, which allowed using the contactless
optical measurement technique to investigate the swirling flow. For creating different types of vortex structures, special diaphragms with orifices were placed at the outlet of the vortex chamber. The diameter of the orifice in the diaphragm was 70 mm. In the first case, the hole was placed at the center of the channel, and the second orifice was shifted by 70 mm from the channel axis. The working fluid was delivered into the chamber, using 12 tangential direct-flow rectangular nozzles, combined into the corner blocks (Fig. 1.a).

The main parameters in our work were the design swirl parameter \( S \) and Reynolds number \( \text{Re} \). The design swirl parameter was determined from the geometry of the vortex chamber: 
\[
S = \frac{D^2 \sin(\gamma)}{N \sigma_n},
\]
where \( D = 190 \text{ mm} \) was the chamber diameter, \( N = 12 \) was the number of nozzles, \( \sigma_n = 14 \times 23 = 322 \text{ mm}^2 \) was the area of the nozzle, and \( \gamma = 45 \) was the angle of nozzle rotation relative to the center of the chamber. Thus, the swirl parameter remained equal to 6.6. The Reynolds number was determined as 
\[
\text{Re} = \frac{D U_0}{\nu},
\]
where \( D = 190 \text{ mm} \) was the chamber diameter, \( U_0 = Q / \sigma \) was the average velocity, calculated using the flow rate \( Q = 15 \text{ m}^3 / \text{h} \) and the cross section of the vortex chamber \( \sigma = \pi D^2 / 4 \), and \( \nu \) was the kinematic viscosity of water. Accordingly, the Reynolds number equaled to 30000.

3. The experiment and results.

The first stage of the experiment was flow visualization. The used light source was LED projector with an aperture ratio of 7000 lm. The tracers for visualization were air bubbles with a diameter of about 1 mm, which were sucked out of the atmosphere into the flow. The flow structure image was obtained using a digital camera CanonEOS 7Dc with a resolution of 18Mpx and video recording frequency of 30 Hz. The visualization has revealed the presence of two major vortex structures: the central stationary direct-flow vortex and the stationary swirl vortex, appearing in the form of a thin elongated concentrated vortex filament. In addition, the researchers used experimental data on precession double vortex [3].
Figure 2. Visualization of different vortex flow regimes. Spiral vortex (left). Axial vortex (in the center). Two spiral vortex structures (right) [3].

Velocity profiles were measured using laser Doppler anemometry (LDA). Anemometer LAD-05 was manufactured at the Kutateladze Institute of Thermophysics SB RAS, in Novosibirsk. The measurements were carried out at the height of cross section of the vortex chamber z = 350, 400, 450, 500 mm for the central vortex, and z = 413, 428, 438, 453 mm for the spiral vortex. Coordinate x took values from -0.5 D to 0.5 D, D = 190 mm, and coordinate y = 0 remained constant for both vortex structures. LDA was used to measure two projections of the velocity vector V(y) and V(z) in the range from 0.001 to 30 m/s. The relative error did not exceed 0.1%. The size of the measuring volume was...
equal to 0.1x0.1x0.5 mm with an accuracy of 0.1 mm. A coordinate-shifting device (CPU) allowed shifting the measuring volume within 250x250x250 mm with an accuracy of 0.1 mm. The number of measurements in each was 10000, 5000 for each projection of the velocity vector. The maximum measurement time in the point was 120 s. The measuring accuracy of the average velocity was guaranteed at 95%. The used tracers for obtaining a Doppler signal were polystyrene particles with a density of 1.069 – 1.225 g / cm$^3$ and a size of 20-50 microns.

Figures 3-6 show distributions of tangential and axial velocities for the central vortex at different heights of the cross section of the vortex chamber, measured using the LDA method. The design swirl parameter was equal to 6.6, and the flow rate was maintained equal to 15 m$^3$/h. For convenience, graphs are presented in a dimensionless form. On the x-axis there is a laid off x-coordinate, related to the chamber radius, and on the y-axis there is the velocity $U$, related to the average velocity $U_0$ at the given flow rate. According to figures 3-6, the flow structure remains the same regardless of the height of measurement, since the dimensionless velocity profiles remain unchanged.

![Figure 7-10](image)

**Figure 7-10.** Profiles of tangential and axial velocities for the spiral vortex at different heights of the cross section of the vortex chamber.

A similar situation is observed in the case of a spiral vortex. Figures 7-10 illustrate distributions of tangential and axial velocity for a spiral vortex. The liquid flow rate and the swirl parameter do not change. It should be noted that graphs 7, 8 and 9, 10 are built for different positions of the diaphragm at the outlet of the vortex chamber. The difference lies in the rotation of the output orifice of the diaphragm by 90 degrees. The velocity profiles remain unchanged in both measurements. In addition, the figures clearly show the displacement of the vortex core relative to the center of the vortex chamber.

On the basis of the measured velocity profiles it is possible to determine the geometric parameters of the vortex core. The size of the vortex core is defined as the distance between zero and maximum values of the tangential velocity. Thus, from figures 3-6, it follows that the size of the vortex core $\varepsilon$ of the central vortex on average is $\varepsilon = 13.96$ mm, and for the spiral vortex $\varepsilon = 14.89$ mm. Knowing the vortex core size and the maximum value of tangential velocity, we can calculate the circulation rate $\Gamma = 2\pi \varepsilon U_{\text{max}}$. The velocity circulation is 0.111 m$^2$/s and 0.075 m$^2$/s for the central and spiral
The velocity circulation in the spiral vortex should have a smaller value than in the central one, as part of it goes for the creation of a complex flow structure. It should also be noted that the calculations do not take into account the inclination angle of the helical line of the vortex. Because of the inclination, the peaks of tangential velocity will be somewhat less; therefore, the circulation for the spiral vortex will also have a smaller value. The central vortex is formed on the central axis of the vortex chamber, so its deviation from the geometric center of the chamber equals zero. For the spiral vortex, the deviation is determined as the distance between the chamber center and the zero value of tangential velocity, and is 22 mm. The step of the helical line is calculated from the following dependence: $$U_z(r) = U_0 - \frac{r \cdot U_\phi(r)}{L}$$, where $r$ is the radial coordinate, $U_z(r)$ is the axial velocity at the point $r$, $U_0$ is the axial velocity in the center of the chamber, $U_\phi(r)$ is the tangential velocity, and $L$ is the helix step. For the spiral vortex, the step of the helical line is 193 mm, and for the central vortex, the step of the helix tends to infinity.

| Vortex Structure | $a/R$ | $\Gamma / 2\pi RU_0$ | $a/z$ | $L/R$ |
|------------------|-----|-------------------|-----|-----|
| Central          | 0.147 | 1.257             | 0   | $\infty$ |
| Spiral           | 0.156 | 0.849             | 0.234 | 0.3205 |
| Double           | 0.211 | 0.3031            | 0.296 | 0.421 |

Table 1 presents the abovementioned parameters in a dimensionless form. To obtain the parameters of the double vortex the experimental data from [3] were used.

**Conclusion**

The paper presents an experimental study of large-scale vortex structures in a tangential vortex chamber. At the first stage of the experiment, visualization of a swirling flow was performed. It has revealed the presence of thin concentrated vortex filaments in the flow. The optical technique of laser Doppler anemometry was used for quantitative measurements of vortex flows. The velocity profiles have showed the presence of a vortex core in the flow. The flow pattern remained the same in all sections at a changing height of the measurement. The main parameters of the vortex core have been determined on the basis of the measured profiles.

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