An experimental investigation of the interaction between a pair of precessing vortices in a tangential vortex chamber

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Abstract. This paper is devoted to experimental investigation of the interaction between the pair of precessing vortices in a tangential vortex chamber. The test section was the tangential vortex chamber with a cylindrical working area. The liquid was tangentially fed into the chamber through 12 rectangular nozzles. The swirl parameter varied in the range 0 ÷ 6.6, and the Reynolds number varied within 6000 ÷ 52000. On the basis of visualization materials the dependence of the precession frequency of the system of two vortices was obtained. For the quantitative investigation the optical methods of laser Doppler anemometry (LDA) and the Particle Image Velocimetry (PIV) were used. Information about vortices and recirculation zones was obtained from the optical measurements.

1. Introduction

The investigations of large-scale vortex structures are topical, because such structures regularly occur in nature and are frequently encountered in technical devices, such as combustion chambers [1, 2]. Special attention should be paid to the vortex structures which are generated in hydraulic turbines operating under off-design conditions. It has been identified that the double vortex structure may be formed behind the hydraulic turbine runner. Transition from single-helical to double-helical configuration even for a short time can lead to a considerable change in precession frequency beyond the design values [3, 4]. Despite the available investigations including the above mentioned parameters the transition from single to double vortex has not been fully defined. Thus it makes the study of the double vortex structure and defining its characteristics very important and useful. Besides its significance for practical applications, it is also of a great interest from scientific point of view [5].

The aim of this work is the experimental study of the interaction between the pair of precessing vortices in the tangential vortex chamber.

The experiments were carried out in a closed hydrodynamic loop for different values of input parameters. The fluid, sc. the distilled water, was supplied via the centrifugal pump from the tank to the working section (fig. 1). The flow rate was varied in the range from 3 to 25 m3/h and was measured by an ultrasonic flow meter with an error less than 1.5%. The work area where the double vortex structure emerged was a cylindrical channel with diameter D = 190 mm and a length of 600 mm. The working section was made of transparent Plexiglas, which enabled the flow investigation using optical methods. Fluid was fed into the chamber through 12 tangential rectangular nozzles that were arranged in three tiers and grouped in corner blocks (fig. 1).

The main parameters were the geometrical swirl parameter S and the Reynolds number Re. The geometrical swirl parameter was determined as follows: $S = D^2 \sin(\gamma) / (N \sigma_n)$, where, $N = 12$ is the...
number of nozzles, $\sigma_n = 14 \text{mm} \times 23 \text{mm} = 322 \text{ mm}^2$ is the nozzle cross-section area, and $\gamma$ is the nozzle turning angle relative to the channel center. The angle $\gamma$ was varied from 0 to 45 degrees. The flow rate $Q$ was maintained in the range from 3 to 25 m$^3$/h. The swirl parameter was changed in the range $0 \div 6.6$. The Reynolds number was defined as $Re = DU_0/\nu$, where $D = 190 \text{ mm}$ was the chamber diameter, $U_0 = Q / N\sigma_n$ was the mean velocity calculated by dividing the flow rate $Q$ by the nozzle cross-section area $N\sigma_n$ and $\nu$ was the kinematic viscosity of water. The Reynolds number varied in the range of $6000 \div 52000$.

2. Experimental Methods and Results
The first stage of the work was the flow visualization using the LED light source to illuminate the working area from the bottom (fig. 6). The flow pattern was captured by the camera Canon EOS 7D (fig. 2) which allowed taking still images of the flow structure and video recording with a frame rate of 60 Hz. The visualization has revealed the presence of two twisted precessing vortices (fig.2).

Based on visualization materials the dependence of the precession frequency of the system of two vortices on the fluid flow rate has been built. The dependence is described by a linear function (1) within an error of 10 % (fig. 3).

$$f [\text{Hz}] = 0.97 \cdot Q [\text{m}^3/\text{h}] -0.45$$  \hspace{1cm} (1)

Figure 4 shows the regime map of helical vortex pair generation. The filled circles correspond to the existence of the vortex pair. The transparent circles show parameters where the vortex structure is not observed. When the swirl parameter takes values in the range from 0 to 1.2, the precessing vortex pair does not appear, but with an increase in the flow swirling the vortex structure becomes visible. At maximum swirl parameter $S = 6.6$ the double helix can be observed at a flow rate above $9.5 \text{ m}^3/\text{h}$. With the flow rate decrease below this value the helical vortex structure begins to vanish (fig. 4).
The velocity profiles in the vortex chamber were measured using the laser Doppler anemometer (LDA) LAD-05 with an adaptive temporal selection of the velocity vector. The LDA was designed and manufactured at the Kutateladze Institute of Thermophysics SB RAS in Novosibirsk. The scheme of velocity measurement in the vortex chamber is shown in fig. 5. The measurements were carried out at height $Z = 484$ mm and $Y = 0$ in the range of the coordinate $X = -0.5 \ D \div 0.5 \ D$. The LDA served to measure two projections of the velocity vector $V_y$ and $V_z$ in the range $0.001-30$ m/s. The relative error did not exceed 0.1%. The size of the measuring volume was $0.1x0.1x0.5$ mm. The positioning device allowed moving the control volume in the region of $250 \times 250 \times 250$ mm with an accuracy of 0.1 mm. The number of LDA measurements at each point was equal to 5000, and the maximum acquisition time was 60 seconds. The reliability of determining the average rate was guaranteed at a level of 95%. As scattering particles for obtaining the Doppler signal the polystyrene particles with 20 microns diameter and 1.069 g/mm$^3$ density were used.

For instantaneous flow field diagnostics the 2D PIV instrumentation of POLIS Company was used. The PIV system was designed and manufactured at the Kutateladze Institute of
Thermophysics SB RAS. As an optical source for forming the light sheet we used Nd: YAG pulsed laser POLIS v3.2 with the following characteristics: wavelength of 532 nm, light sheet thickness of 1 mm, the energy pulse power of 120 mJ, and the operation frequency of 2 Hz. Measurements were performed in a vertical cross-section with coordinates Z = 451 ÷ 517 mm and Y = -95 ÷ 95 mm. To study the vorticity field and the tangential velocity in horizontal sections the measurements were performed at three heights Z1 = 344 mm, Z2 = 484 mm and Z3 = 504 mm (fig. 5) in the areas X = -55 ÷ 55 mm and Y = -33 ÷ 33 mm and X = -55 ÷ 55 mm and Y = -55 ÷ 55 mm. Images were registered by POLIS camera v1.0 with lenses Nikon AF 28 mm f/2.8D Nikkor at a resolution of 1280x768. To calculate the two-dimensional velocity field the Actual flow software Version 1.16.7.0 was used.

**Figure 7.** Profiles of tangential velocity at different fluid flow rates. The swirl parameter S = 6.6.

**Figure 8.** Profiles of axial velocity at different fluid flow rates. The swirl parameter S = 6.6.

**Figure 9.** Profiles of tangential velocity at different values of swirl parameter. Flow rate Q = 11.6 m³/h.

**Figure 10.** The dependence of the axial velocity on the swirl parameter. Flow rate Q = 11.6 m³/h.

Figures 7, 8, 9, and 10 show the profiles of tangential and axial velocity components, obtained by the LDA technique for various values of Reynolds number and swirl parameter. Figures 7 and 8 illustrate the dependence of the tangential and axial velocity on the flow rate. The geometric swirl parameter remains constant and has a value of 6.6. According to graphs 7 and 8 the flow rate does not affect the flow pattern. The dimensionless velocity profiles remain unchanged. Figures 9 and 10 show the dependence of the tangential and axial velocity on the geometric swirl parameter. For these profiles the flow rate remains constant at 11.6 m³/h. The axial velocity profiles indicate the presence of the reverse flow zone in the range X/R = -0.25 ÷ 0.25 (fig. 8). From the last two dependencies (figs. 9 and 10) it can be seen that velocity profiles change with different swirl parameters. Even if the value of the geometric swirl parameter is equal to zero, the flow swirl is present. This is due to the fact that the real swirl parameter is not zero, since it was impossible to ideally direct all incoming nozzle jets in the center of the vortex chamber. As expected this leads to
flow swirling. On the other hand, the system is not fully isolated and flow swirling occurs under the action of external forces. Interesting effects can be seen in the fig 10. With reducing the swirl parameter the recirculation zone, which correlates with negative values of the dimensionless axial velocity, decreases until complete disappearance in spite of significant tangential velocity. Absence of the reverse flow zone at the parameter S close to zero explains why we did not see the double vortex precession at low swirl. It is usually supposed that namely the central recirculation zone is associated with the formation of a precessing vortex structure [2].

Figure 11. Tangential velocity profiles in different horizontal cross-section.

Figure 12. The velocity RMS.

Figure 13. The field of mean velocity in horizontal cross-section with height z = 484 mm. The contour map presents the velocity vector length.

Figure 14. The average vorticity distribution in the horizontal cross-section with height z = 484 mm.

Figure 11 presents the tangential velocity profiles for three different cross-sections of the vortex chamber. The difference between the velocity values in sections at heights Z₁ = 504 mm, Z₂ = 484 mm and Z₃ = 344 mm can be explained by the fact that the first two cross-section heights differ by only 20 mm and, therefore, have a similar profile. Section at height Z₁ = 344 mm is located much lower than Z₁ and Z₂ and slightly above the top nozzle of the vortex chamber. In this section, the velocity was measured at a strong influence of the flow from the nozzle. This mean flow velocity in the nozzle is larger than the mean flow velocity in the working section.

Figure 12 presents the standard deviation of velocity. Since the vortices induce velocities with different signs in the center of the vortex chamber the resulting velocity value at that point tends to zero and the pulsations tend to minimum. Two peaks correspond to the radius of the vortex core localization. In that area the pulsations tend to maximum.

Figure 13 shows the mean velocity field in the cross section at z = 484 mm, depicted by the vector and contour plots. The velocity reaches its maximum value at the edges of the frame and is minimal at
the center. Figure 14 presents the mean vorticity field in the vortex chamber cross-section. The mean vorticity was calculated based on 100 samples. The vorticity field had a shape of a ring, which visually matched to the area of vortex precession.

**Figure 15.** Phase averaged velocity field of interacting precessing vortex cores. The contour map shows the velocity vector length

**Figure 16.** Phase averaged vorticity field.

Figure 15 illustrates the phase averaged velocity field of interacting precessing vortex cores. There is also a contour map showing the velocity. The central region of low velocity corresponds to the interaction of two rotating vortex cores. Figure 16 illustrates the instantaneous (phase averaged) vorticity field with clearly visible vortex cores. Averaging was performed over 50 images, taken in the same phase.

**Conclusions**
The paper presents an experimental study of the interaction between the pair of precessing vortices in the tangential vortex chamber. At the first stage the flow visualization was performed. It showed the presence of two twisted precessing vortices, unvaryingly reproduced in a broad range of operating parameters. The regime map was drawn on the basis of the visualization data. The dependence of the precession frequency of two vortices on the flow rate was obtained. Optical methods of Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) were used for quantitative investigations of the vortex structure. Velocity profiles proved the presence of the reversal flow zone and of the two vortices inside the vortex chamber. The interaction of the vortices was shown to form the region with a zero instantaneous circumferential velocity in the center of the channel. The vortices position was determined in the horizontal cross-section by the vorticity field.

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