Applying phase averaging technique to analysis of unsteady twin vortex structure observed in tangential vortex chamber

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Abstract. This paper is devoted to experimental investigation of formation of precessing vortices pair in a vortex chamber with a cylindrical working area. Flow structure was registered by means of a high-speed visualization technique. Quantitative measurements characterizing the vortex properties were carried out using a 2D particle image velocimetry (PIV) technique synchronized with wall pressure measurements. The results show that two symmetrical precessing helical vortices are present downstream of the tangential nozzles. The phase-averaged analysis confirms the presence of large-scale twin vortex structure that visualized by small air bubbles dissolved in water.

1. Introduction

Turbulent vortex flow can be found in many engineering applications such as separators, vortex burners, hydraulic machineries. Frequently swirling flow is accompanied by presence of coherent large-scale vortex structures that forms at critical swirl number. It is associated with spiral vortex breakdown phenomena also known as precessing vortex core (PVC) well described in [1–3]. Stable vortex structures representing the interlacing of two vortices are much less common in nature and technical applications than single-spiral vortex decay. In practice, the observation of such nonstationary structures is difficult because of the instability of their interaction, often leading to their merging. The formation of two or more vortex structures leads to a significant decrease in the intensity of each vortex spiral that also complicates their detection and study.

One of the manifestations of the double-spiral decay of the vortex core can be observed for the impeller wheel working in non-optimal mode [4,5]. Another manifestation is the formation of pair of strong vortices at high swirl number S = 2.02 in a swirl burner under combustion conditions [6], but authors noted that double PVC disappeared and replaced by a more stable single PVC at higher Re of a pair of PVCs. Compared with [9, 10] deals with stationary twin vortex, we observe the precessing double vortex structure, which rotates around the central axis of symmetry.

Analytical theories which make it possible to describe a vortex structure are actively developing and require experimental data containing spatial velocity distributions[7]. The mean velocity field loses information about the coherent vortex structure, which requires obtaining phase-average velocity fields. Decomposition velocity scheme introduced in [8] for velocity measured at a some point in a flow can be expressed as:

\[ U(t) = \bar{U} + U' + \bar{U} \]
where $U$ is the time-independent velocity component, $U'$ is the random turbulent velocity fluctuation, $\bar{U}$ is the periodic velocity component devoted to coherent vortex structure.

Phase averaging techniques are actively applied to the flow in a vortex burner, where coherent vortex structures play an important role in efficiency. Examples of using LDA and PIV phase averaging can be found in [9–11]. Thus in [10] based on the analysis of the phase-averaged data, three major spiral vortex structures, the primary vortex, the inner secondary vortex and the outer secondary vortex are revealed. Also it should be paid attention the novel phase average technique proposed in [12]. In contrast with classical phase average technique it does not require a periodic external signal to synchronize experimental data with the periodic flow fluctuation.

The present experimental work deals with double coherent vortex structure into high turbulent swirling flow in the simplified test section of swirl-stabilized burner.

2. Experimental Setup and technique

The experiment was performed on a closed hydrodynamic circuit at fixed values of flow rate and swirl parameter. The water is injected into cylindrical transparent section (Figure 1) via 12 small straight nozzles placed tangentially. It allows obtaining well symmetrical geometrical conditions for uniform flow mixing. This experimental test section is a simplified modified isothermal model of vortex burner previously investigated in [13]. Precise tune of nozzles angles relative to central axis allows for accurate change the swirl number. The work section was a thin-walled cylindrical channel made of transparent polymethyl methacrylate with internal diameter D = 190 mm and height of 600 mm placed into an external container filled with water, which could significantly reduce optical aberrations when using PIV technique.

By means of a centrifugal pump, water from the storage tank was supplied through the distribution system of tubes to the vortex chamber. The flow rate of liquid was measured by an ultrasonic flow meter and varied in experiments within 10 – 25 m³/h with a relative error not exceeding 1%. The flow regime in a vortex reactor with a tangential type of swirl can be characterized by two main parameters: Reynolds number ($Re$) and flow swirl parameter ($S$). Commonly, swirl number is defined by ratio of tangential to axial momentum flux [14,15]:

$$S = \frac{F_{mm}}{l \cdot F_m}$$

where $F_{mm}$ is the flux of angular momentum in axial direction, and $F_m$ is momentum flux in axial direction. According to Alekseenko et al. [7], $F_m$ and $F_{mm}$ for cylindrical working section with tangential nozzles can be evaluated as

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{View of experimental test facility. 1 – cylindrical working area with transparent flat wall, 2 – ultrasonic flowmeter, 3 – feeding pump up to 20 m³/h, 4 – blocks of tangential nozzles grouped by three, 5 – water reservoir for thermal stabilization.}
\end{figure}
\[ F_{mm} = \sum_{i=1}^{n} (G V d / 2)_{i} = \frac{G^2 d}{2 \rho S} \]

\[ F_{m} = GV = \frac{G^2}{\rho S^2} \]

where \( G \) - mass flow rate, \( S \) – area of cylindrical cross section, \( d \) – inlet diameter considering nozzles direction, \( \rho \) – water density.

Summarizing the contribution from each of the tangential nozzles (assuming their identity) and ultimately obtaining for \( S \):

\[ S = D^2 \sin (\gamma) / N \sigma \]

where \( \gamma \) is the angle of nozzle turn relative to the chamber center, \( N \) - number of nozzles and \( \sigma \) - nozzle cross section.

The maximum value of swirl parameter \( S = 6.6 \) is reached when all the nozzles are turned at the maximal angle to the vertical axis. Exactly in this regime a double precessing vortex helix is formed for a wide range of Re numbers \((10^5 - 6 \times 10^5)\). The PIV experiment was carried out in several horizontal sections with 3000 images statistics. Polystyrene particles with a diameter of 20-40 μm and density of 1.069 g/cm³, allowing minimization the buoyancy effects were used as tracers. The camera was located perpendicular to the working area through a mirror installed at an angle of 45 degrees under the cylindrical working area. The laser was moved to an automated traversing device, with an accuracy of 0.2 mm. Simultaneously with laser flashes, a pressure signal was recorded from piezoelectric pressure sensors mounted on the inner wall of the cylindrical work area. Laser flashes were also detected by a photodiode located opposite the laser knife. In order to conduct phase averaging, it is necessary to choose a time window. Since the average precession frequency was 2 Hz, the window width was chosen as \( 0.05/f_{PVC} \). In other words, the velocity field dispersion occurred within 5%.

3. Results

At maximal flow swirl, corresponding to the maximal angle of rotation of tangential nozzles, a stable precessing double helix is formed in the working section, extending along the entire length of section from the lower end wall to the output (Figure 2). Small air bubbles visualize vortex structure concentrated in low pressure area forming twin helical streams. When the swirl parameter decreases, the double vortex structure becomes unstable and it is replaced by an unstable quasispiral single vortex.

![Figure 2. Visualization of twin precessing vortex structure observed at high swirl number, Q = 14 m³/h.](image-url)
Next, figure 3 presents the results of PIV measurements associated with the pressure reference signal in a single phase of the twin vortex.

![Figure 3](image)

**Figure 3.** The velocity field is averaged over 3000 frames (left), phase-averaged by 120 frames the vorticity of the vortex component of the velocity field and the streamline (right). The mean velocity field is completely symmetrical with respect to the central axis and does not contain information about coherent vortex structures, in turn in figure 3 (right) we observe the formation of two large-scale vortex structures in opposite phases. The presence of two less intense vortices with the opposite direction of vorticity, rotating in the opposite direction to the main flow, is also visible.

**Conclusion**

The present study reveals some features of the swirling motion induced by 12 tangential nozzles combined into 4 symmetrical blocks. At high swirl number twin precessing vortex structure is formed. Extracting the vortex component of the velocity field, it was obtained that, in addition to the two main vortices rotating in the direction of the main flow, two vortices with a smaller vorticity is orthogonally formed rotating in the opposite direction, which cannot be identified without phase averaging. Based on the data obtained, it is planned to reconstruct the 3D geometry of the double vortex structure. In the future, this will be used to develop the theory of screw structures, which practically does not consider such complex systems. Experimental data may also be useful in verifying numerical calculations performed to increase the effectiveness of such vortex devices.

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