Visualization of vortex structures and analysis of frequency of PVC

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Abstract. The paper presents the results of the study of large-scale vortex structures in a model chamber. Methods of forming quasi-stationary vortices of various shapes by changing the geometric parameters of the chamber have been proposed. In the model chamber with a tangential swirl of the flow, a rectilinear vortex, single helical and double helical vortices were obtained. The double helical structure of the vortex is unique due to its immovability around the axis of the chamber. The resulting structures slowly oscillate around their own axises, which is called the vortex core precession; while the oscillation frequency depends linearly on the liquid flow rate. The use of stationary vortex structures in power plants will increase the efficiency of combustion chambers and reduce slagging.

1. Introduction and experimental method

The feature of the swirling flow in the model of a tangential furnace is the formation of spatially complex large-scale vortices that completely determine the global flow structure [1]. Setting up the experiment, the hydrodynamic bench was designed to experimentally study the vortex structures, formed in the working chamber with a tangential swirl of the flow (Fig. 1).

It was earlier shown experimentally in [2, 3] that in the studied vortex tangential chamber with a fully open outlet, a swirling flow has a complex structure. When the boundary conditions are modified, namely, setting the diaphragm at the outlet, the vortex structure becomes stationary, has a rectilinear shape and extends from the bottom of the chamber to the outlet.

Let’s consider in more detail the flow in a tangential chamber with the formation of stationary vortex structures. It should be noted that the vortex structures under study are related to concentrated vortex filaments. In such vortices, strong localization (concentration) of vorticity is observed. The term “vortex filament” is used for vortices in which the transverse dimension (core diameter) is much smaller than the chamber dimensions and the vortex length.

The scheme of the hydrodynamic bench is shown in Fig. 1. Water was used as a working fluid, and visualization was carried out with small air bubbles. The swirling flow was generated by means of twelve tangentially directed nozzles, arranged in three layers and combined in four corner blocks. The flow swirl intensity was determined using a design swirl parameter, calculated as \( S = 12 \sin \alpha \). The angle \( \alpha \) was equal to 45° for the flow with rectilinear and spiral vortex; and in the case of double structure, the turning angle of the nozzles \( \alpha \) was equal to 30°, that is in line with the values of \( S = 8.5 \) and \( S = 6 \), respectively. The height of the chamber from the bottom to the output orifice was 420 and...
560 mm, depending on the position of the output diaphragm, the chamber width $b$ was 188 mm, and the diameter of the diaphragm orifice $d_e$ equaled 70 mm. For the chamber geometry with a two-ramp bottom insert plates mounted at an angle of $50^\circ$ to the horizon were used.

![Figure 1](image)

**Figure 1.** Scheme of the hydrodynamic stand: 1 – work area, 2 – water tank, 3 – pump, 4 – laser illumination, 5 – flowmeter, 6 – measuring section of the flowmeter.

The flow visualization was carried out by small air bubbles, which were fed into the flow in front of the working area. The flow backlighting was performed with a laser sheet of 3 W of a continuous solid-state laser. To register the flow pattern we used digital camera Canon 7d with a number of characteristics typical for professional models.

Although the vortex chamber used in the experiment is not a canonical object due to the square shape of the cross section, it nevertheless proved to be very suitable for studying various vortex structures. Moreover, with the help of cylindrical inserts, it was shown that in the regimes with concentrated vortices the flow patterns in the axial region of the cylindrical and rectangular channels practically do not differ from each other.

2. Visualization of the vortices and frequency characteristics

Suppose that a flat bottom is installed in the lower part of the vortex chamber, and a diaphragm with an outlet $d_e$ is located in the output section at height $h_e$. The central position of the outlet leads to formation of a stable rectilinear vortex (Fig. 2). The vortex structure is a thin vortex filament running from the bottom of the chamber to the outlet. The vortex filament expands approaching the outlet. The particles in the vortex chamber move spirally. The vortex structure is fixed for all realized liquid flow rates and does not change its shape.

![Figure 2](image)

**Figure 2.** Rectilinear vortex filament: $h_e = 560$ mm, $d_e = 70$ mm, $Re = 20000$, $S = 8.5$.

The displacement of the outlet with a diameter $d_e$ at a distance $\delta_e$ relative to the axis of the chamber leads to radical changes in the flow structure (Fig. 3). The air filament, which visualizes the axis of the
vortex, is folded into a coil of a spiral. In this case, the helical vortex is stationary and stable, the fluid particles move around the spiral axis, thus making a double spiral motion. Areas with a return flow are also fixed. When the flow rate of the liquid varies, the vortex structure remains stable, the helical shape of the vortex is fixed for all realized liquid flow rates.

Figure 3. The geometric feature of the chamber and the vortex structure formed in it. \( h_e = 560 \text{ mm}, d_e = 70 \text{ mm}, \delta_e = 60 \text{ mm}, Re = 13\,000, S = 8.5 \).

The experimentally observed structures described above refer to single vortex filaments. Theoretical analysis allows the formation of any number of vortex filaments [4], but in practice the observation of vortex structures consisting of more than one vortex filament is hampered by the instability of the vortex interaction. Indeed, we can assume that the observation of such spirals is very difficult. However, there are a large number of publications on the formation of a nonstationary double helical structure in the decay of a vortex, for example, [5, 6], as well as in a mixing layer with natural convection [7]; however, the existence of a large-scale stationary double-helical vortex is not mentioned in the literature.

Attempts to generate stationary double helical vortex in a tangential chamber were undertaken after observing stable single helical filaments. And these attempts have been successful in a variety of options [2, 3, 8]. Such a double helix appears in the vortex chamber with a centrally located outlet and two flat ramps at the bottom of the chamber (Fig. 4).

Figure 3. Double helical vortex. \( h_e = 420 \text{ mm}, d_e = 70 \text{ mm}, Re = 40\,000, S = 6 \).

The structure is two intertwined helical vortex filaments of the same sign. The presence of two inclined ramps on the bottom is associated with the need to specify the initial deformation of the vortex axes. Unlike a very stable single-helical vortex flow, the double-helix regime should be considered as quasi-stationary for the following reasons. First, the air filaments that visualize the vortex axes are somewhat blurred, chaotically oscillate and sometimes disintegrate. Secondly, one of the threads always tends to dominate. But in general, as can be seen in photo (Fig. 4), the double-helical regime of the vortex motion is fixed distinctly.
The Reynolds number has no noticeable effect on the vortex structure, as in the case of single-helical vortices. However, when the Reynolds number is varied, the decay and formation of the vortex filaments occur at different intervals. So, after analyzing the video recordings, we can say that the best way is a double helix at \( Re = 40,000 \) and swirl parameter \( S = 6 \). With these parameters, there is no complete decay of the vortex filament, but only the blurring of one or two threads with a periodicity of about 10 seconds.

It should be noted that the investigated vortex filaments are quasistationary and perform small periodic oscillations around the vortex axis; in the case of a rectilinear vortex, the axis of rotation coincides with the axis of the chamber. Let us consider in more details the frequency characteristics for vortices. The frequency of vortex precession was calculated from the analysis of video records by high-speed camera at the rate of 60 frames per second. For single vortices, precession frequencies were also obtained with a hydrophone.

![Figure 5](image.png)

**Figure 5.** Dependence of precession frequency on liquid flow rate of (a); dependence of Strouhal number on Reynolds number (b).

Figure 5a shows the dependence of the vortex precession frequency on the fluid flow rate. In the case of a double-helical vortex, the precession frequency was defined as the frequency of oscillations of one vortex, which is dominant. The frequency of the precession of the vortices is linearly dependent on the flow rate of the liquid in the chamber, and when the data is extrapolated, it vanishes at zero liquid flow rate.

It is also interesting to look at the dependence of Strouhal number on Reynolds number (Fig. 5b). The Strouhal number is defined as \( Sh = f b / W \), where \( f \) is the vorticity precession frequency, \( b \) is the transverse chamber size, and \( W \) is the average flow velocity. In all the vortex flows represented, the Strouhal number does not depend on the Reynolds number.

The Strouhal number characterizes [9] the order of the ratio of local and convective derivatives in the total derivative in the equation of motion. If the Strouhal number is small, \( Sh << 1 \), then the term containing the time derivative can be neglected, and the flow may be approximately treated as stationary or quasistationary [9]. The values of Strouhal number in the case of single vortices \( Sh = 0.12 ; 0.14 << 1 \), which indicates the stationarity of the investigated regime. For a double-helix regime, the Strouhal number \( Sh = 0.41 <1 \), and according to [9], this regime should be considered as quasistationary, which, in turn, is confirmed by the data on visualization of the double-helix regime.

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