Features of the near-wall flow in a vortex chamber with an end-wall swirler

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Abstract. The results of a study of the near-wall flow of air in a vortex chamber with an end-wall swirler by the method of oil-flow visualization are presented. The influence of the mass flow rate on a near-wall flow of the vortex chamber is studied. The experimental results demonstrate the presence of separation flow on the cylindrical surface near the blind end-wall, and the non-uniformity of the near-wall flow on the end-wall with swirler. It is shown that when increasing the mass flow rate, the separation zone shifts to the blind end-wall, and its width decreases. In addition, distributions of the swirl angle of the flow on the cylindrical wall along the height of the chamber are obtained.

1. Introduction
To optimize the design of the vortex chambers, reduce hydraulic losses, and, consequently, increase efficiency, one should comprehend the features of the flow inside the chamber. The near-wall flow in a vortex chamber has an insignificant thickness, but the gradients of the quantities that determine the flow parameters can be quite essential. This condition restricts the size of the measuring probe or the registration area of the non-contact measurement method. The method of oil flow visualization is free from this drawback. The method is quite simple, informative, and has good prospects for studying flows inside devices where the swirling flow is used. In [1], devoted to a review of various methods of aerophysical experiment, the author also gives a brief description of the method of oil flow visualization. This technique allows determining the direction of the flow, the position of flow separation and its reattachment, as well as the transition from laminar to turbulent flow. The results of applying this technique are not only qualitative in nature, but the method also serves to obtain some quantitative data.

The application of this technique for studying limited swirling flows is not often found in the literature. In [2], the three-dimensional structure of the flow on the end surfaces of the vortex chamber was studied by numerical and experimental methods. In the experiment, such methods as LDA, stereo PIV, and one of the modifications of the oil flow visualization of surface streamlines (oil dots) were used. It can be noted that this was a useful side effect of the PIV method. Aerosol oil particles, used as tracers for PIV measurements, were settled from the flow onto a transparent wall and spread along the wall under the action of shear stress. Oil droplets smeared on the surface formed a streaky structure, which visualized surface streamlines. Based on the obtained experimental data and numerical simulations, the authors concluded that the near-wall flow on the end-wall is inhomogeneous. In [3], various meth-
ods were used to visualize the flow in a vortex chamber, including oil flow visualization. Based on the analysis of the visualization images and obtained quantitative data, the authors reconstructed large-scale structures in near-wall flows of the vortex chamber. In [4], the authors investigated the aerodynamic characteristics of the diffuser/collector located behind the gas turbine of the power station for various geometric parameters of bearing housing.

As can be seen, the method of oil flow visualization is very simple to implement and quite informative. Using this method, it is possible to obtain data in cases where the application of other methods can give a large error or it is generally impossible to apply them in the given conditions. Restricted swirling flows are just such objects that are difficult enough for experimental research.

2. The experimental setup and experimental technique
The experiments were carried out using a setup schematically shown in Figure 1. The diameter of the internal volume of the vortex chamber (1) was \( D_K = 74 \) mm, and the height was \( H_K = 89 \) mm. The flow was swirled by a swirler (2), made integral with the lower end-wall of the chamber, and consisted of 12 cylindrical channels with a diameter of \( d_{IN} = 2 \) mm uniformly distributed relative to the axis of the chamber symmetry. The axes of the swirler channels were located at angle \( \varphi_{IN} = 7^\circ \) to the end-wall of the chamber. At that, the channels were located tangentially in relation to the inner cylindrical surface. The outlet had diameter \( d_{OUT} = 18 \) mm and was located at one end-wall with the swirler. The opposite end-wall was closed.

![Figure 1](image)

A controlled fan (7) pumped out air, from the vortex chamber (1) through a pipeline (5). Inside the chamber, the pressure was decreased and air from the environment enters the inside of the chamber, passing through the swirler (2), acquiring the swirl. The mass flow rate was monitored with an electronic differential pressure gauge (8), which was attached to the Pitot tube (6) and a receiver of static pressure embedded in the pipeline wall. A compound pressure gauge (9) was also connected to a receiver of static pressure, which was necessary to assess the density of moist air that entered the vortex chamber from the environment. Relative humidity and air temperature were measured using a psychrometer (10) and a thermometer (11).

The experiments were carried out for three values of mass flow rates: \( G_K = 4.5 \) (g·s\(^{-1}\)), 5.1, and 6.5.

The oil flow visualization procedure was as follows. A white PVC film 0.07 mm thick was glued to the walls of the internal volume of the vortex chamber. A coloring mixture of kerosene and black ink for offset printing was applied to the film. The mixture was prepared in a ratio of \( \sim 14/1 \), by weight.
After applying the mixture, the chamber was closed, and atmospheric air was pumped through the vortex chamber. The film of mixture moved along the surface under shear stress, kerosene evaporates into the stream and a dye remained on the surface, and this formed a striped pattern. In the separation zones, the dye was more concentrated, creating extended, uniformly colored spots.

After purging, the dyed PVC film was separated from the surfaces of the vortex chamber and glued to the paper. After the final drying, the obtained images were digitized. Subsequently, digital images were processed in the ImageJ application. The positions of the axis of the separation zones $h^*$ relative to the end-wall with the swirler and its width $\delta$ were measured. Also, the swirl angle $\varphi$ on a cylindrical surface along the height was measured, from the inlet end-wall to the separation zone.

3. Experimental data

Figure 2 shows a sweep of oil flow visualization on the lateral cylindrical surface of the vortex chamber at $G_K = 4.5 \text{ (g\cdot s}^{-1})$.

![Figure 2](image-url)

Figure 2. Oil flow visualization of the near-wall flow on the cylindrical wall of the vortex chamber at $G_K = 4.5 \text{ (g\cdot s}^{-1})$.

Since for other values of the mass flow rate, images of oil flow visualization on a cylindrical surface are similar, except for small nuances, they are not given here to save space.

Figure 3 shows the height of the separation vortex axis relative to the end-wall with the swirler $h^* = h + 2.5 \text{ mm}$ and the width of the separation zone $\delta$, depending on the mass flow rate.
Figure 3. The position of the axis of separation vortex relative to the inlet end-wall $h^* - 1$, the width of the separation zone $\delta - 2$.

It is seen that with an increase in the mass flow rate, the axis of the separation vortex shifts closer to the blind end-wall, and the width of the separation zone decreases.

Figure 4 shows the distribution of the swirl angle $\varphi$ along the height of the vortex chamber at different mass flow rates. The $\varphi$ values were estimated up to the vicinity of the separation vortex. As can be seen from the figure, $\varphi$ distributions are similar and depend weakly on the mass flow rate. Distribution of $\varphi$ can be roughly divided into 3 characteristic sections. In section I, $\varphi$ increases. In section II, $\varphi$ is almost constant. In section III, $\varphi$ begins to decrease again.

Figure 4. The distribution of the swirl angle $\varphi$ on the side surface of the vortex chamber. $1 - G_K = 4.5$ (g·s$^{-1}$); $2 - 5.1; 3 - 6.5$.

Figure 5 shows the images of oil flow visualization at the inlet end-wall of the vortex chamber at a different mass flow rate.
**Figure 5.** Oil flow visualization at the inlet end-wall of the chamber at different mass flow rates:
(a) – $G_k = 4.5$ (g·s$^{-1}$); (b) – 5.1; (c) – 6.5.

The figure shows that the near-wall flow is heterogeneous at this end-wall. The higher the mass flow rates through the chamber, the greater is the heterogeneity. Heterogeneity is caused by the interaction of nearby jets that flow into the vortex chamber through the swirler holes. In [5], the flow was studied on a plate, whose longitudinal axis was located at an angle of 64º to the free stream. The studies were carried out using oil flow visualization and smoke visualization with a laser sheet. The oil flow visualization showed a separation region on the plate, while a laser sheet allowed visualizing the structure of the longitudinal vortex.

It seems difficult to visualize the interaction of jets at the ends using a laser sheet. With comparable air flow rates, the height is very small, about 1.5-2 mm. Therefore, using the analogy, we can reconstruct the flow of interacting jets above the end-wall of the vortex chamber. In Figure 5 (b), dashed lines indicate the axes of the separation regions, and arrows indicate jets spreading along the end-wall from the swirler to the outlet. Figure 6 shows a diagram of the flow cross-section A-A. Spiral lines denote separation vortex formed during the interaction of two closely spaced jets.

![Diagram](image)

**Figure 6.** Reconstruction of the cross-section A-A flow above the inlet end-wall of the vortex chamber.
Figure 7. Oil flow visualization at the blind end-wall of the chamber at different mass flow rates: (a) – \( G_K = 4.5 \) (g·s\(^{-1}\)); (b) – 5.1; (c) – 6.5.

It can be seen from the figure that at a low mass flow rate, the flow at the blind end-wall is heterogeneous. However, as the mass flow rate increases, the heterogeneity of the flow disappears.

Conclusions
Using the results obtained, the following main conclusions can be drawn:

- The flow on the cylindrical surface is not monotonic. In section I, the swirl angle \( \varphi \) decreases, the flow near the wall is accelerated in the axial direction. In section II, the flow moves without acceleration in the axial direction, the swirl angle \( \varphi \) does not change. In section III, when approaching the separation vortex, the flow starts to slow down in the axial direction, the swirl angle \( \varphi \) decreases.
- With increasing mass flow rate \( G_K \), the separation vortex on the cylindrical wall of the chamber is pushed off from the inlet end-wall, and the width of the separation zone decreases.
- The near-wall flow at the end-wall with the swirler is heterogeneous and is a set of closely spaced jets that interact with each other.

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