The Phenomenon of Hysteresis in a Swirling Stream

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Abstract. The article considers a swirling current with a sudden expansion. As a result of an experimental study, it was found that two flow modes can exist under these conditions. In the first case, there is an intense twist at the outlet of the vortex device, a zone of return currents and precessional oscillations. In the second case, there is no zone of return currents and precession. At the same time, the gas flow through the device increases abruptly.

1. Introduction
The swirling flows created in the channels have a complex gas-dynamic structure [1-6]. The nature of this structure depends on the geometric features of the channel and the speed of the swirling flow in it. The currents with a strong twist are of the greatest interest. In this case, several large-scale structures can be distinguished in the swirling flow [1], which are shown in Figure 1.

![Figure 1. Diagram of a strongly swirled jet with a double recirculation zone](image)

1-curl, 2-narrowing channel, 3 - the first recirculation zone, 4-the vortex core, 5-the second recirculation zone

Following the authors of [1], the gas-dynamic structure shown can be explained as follows. An intensely swirling flow is created by the swirler 1. Then the flow moves along the narrowing channel 2. In the near-axial region, due to the action of centrifugal forces, a zone of reduced pressure arises. Gas flows into this zone from the peripheral region. As a result, a vortex is formed in the form of a toroid. In this vortex, closer to the axis, the gas moves in the direction opposite to the main flow. In this regard, the region 3 occupied by the toroidal vortex is called the recirculation zone or the first recirculation zone.

In the near-axial region, behind the first recirculation zone, a swirling flow 4 is formed downstream, the law of rotation of which is close to the law of rotation of a solid body. The nature of...
the rotation of this region, its axial velocity, turbulent structure and other properties are very different from the peripheral flow. For this reason, it is an independent gas-dynamic structure and is called a vortex core.

When moving downstream, the swirling flow expands. This happens when it gets out of the channel into the environment. In this case, masses of gas from the environment rush into the area of axial discharge. Thus, there is an echoing recirculation zone 5. The vortex core interacts with the second recirculation zone. As a result of this interaction, it shifts, goes around the recirculation zone and begins to make a rotational movement around it. This rotational motion is called precession [1,2,7-9].

The resulting precessional oscillations of the vortex core are accompanied by intense acoustic radiation into the environment. The radiation frequency corresponds to the precession frequency. At present, there is no complete clarity regarding some issues arising from the presented picture of the swirling current. This refers to the mechanism of interaction between the vortex core and the secondary recirculation zone. The dynamics of the development of recirculation zones, the relationship of the energy and angular momentum of these zones with the input parameters of the flow are not fully elucidated. To solve these problems, it is necessary to conduct experimental studies of the dynamic and acoustic characteristics of the swirling flow.

2. The problem formulation and results of the study
As it was shown in the introduction, the precessional motion of the vortex core leads to intense sound radiation. By measuring the frequency of sound, it is thus possible to determine the angular velocity of precession.

To conduct an experimental study, a vortex device corresponding to a vortex vacuum pump was developed, the scheme of which is shown in Figure 2.

![Diagram of the vortex device](image)

**Figure 2. Diagram of the vortex device**
1 – swirler, 2 – swirler chamber, 3-vortex chamber, 4-gas supply surface, 5-narrow channel, 6-output section.

Compressed air, through the tangential inlet 1, enters the chamber 2 with a diameter of 40 mm and then into the vortex chamber 3 with a diameter of 20 mm. Chamber 2 is usually not made, but in this work it forms a swirler together with the tangential input. The peculiarity of such a swirler is that the supply of the swirling flow to the main vortex chamber 3 is distributed along the cylindrical surface 4. After passing the vortex chamber, the flow enters the chamber 5 with a diameter of 10 mm, after which it exits through the section 6 into the atmosphere. This structure of the vortex device corresponds to the structure of the vortex whistle.

Figure 3 shows the schematic diagram of the experimental setup. The work of the experimental installation was carried out as follows.
Figure 3. Diagram of the experimental installation
1-compressor, 2-pressure gauge, 3-flow meter, 4-vortex device, 5-microphone.

The compressed gas enters the main line from compressor 1. The pressure is measured using a pressure gauge 1, the gas flow rate using a flow meter 3. Then the compressed gas enters the vortex device 4. A microphone 5 was located at a distance of 1 meter from the vortex device.

The experimental work was carried out in two stages. At the first stage, the dependence of the gas flow through the vortex device on the pressure at the inlet to it was measured. As a result, an interesting phenomenon was discovered, which can be called gas-dynamic hysteresis.

As the pressure increased, a gradual increase in the flow rate occurred (figure 4 before). However, when the pressure reached 2.9 atm., there was a sharp, abrupt, increase in the flow rate, as shown in Figure 4. After that, the process of change again became smooth.

Figure 4. Flow rate dependence on inlet pressure

When the inlet pressure decreased, the flow rate decreased (figure 4 after). But, having reached the pressure of 2.5 atm. there was a jump in the flow rate in the direction of decrease. Thus, on the graph of the flow rate dependence on pressure, a loop similar to a hysteresis loop was obtained.

At the second stage of the experimental study, the acoustic characteristics of the vortex device were measured. During the operation of the vortex device, pure tone radiation was observed, the frequency of which depended on the inlet pressure. The measurement results are shown in Figure 5.

Figure 5a shows the sound spectrum before the flow adjustment. On this spectrum, one can see the dominant frequency $f = 6.26$ kHz, which is supposed to be associated with precessional oscillations of the vortex core. It can be seen from Figure 5b that there are no dominant frequencies after the flow is rearranged.
Figure 5. The sound spectrum
a) before the flow adjustment P = 1.39 atm; b) after the flow adjustment P = 2.95 atm

The sound signal generated by the vortex device turned into broadband noise. This indicates that there is an internal restructuring of its structure in the swirling flow. For a more detailed determination of the nature of this restructuring, a visualization of the flow exiting into the atmosphere was carried out.

Visualization was carried out using threads attached to the end side at the outlet of the vortex device. The visualization results presented in Figures 6 and 7 showed that at the initial increase in pressure and flow rate to the first critical point P = 2.9 atm, there is an intense twist and the jet at the outlet has a fan-shaped flow character.

Figure 6. View of the flow before the rebuild
Figure 7. View of the flow after the rebuild

The gas flow after exiting the vortex device diverged due to a strong twist in a predominantly radial direction. At the same time, an intense axial flow of gas into the vortex device was observed, which formed a second recirculation zone.

When passing the first critical point, as the visualization showed, the radial fan flow stops and the swirled jet exits in a narrow cone with a low twist intensity. The reverse current zones, i.e. the second
recirculation zone is not observed. The simultaneous disappearance of the recirculation zone and precession fluctuations indicates a close relationship between them.

Flow diagrams obtained as a result of visualization are shown in Figures 8 and 9.

![Figure 8. Flow diagram before the rebuild](image1)

![Figure 9. Flow diagram after the rebuild](image2)

The increase in the flow rate after passing the first critical one is due to the fact that the second recirculation zone restricts the output of the main swirling flow. When this zone is eliminated, the resistance to movement decreases, and the energy losses associated with precessional oscillations of the vortex core also decrease.

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