About the flowage of vortex chamber with outlet diaphragm and side slot swirler

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Abstract. The vortex chambers are the widespread equipment in energy, chemical and mining industries. The upgrade of existing equipment and development of new models of vortex chambers require the detail analysis of swirling flow structure. This paper presents results of numerical modeling of the airflow dynamic in a vortex chamber with the outlet diaphragm and side slot swirler. The main attention is paid to the end boundary layers and to their influence on the flowage of vortex chambers. The study has been done for a wide range of swirl angles with Reynolds numbers of up to 1720.

1. Introduction
The vortex chambers have been used to organize various high-intensity physicochemical processes in gases, liquids or multi-phase flows. Wide-known cyclone separators for gas-liquid and dust-gas flows are applied in chemical, mining and metallurgical industries [1-3]. The vortex energy separators based on the Ranque-Hilsch effect are applied in local cooling systems of gas flows and conditioning systems [4-6]. In energy industry, the vortex burners are used to increase completeness of liquid and solid fuel combustion; the vortex cyclones are applied to clear combustion products from slag and harmful impurities [1, 7 and 8]. The vortex technologies allow increasing the specific productivity of devices and decreasing their mass and dimensions. At the same time, the absence of effective calculation methods for flow dynamic, heat and mass transfer analysis in vortex chambers and incompleteness criterion set for development of engineering calculation methods and methods of scaling this equipment slow down the progress of vortex technologies [9].

The studies of vortex chambers with side slot swirler are presented in [9, 10]. It is shown that the side slot swirler provides better uniformity of gas flow, lesser turbulent pulsations of axial jet, lesser hydraulic resistance of vortex chamber and swirler. In paper [9], the results of complete experimental study of the influence of the inlet slot area, swirl angle, diameter of outlet diaphragm, height of chamber and outlet branch pipe on the flow dynamic in the bulk of vortex chamber are presented. The influence of end boundary layers on the flow dynamic was not considered. All data was obtained by means of multichannel air pressure probes. The semiempirical method of calculation of the velocity and pressure fields in the bulk of vortex chamber was suggested.

The studies of flow dynamic in the end boundary layers are presented in papers [10, 11]. The experimental measurements of flow velocity were carried out both by probe method and non-perturbative optical Laser Doppler Anemometry (LDA) [12, 13]. The swirl angle of the inlet flow, where the flow regime is switch to new configuration, was obtained. For the new regime, the inlet mass of gas flows along the sidewall into the end boundary layers, than it turns out along the chamber.
axis and exits through the outlet diaphragm. The radial mass flow in the bulk of vortex chamber closes to zero and therefore the new regime was named “unflowage”.

This paper presents the results of numerical modeling of air flow dynamic in the vortex chamber with the side slot swirler at various mass flow rates and swirl angles. The analysis of flow configuration is done based on obtained results. The mass flow rates through the bulk of chamber and the end boundary layers are calculated for a wide range of swirl angles. The influence of reverse flow into the chamber through the outlet diaphragm on it flowage is shown.

2. Statement of the problem and numerical approach
The air flow through the vortex chamber with the side slot swirler and outlet diaphragm is considered. The geometry of chamber is presented in figure 1. The diameter of vortex chamber is \( D_v = 160 \text{ mm} \), height is \( H = 196 \text{ mm} \), \( H/D_v = 1.225 \). The outlet diaphragm with diameter \( d_f = 32 \text{ mm} \) is installed at the chamber axis, the clamping factor is \( d_f/D_v = 0.2 \). The heights of slots in side swirler are equal to the chamber height. The swirl angle \( \alpha \) is varied from 0.5 to 90º. The width of outlet cross section for each slot \( l \) is constant to all swirl angles and equals \( s/\sin 45º \) for slot width \( s = 1 \text{ mm} \). It is equivalent to varying the slot width as \( s = \sin \alpha / \sin 45º \). The number of slots \( n \) is 12. The slots are uniformly spaced over the circular of sidewall.

![Figure 1. The geometry of vortex chamber (on the left) and calculation domain with boundary conditions (on the right).](image)

The calculation domain for 3D modeling is the sector with opening angle \( \beta = 360º/n \). On the cylindrical face, the rectangular space with width \( l \) is separated as the outlet cross section of swirler slot or equivalent the inlet flow boundary (see figure 1 on the right). On the axis of top face, the sector with radius \( d_f/2 \) is separated as the outlet flow boundary. The lateral faces are joined by periodic boundary conditions.

The mesh is generated by in-home code GGN. The mesh consists of the hexahedral cells in the bulk and wedge sells near the axis. The exponent compression is used to the walls, periodic boundaries and radial section separating the diaphragm and bulk of the chamber. The number of nodes is 720000.

The mass rate of inlet flow \( G \) is 1, 2.33 and 4 \( \text{gr/s} \). The pressure \( p_0 \) and temperature \( T_0 \) on the outlet boundary are 1 atm and 300 K, respectively. The air is supposed incompressible with constant viscosity \( \mu = 1.85 \cdot 10^{-5} \text{ Pa\cdot s} \) and density \( \rho = 1.17 \text{ kg/m}^3 \). The Reynolds numbers built on the diameter of vortex chamber \( Re_v = 4G/\pi \mu D_v \) for studied mass flow rates equal 430, 1000 and 1720.

We solved the problem by the SIMPLE numerical method, based on the 3D RANS equations for the steady and unsteady flows with the second order scheme for pressure and third order scheme for momentum equations. ANSYS Fluent solver was licensed for SSCC SB RAS. For studying the
Reynolds number range, the flow regime in the bulk of chamber is laminar, but in the vortex decay area on the bottom wall the flow configuration is very complex. To consider the influence of possible turbulent effect for a small swirl angle, we used the RSM turbulence model with calculation of turbulence dissipation by means of k-ε model and standard wall functions. The convergence for all variables and mass flow rates are provided with maximum error $10^{-4}$.

3. Result and discussion

3.1. Validation of numerical approach

Figure 2 shows the circumferential and radial velocity distributions across the bottom end boundary layer. For this case, the air is supplied to the vortex chamber through the 12th slots side swirler with geometrical swirl angle of 45º. The slots width $s$ is 1 mm. The mass flow rate is 2.33 gr/s ($Re = 430$).

![Figure 2](image)

**Figure 2.** Circumferential velocity ($u_r$) and radial velocity ($u_\phi$) distributions across the bottom end boundary layer in the sections at 70, 60.4, 54, 46.2, 38.2, 30, 22 and 13 mm from the axis of vortex chamber: points – experimental data; black lines – numerical modeling without turbulence model; red lines – numerical modeling with RSM turbulence model.

The points present the experimental data [15] obtained by LDA methods in the radial sections at 70, 60.4, 54, 46.2, 38.2, 30, 22 and 13 mm from the axis of vortex chamber. The black line shows the modeling data obtained without using the turbulence model, the red line show the data obtained with the use of above-described RSM turbulence model. As we can see, the results of modeling with RSM
model correlate better with experimental data. A certain difference in the circumferential velocity distribution we can see near the side swirler and near the chamber axis. Near the side swirler, the radial velocity obtained in modelling has a lesser value than that obtained in experiment. It can be explained by the smooth edge of the slot in experiment and the sharp edge in the model. Different forms lead to the different widths and angles of flat jets on the slots outlet. Near the axis, the flow is unstable. It was noted in experiment description that the axial swirl jet in the vortex chamber has weak precession rotation around the geometrical axis with frequencies of few Hertz. The LDA measurements were not synchronized with the position of own axis of swirl jet, and therefore the experimental data were averaged over the random sample of flow configurations near the axis. The used numerical modeling method does not allow solving the problems with precessing axial jet. Figure 2 presents the results of steady solution.

Figure 3 shows the dimensionless circumferential velocity depending on the dimensionless radius of vortex chamber for the axial cross section at the distance from the bottom wall of 100 mm. The numerical data are compared with the experimental results [9]. The parameters of the flow are the same as in Figure 2. We can clearly see that the flat jet is pressed to the sidewall near the swirler. The circumferential velocity has the maximum in this area. The maximum of circumferential velocity near the axis lies at the half radius of diaphragm and it is agreed with the experiment.

The comparison of the modeling data with the generalized experimental data of dimensionless circulation obtained to the various vortex chambers with outlet diaphragm [9] is presented in Figure 4. The red points correspond to the same geometry of vortex chamber as we modeled. As we can see, circulation has constant distribution along the radius in the bulk area, tends to zero at the axis and has the maximum near the swirler. The slot swirler perturbs the flow near the sidewall, but its influence is significant only, if the distance from the axis of the chamber exceeds 0.45

3.2. Flowage of vortex chamber with the outlet diaphragm and side slot swirler

A flowage criterion is the ratio of the summarized mass flow rate through the top and bottom end boundary layers \( G_b \) to the full mass flow rate through the vortex chamber \( G_r \). The complexity of flowage analysis is associated with choosing a radial section, where the velocity both in the end boundary layers and in bulk of the chamber has the most characteristic distribution. Obviously, the full mass flow rate through the section on the sidewall is equal to the defined inlet mass flow rate, and the mass flow rate through the end boundary layers is equal to zero. As Figure 2 shows, the flow near the bottom wall is radially accelerated, therefore the gas flows into the bottom end boundary layer through the upper bound along the radius. The mass flow rate of gas in the end boundary layers increases from the sidewall to axis. If we choose the radial cross section near the axis or bound of outlet diaphragm, the mass flow rate through the end boundary layers is close to zero too. In this area, the flow is radially decelerated and axially accelerated; the axial swirl jet is formed. For the small swirl angle the recirculation area is formed near the axis, therefore the full mass flow rate through the vortex chamber is increased, often several times as compared with the defined inlet mass flow rate through the slots swirler. Obviously, the increasing full mass flow should be taken into account in flowage analysis.

In present study, the control section for calculation of flowage criterion is chosen as the radial section at the distance 60.4 mm (0.38\( D_v \)) from the axis. This section is located far from the axial swirl jet influence area and is characterized the constant circulation in the bulk of chamber and well-developed flow in the end boundary layers. As it's showed in previous section for the studied Reynolds number range the thickness of bottom end boundary layer is not exceed the 5 mm. The modeling data shows the top end boundary layer thickness is equal to 5 mm too. For the flowage analysis the mass flow rate through the end boundary layers is determined as the part of full mass flow rate through the parts of chosen axial section with the height of 5 mm to each part near the top and bottom walls. Figure 5 clearly shows the areas of end boundary layers in comparison with the bulk of the chamber.
The results of calculation of flowage criterion for the studied vortex cambers $G_b/G_c$ depending on the tangents of geometric swirl angle of side slot swirler are presented in Figure 6. The numerical modeling data for various inlet mass flow rates are shown by points. As we can see, the decreasing swirl angle from 90° to 30° leads to increasing mass flow rate through the end boundary layers, but the flowage criterion is still lesser than 1. The full mass flow rate through the control section is higher than the mass flow through the end boundary layers. The further decreasing the swirl angle leads to the switch in flow configuration. The air flow is pressed to the sidewall. The axial swirl jet is swelled and its diameter is increased. Two or more toroidal vortexes are formed in the bulk of the chamber. The flow through the end boundary layers is still non-intensive. The flow pattern is presented in Figure 5 (a). The further decreasing the swirl angle leads to formation of the recirculating flow area on the diaphragm axis. The axial swirl jet turns to the unstable flow regime. As we can see in Figure 6, in this regime the flowage criterion can be higher than 1, close to 0 or even lesser than 0. The data dispersion is presented in Figure 6 by grey field. The changing of flowage criterion is associated with the increasing full mass flow rate through the control section due to gas inflows through the diaphragm and unstable axial flow. The characteristic phases during flow reconfiguration from the flowage to unflowage regime are presented in Figure 5. As the conclusion, the flowage of vortex chamber for the small swirl angle and unsteady regime of the flow is the conditional criterion. At various time moments, the vortex chamber could be the flowage or unflowage. The determination of the characteristic frequencies of transition from flowage to unflowage regime and identification of the main factors influencing the transition is the interesting problem for the further studies.
Acknowledgments

This work was supported by the Russian Science Foundation, grant 14-19-00402.

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