Evaluation of the efficiency of using the swirl flow with the formation of helical vortices

Elizaveta S Gesheva¹, Sergey I Shtork¹² and Sergey V Alekseenko¹²

¹Kutateladze Institute of Thermophysics, Siberian Branch of Russian Academy of Sciences, Lavrentyev Ave. 1, Novosibirsk, 630090 Russia
²Novosibirsk State University, Pirogova Str. 2, Novosibirsk, 630090 Russia
gesheva_es@itp.nsc.ru

Abstract. The paper reports on the results of numerical simulation of large-scale stationary vortices forming in hydrodynamical model of a vortex combustor. In particular, the effect of boundary conditions on the residence time and path length of the fluid particles has been explored. Validity of the numerical procedure has been verified by comparison of the simulation results with the experimental data obtained by measuring the velocity fields using a PIV method. On the basis of the data obtained, it is shown that the average residence time of the fluid particles in the vortex chamber in the case of formation of a single-helix and a double-helical vortex is substantially higher than the residence time of the particles in the flow regime with a rectilinear vortex. The average distance traveled by the particles also increases noticeably in case of the flow regime with the spiral structure’s formation. Thus, based on the work results, it is possible to draw a conclusion about the increased effectiveness of the use of operating modes with the formation of spiral vortex structures.

1. Introduction and experimental method

Using a swirling flow can significantly increase the efficiency of the combustion devices, accelerate the processes that occur in the combustion chambers and reduce the dimensions of the installations. As an initial stage of design of combustion chambers approximate isothermal modeling is used on scaled down laboratory models [1, 2]. In this paper the particle trajectories calculated using a numerical code were analyzed. The numerical procedure was verified by experimental data obtained with the aid of the PIV experiment and visualization of the vortices in a hydraulic model chamber with a square cross-section and a tangential inlet of the flow [3]. The scheme of the hydrodynamic bench is shown in figure 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. Figure 2 shows a diagram of the flow swirl, which 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 base 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 600 mm, depending on the position of the output diaphragm, the chamber width $b$ is 188 mm and the diameter of the diaphragm orifice $d_t$ equals to 60 mm. For the chamber geometry with a two-slope bottom two insert plates mounted at an angle of 50° to the horizon were used.
2. Visualization of the vortices and modeling results

In this model chamber various large-scale vortex structures were observed (figure 3) [4]. The shape of the vortex depends on the geometrical parameters of the chamber. At diaphragm with a symmetrical output orifice and a plane lower end the base rectilinear vortex is formed extending from the bottom of the chamber to the output orifice (figure 3, a).

When introducing asymmetry at the output, namely by shifting the output orifice, the base vortex is bended into a helical coil, thereby forming a spiral vortex (figure 3, b). For the double vortex to form,
there is a need in a two-slope bottom and a central diaphragm (figure 3, c). Thus, by varying the geometric parameters of the chamber, a family of different stationary vortex structures may be realized.

Numerical computations of the swirling flow were carried out using three basic modeling techniques: RANS, DES, and LES [5]. A mesh with polyhedral cells and a prismatic layer was built for the working chamber. The mesh was further refined in the vortex axis region. Thus, it consisted of 1.6 million cells, and the characteristic linear size of its cell was 3.4 mm. It was used the simulation grid with maximum possible resolution for given computer. Perhaps with a more detailed grid, the simulation results would be improved. Boundary conditions were set based on the fluid flow at the inlet and incompressibility of the fluid. In this study we used the "segregated flow" algorithm for the non-stationary implicit problem. The time step was set at 0.05, and about 15,000 iterations were calculated.

Verification of applied modeling techniques required comparison of the obtained fields and profiles of velocity with experimental data of the PIV experiment. This comparison of the fields and velocity profiles in different sections showed that the LES method the most accurately describes the pattern of the swirling flow in the working chamber figure 4). While the RANS and DES methods do not give an adequate representation of the vortex flow. Further we will consider the simulation results, obtained by LES.

![Profile of tangential velocity. Comparison of experimental data with results of numerical simulations.](image)

To assess the effectiveness of the use of the flow swirling the residence time of particles released from the centers of all nozzles was calculated for each geometry. The numbering of the nozzle blocks and layers is shown in figure 5 (in the two-digit number of the nozzle NM, the first digit indicates the number of the nozzle block, and the second is for the layer number).

Examples of particle trajectories for base, spiral and double modes are shown in figure 6. It is seen that the lengths of trajectories for the modes with helical vortices are much larger than for the base vortex. This is proved by the analysis of the quantitative data from the table 1, which shows that in the case of the base vortex, the average residence time of particles in the chamber amounted to $T = 2.8$ s, whereas in the chamber with the shifted output orifice $T = 5.5$ s. The average path length also increased from $L = 2.63$ m to $L = 4.25$ m. Thus, the output orifice shift gives a significant increase in the residence time of particles in the chamber $T_{sp} / T_b = 5.485 / 2.809 = 1.953$ and in the travelled distance $L_{sp} / L_b = 4.251 / 2.631 = 1.513$ while the chamber height does not change ($H_{sp} / H_b = 1$). For the double mode, the ratio of the average residence time of particles in the chamber amounted to $T_{db} / T_b = 3.723 / 2.809 = 1.325$ (the ratio of the chamber heights at that was $H_{db} / H_b = 420 / 600 = 0.7$), and the ratio of the travelled distance $L_{db} / L_b = 2.86 / 2.631 = 1.09$. Even at a much lower chamber height in the case of a two-slope bottom, there is a noticeable increase in the average residence time of particles and in the travelled distance. In the case of the spiral vortex, the average residence time increases almost 2 times.
Figure 5. Numbering of nozzle blocks in the layer N (a) (top view) and levels M (b). The circle indicates the position of the output orifice for the mode with a helical vortex.

Figure 6. The trajectory of particles for different flow regimes: base vortex, b – spiral vortex, c – double vortex.

Table 1 below shows the values of travelled distance \( L \) and the residence time \( T \) of the particles released from the centers of the nozzles for the modes with base, spiral and double vortexes.

Thus, the study of the influence of output orifice shift and two-slope bottom on the residence time of particles in the combustion chamber and on the travelled distance confirms that the modes with helical vortex structures may be more optimal in terms of ensuring more complete combustion of the fuel.

Acknowledgments
The study was funded by the grant of the Russian Science Foundation (project No.14-29-00093).
Table 1. Values of travelled distance (path) $L$ and residence time $T$ in the chamber for the particles, released from the nozzle center for different flow regimes.

|     |   |     |     |     |     |     |     |
|-----|---|-----|-----|-----|-----|-----|-----|
|     | base |     |     |     |     |     |     |
| NM  | $L$, м | $T$, с | $L$, м | $T$, с | $L$, м | $T$, с |
| 11  | 4.62 | 4.6 | 2 | 1.63 | 4.5 | 5.89 |
| 12  | 4.75 | 5.3 | 6.2 | 8.84 | 3.85 | 5   |
| 13  | 1.1 | 1.36 | 0.84 | 1.02 | 3.27 | 4.47 |
| 21  | 3.4 | 4.43 | 7.35 | 10.63 | 2.35 | 2.92 |
| 22  | 1.57 | 1.91 | 5.13 | 6.31 | 2.05 | 2.55 |
| 23  | 1.4 | 1.65 | 2.65 | 4.56 | 2.31 | 3.29 |
| 31  | 2.8 | 1.53 | 1.7 | 0.72 | 2.2 | 2.36 |
| 32  | 3.4 | 3.3 | 5.1 | 5.67 | 2.8 | 3.86 |
| 33  | 0.84 | 1   | 7.1 | 10.08 | 2.8 | 3.75 |
| 41  | 4   | 4.19 | 7.9 | 10.98 | 2.5 | 3.02 |
| 42  | 2.5 | 3.39 | 3.8 | 4.35 | 2.9 | 3.82 |
| 43  | 1.2 | 1.03 | 1.25 | 1.03 | 2.8 | 3.73 |
| mean | 2.63 | 2.8 | 4.25 | 5.48 | 2.86 | 3.72 |

References
[1] Anufriev I S, Sharypov O V and Shadrin E Yu 2013 *Technical Physics Letters* 39 466–8
[2] Alekseenko S V and Shtork S I 1994 *JETP Letters* 59 746-50
[3] Gesheva E S, Shtork S I and Alekseenko S V 2014 *NSU Bulletin. Series: Physics* 9, 39-48
[4] Alekseenko S V, Kuibin P A, Okulov V L and Shtork S I 1999 *Journal of Fluid Mechanics* 382 195-243
[5] Garbaruk A V, Strelets M Kh and Shur M L 2012 *SPb: Polytechnical University Press* 88