Simulation of large-scale vortex structures in a model chamber of the tangential type

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Abstract. The work is aimed at studying large-scale helical vortex structures emerging in a high turbulent intensively swirling flow in detail. The paper presents numerical simulation of vortex structures by various methods of turbulence. It is shown that the LES method most accurately describes flows in a chamber with a swirling flow. As a result of studies, a strong influence of the geometric parameters of the chamber on the shape of the vortex structures is shown. Steady-state vortex structures are formed in a chamber with a diaphragmatic outlet, while the vortices perform small-scale oscillations around their own axis, called the precession of a vortex core.

1. Application of swirl flows
Vortex structures in nature have a great impact on human life, such as cyclones and tornadoes, which are often the causes of disasters and cause huge damage [1-3]. This topic attracts great attention due to the extensive use of vortex flows in engineering.

Recently, the efforts of researchers have been aimed at understanding and describing the aerodynamics of swirling flows with the combustion processes of gaseous, liquid and solid fuels. Economical design and environmental friendliness of combustion-related engineering devices can be greatly improved by additional experiments and model studies. In this case, experimental and theoretical dynamics of flows are used together with complex methods of computational hydrodynamics. The development and improvement of these methods will significantly reduce the time and money spent on programs for the development of new devices [4].

The object of the study is a model chamber with a square cross-section with a tangential swirl flow, the characteristic chamber dimensions are 600 × 188 × 188 mm. Swirl of the flow was carried out through four nozzle blocks installed in the ends of the chamber, three tiers in each. The main calculations were carried out at a flow rate of 4 l / s, which corresponds to a velocity of 1 m / s at the inlet to the nozzle. Water was used as the working fluid. At the output, a diaphragm with aperture was installed, including a displaced aperture opening.

A feature of the swirling flow in the model of tangential chamber is the formation of spatially-complex large-scale eddies that completely determine the global structure of the flow. In this paper, the simulation of a swirling flow is performed using the CFD (Computation Fluid Dynamics) package Star CCM+. STAR-CCM+ is a modern software package designed to solve the problems of continuous media mechanics. It includes the latest numerical algorithms, the ability to build various grids, a large set of physical models, powerful visualization tools, etc. [5].
Among the basic methods of numerical simulation of turbulent flows, direct numerical simulation (DNS), large eddy simulation (LES) and the solution of Reynolds-averaged Navier-Stokes equations (RANS) are distinguished. There are also intermediate (hybrid) approaches that combine some of the features of the DNS, RANS and LES, in particular, the modeling of detached vortices [6] (DES). Obstacles to the wide use of DNS are associated with high requirements for difference schemes, satisfaction of initial and boundary conditions, and also limited resources of computer technology [6, 7].

2. Simulation and Results

The computed geometry of the chamber was created in the similitude of the experimental vortex chamber studied in this work (figure 1). All of the presented methods for simulating turbulent flows were used: RANS, DES, LES, while modeling a vortex flow in a tangential chamber. For the chamber, a grid was constructed with polyhedral cells and a prismatic layer. Also, additional mesh details were made in the near-axis region (vortex area), so the grid consisted of 1.7 million cells, the characteristic linear cell size was 3.2 mm. The boundary conditions were set basing on the flow rate of the liquid at the inlet and the incompressibility of the liquid. The algorithm used segregated flow for a non-stationary implicit task. The time step was set to 0.05 s, and about 20,000 iterations have been calculated.

RANS requires the least amount of computing resources and allows the wall layers to be well resolved, but at the same time lowers the turbulent pulsations in a swirl flow. To improve the simulation of nonstationary turbulent swirling flows, vortex-resolving methods are used, such as, for example, Large Eddy Simulation (LES). However, its use requires a very detailed mesh, especially near the walls. To combine the merits of these approaches, the Detached Eddy Simulation method (DES) was proposed.

Modeling a swirling flow using the RANS approach in our case did not yield adequate results, which is also observed in similar studies on the simulation of swirling flows [8-12]. The vector field of the tangential velocity, calculated using the RANS method, is shown in figure 2. According to the theoretical description of vortices, it was expected to obtain a localized region with high values of the tangential velocity. However, figure 2 shows that the maximum velocity is not observed in the vortex region, and vortices are pressed against the walls of the chamber.

![Figure 1](image1.png)

**Figure 1.** The calculated geometry of the chamber is to the left, the calculated grid in the cross section of the chamber is to the right.
Figure 2. Tangential velocity field obtained by the RANS method.

Figure 3. Comparison of the tangential velocity profiles for a rectilinear vortex. The height of the section of the chamber is $h = 85$ mm.

Figure 3 shows the tangential velocity profiles calculated by various methods, where it is clearly visible that the RANS method does not provide reliable information about the structure of the vortex flow.

Basing on the description of turbulence models and their applicability to various tasks, it was decided to simulate a swirling flow using modern methods for modeling large-scale vortex structures: Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) simulation.

The methods of LES and DES give very similar results. Nevertheless, the extremum of the speed calculated by the DES method is much lower than the LES profile, this indicates that this method does not allow calculating the velocity pulsations due to the average made in the method. However, with increasing altitude, the maximum of the tangential velocity obtained by modeling the LES and DES methods differ insignificantly.

It is known that the tangential velocity profile of a vortex in a swirling flow is well described by the viscous Burgers vortex model [13, 14]. The Burgers vortex belongs to the class of axisymmetric exact solutions of the Navier-Stokes equations, where the tangential component is described by formula (1)

$$V = \frac{\Gamma}{2\pi r} \left[ 1 - \exp(-\alpha r^2/4\nu) \right]$$  \hspace{1cm} (1)

$$r_m = 2,242 \sqrt{v/\alpha}$$ \hspace{1cm} (2)

$$V_m = 0,16 \frac{\Gamma}{\pi} \sqrt{\frac{\alpha}{\nu}} = \frac{0,36\Gamma}{\pi r_m}$$ \hspace{1cm} (3)

and the values (2) and (3) correspond to the extremum of the tangential velocity, where $\nu$ is the kinematic viscosity, and $\alpha$ is a constant, the value of $r_m$ is usually interpreted as the effective radius of the vortex [15].

Figure 4 shows a comparison of the data with the Burgers vortex model [13], where the LES simulation data with a good accuracy fall on the curve describing the Burgers vortex. It is also evident that the profile calculated by the DES method does not agree with the viscous model of the Burgers vortex.

Based on the received information, further calculation data will be presented comprising of the LES method.

Figure 5 shows the visualization of vortex structures based on numerical simulation by the LES method. The visualizing surfaces are constructed using the Lambda2 criterion. Lambda2 is a scalar quantity defined as the mean eigenvalue $\lambda_2 = S_2 + \Omega_2$, where $S$ is the symmetric component of the
velocity gradient, and Ω is the antisymmetric component [16]. Values of Lambda2 below zero should be interpreted as vortices, while values greater than or equal to zero do not have a physical meaning.

The resulting vortex structures are fixed from the bottom to the exit aperture of the diaphragm. For single vortices, an increase in the radius of the vortex with increasing altitude is observed. The double-helical structure is clearly fixed, while the vortices around the nozzle blocks are noticeably weakened.

When modeling the vortex flow, a non-stationary problem was solved. Earlier it was experimentally shown that the vortex structure makes small oscillations about the axis of the vortex. Thus, basing on the numerical simulation, the vibration frequencies of the vortex core were extracted. Figure 6 shows the dependence of the oscillation frequency on the flow rate of the liquid, where the color points indicate the simulation data. It turned out that the frequency of precession of a vortex is well predicted by both modeling methods, and the obtained points lie on a straight line which, when approximated, intersects the abscissa axis at zero.

3. Conclusion
When simulating swirling flows in a tangential combustion chamber, three basic approaches to simulating turbulent flows were tested and it was shown that the LES method gives an adequate flow pattern consistent with the Burgers vortex model. The geometric parameters of the chamber, namely the boundary conditions: the shape of the bottom and the diaphragm and displacement of the outlet,
determine the shape of large-scale eddies. Thus, rectilinear, single-helical and double-helical vortex structures were obtained, while the structures were quasi-stationary and performed only small-scale oscillations around the vortex axis. These oscillations are usually called the precession of a vortex core. As shown by the experimental data, the precession frequency depends linearly on the fluid flow rate and, accordingly, on the Reynolds number. Proceeding from this, it can be concluded that the shape of the vortex does not depend on the fluid flow and the swirling flows are self-similar in the Reynolds number.

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