Investigation of aerodynamic structure of isothermal swirl flow in a two-stage burner

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Abstract. The work is devoted to experimental and numerical study of aerodynamic structure of a swirl flow in isothermal model of a vortex burner device that is characterized by the fluid flow supply via two sequentially-mounted tangential swirlers. Depending on the way of the flow supply into the second-stage swirler, either co-swirl or counter-swirl of two flows can be realized. The effect of the second-stage supply direction on the resulting aerodynamic structure has been investigated. Using LDA measurement system the profiles of averaged axial and tangential velocity components were obtained. Experiments have shown that in the co-swirl case the flow inside the vortex burner model is characterized by strong non-uniformity, while in the counter-swirl regime a rapid mixing of the flows from the first and second stages occurs, resulting in a uniform distribution of the flow across the chamber section. Numerical simulation of 3D isothermal turbulent flow has been performed for the counter-swirl regime using the differential Reynolds stress model in the time-dependent formulation. Using the $Q$-criterion for the identification of vortices in numerical data arrays, the evolution of large-scale vortex structures of the swirl flow inside the vortex chamber has been visualized, indicating the presence of two spiral-shape vortex filaments in the vortex chamber. The periodic character of dynamics of these vortex structures has been revealed.

1. Introduction
Swirl flows are widely used in many technical devices, including those for mixing liquids, spraying liquid fuels and stabilizing the flames. The actual task for nowadays is the study of the behavior of co-axial swirl flows [1]. For combustion chambers a characteristic feature is the swirl imparted to the flow. The flow swirling contributes to an enhancing the fuel and oxidizer mixing and improving the flame stabilization that occur due to the formation of a central recirculation zone. The degree of swirl of the flow generally has a strong effect on the formation of turbulence in the flow, which in turn characterizes the region of mixing of co-axial swirl flows [2].

The present work is devoted to an isothermal modeling the aerodynamic flow structure in a two-stage vortex burner with a tangential swirl of the flow. In view of the geometry simplicity, the burners with a tangential or scroll swirlers are often used in practice for example for the combustion of fine pulverized coal [3]. In turn, the two-stage design of the burners can be used in the schemes for burning pulverized-coal fuel, when the first ignition stage is fed with more reactive fuel subjected to mechanochemical activation and the second stage is used for combustion of the lower-reactive coal fuel prepared by the regular method [4].

Isothermal modeling, which allows to determine with relatively low costs the direction of the burner design optimization with respect to operating modes and geometry of the working area, was widely used earlier for the development of power plants [5]. This approach remains to be relevant and
is currently supplemented by the capabilities of modern non-intrusive optical systems (laser Doppler anemometry – LDA, Particle image velocimetry – PIV) for a detailed analysis of internal structure of the flows [6, 7]. Moreover, the physical experiment provides also an empirical information for verifying the results of mathematical modeling [8, 9].

2. Experimental setup

A hydrodynamic model of a two-stage vortex burner is used as a working area (figure 1). To provide optical access the model chamber is made of transparent material - Plexiglas. The inlet part of the working chamber consists of two sequentially connected swirlers with a diameter of 185 mm, in which a swirling of the flow is realized by means of a tangential inlet through pipes with an internal diameter of 40 mm. The fluid flow initially gains a swirl on the swirler (1) and then passes through the nozzle into the area of sudden expansion. Later in this area it interacts with a flow that acquire a swirl on the second swirler (3). It is possible to change the swirl of the flow in the second stage of the model by closing or opening the corresponding supply pipes with the help of stopcocks. Depending on the way of fluid supply to the second swirler, co-swirl (white arrows) and counter-swirl (dark arrows) of two flows are realized between the swirlers of the first and second stages of the working section. The resultant flow from the cylindrical zone of 104-mm diameter (4) is fed to the outlet section (5), and it leaves it through four symmetrical pipes with the inner diameter of 20 mm.

The total flow rate in the working area for this series of experiments was of the order of 10 m$^3$/h, which correspond to a turbulent flow regime with a Reynolds number of the order of 10$^5$. These conditions characteristic for the operation of practical devices correspond to the self-similarity region when the flow structure does not depend on the Reynolds number [5, 8].

![Figure 1. Scheme of hydrodynamic model of two-stage burner. 1 and 3 – swirlers of the first and second stages of the burner, respectively, 2 – shaped nozzle, 4 – zone of sudden expansion, 5 – outlet section with exit pipes and deswirler blades.](image)

3. Results and discussion

3.1. LDA-measurements

To acquire quantitative information about the flow field, the two-component laser Doppler anemometer (LDA) LAD-06i was used. Time-averaged axial and tangential velocity components were measured along one line in the cross-section of the cylindrical zone of sudden expansion (figure 3). The characteristic distance from the exit of the second-stage flow swirler to the measured cross section shown in figure 2. The presented results were obtained for the fluid flow rate of 4 m$^3$/h at the first
swirler and 6 m³/h at the second swirler. The distance from the central axis $x$ is normalized to radius $R_0$ of the cylindrical area of sudden expansion (figure 1 (4)).

Figure 3 shows the profiles of the axial and tangential velocity components. Axial velocity distributions show that in cases with co-swirl flows the formation of a non-uniform axial flow distribution in the transversal cross-section with an intense flow along the walls and a broad region of stagnant flow along the axis of the chamber takes place. The jet flow from the nozzle of the first stage of the swirler partially fills the central gap so that the axial velocity profiles near the axis have a backward bend. In the regime with counter-swirl flows, the resulting flow structure is characterized by a fairly uniform distribution of the axial velocity along the transversal cross-section.

In counter-swirl mode the flow of the second stage rotates the resulting flow in the opposite direction. Due to the effect of mutual suppression of the swirl, the level of tangential velocities becomes lower. And the swirl is more localized near the channel wall, and the central region has a very weak level of swirl, with a tendency to change the sign of rotation.

Thus, the measurement results show that the counter-swirl of the flows in the first and second stages contributes to the formation of a more optimal aerodynamic flow structure characterized by a uniform distribution of the axial velocity along the cross section in combination with a sufficiently pronounced general rotational motion of the flow in the working section.

3.2. Numerical predictions
Numerical modelling of isothermal turbulent flow in the studied laboratory model of the swirl burner has been performed in the case of counter-swirl burner regime. In the framework of unsteady RANS (URANS) second-moment closure approach to turbulence modelling, the differential Reynolds stress model (DRSM) based on the linear pressure-strain correlation (LRR) and the transport equation for $\omega$ (r.m.s. vorticity of turbulent eddies) has been applied. This DRSM LRR-$\omega$ model [10] allows to account for non-isotropy of turbulent field and therefore to improve the accuracy of turbulence modelling [10] in the complex 3D swirl flow. Inlet conditions prescribed in numerical simulation
correspond to those used in experiments on the counter-swirl flow regime. The numerical 3D solution was obtained on unstructured computational grid consisting of $1.45 \times 10^6$ polyhedral cells. At each time step $\Delta t = 2$ ms up to 50 sub-iterations were done using the SIMPLEC algorithm [11] for pressure-velocity decoupling until the convergence of discretized system of governing equations. Computations have been carried out with the use of CFD package ANSYS FLUENT.

From numerical simulation the ensemble of instantaneous flow fields has been computed for the period of ~24 s of the flow evolution, and the fields of mean and turbulent quantities have been obtained by the time-averaging over the period of 6.3 s. In figure 4 the comparison between the numerical and experimental results is shown for the profiles of mean axial and tangential velocity components plotted at cross-section $z=80$ mm of the vortex chamber. With the use of known $Q$-criterion of a vortex identification [12], visualization of large-scale vortex structures and their evolution inside the swirl burner model has been performed – a typical 3D picture of isosurfaces $Q = 750$ s$^{-2}$ educed from computational data (at time moment $t = 22.8$ s) is demonstrated in figure 5. The visualization analysis allowed to reveal the presence and evolution of two spiral-form vortex core filaments in the vortex chamber, which have also been observed in experiments. The spectra obtained from URANS simulation (see figure 6) indicate a periodic character of dynamics of these vortex structures, and the typical frequency $f_p = 3.945$ Hz manifesting the maximal pulsations of total pressure in the vortex chamber has been found from the spectra analysis.

![Figure 4](image4.png)

**Figure 4.** Comparison of the velocity profiles at cross-section $z = 80$ mm for the counter-swirl regime of flows in LDA measurements and numerical simulation. (a) - axial velocity component, (b) - tangential velocity component.

![Figure 5](image5.png)

**Figure 5.** Isosurfaces of $Q$-criterion ($Q = 750$ s$^{-2}$) in the swirl burner model at time $t = 22.8$ s (URANS simulation).

![Figure 6](image6.png)

**Figure 6.** Spectrum of total pressure pulsations in the vortex chamber (URANS simulation).
4. Conclusions
The effect of the second-stage supply direction on the resulting aerodynamic structure of a swirl flow in the laboratory isothermal model of a swirl burner has been investigated. Using LDA measurement system the profiles of axial and tangential mean velocity components have been obtained. Experiments have shown that in the counter-swirl case the flow inside the model vortex chamber is characterized by strong non-uniformity, namely, the primary fluid flow moves along the side wall, but an extended stagnant region is formed along the chamber axis. On the contrary, in the counter-swirl regime a rapid mixing of the flows from the first and second stages occurs, resulting in a more uniform distribution of the flow across the chamber section. Therefore the counter-swirl mode appears to be more preferable for the use in a two-stage burner device.

Numerical simulation of 3D isothermal turbulent flow in the studied laboratory model of two-stage burner has been performed for the counter-swirl regime, using URANS approach with DRSM LRR-ω model. The comparison between the numerical and experimental results has shown a consistency of numerical predictions with LDA measurements on axial mean velocity component, however some quantitative discrepancy in the profile of tangential mean velocity component is observed. With the use of known Q-criterion of a vortex identification, the evolution of large-scale vortex structures of the swirl flow inside the vortex chamber has been visualized from numerical data, indicating the presence of two spiral-shape vortex filaments in the vortex chamber. The periodic character of dynamics of these vortex structures has been revealed and the frequency of maximal pulsations of total pressure inside the vortex chamber has been found from the spectra analysis.

5. References
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