Identification of geometrical vortex parameters in tangential swirler

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Abstract. This experimental work identifies spatial vortex parameters at the exit of the tangential swirler based directly on velocity distributions obtained by Stereo-PIV method with using pressure pulsations in the acoustic field of swirling jets. The velocity measurements are carried out for high swirl jet close to exit of swirler nozzle ($Re = 23000$ and $Sh = 1.54$). The spatial distribution of the PVC is captured with statistical analysis of instantaneous velocity fields and phase-averaged vorticity distribution.

1. Introduction

To create high swirl parameters ($S > 1$) in practice tangential swirlers are used. In this case, the flow forms a stable central recirculation zone and an area of low pressure. Work of many burners and separating technological devices would be impossible in the absence of the central recirculation zone (CRZ).

One of the features of the swirl flow in the case of a sudden expansion is the formation of unsteady vortex effect, known as the precession of the vortex core (PVC), which is a type of helical breakdown of vortex, occurring in the conditions of a sudden expansion of the swirl flow. In literature it is noted that the effect influences the processes of combustion or separation, occurring in the chambers [1]. Modern methods of flow diagnostics, such as advanced Particle Image Velocimetry (PIV), provided the impetus for the detailed experimental works [2–4], studying the PVC and secondary vortex structures, arising behind the layer of swirling jet mixing. Those parameters are required to apply the model of a helical precessing vortex and to prove the adequacy of this model for real swirling flow. Nonstationarity of vortex motion makes difficulties for determination of the PVC main spatial characteristics. Therefore, an important task is to predict the effect of PVC for different designs of swirlers still at the stage of development.

In the current work, spatial vortex parameters are obtained by algorithms based on the work of Graftieaux et al [5] and phase-averaged procedure of vorticity field from previous work [6]. This article aims at direct determination of vortex parameters, required for further applying the model of a helical precessing vortex (see [6,7]), to prove the adequacy of this model for real swirling flow.

2. Experimental setup

Study was conducted on an air tangential swirler, which is an axisymmetric chamber with two inlets and one exit nozzle of $D = 52$ mm diameter (figure 1a), the same as in [6] at air flow rate of 15 l/s and
bulk velocity at the nozzle exit $U_0 = 7.06$ m/s. To measure instantaneous velocity fields we used Stereo-PIV system "POLIS" consisting of a double pulse laser Nd:YAG Laser (70 MJ at a pulse with duration of 10 ns), two CCD cameras "IMERX" (2060 × 2056 pixels, 8-bit) and a synchronizing processor. To form a laser sheet the focusing and cylindrical lenses were used. The laser sheet lied in the plane $x$-$y$, and the measuring section $z=0$ was located at a height of 0.5 mm from the nozzle section. Stereo PIV cameras were located at an angle of ±30° relative to the measurement plane. They were equipped with special turning lenses, allowing focusing the object, observed at an angle relative to the camera axis, on the matrix plane. For optical system calibration we used the planar 3-level calibration target of 100 × 100 mm size with circumferences on the Cartesian grid with a step of 5 mm. In addition, the correction algorithm of possible mismatch of the target and the measuring plane was used to improve the accuracy of measurements. The delay between a pair of flashes was 25 μs, and the frequency of the laser flashes was 1.4 Hz; at that, statistics of 5000 images was collected for each section. The flow was seeded with particles of paraffin oil using self-made Laskin nozzle generator.

Conventional phase averaging was performed by the ADC board, which registered data of two channels with 10 kHz frequency: the first channel provided the time of laser flashes, and the second one provided the phases of the vortex structure, registered with the microphone. Phase averaging, as a rule, was carried out on 100 images.

3. Results

3.1. Characteristics of the flow

The tangential swirler generates stable flow pulsations that are clearly identifiable in the pressure signals. The self-oscillating process is implemented at a constant Strouhal number $Sh = fD/U_0$ ($f$ is a frequency of PVC) relative to $Re = U_0 D/\nu$ ($\nu$ is the kinematic viscosity) (figure 2a). The fundamental harmonic of the spectrum, determined by the periodic motion of the vortex, is associated with the PVC frequency and corresponds to $Sh = 1.54$, and the second harmonic in the power spectrum corresponds to $Sh = 3.08$ (figure 2b). This allows generalizing the obtained results for other $Re$ numbers.

Figure 3 presents isocontours of the root mean square (RMS) of the axial velocity pulsations and streamlines obtained in the $x$-$z$ plane. This location of the maximum level of pulsations corresponds to the center of the inner shear layer i.e. the stream surface dividing the reverse from the direct flow. It also corresponds roughly to the maximum mean velocity gradient and the additional source of turbulence. The coherent pulsations due to flow unsteadiness and PVC have a major impact on the RMS distribution.

According the work [5], two scalar functions $\Gamma_{1,2}$ could identify the locations of the center and the boundary of the vortexes on the basis of the PIV two-component velocity field. $\Gamma_1$ is defined as follows:
\[ \Gamma_1(P) = \frac{1}{N} \sum_{S} \frac{PM \times U_M}{\|U_M\|} \]  

(1)

where S is a rectangular domain of fixed size and geometry, centered on point P, control point M lies in area S, \( U_M \) is the velocity vector, and N is the number of points M inside S. The number of N points acts as a spatial filter and equals 11.

The vortex size identification method takes into account a local convection velocity \( \bar{U}_p \) around point P:

\[ \Gamma_2(P) = \frac{1}{N} \sum_{S} \frac{PM \times (U_M - \bar{U}_p)}{\|U_M - \bar{U}_p\|} \]  

(2)

where \( \bar{U}_p = (1/N) \sum S U_M \). It was shown, when these scalars exceed the thresholds of \( |\Gamma_1| > 0.95 \) a vortex centre is identified and when \( 2/\pi < |\Gamma_2| < 1 \) this point is defined as a vortex size.

Figure 4 shows the loci of vortex-center obtained with the \( \Gamma_1 \) function, which was applied for all 5 thousands of instantaneous PIV velocity fields (for cross-section z/D = 0.1). About 1500 snapshots were excluded from consideration, because vortex centers were laid out of the nozzle area. Figure 5 shows the histogram of normalized parameter \( a/D \) (radius of PVC) obtained with the \( \Gamma_1 \) function. It is clearly seen that the positions of the vortex cores in time vary slightly (\( a \approx 0.25D \)). This result allows regarding the flow as quasiperiodic in space and use phase-averaged distributions to find the geometric parameters of the vortex.

Figure 6 shows histograms of the distribution of the vortex core radius (\( \varepsilon \)) and the circulation (\( I_1 \)), calculated by the function \( \Gamma_2 \). It can be seen that the standard deviations of the \( \varepsilon \) and \( I_1 \) distributions are quite substantial and equal \( \approx 30\% \) of mean value. It should be noted that time of data acquisition includes more than 700 thousand of precessing periods.

The mean values of vortex parameters (\( a, \varepsilon, I_1 \)) are in the good correlation with parameters obtained.

![Figure 2](image1.png)  
**Figure 2.** Dependence \( Sh \) on \( Re \) (a) and power spectral density for pressure pulsations measured with a microphone (b).  

![Figure 3](image2.png)  
**Figure 3.** RMS isocontours of axial velocity pulsations and streamlines of flow (\( Re=23\cdot10^3 \)).
from phase-averaged vorticity distributions in work [6] (table 1). This fact proves that functions $\Gamma_{1,2}$ give acceptable estimates of vortex centre location and size of the unsteady vortex.

| Table 1. Comparison of vortex parameters obtained with different methods. |
|-------------------------------|-------|-------|-------|
| $\Gamma/\bar{U}_0$ | $a/D$ | $\varepsilon/D$ |
| Work [6]  | 6.4  | 0.257 | 0.195 |
| This work | 5.47 | 0.25  | 0.16  |

To determine the helical pitch of the vortex it is necessary to analyze the distribution of vorticity in the volume, because it is impossible to directly extract information about the helical structure of the vortex only from one cross-section. Therefore, the experiments were carried out for several cross-sections along the z axis with 5 mm step, which enabled recovery of vorticity distribution in space (figure 7a) with reference to the vortex phase. It is impossible to identify the vortex core from the vorticity distribution for cross-section $z/D > 0.58$ due to fast elimination of the PVC structure in the axial direction (figure 7b). Since azimuthal angle of the maximum of the vorticity distribution is the linear function of the height, it allows estimating a local helical pitch near the swirler nozzle.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** Loci of the vortex-centre locations (crosses) obtained with $\Gamma_1$ function (~3500 PIV snapshots, $z/D = 0.1$).

**Figure 5.** Histogram of normalized $a/D$ (radius of PVC) obtained with $\Gamma_1$ function.

![Figure 6a](image3.png)  ![Figure 6b](image4.png)

**Figure 6.** Histograms of normalized $\varepsilon/D$ (radius of vortex core) (a) and normalized PVC intensity $\Gamma/\bar{U}_0$ (b) obtained with $\Gamma_2$ function.
4. Summary
We have experimentally identified the unsteady vortex parameters in the swirling flow in the tangential swirler. Geometrical parameters have been directly estimated from instantaneous velocity distributions. Spatial vortex parameters have been obtained by algorithms based on the work of Graftieaux et al. [5] and have shown good correlation with parameters from previous work [6] by phase-averaged procedure of vorticity field. This result allows regarding the flow as quasiperiodic in space and using phase-averaged distributions to find the geometric parameters of the vortex. These parameters are required to apply the model of a helical precessing vortex for real swirling flow.

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