Study of strongly swirling flow and finding of spatial parameters of a helical precessing vortex by stereo-PIV and acoustic sensors

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Abstract We present an experimental study of a strongly swirling flow with formation of a precessing vortex core that appears at the outlet of a tangential swirler nozzle. The studies were carried out using a stereo-PIV system and two acoustic pressure sensors. Analysis of the velocity fields measured by the proper orthogonal decomposition (POD) showed that the precession motion of the vortex makes a significant contribution (more than 30%) to the turbulence kinetic energy, which makes it possible to consider the effect as a bright and convenient object for testing the model of a helical precessing vortex. Estimates of the model parameters of a helical vortex (such as vortex core radius, vortex precession radius, and vortex intensity), based on statistical data obtained from uncorrelated PIV images, are presented. The estimated parameters were also compared with the parameters obtained by the technique of phase-averaging of PIV snapshots, as a result of which the three-component velocity distributions were obtained with reference to the vortex positions. Analysis showed that the precession radius can vary over time within deviation 10%, and the core size and the circulation can vary within 25 and 30%, respectively.

Keywords: PVC, helical vortex model, Stereo-PIV, acoustic probes, POD

1 Introduction

High swirl flows are widely used in different technical application such as fossil fuel burners, cyclone separators, Ranque–Hilsch tubes, vortex diodes and solar vortex reactors. The main feature of such high swirl flows is the formation of a region with low pressure and a strongly pronounced region of reverse flow. This makes it possible to use flow swirling for particle separation, chemical mixing, combustion, and energy separation. A tangential swirler is the most common type of swirl generators to provide high swirl numbers compared with other types, such as vane and rotary swirlers. In general, a tangential swirler has a simple geometry consisting of just one or few tangential inlets and exit nozzle and no moving parts that makes it suitable for long operation life.

In the current work, we present a comprehensive approach to experimental estimating the spatial parameters of the precessing vortex directly from the experiment using the standard stereo-PIV with conditional averaging by the precession phase and using two acoustic sensors in the case of a strong swirl of the flow (\(S = 1.4-2.4\), \(Re = 2\cdot10^4-4\cdot10^4\)). The relationship of the Strouhal number with the Reynolds number is evident, showing an independent relationship at high \(Re\) [1]. The relationship of the Strouhal number with swirl number also observed in the papers [2,3] and represented a power law. For this reason, detailed analysis in the current study is limited to the reference experimental conditions with \(S = 2.4\) and \(Re = 2.3\cdot10^4\). We compared phase-averaging methods with reconstruction method by using the first two most energetic POD modes and by analysis of the whole PIV statistics with using of scalar functions, proposed by [4]. Spatial parameters were used for calculation of precession frequency by a formula derived from the helical vortex model.

2 Experimental set-up

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, the same as in [5] 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 with use of self-made Laskin nozzle generator.

4 Results

To estimate the vortex parameters directly from the whole PIV statistics, we used instantaneous three-component velocity distributions in the horizontal cross-section at height $z = 0.01D$. The locus of vortex center points, determined with the help of scalar function $\Gamma_1$ [4], which was calculated for each of 5000 instantaneous velocity distributions. Approximately 300 PIV images were excluded (6% of total value), so the vortex core was not identified within the nozzle area. As can be seen from the figure, the trajectory of the precessing core in this cross-section is close to a circle (ellipticity is less than 4%). Fig. 1b shows the histogram of the dimensionless precession radius $a/D = \sqrt{x^2 + y^2}/D$, plotted by the locus of vortex centers. If we accept the hypothesis of distribution normality, then we can estimate the average value of precessing radius $a/D$ as 0.26 with standard deviation 0.027. This result indicates that the flow is quasi-periodic in space.

![Fig. 1 Determination of spatial vortex parameters: locus of vortex center from instantaneous velocity distributions (a), histogram of dimensionless radius of precession $a/D$ (b), vortex radius $\varepsilon/D$ (c) and vortex circulation $\Gamma/D$ (d)](image-url)
The equivalent vortex radius \( \varepsilon \) was calculated as \( \varepsilon = \sqrt{\frac{\Sigma}{\pi}} \), where \( \Sigma \) is an area, occupied by vortex core (criteria \( 2/\pi < |\Gamma| < 1 \)). The histogram of dimensionless vortex core radius \( \varepsilon/D \) calculated by the function \( \Gamma \) [4] are presented in Fig. 1c. We can accept the hypothesis of distribution normality, then we can estimate the average value of precessing radius \( \varepsilon/D \) as 0.16 with standard deviation \( \sigma = 0.037 \). Vortex circulation \( \Gamma/DU_0 \) was calculated with using integral definition \( \Gamma = \int_{\varepsilon} \alpha d\sigma \). So we can estimate the average value of circulation of vortex \( \Gamma/DU_0 \) as 5.5 with standard deviation \( \sigma = 1.51 \) (Fig. 1d).

It should be noted that the above statistics are obtained for more than 750 thousand precession periods, which also indicates that precession of the vortex core under these conditions is a highly quasi-periodic process in time and space.

5 Conclusions

With the help of two scalar functions \( \Gamma_{1,2} \), estimates of the model vortex parameters (core radius, vortex precession radius, and vortex intensity) were derived using statistical data of vortex locations from uncorrelated PIV images, when the precession motion phase is random at the time of velocity measurement. The phase-averaged data showed that the size of the core and radius of precession vary insignificantly. The statistical analysis of the vortex parameters obtained with the help of scalar functions \( \Gamma_{1,2} \), has shown that the radius of precession changes by 10%, and the core radius changes by 25% and vortex circulation changes by not more that 30%.

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References