The unsteady swirling jet in a model of radial burner

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Abstract. The experimental study of an isothermal swirl flow with the formation of a precessing vortex core in the radial swirler upon non-confinement and confinement conditions is carried out. Velocity profiles are obtained with varying Reynolds parameter and guide vane angle, changing the swirl number S. Four acoustic sensors and LDA system are used to measure Strouhal number as the function of the integral swirl number in the range from 0.5 < S < 0.8. It is shown that the unsteady flow with PVC effect significantly changes upon non-confinement and confinement conditions.

1. Introduction

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). It is a type of spiral breakdown of vortex accompanied by central recirculation zone (CRZ), 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 vortex devices [1]. The hydrodynamic phenomenon causes regular pressure pulsations in the flow, and even leads to nonlinear interaction between the swirl and flame [2]. Frequency response of the unsteady flow with the PVC is an important unknown flow characteristic, which should be considered at the design stage of vortex devices.

This paper presents an experimental study of the PVC effect and frequency characteristics of the flow in a model of radial swirler. Velocity profiles are obtained with varying Reynolds parameter and guide vane angle, changing the swirl number. Strouhal number is measured as the function of the integral swirl number in the range from 0.5 < S < 0.8 with the use of four acoustic sensors and laser-Doppler anemometer (LDA). Experiments are carried out upon confinement and non-confinement conditions.

2. Experimental set-up

In the paper a radial type swirler is used. The geometry of the swirler is similar to the typical gas turbine devices [3]. Air is supplied by the blower and is measured by an ultrasonic flow meter within 1.5% uncertainty. The air passes a plenum with a diameter of 500 mm and a height of 800 mm, and goes to guide vanes of radial swirler and then, through the profiled tube, into the open space or confined space (Fig. 1). A glass tube with the length of 150 mm and the inlet diameter $D_c$ of 100 mm is used as confinement. The angle of guide vanes $\alpha$ is controlled using a stepper motor with an uncertainty of 2°. In this work, the angle $\alpha$ varies from 0° to 76°. Reynolds number is determined as
Re=$U_0D/\nu$ ($U_0$ is the bulk velocity at the outlet of the nozzle, $D$ is the diameter of the nozzle 50 mm, and $\nu$ is the kinematic viscosity of air at 25 °C).

Velocity distributions are measured using a laser-doppler anemometer (LDA) "LAD 06-C". In each measuring point of the velocity profiles, statistics for $5\times10^3$ bursts are collected. The tracers are drops of vegetable oil, generated in the Laskin nozzle. An additional air flow (1 m$^3$/h) with tracers is mixed with the main flow rate.

The frequency of pressure pulsations is measured by four acoustic sensors, which are mounted in the bottom (Fig. 1). The acoustic sensors are measuring microphones Behringer ECM8000 coupled with tube probes [4]. The dominant frequency in the spectrum of the signal $p = p_1 - (p_1 + p_2 + p_3 + p_4)/4$ is associated with the PVC frequency.

![Figure 1. Experimental setup of the radial swirler.](image)

3. Results

Figure 2 shows the axial velocity profiles without swirling ($\alpha = 0^\circ$). LDA measuring points are located every 2 mm along the $x$ and $y$ axis at the height $z/D =0.34$ above the nozzle. Velocity values are nondimensionalized by bulk velocity $U_0 = 6.8$ m / s ($Re = 21700$). From the graph, it can be seen that the flow is symmetrical, and the plenum of the radial swirler operates optimally. Velocity profiles are symmetrical, so only the half-length velocity profiles are shown further.

![Figure 2. Distribution of the mean axial velocity ($\alpha=0^\circ$): 1 is the velocity profile along the $x$ axis, 2 is the velocity profile along the $x$ axis.](image)
The Re number effect on the velocity profiles is considered in Fig. 3. Velocity profiles are measured for \( \alpha = 45^\circ \) at a height \( z/D = 0.34 \) above the nozzle. The results show the independence of the swirl flow on the Re numbers starting from the value of \( 1.6 \times 10^4 \) [4].

In order to characterize the effect of swirl on velocity profiles, the swirl number definition should be considered. According to [1], the integral parameter of the swirl number can be represented in the following form:

\[
S_{sw} = \int_0^\infty V_{ax}(r) r \, dr / \int_0^\infty (V_{ax}^2 + (p-p_\infty)) r \, dr,
\]

where \( V_{ax}(r) \) and \( V_{tan}(r) \) are the mean axial and tangential velocity components, \( R \) is the radius of the vortex chamber, and \( p-p_\infty \) is the contribution of pressure, which can be defined as \( -\int_\infty^r \frac{V_{tan}^2 \, d\xi}{r} \) based on the effect of swirling on the pressure gradient.

**Figure 3.** Impact of Re number on velocity profiles: 1 – \( 11 \times 10^3 \), 2 – \( 1.6 \times 10^4 \), 3 – \( 2.2 \times 10^4 \), 4 – \( 2.7 \times 10^4 \), 5 – \( 3.3 \times 10^4 \) \((\alpha = 45^\circ)\), (a) is the tangential component of velocity, (b) is the axial component of velocity).

Figure 4 shows four profiles of the mean velocity for a fixed value of \( Re = 16500 \) \((U_0 = 4.95 \text{ m/s})\) in the range of the swirl number \( S = 0.5 – 1.18 \). From the four half-profiles of the tangential velocity for different swirl numbers \( S \) (Fig. 4, (a)), it can be seen that with increasing swirl number values, the position of the maximum shifts to the periphery. The confinement significantly shifts the radial position of the maximum of the velocity to the walls. In addition, the maximum value of the tangential component velocity increases. When considering the axial velocity profiles, it may be seen that the effect of swirl number increases the value and area of CRZ, which is accompanied by PVC formation [1]. The confinement significantly increases the width of CRZ and the maximum value of axial jet on the periphery as was previously shown in [5].

The frequency response of the PVC effect at the exit of the burner nozzle is measured by pressure probes. Figure 5 shows the dependences of the dimensionless PVC frequency in the form of the Strouhal number \( Sh = f_0 U_0 / D \) \((f_0 \text{ is the PVC frequency in Hz})\) on the integral swirl number \( S \) for confinement and non-confinement cases (the swirl number is calculated for non-confinement conditions). As can be seen from the dependence \( Sh(S) \), the dominant PVC frequency in the pressure pulsation signal appears in the flow when the swirl number exceeds the critical value 0.5. In a previous study [6], a similar dependence \( Sh(S) \) with a minimum of the PVC frequency was found for an axial swirler model. Nevertheless, \( Sh \) as function of \( S \) has the strongest uptrend upon confinement. It means that confinement significantly changes spatial PVC parameters.
Figure 4. Impact of $S$ and the confinement tube on velocity profiles ($Re=16500$) at a height $z/D=0.34$ above the nozzle.

Figure 5. Dependence of $Sh$ as a function of $S$ upon non-confinement and confinement conditions.

4. Summary
The isothermal swirl flow with the formation of a precessing vortex core in the radial swirler upon non-confinement and confinement conditions has been studied experimentally. Velocity profiles have been obtained with varying Re and guide vane angle, changing the swirl number $S$. Strouhal number as the function of the integral swirl number in the range from $0.5 < S < 0.8$ has been measured with the
using of four acoustic sensors and LDA system. The unsteady flow with PVC effect is shown to significantly change upon non-confinement and confinement conditions.

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