Swirl effect on flow structure and mixing in a turbulent jet

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Abstract. The paper reports on experimental study of turbulent transport in the initial region of swirling turbulent jets. The particle image velocimetry and planar laser-induced fluorescence techniques are used to investigate the flow structure and passive scalar concentration, respectively, in free air jet with acetone vapor. Three flow cases are considered, viz., non-swirling jets and swirling jets with and without vortex breakdown and central recirculation zone. Without vortex breakdown, the swirl is shown to promote jet mixing with surrounding air and to decrease the jet core length. The vortex core breakdown further enhances mixing as the jet core disintegrates at the nozzle exit.

1. Introduction

Swirling jets are widely used in combustors to stabilize the flame by means of a swirl-induced recirculation zone [1]. The swirl intensifies processes of turbulent heat and mass transfer and increases efficiency of mixers and burners. This is achieved via formation of longitudinal vortices in jet flows. For jets with swirl rate above the critical value, a vortex breakdown occurs, leading to unsteady flow dynamics for high swirl rates. The vortex breakdown associated with formation of stagnation point is followed by a recirculation region downstream [2]. The recirculation zone often triggers unsteady jet rotation, corresponding to vortex core precession [3]. It has been shown in several papers that the swirl has a positive effect on the mixing processes [4]. However, there is still a lack of experimental studies of flow structure and mixing in turbulent swirling jets with detailed information on the instantaneous velocity and concentration fields.

The planar laser-induced fluorescence (PLIF) technique is widely used to measure concentration distribution [5, 6]. This approach is based on registration of local fluorescence of passive admixture molecules in the measurement plane, excited by laser radiation. The PLIF method is an almost non-intrusive technique. Another technique, the particle image velocimetry (PIV) is used to measure the instantaneous velocity fields. The method is based on double illumination of tracer particles in the measurement plane and evaluation of their local displacement from image correlation analysis. The aim of the present work was to study the turbulent transport and mixing in the initial region of a turbulent jet for various swirl rates, using PIV and PLIF. The paper reports on swirl effect on the mean concentration and velocity fields.
2. Experimental setup

The swirling jet flow was organized by a contraction nozzle with changeable vane swirlers mounted inside. Details on the nozzle may be found in [7]. Swirlers with different inclination angles of the vanes had swirl rate $S$ (the definition is taken from [1]) equal to 0.41 and 1.0.

$$S = \frac{2}{3} \left( \frac{1 - (d_1/d_2)^3}{1 - (d_1/d_2)^2} \right) \tan(\psi)$$

(1)

Here, $d_1 = 7$ mm is the diameter of the centre body supporting the vanes, $d_2 = 27$ mm is the external diameter of the swirler, and $\psi$ is the vanes inclination angle relative to the axis. The swirler was mounted inside the nozzle as demonstrated in Figure 1 (bottom left corner). The nozzle exit diameter $d$ was 15 mm. The Reynolds number, defined as $\text{Re} = U_0 d / \nu$ ($U_0$ is the bulk flow velocity of the jet; $\nu$ is the air kinematic viscosity), was 5 000.

The air flow was supplied from air-pressure line, and its flow rate was precisely controlled by mass flow meters (Bronkhorst). An acetone seeder was used to introduce acetone vapour into the main air flow. The seeder was a container with liquid acetone, placed in a heated water bath to provide thermal stabilization. The air flow was bubbled through the liquid acetone. The temperature of air with acetone vapour at the nozzle exit was monitored by a thermocouple. The surrounding air was seeded by a fog machine.

![Figure 1. Photograph of the PIV/PLIF setup and calibration cuvette](image)

Figure 1 shows the photographs of PIV/PLIF equipment and beam alignment optics. Double-head Nd:YAG laser (Quantel, EverGreen) was used to illuminate the particles tracer for PIV measurements. The laser beam was converted into a collimated laser sheet with the width of 50 mm and thickness below 0.8 mm by using a system of cylindrical and spherical lenses. On average it was 53 mJ after the
laser sheet optics (measured by a power meter Coherent LabMax). Particle images were captured by a pair of CCD cameras (Bobcat ImperX). A narrow band-pass optical filter (532 nm ± 10 nm) was used. The laser and camera were synchronized via TTL signal. The PIV images (2048×2048 pixels is size) were processed using in-house software "ActualFlow". The images were pre-processed to remove background (minimal intensity for each pixel). During four iterations of an adaptive cross-correlation algorithm the interrogation area size was reduced from 64×64 to 32×32 pixels. The spatial overlap rate between the interrogation areas was 50%. The velocity fields were validated by signal-to-noise criterion.

The fourth harmonic (266 nm) of a pulsed Nd:YAG laser (Quantel, Brilliant B) was used for acetone PLIF excitation. A small portion of laser radiation was directed to a power meter, using a semi-transparent mirror. The energy of each laser pulse was measured for exact comparison of the instantaneous fluorescence images. The energy of the laser radiation in the wavelength range of 266 nm was approximately 60 mJ. The laser beam was aligned with that of the PIV system, using a dichroic mirror, and transformed into a collimated sheet. Image intensifier (LaVision IRO) based on a UV-sensitive photocathode S20 (multialkali) and multi-channel amplifier were used to register the fluorescence signal of the acetone vapor. The quantum efficiency of the photocathode was about 25% at the considered wavelength range (280-320 nm). The image intensifier was equipped with a quartz lens (LaVision UV-lens, f # 2.8, 100 mm) and an optical band-pass filter (300-320 nm). The optical filter was used to remove the unwanted intensity at the laser wavelength, including reflections from the nozzle. The signal was recorded by sCMOS camera (16-bit images with resolution of 2560 × 2160 pixels). The images were processed by DaVis software from LaVision.

PLIF data were processed using a number of routines. The correction associated with non-uniform spatial sensitivity of the detector was performed using an image of a white paper list. The paper was placed away from the focus plane of the optics and was uniformly illuminated by a diffusive light source. The sensitivity between the center and the corners differed up to 20%. The energy distribution across the laser beam was not uniform either. To take into account this effect, an image of the laser sheet intensity inside a calibration cuvette, uniformly filled with acetone vapor, was captured. The PLIF data were averaged over the cells in order to correspond to the velocity fields.

3. Results

![Image](image.png)

**Figure 2.** Normalized mean velocity (left) and concentration (right) fields for the jet at S=0

The time-averaged two-component velocity field is shown by the vectors in Figure 2 (left). The averaging is based on 3 000 snapshots of the velocity fields. The axial velocity component is shown by color. The spatial distribution of the concentration, normalized by the value at the nozzle exit, is shown in Figure 2 (right). For the case without swirl, the concentration distribution is seen to have the
shape of a cone. The concentration in the jet core falls downstream. For the non-swirling jet there is a conical jet core, surrounded by the mixing layer.

Figure 3 (left) shows the time-averaged velocity field for the swirling jet with swirl rate $S = 0.41$. The normal-to-plane component is shown by color. For this swirl rate there is no recirculation zone at the jet center. The normalized concentration distribution is shown in Figure 2 (right). The swirl intensifies mixing and results in a greater opening angle, and the concentration core is frustum of a cone.

![Figure 3](image1.png)

**Figure 3.** Normalized mean velocity (left) and concentration (right) fields for the jet at $S=0.41$

Figure 4 (left) shows the averaged velocity field for the jet with the swirl number $S = 1$. There is a bubble-type recirculation zone at the jet axis. It results in a much greater opening angle of the jet. The mean concentration of the scalar supplied by the jet is shown in Figure 4 (right). The concentration core disintegrates quickly, as the jet comes out of the nozzle. Thus, the concentration is typically below 70% downstream $y/d = 0.5$.

![Figure 4](image2.png)

**Figure 4.** Normalized mean velocity (left) and concentration (right) fields for the jet at $S = 1$

Profiles of the axial component of mean velocity and the mean concentration are shown in Figure 5 for the cross-section at $y/d = 1.5$. In general, the swirl provides a wider jet and a region of the jet velocity deceleration around the jet axis. For the swirling jet with vortex breakdown the axial velocity reaches negative values, the jet is considerably wider, and the concentration profile is much flatter. Figure 5 also shows the axial velocity data from the study [8], where the jet was produced by tangential inlets inside the nozzle. One can observe that shapes of the axial velocity profiles are similar despite that the jets were produced by nozzles with fundamentally different configurations.
4. Conclusions

The flow structure and mixing in the initial region of a swirling turbulent jet were experimentally studied using the planar optical methods for velocity and concentration measurements. The Reynolds number of the jet was 5000. Three cases of the swirl rate were considered, viz., non-swirling jet, low-swirl jet without central recirculation zone and high-swirl jet with bubble-type vortex breakdown and central recirculation zone. The swirl was observed to result in a wider jet flow and to intensify mixing. For the case of vortex breakdown, the mean concentration decreases immediately downstream the nozzle exit and is found to be below 70% for the distance of 0.5d from the nozzle.

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