Investigation of mass transfer in swirling turbulent flames

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Abstract. The present paper reports on analysis of flow structure and turbulent transport in swirling flames. The particle image velocimetry and spontaneous Raman scattering techniques were used for the measurements of 2D velocity and density distributions. The focus was placed on comparison between low- and high-swirl flows. A pronounced bubble-type vortex breakdown with strong flow precession took place in the latter case.

1. Introduction

Lean premixed combustion regimes are implemented in burners to achieve reduced emission of NO\textsubscript{x} \cite{1}. However, lean combustion regimes are known to be sensitive to different types of perturbations. In particular, a minor change in equivalence ratio can result in unwanted thermoacoustic instability \cite{2}, \cite{3}, \cite{4}. Flow swirl is often used for flame stabilization, especially under severe conditions, such as combustion of ultra-lean mixtures with equivalence ratio close to the flammability limit. Vortex breakdown phenomenon is a feature of high-swirl flows. When the swirl rate (the axial flux of the angular momentum divided by the flux of the axial momentum and nozzle radius) of a non-reacting swirling jet exceeds a critical value of $S_C$ (this value is found to be different in various papers: $S_C \approx 0.6$ in \cite{5}, $S_C \approx 1.1$ in \cite{6}, $S_C \approx 0.88$ in \cite{7}), the vortex core breakdown takes place and a central recirculation zone often occurs \cite{7}.

Flow structure of swirling jets with combustion is more complex due to heat release, induced density gradients and other effects. It is known that shape of the vortex breakdown is sensitive to temperature differences between the jet and the surrounding fluid \cite{8}, \cite{9}. Vortex breakdown can be delayed or, on the contrary, can be induced by the combustion. A number of studies were carried out by Cheng and others (e.g., \cite{1}, \cite{10}, \cite{11}, \cite{12}) demonstrating that moderate swirl (without central recirculation zone) can be used for flame stabilization and provides less NO\textsubscript{x} emissions in comparison to high-swirl flows with the recirculation zone. In this context it is clear that the flow organisation is important for flame stability, combustion efficiency, and emission levels for swirl burners. Comprehensive experimental data on flow structure and dynamics in swirl-stabilized combustors is necessary for deeper understanding of the flame behaviour and for development of more efficient burners. In the present study Particle image velocimetry (PIV) and spontaneous Raman scattering (SRS) are optical measurement tools were used to retrieve information about fluid structure, heat and mass transfer processes in swirling flames for moderate and high swirl rates.
2. Experimental setup

Sketch of the experimental setup for 2D measurements is shown in figure 1. The measurements were carried out in a combustion rig consisted of a swirling nozzle, flow seeding device, premixing pipe and section for the air and propane flow rate control. A vane swirler inside the contraction nozzle (exit diameter \(d = 15\, \text{mm}\)) could be changed to vary the swirl rate. By using two swirlers with different inclination angle of blades, the swirl rate \(S\) (based on the definition in [5]) was 0.41 and 1.0. The Reynolds number \(\text{Re}_{\text{air}}\) (based on \(d\), the bulk velocity \(U_0\), and viscosity of the air) was 5 000. The equivalence ratio \(\Phi\) of the propane-air mixture was 0.7.

In order to provide PIV measurements, the flows were seeded by TiO\(_2\) particles with the average diameter of one micrometer. The seeding device instantly introduced solid particles to the air flow by using a stirring rod. The PIV system composed of a double-pulsed Nd:YLF Pegasus PIV laser and a pair of PCO 1200HS CMOS cameras. System was running at approximately 770 Hz frequency. A laser sheet, formed by the system of lenses, passed thru the central plane of the flows and had a thickness of 0.8 mm in the measurement region. The cameras were equipped with narrow-bandwidth optical filters admitting the light from the laser and suppressing the radiation of the flame. The system was operated by a computer with "ActualFlow" software. Stereo calibration was performed using the multi-level calibration target and a 3rd-order polynomial transform. For each flow case, 2400 instantaneous three-component velocity fields were measured.

![Figure 1. Sketch of the experimental setup for 2D SRS and stereo PIV system](image)

The second (532 nm) harmonic of a pulsed Nd:YAG laser (Quanta-Ray) was used for the illumination of a sampling volume. The energy of 6 ns laser pulses was monitored by an energy meter (Coherent LabMax-TOP). On average, the energy was 690 mJ for 532 nm, with 5% RMS fluctuations. For registration of 2D images of the average SRS signal, a 16-bit ICCD camera (Princeton instruments PI-MAX-4) equipped with a tunable optical filter (VariSpec LC), based on liquid crystals, was used to collect the emission of the vibronic transitions (e.g., 607.3 nm and 473.3 for Stokes and anti-Stokes lines of ro-vibrational transition of nitrogen when excited by 532 nm). To provide planar illumination, the cylindrical laser beam was transformed into a laser sheet by using collimating optics. An additional multi-notch holographic filter was used to block the emission from Rayleigh scattering, which is about \(10^4\) times greater than the SRS and was not blocked completely by the tunable filter. The scattered light from 200 laser pulses was accumulated during acquisition of each image with 8×8 pixels binning.
The collection time of each pulse was 200 ns. Thirty frames were captured and averaged for each measured flame regime to reduce influence of CCD noise.

The data processing procedure of 2D SRS signal is similar to that of Rabenstein and Leipertz [13]. The laser sheet was passed through the room air and the flame. The room air was considered as the control volume (temperature of the air was monitored). Following Egermann et al. [14], the SRS signal were recorded for two perpendicular polarizations of the laser light. In order to minimize influence of the dark-current, reflections, and possible fluorescence the images for the P-polarization were subtracted from images for the S-polarization. Intensity of the Stokes lines depends on the temperature and volume fraction of the molecules. Intensity of the Stokes and anti-Stokes lines of SRS by nitrogen molecules was used to evaluate ratio between density in the flame and room air. According to [13], the dependence of the effective SRS cross-section on temperature was evaluated from calculations by RAMSES code [15].

3. Results

Average flow characteristics for the cases $S = 0.41$ and $S = 1.0$ are presented in figure 2. For the low-swirl jet ($S = 0.41$), the local minimum of the axial mean velocity is observed within the jet center. The positive value of the mean axial velocity indicates the absence of a permanent recirculation zone, and no clear vortex breakdown could be determined from the average velocity field. At the same time, weak local reserve flows were observed in realizations of the instantaneous velocity fields near the jet axis.

Shear of the axial velocity near the jet axis and outer mixing layer resulted in roll-up of eddies, which induced velocity fluctuations. For the high-swirl jet at ($S = 1.0$) a pronounced vortex breakdown took place with a bubble-type central recirculation zone. The mean velocity reached negative minimum value at the jet axis. From analysis of instantaneous velocity fields it was found that large-scale vortices emerged inside the recirculation zone and in the outer mixing layer were more intensive than in low-swirl case.
Figure 3 shows the photographs and distributions of the average concentration of molecular nitrogen in the premixed swirling flames measured by 2D SRS approach. Shape of the low-swirl flame corresponds to an inverted cone with the apex above the nozzle exit. The high-swirl flame is also an inverted cone with the apex inside the nozzle.

![Figure 3. Photographs (top row) and distributions (bottom row) of the average density of nitrogen in low-swirl ($S = 0.41$) and high-swirl ($S = 1.0$) lean propane-air flames ($\Phi = 0.7$) measured by 2D SRS](image)

Analysis of the spatial distributions of the density in the propane-air swirling flames revealed presence of a low-density region around the jet axis, inside the recirculation zone (inside the flame cone) and in the inner mixing layer around it. Low gas density was also detected in the outer mixing layer of the low-swirl flame due to the heat transfer from the center of the swirling flow. For analysis of the turbulent transport one can analyse the averaged equation of $N_2$ mass conversation [16]:

$$\dot{r}_{N_2} = \rho \vec{v} \cdot \nabla \rho_{N_2} + \nabla \cdot \left( \rho \omega_{N_2} \vec{v} \right) + \nabla \cdot \left( \rho' \omega'_{N_2} \vec{v} \right) - \nabla \cdot \left( D_{N_2} \rho \vec{v} \cdot \nabla \omega_{N_2} \right) = 0$$  \hspace{1cm} (1)

Where $\rho$ and $\vec{v}$ are the local gas density and velocity, correspondingly; $\omega_{N_2}$ is the local mass fraction of nitrogen molecules; $r_{N_2}$ is production/consumption rate of $N_2$ during chemical reactions; $D_{N_2}$ is the diffusion coefficient for nitrogen. Dot, brackets, and prime symbols denote temporal derivative, ensemble averaging, and fluctuating part, respectively. Local concentration of nitrogen molecules $C_{N_2}$ is linearly proportional to $\rho \omega_{N_2}$. The first term in the left hand side of the equation vanishes for stationary turbulent flows. The second and third terms are convective and turbulent transports respectively. The fourth term is the diffusion, which is small for turbulent flows. The production/consumption rate of the nitrogen can be considered to be negligible. Thus, one can obtain:
\[ -\text{div} \left( \rho' \omega_{N_2} v' \right) \approx \text{div} \left( \rho \omega_{N_2} \left\langle v' \right\rangle \right) - \frac{\partial C_{N_2} V_x}{\partial x} + \frac{\partial C_{N_2} V_y}{\partial y} \]  \tag{2}

Figure 4. Convective transport terms of nitrogen molecules in low- \((S = 0.41)\) and high-swirl \((S = 1.0)\) flames

Figure 4 shows components of the convective transport term in the low- and high-swirl jets. Significant differences were observed between two cases near the jet axis. In the case of the high-swirl flame the presence of the permanent recirculation zone resulted in negative values of \(\partial (C_{N_2} V_y)/\partial y\) in the inner mixing layer and positive values around the jet axis.

4. Conclusion

2D spontaneous Raman scattering and particle image velocimetry techniques have been used to study flow structure and transport in swirling lean propane-air premixed flames. Average flow velocity and local density of nitrogen were analysed. The focus was placed on comparison between low- and high-swirl flows with swirl rate \(S = 0.41\) and 1.0, respectively. The results showed that the low-swirl flow had a local minimum of the axial mean velocity at the jet axis. Positive value of the mean axial velocity indicated the absence of permanent recirculation zone. For the high-swirl flow, a pronounced vortex breakdown took place with bubble-type central recirculation zone. From the analysis of convective transport term it was concluded that the high-swirl flame was characterized by recirculation of the hot gas between the inner mixing layer and reverse flow.

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