Investigation of combustion noise with real time laser measurement techniques

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Introduction

The interaction of turbulence, mixture and reaction is an important subject in combustion noise research, particularly since environmental aspects gain increasing importance and noise reduction in general has attained public awareness. Without suitable optical techniques the specific temporal and local characteristics of turbulent noise generation cannot be investigated in sufficient detail to improve the physical understanding of the governing phenomena. As a consequence, the investigation of stochastic processes in combustion in real time offers challenges for the experimentalist and the developer of new instruments. Of particular interest are methods for the detection of the heat release in turbulent flames of high Reynolds number with adequate temporal and spatial resolution. The novel technique presented subsequently is based on classical LIF setups, which have been modified and improved for combustion noise studies.

Governing parameters for the noise production in turbulent premixed flames

In turbulent premixed flames noise is produced by local temporal volume fluctuations. This process is caused by the interaction of chemical reactions and the convective transport of turbulence into the flame front. The broadband continuous frequency spectrum of the turbulence results in a broadband production of noise, which decreases with high frequencies. A complicated mechanism of propagation and interference of acoustic waves occurs in and near the flame. However, since the wave lengths are much larger than the flame size in the entire energy containing spectrum, a global and more effective approach is treating the flame as one source of acoustic waves. For low Mach numbers it has been shown that an unconfined flame as a source of combustion noise can be approximated reasonably by a monopole (Boineau et al. [1]):

$$p'(\vec{x_0},t) = \frac{1}{4\pi r_i}\frac{\gamma-1}{c_0^2}\frac{\partial}{\partial t}\int_V Q'(\vec{x_i},t-\frac{r_i}{c_0})dV_i \qquad (1)$$

where $\vec{x_0}$ is the observation point, $\vec{x_i}$ the source point, t the time, r_i the distance between x_0 and x_i, γ the ratio of specific heat capacities, c_0 the sound speed, Q' the fluctuating heat release rate and V the sources volume. Thus, the noise emission does hardly depend on the direction and can be described by a sphere with stochastic volume pulsations. A direct calculation of the noise requires the determination of the fluctuation of the total heat release with time.

For weakly turbulent flames the outer volume fluctuation can be transferred into a model, which postulates that fluctuations of the local chemical reactions are being caused only by variations of the flame surface. If the effects of flame quenching and curvature on the local heat release are neglected, this approach yields for the noise production in pseudo-laminar flame fronts or flamelets (Clavin et al. [2])

$$I = \frac{1}{4\pi c_0}\left(\frac{1}{\rho_b}-\frac{1}{\rho_u}\right)^2 \rho_b(\rho_u s_l)^2 \overline{\left(\frac{dA_{fl}}{dt}\right)^2} \qquad (2)$$

with acoustic velocity c_0, density of reaction products ρ_b and ρ_u, laminar flame speed s_l und total flame surface $A_{fl}(t)$. Eq. 2 reveals that the noise calculation requires proper knowledge of the flame surface history $A_{fl}(t)$.

Experimental Setup

For the experiments a "Movable Blocks Burner" was used (figure 1). The outer diameter of the nozzle is $D_{nozzle} = 40\ mm$. The air and fuel supply is controlled by two Bronkhorst thermal flow controllers. As fuel, natural gas is used. For premixed combustion, a static mixer is implemented upstream. The flame described below is a 30 kW premixed swirl stabilised flame with an equivalence ratio of 0.85. The swirl number was measured with a 3D PIV system and validated with numerical results. Swirl numbers of 0...0.7 were found at the burner exit. The mean axial velocity at the burner exit is 10 m/s. These parameters indicate that the flame is in the wrinkled flamelet regime, according to the Borghi diagram.

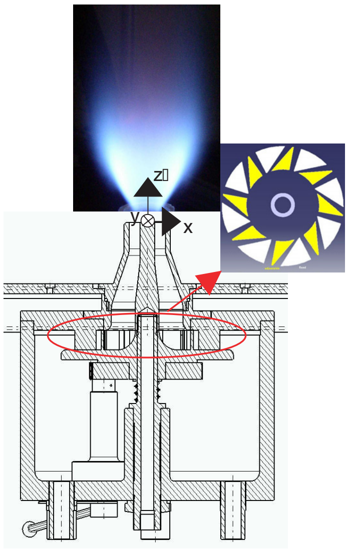

Figure 1: Movable Blocks Burner

Measurement techniques

For the measurement of the total flame surface the OH-LIF technique was improved from a single shot system with statistical evaluation methods to a real time system with high temporal resolution. OH-molecules are supposed to be a key species in hydrocarbon mechanisms and thus are considered to be an indicator for flame fronts even if the decay of their concentration in the combustion products is moderate. The OH molecules were excited by a Nd:YAG pumped dye laser (Lambda Physics Scanmate) tuned to the $Q_1(6)$ line (283 nm) in the $A^2\Sigma^+ X^2\Pi(1,0)$ transition (Kröner [3]). The key feature of the setup is the high repetition rate of the pump laser of 1000 Hz. The inelastic scattered light from the molecules is captured at right angle with a KODAK Ektapro Motion Analyzer 4540, equipped with a lens-optical coupled intensifier (Proxitronic) and a Nikon lens (UV-NIKKOR 105 mm, 1:4.5) that is focussed on the light sheet plane. Because of the low intensity of high repetition laser systems - the specified single shot energy was 80 μJ - the light sheet was directed through the flame volume three times by two planconcave mirrors (figure 2), each of them intersecting the burner axes. With this arrangement a higher intensity leading to a better signal to noise ratio is obtained and the observation area could be increased to 2.5 D_{nozzle}. Each reflection results in an intensity loss, which is exponential along the vertical axis. Thus a software correction of the measured intensity was applied.

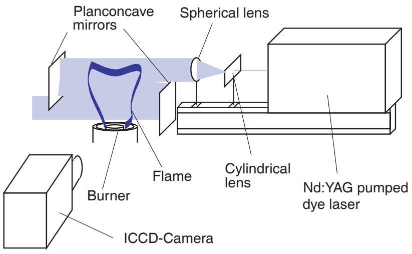

Figure 2: Setup for OH-LIF measurements

First Results

The LIF measurement technique allows the detection of instantaneous combustion processes with a temporal resolution of 1 ms over 1024 frames. With this technique the development and displacement of large areas of simultaneous heat release generated by large vortices can be tracked. One example is visible in figure 3 on the right hand side of the flame. The outer border of the cross section image is detected by a snake algorithm, which is based on advanced edge detection algorithms. This procedure yields the location of the flame front. In the next step the flame surface for each picture can be estimated by a radius-weighted summation of the flame front pixels. Figure 4 shows a fourier transformed time series calculated with this method. The surface fluctuates within 20% of the mean value. Interestingly, the frequency spectrum is very low above 150 Hz. This is consistent with microphone noise measurements, which also indicate that the surface fluctuations mainly produce a broad band signal at low frequencies.

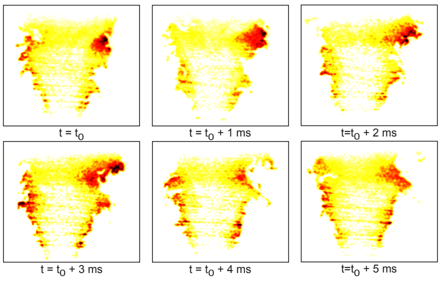

Figure 3: A representative sequence of OH-LIF with high temporal resolution

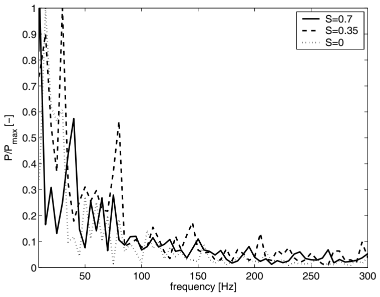

Figure 4: Flame surface fluctuation for different swirl numbers

Conclusion

The detailed investigation of combustion noise requires measurement techniques with a frequency response in the kHz range. In the paper the evolution of the classical planar LIF method towards a high speed technique was shown. This method allows the qualitative two-dimensional evaluation of the flame surface history, a key parameter governing combustion noise levels.

Acknowledgements

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