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INVESTIGATION OF FLAME ACCELERATION IN A DUCT USING THE OH PLIF TECHNIQUE AT HIGH REPETITION RATE

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OH PLIF, Flame acceleration, Combustion, Hydrogen

Abstract

Flame acceleration in a closed duct filled with highly explosive hydrogen-air mixtures is investigated using the OH PLIF technique. The applied laser system comprising a pump laser and a dye laser allows for repetition rates up to 40 kHz. Temporal evolution of the flame surface area during the process of flame acceleration is a key parameter. Therefore, a Matlab script was developed for image processing and flame front detection. Results are presented underlining the usefulness of highly time-resolved OH PLIF in transient combustion diagnostics.

Introduction

Explosion of hydrogen-air mixtures as a consequence of accidental hydrogen release and ignition poses a tremendous threat to a large variety of practical applications where hydrogen is involved. Flame acceleration is the process starting with ignition of the mixture, potentially leading to high flame speeds up to 1000 m/s and even to transition to detonation coupled with overpressures being highly destructive for containing structure [1]. Generating a comprehensive understanding of the underlying physical mechanisms is of vital importance for the development of safety concepts and guidelines. For a comprehensive review on the topic, please refer to [4, 6]. In order to address the need for further research in this field, experimental work is being carried out at the Lehrstuhl für Thermodynamik, Technische Universität München. Primarily the application of highly time-resolved optical measurement techniques allows for deep insight into the highly transient phenomena under investigation. While the OH PLIF technique (Planar Laser Induced Fluorescence) at low repetition rates around 10 Hz is well established in combustion diagnostics [9], systems running at high repetition rates in the kHz range are rather rarely used. In particular, as far as we know, high-speed OH PLIF has not been applied in the context of flame acceleration in ducts before, although considerable information on the characteristics of flame propagation can be gained.

Experiment

The experimental facility is a 5.1 m long rectangular duct closed at both ends, which was designed to withstand static overpressures up to 200 bar. The cross section measures 60 mm (height) x 300 mm (width).

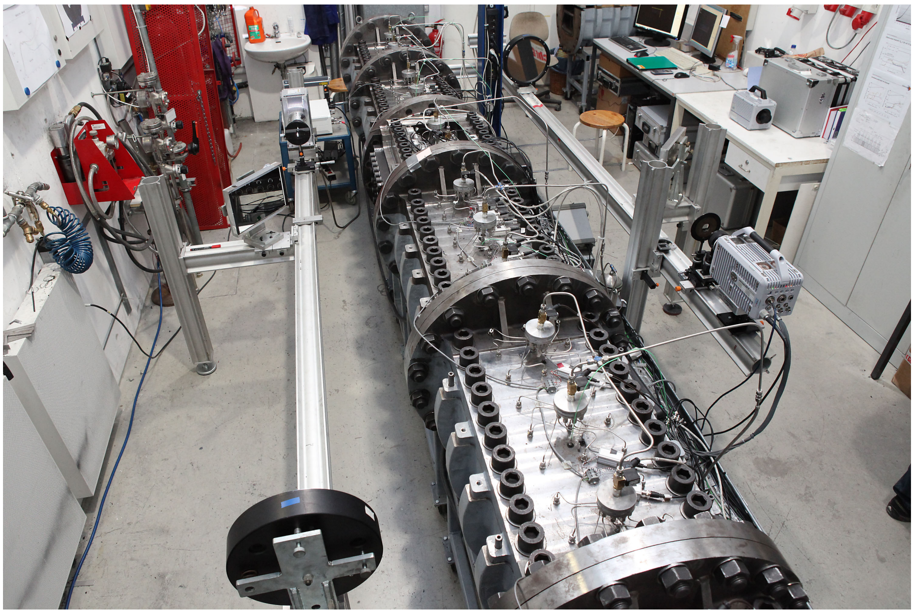


Fig. 1: Explosion laboratory at the Lehrstuhl für Thermodynamik, Technische Universität München.

Within one experiment, a hydrogen-air mixture with a defined fuel-oxidizer ratio is prepared inside the duct and ignited at the front plate with an electric spark plug. The emerging flame propagates from the point of ignition towards the opposite end plate. During propagation, the flame can accelerate to high velocities of up to about 1000 m/s and eventually undergo transition to detonation. Self-sustaining detonations in hydrogen-air mixtures can propagate at velocities up to about 2000 m/s being connected with high overpressures [1, 3]. As the acceleration process is a necessary precursor for the transition to detonation in case of a low-energy ignition source, we set a special focus on its investigation. In this paper, early flame acceleration shortly after ignition is studied. One particular feature of the experimental facility is a mechanism to generate hydrogen-air mixtures with vertical concentration gradients of defined steepness. Distributions with high hydrogen concentrations at the channel top and low concentrations at the bottom portray realistic conditions in accident scenarios due to the low density of hydrogen compared to air and comparably slow diffusion processes. For further details on the facility, please refer to [3, 10, 11].

Measurement System

The essential component of the laser system is a pulsed, frequency doubled Nd:YVO4 pump laser (Edgewave IS8II) emitting radiation at 532 nm from two cavities. Each of the cavities can be individually triggered at repetition rates up to 20 kHz with pulse widths of 8 ns. A design pulse energy of 2 mJ leads to an overall average power of 80 W. This laser is combined with a tunable dye laser (Sirah Credo) designed for the respective repetition rates and pulse energies. Rhodamine 6G is used as a dye. The dye laser assembly comprises two dye cells (resonator and amplifier), a frequency conversion stage (second harmonics generator: temperature stabilized BBO cristal and compensator) and a wavelength separation unit with four Pelin-Broca prisms.

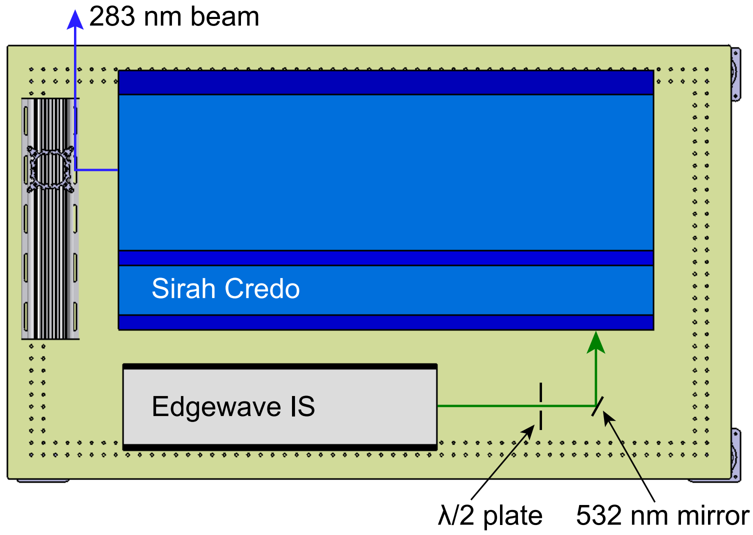


Fig. 2: OH PLIF laser assembly.

The aim of this assembly is to exactly adjust the dye laser output wavelength to the required value for effective excitation of the hydroxyl radical (OH), which appears as an intermediate species in the reaction zone of the investigated hydrogen-air flames. Excitation of the $X^2\Pi(v'' = 0) \rightarrow A^2\Sigma(v' = 1)$ transition ($Q_1(6)$ line) at 282.925 nm offers a high absorption coefficient within the tuning range of the system. Due to the limited maximum dye efficiency (about 28 % for Rhodamine 6G) and considerable losses during frequency conversion (SHG efficiency less than 20 %), the achieved output pulse energy is 120 μJ or less depending on the system configuration. Well-established low speed LIF systems deliver pulse energies of several mJ (pumped dye lasers) or even a few 100 mJ (excimer lasers) [9]. The dye laser is optimized for being pumped with vertically polarized radiation (s-pol). As the two cavities have different polarizations (s-pol and p-pol) to enable beam overlap, the conversion efficiency for s-pol is as desired, but the efficiency for p-pol is poor. What can be done to address this imbalance is to apply a $\lambda/2$ plate between pump and dye laser and thus rotate the polarization orientation of both beams at an angle of 45°. The rotational position of the $\lambda/2$ plate is finely adjusted for equal dye laser output pulse energies for both pump laser cavities. It must be noted that this measure leads to lower pulse energies of about 70 μJ compared to the use of the s-pol cavity only without a $\lambda/2$ plate. Accordingly, it is advantageous to use the $\lambda/2$ plate only if a 40 kHz repetition rate is required and otherwise operate the s-pol cavity only. As outlined before, the pulse energies achieved are comparably low, but still sufficient for OH PLIF measurement. An image intensifier (Hamamatsu C10880-03) is combined with a high-speed camera (Photron SA-X or SA5) for image recording.The gate time of the image intensifier is 30 ns in order to separate the OH PLIF signal from flame luminescence. A 320±20 nm bandpass filter is applied to the camera optics for detection of the OH PLIF signal, which appears predominantly around 309 nm. Synchronization of the pump laser cavities, camera and image intensifier as well as optional further cameras for simultaneous application of other measurement techniques like schlieren or OH* chemiluminescence is accomplished by two Sanford Research Digital Delay Generators (DG535 and DG645). The dye laser output beam is unidirectionally expanded by a UV coated cylindrical lens and focussed to a parallel light sheet by a sperical lens. Light sheet widths of 50-100 mm are used in current applications.

Preliminary Tests

As a first preliminary test, a premixed turbulent hydrogen-air swirl flame was investigated using the OH PLIF system. This test constitutes an ideal experimental setup for simple verification of the system's applicability to premixed hydrogen-air flames. Additionally, the temporal resolution of the measurement system can be used to portray the interaction of turbulent flow and flame. The test was successful with respect to the achieved signal intensities leading to a remarkable image quality. Figure 3 shows a submatrix of images from a 40 kHz measurement.

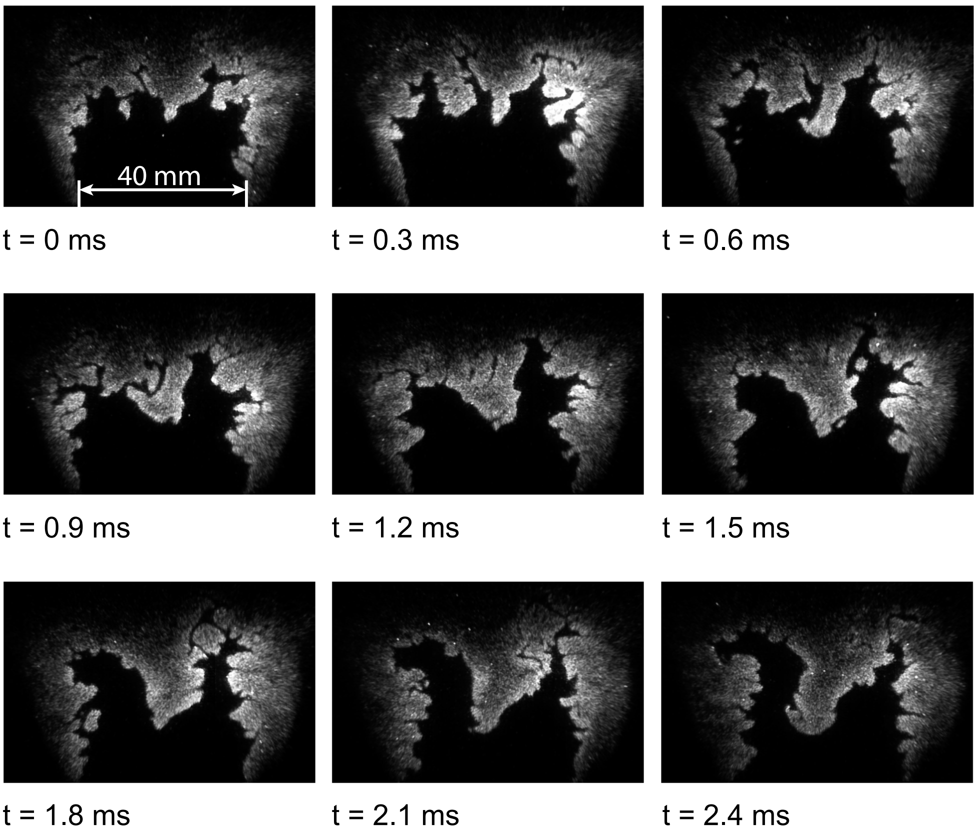


Fig. 3: OH PLIF images of a premixed hydrogen-air swirl flame.

Flame Front Detection

As one of the central goals in applying the OH PLIF technique to a flame acceleration experiment is to get information on the flame front location, flame surface area and dynamics, a method for flame front detection from OH PLIF images needed to be developed. It was implemented as a Matlab script using the 'Image Processing Toolbox'. Figure 4 shows the essential steps performed by the script beginning with the raw OH PLIF image and finally yielding the flame front reconstruction. An exemplary raw image with a significantly low signal intensity was chosen deliberately in order to demonstrate the robustness of the image processing methodology.

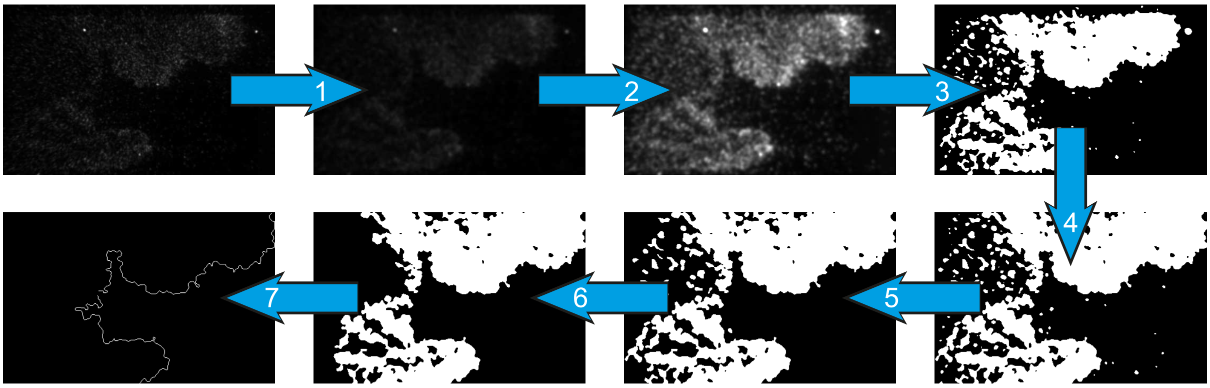
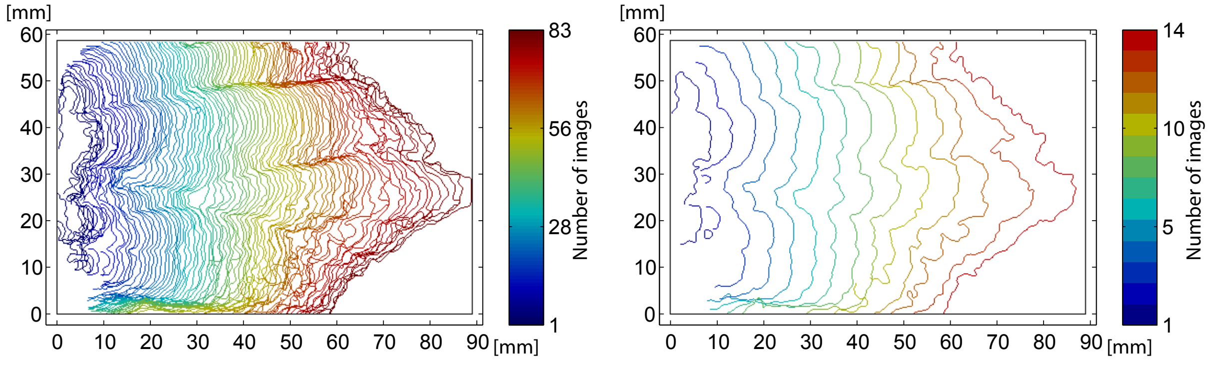


Fig. 4: Image processing for flame front detection.

1. Fast Fourier Transformation and lowpass filtering with Gaussian profile for image noise supression according to Gonzales [7]
2. Optimization of image contrast with possibility of local light sheet and absorption correction
3. Binarization according to user-prescribed value for threshold intensity
4. Image crop to boundaries provided by a target image
5. Removal of small disturbances, mostly arising from image intensifier noise and flame luminescence
6. Selection of relevant flame structures
7. Interpretation of the flame front using the 'bwboundaries' method in Matlab with a restriction criterion for exclusion of the rear flame boundary

Results for Flame Acceleration

Two exemplary results extracted from OH PLIF measurements are presented and their relevance for the description of the flame acceleration process is outlined. Firstly, the influence of mixture inhomogeneity on early flame acceleration 150 mm after ignition was studied where the flame velocity is below 30 m/s . Flame shapes were recorded in a mixture with a vertical concentration gradient and compared to those in a homogeneous mixture. In the homoge-

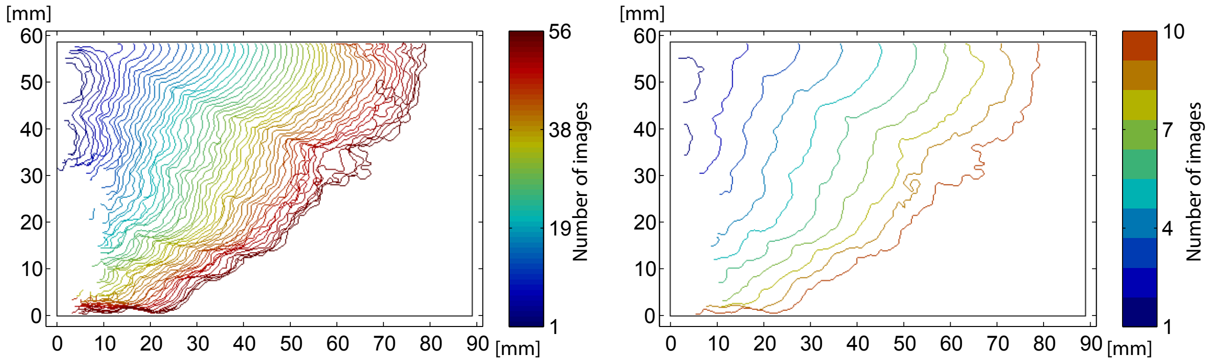


(a) Entire sequence, Δt = 0.05 ms between images

(b) Reduced sequence, Δ t = 0.3 ms

Fig. 5: Flame propagation in homogeneous mixture, 20 %vol hydrogen in air

neous mixture (Figure 5) the flame front is nearly symmetrical with respect to the channel axis with a cellular flame structure which is typical for lean hydrogen-air mixtures. The length of the flame front obtained from the presented algorithm remains constant at values around 82 mm as soon as the flame has completely entered the window. Towards the last few images, the flame stretches at the center of the channel as it approaches a symmetrical flat plate obstacle right behind the plotted area. This leads to a measurable increase in flame front length up to 92 mm. In the mixture with a concentration gradient (Figure 6), the flame shape is fundamen-



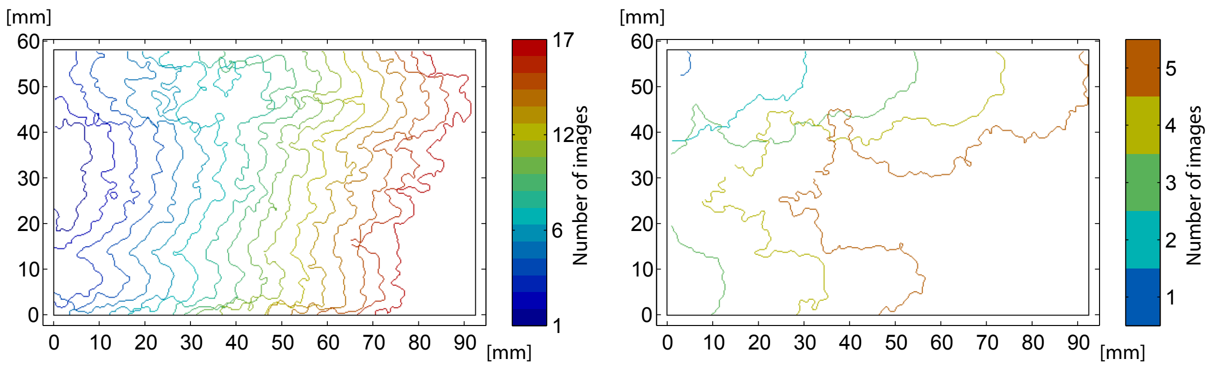
(a) Entire sequence, Δt = 0.05 ms

(b) Reduced sequence, Δt = 0.3 ms

Fig. 6: Flame propagation in mixture with concentration gradient, 20 %vol hydrogen in air

tally different. Starting as a hemispherical flame at the point of ignition, the flame propagates faster in the fuel-rich region at the channel top than at the bottom. This leads to a transient development of a streched flame with the leading flame tip located at the top, see also [2]. The inclination of the flame front grows over time, which means that the flame surface area undergoes a monotonic growth. Larger flame surface areas (flame front length of up to 113 mm at the last frame) effect higher overall burning rates leading to stronger flame acceleration. Although flame tip velocities are still comparable for the homogeneous and the inhomogeneous

mixture at the early stage viewed, the effect of enlarged flame surface area subsequently leads to much stronger acceleration in the rear part of the channel [2].
Another interesting phenomenon can be observed at a position in the channel further downstream where flame velocities are in the range of 100 m/s. At this point, different flame propagation modes can be found without varying the experimental parameters. One possibility is the straight or slightly convex flame which was also observed at the early position in Figure 5. The other mode is the so-called tulip-shape flame. In this case, leading flame tips are located both in the upper and lower region close to the wall. This phenomenon has been adressed by numerous authors, e.g. in [5, 8]. However, there are various mechanisms proposed that may explain the observed flame shape inversion. The OH PLIF technique may provide additional insight, especially in combination with a simultaneous measurement of the planar velocity field by PIV.



(a) Straight flame shape, Δt = 0.05 ms

(b) Tulip flame shape, Δt = 0.2 ms

Fig. 7: Flame propagation in homogeneous mixture, 20 %vol hydrogen in air

Conclusions

A laser system for OH PLIF measurement at high repetition rates up to 40 kHz was implemented and applied for the investigation of flame acceleration in hydrogen-air mixtures in a closed duct. In order to meet the experiment's requirements, a dual cavity pump laser was combined with a dye laser operating with Rhodamine 6G as a dye. With an output wavelength of 282.925 nm the hydroxyl radical (OH), which is an intermediate species in combustion of hydrogen and air, can be excited and light emission around 309 nm can be recorded by an image intensified camera assembly. The system was sucessfully tested with a hydrogen-air swirl flame and afterwards implemented at the explosion channel. A Matlab-based script for flame front detection was developed. Investigation of flame acceleration showed good applicability of the OH PLIF technique to the experiment. Important information on flame propagation in homogeneous and inhomogeneous mixtures could be gained. Additionally, different flame propagation modes were observed and will be studied in detail in the future.

Acknowledgement

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