

Application of High-Speed OH-PLIF to DDT Experiments

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1 Introduction

OH-PLIF (Planar Laser-Induced Fluorescence) allows for capturing two-dimensional images of flame fronts by visualizing OH radicals. While it is widely used for diagnostics of scientific and technical flames, its application to explosion experiments is less common and has mostly been limited to single-shot PLIF so far. Low speed PLIF systems (around 10 Hz repetition rate) deliver pulse energies of several mJ (pumped dye lasers) or even a few 100 mJ (excimer lasers). Resolving explosion processes and in particular the fast deflagration regime in time requires repetition rates in the kHz range. Pulse energies thereby reduce to about 100 μJ in typical commercially available dye laser systems. This work presents—to the best of our knowledge—the first application of HS (High Speed) OH-PLIF to an explosion experiment with fast deflagrations. Our intention is to particularly discuss the potential and limitations of HS OH-PLIF and thereby provide practical guidance.

2 PLIF Laser and Camera System

The laser system employed in this work consists of a double-cavity pump laser (frequency doubled Edge-wave IS8II, Nd:YVO₄, 532 nm, 2x20 kHz, 2 mJ/pulse, 8 ns pulse width) and a dye laser (Sirah Credo). Only the vertically polarized laser cavity is operated. Rhodamine 6G is used as a dye. The dye laser comprises resonator and amplifier stages, a frequency conversion stage (temperature stabilized BBO crystal and compensator) and a wavelength separation unit (four Pellin-Broca prisms). The system is triggered and synchronized by means of a delay generator (Stanford Research DG645). The dye laser is set to a UV output wavelength of 282.945 nm (absolute precision 30 pm) at a 1.8 pm Full Width at Half Maximum (FWHM). This wavelength corresponds to the Q1(6) transition of the OH radical. The laser light sheet is formed by cylindrical and spherical lenses. The optics is adjusted to a light sheet width of 100 mm and thickness of about 0.3 mm.

The fluorescence signal is detected by a Photron SA-X high speed camera combined with a Hamamatsu C10880-03 image intensifier. The image intensifier gate time is set to 30 ns to minimize the influence of flame luminescence. A UV camera lens (UV-CERCO-SODERN 45 mm 1:1.8) with a 320 \pm 20 nm bandpass filter (Semrock BrightLine HC) is employed. Note that all detection components listed here are highly light-sensitive, which is required for HS OH-PLIF.

3 Experimental Setups

DDT experiments were conducted in an entirely closed, rectangular explosion channel (height 0.06 m, width 0.3 m, length 5.1 m). It can be equipped with horizontal flat-plate obstacles to accelerate flames efficiently. Homogeneous H_2 -air mixtures at initially ambient pressure and temperature are examined in the present work. Ignition is performed using a spark plug at one end of the channel. A window section provides optical access through 0.06 m thick side-wall quartz glass windows. The OH-PLIF laser sheet is introduced transversely into the facility through a window in the channel top. Since we focus on the OH-PLIF technique here, we encourage the reader to refer to earlier publications for further details about the experiment [1, 2, 8]. Since quartz glass contains OH, these windows (particularly thick for explosion experiments) strongly absorb laser light at wavelengths used for OH-PLIF. We recommend to pay particular attention to the choice of windows with low OH concentration. Absorption spectra provided by manufacturers typically do not resolve narrow absorption bands.

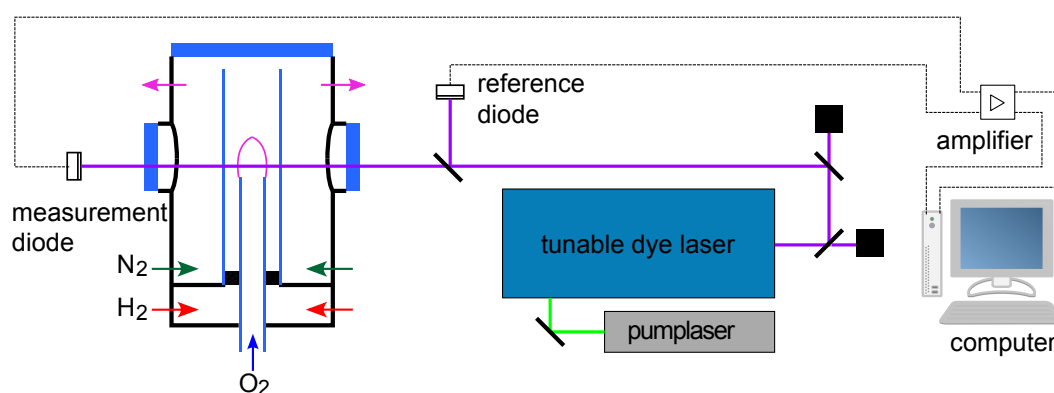


Figure 1: Sketch of the laminar jet flame TDLAS setup.

Additional experiments have been conducted to quantify absorption of radiation around the Q1(6) transition in H_2 - O_2 flames at elevated pressure. A laminar jet flame experiment was used for this purpose. The flame is established by an O_2 jet burning in an H_2 co-flow, Fig. 1. It is shielded by a quartz glass tube from an ambient N_2 flow. The flame is enclosed in a pressure vessel optically accessible through planar quartz glass windows. For further information, please refer to a detailed description of the setup provided in [5]. Absorption is measured by Tunable Dye Laser Absorption Spectroscopy (TDLAS). The wavelength of the above described dye laser is varied between 282.75 nm and 283.15 nm (in air), containing the Q1(6) line at $\lambda_{air} = 282.945$ nm. The collimated 0.5 mm beam passes through the center of the flame. Transmitted radiance is measured by a UV-sensitive SiC photo diode behind the flame. We account for variations in laser power with a reference photo diode at the dye laser exit.

4 Results

Figure 2 shows an OH-PLIF sequence at 20 kHz behind an obstacle of 30 % blockage ratio, compared to shadowgraph images at equal experimental conditions. Mean flame velocity within the field-of-view (FOV) is about 120 m/s. This comparison clearly demonstrates the potential of HS OH-PLIF. Temporal development of the macroscopic flame surface area, which plays a crucial role for flame acceleration (FA), and the microscopic flame structure can be resolved. The major challenge in applying HS OH-PLIF to DDT experiments is to obtain a high signal-to-noise ratio (SNR), defined here as the ratio of fluorescence signal to background noise mainly generated by flame luminescence. The faster flames get during the FA process in a given mixture, the more intense flame luminescence becomes.

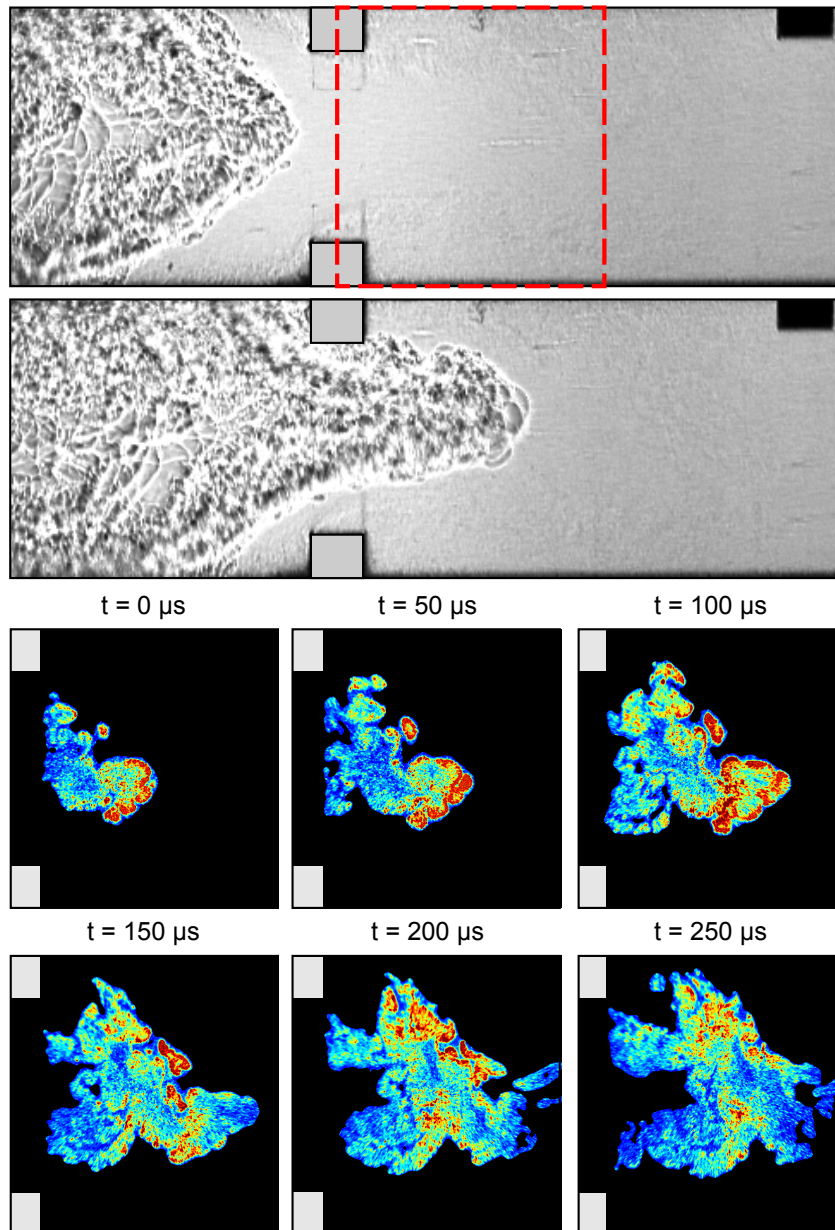


Figure 2: Shadowgraph and OH-PLIF images of slow turbulent deflagration, obstructed channel BR30, 15 vol. % H_2 , $\bar{v} \approx 120 \text{ m/s}$. Red dashed line indicates the OH-PLIF FOV.

Figure 3 shows OH-PLIF images of deflagrations at different velocities in the unobstructed channel at a fixed FOV, including out-of-camera (left) and processed images (right). H_2 concentration was varied between 20 and 30 vol. % to obtain flames in different explosion regimes.

Figure 3 (a) was taken in a 20 vol. % H_2 mixture. The flame propagates at $\bar{v} \approx 50 \text{ m/s}$, thus in the slow deflagration regime. The images are of high quality regarding SNR, which is in a range of 20–50. This value can be estimated by comparing intensities in the region where the light sheet is present (right to the white dashed line) to intensities in the region where only flame luminescence is recorded (left to the white dashed line).

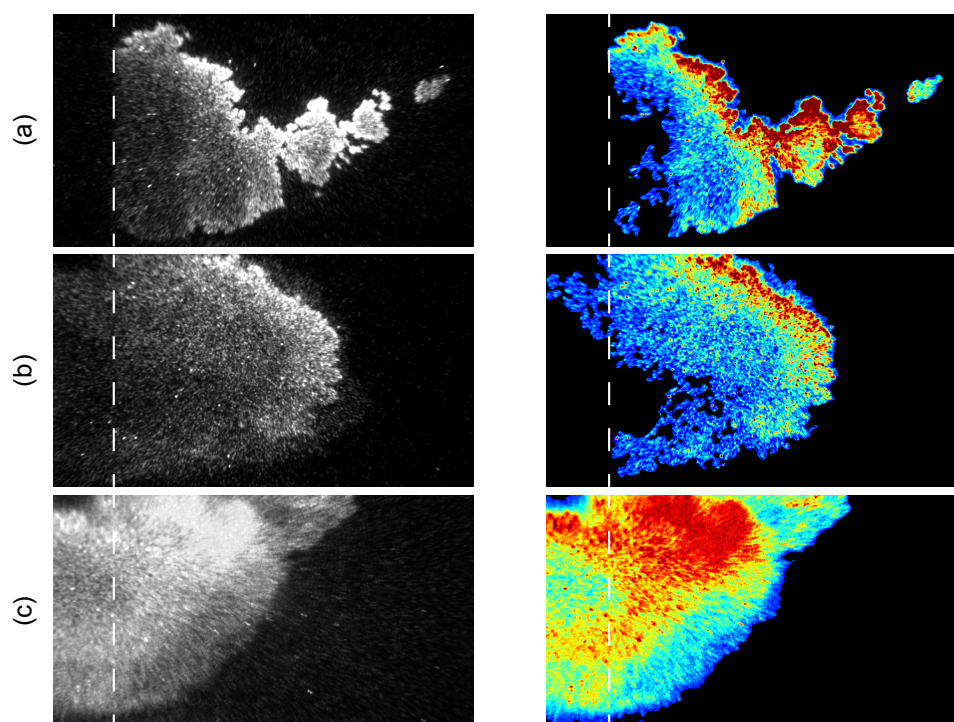


Figure 3: OH-PLIF images of different explosion regimes at $x = 4.9$ m. 20 vol. %, $\bar{v} \approx 50$ m/s (a); 25 vol. %, $\bar{v} \approx 380$ m/s (b); 30 vol. %, $\bar{v} \approx 900$ m/s (c).

Reaching velocities around the speed of sound of the reactants, the SNR is distinctly lower with values around 2–5. About five images of the leading flame tip can be taken within the FOV. Figure 3 (b) gives an example at 25 vol. % H_2 , $\bar{v} \approx 380$ m/s. The region to the left of the light sheet shows flame luminescence, while sharp structures along the leading flame front originate from OH-PLIF. The flame front is still well detectable under these conditions. Absorption of the laser light, passing the flame from the top, is considerable. Fluorescence intensity at the channel bottom is about half compared to the top.

When flame speed approaches the speed of sound of the reaction products, Fig. 3 (c), 30 vol. % H_2 , $\bar{v} \approx 900$ m/s, the SNR sharply decreases to values of unity and below. This makes HS OH-PLIF with pulse energies around $100 \mu\text{J}$ inapplicable at such high flame speeds. The flame front can no longer be detected. This also applies to the detonation regime. In Fig. 3 (c), a local explosion at the channel top additionally overexposes the image. The image intensifier exhibits extensive blooming. Three effects appear to be mainly responsible for the limitation of OH-PLIF towards fast flame propagation:

1. Increased flame luminescence intensity, mainly due to thermal production of OH^* .
2. Strong absorption of both laser and fluorescence light by the flame, also addressed e.g. by [4,6,7].
3. Reduction of fluorescence intensity due to increased collisional quenching rates [7].

Effects 1 and 2 will be discussed in more detail in the following.

As Fiala [5] demonstrates by non-premixed counterflow flamelet simulations, thermal excitation ($\text{OH} + \text{M} \rightarrow \text{OH}^* + \text{M}$) exceeds chemical excitation ($\text{O} + \text{H} + \text{M} \rightarrow \text{OH}^* + \text{M}$) at flame temperatures beyond 2700 K. The thermal excitation rate depends exponentially on temperature, whereas chemical excitation remains fairly constant at a given pressure. Such high local temperatures are reached within

the reaction zone of fast deflagrations through precompression and preheating of reactants by precursor shocks. Thermal excitation of OH causes strong OH* luminescence, exceeding the PLIF signal. In case of CJ detonations, local temperatures of up to 3000 K are reached. At locations of local explosions during transition to detonation, even higher temperatures are expected due to overdriven conditions. This clearly suggests to use single-shot OH-PLIF for regimes close to transition to detonation and beyond due to their higher pulse energy. Examples of single-shot detonation investigations have been published by Eder [4] (LIPF) and Pintgen [7]. We are not aware of successful attempts to capture transition to detonation with OH-PLIF.

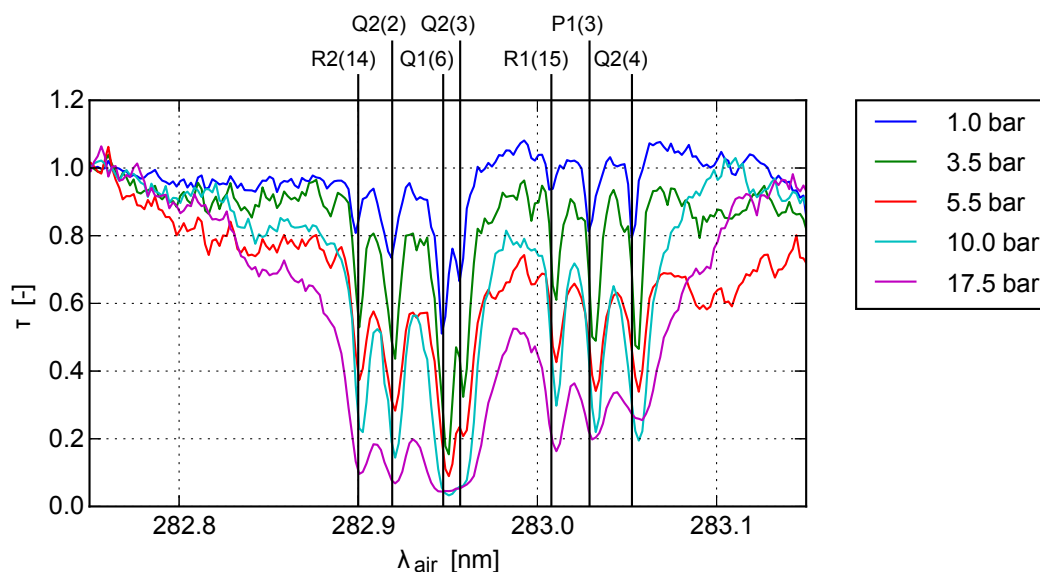


Figure 4: Measured spectral transmittance τ of the laminar jet flame. Variation of pressure.

Absorption within the flame zone as observed in Fig. 3 (b) needs to be considered in the design phase of an OH-PLIF DDT experiment. While absorption is moderate at low pressure, thus in slow deflagrations, it becomes pronounced in fast deflagrations where local overpressure can reach up to 10 bar shortly before transition to detonation [1]. We conducted TDLAS measurements around the Q1(6) transition using a laminar H₂-O₂ diffusion flame as described beforehand. Figure 4 shows measured transmittance, determined by dividing the radiance measured at the measurement diode with the flame burning stationary at a specific pressure by the measured radiance with the flame turned off. Results are in very good agreement with simulations presented in [5], showing the well known energy transitions of the OH radical. With increasing pressure, a growing amount of radiation is attenuated by the flame. At 10 bar, 98% of the radiance at the Q1(6) line is absorbed. Absorption lines broaden through collisional broadening (also termed pressure broadening) and Doppler broadening due to increased temperature. The central wavelength of absorption lines remains fairly constant over pressure. Please note that absolute numbers of transmittance are specific to the particular flame under investigation. General trends are however valid for all flames where OH occurs as an intermediate species. Absorption has two effects on OH-PLIF measurements: First, laser light is attenuated along its path through the flame. This results in an inhomogeneous excitation of OH, and flame zones far away from the laser source appear weaker and remain possibly undetected. Secondly, fluorescence light is absorbed on its way to the camera (self-absorption [3, 5]), leading to lower signal intensity and quantitative uncertainty because of the unknown three-dimensional absorptivity distribution.

5 Conclusions

We showed that HS OH-PLIF is in general applicable for DDT diagnostics in H₂-air at initial ambient pressure and temperature. The technique allows for resolving the dynamics of flame fronts at a high level of detail. However, the limited pulse energy of about 100 μ J restricts measurements to flame speeds well below the speed of sound of reaction products. Neither transition to detonation nor detonation propagation could be resolved with such low pulse energies. This is mainly due to light emission of thermally excited OH at high temperature, which exceeds the fluorescence signal. A thin channel design or employment of vertical local cookie-cutter plates should be considered to decrease recorded line-of-sight integrated flame luminescence intensity. These measures also reduce fluorescence light absorption between PLIF laser sheet and camera. Any means of flame temperature reduction limit thermally excited OH emissions additionally. Strong absorption of laser light in the flame zone particularly at high pressure needs to be considered during experiment design. From a practical perspective, we suggest to guide the laser sheet head-on towards the flame instead of side-on.

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