

Optical Investigation of Combusting Split-Injection Diesel Sprays Under Quiescent Conditions

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ABSTRACT

Multiple-injection strategies are widely used in DI diesel engines. However, the interaction of the injection pulses is not yet fully understood. In this work, a split injection into a combustion vessel is studied by multiple optical imaging diagnostics. The vessel provides quiescent high-temperature, high-pressure ambient conditions. A common-rail injector which is equipped with a three-hole nozzle is used. The spray is visualized by Mie scattering. First and second stage of ignition are probed by formaldehyde laser-induced fluorescence (LIF) and OH* chemiluminescence imaging, respectively. In addition formation of soot is characterized by both laser-induced incandescence (LII) and natural luminosity imaging, showing that low-sooting conditions are established. These qualitative diagnostics yield ensemble-averaged, two-dimensional, time-resolved distributions of the corresponding quantities. Not all of the quantities are measured simultaneously, but the distributions of all quantities can be compared precisely, due to the quiescent, well-controlled conditions in the vessel. Thereby, interfering signals are also analyzed.

In particular, the ignition mechanism of the second injection is investigated. The images indicate that the mixture fields of the first and second pulse get into contact at a certain time during the injection event. After that, a relatively fast ignition of the second pulse is observed. These findings demonstrate that the second pulse is ignited by the combusting first pulse, rather than by an auto-ignition. Thus, the ignition mechanisms of the first and the second injection pulse are fundamentally different. This behavior is found for all investigated dwell times between the pulses.

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1. INTRODUCTION

In many previous DI (direct injection) diesel engine applications, the fuel injection event was split into two parts, a pilot injection and a main injection. This fueling strategy has been used to reduce NO_x, soot, and/or noise emissions [1, 2, 3, 4, 5, 6]. Multiple-injection strategies have also been used in HCCI (homogeneous charge compression ignition) engines, e.g. [7].

According to [1], the NO_x-reduction mechanism was clarified for split injection in a conventional diesel engine as follows. The pilot injection leads to a shorter ignition delay of the main combustion and consequently reduces premixed burning. Thus, the peak flame temperature is also reduced, so that less thermal NO_x is formed. The reduction of the ignition delay of the main combustion was also consistently reported in [2, 3, 6]. Presumably, reduced premixed combustion also leads to less noise emissions.

The effect of pilot injection was also investigated by multiple optical diagnostics in light-duty diesel engines [3, 6]. These previous imaging results indicate that ignition of the main injection may be induced by two different mechanisms. On the one hand, pilot injection leads to increased temperature in the combustion chamber. This may cause fast auto-ignition of the main injection. On the other hand, the pilot injection was found to produce residual flames at the nozzle tip when the main injection started [3] or shortly before main injection [6]. Thus, the main injection may be directly ignited by these reaction zones, resulting from the pilot injection.

In order to investigate the interaction of the injection pulses in even more detail, an optically-accessible combustion vessel is used instead of an engine in the present work. It provides well-controlled ambient high-temperature, high-pressure conditions, which are comparable to the conditions shortly before combustion in engines. A number of different optical diagnostics are used to study the complete

chain of cause and effect from injection to pollutant formation. In particular, the ignition mechanism of the main injection is analyzed. For this purpose, both first and second stage of ignition are visualized by planar formaldehyde (H_2CO) laser-induced fluorescence (LIF) and OH^* chemiluminescence imaging, respectively. Formaldehyde is a relatively stable intermediate species, which is formed in the cool flame and subsequently consumed in high-temperature combustion [8, 9]. In single-pulse diesel sprays, formaldehyde was first detected by LIF at the onset of cool-flame heat release [8, 9]. This seems to be consistent with formaldehyde chemiluminescence measurements in a diesel engine [10].

The LIF of formaldehyde can readily be excited by a frequency-tripled Nd:YAG (neodymium-doped yttrium aluminum garnet) laser, which provides radiation at 355 nm. The temperature dependence of the formaldehyde LIF is discussed in [20]. In addition, severe interfering signals from both polycyclic aromatic hydrocarbons (PAHs) LIF and laser-induced incandescence (LII) from soot may occur in diesel sprays, as discussed in more detail in [8]. This is one reason why LII measurements are also conducted in the present work by operating the Nd:YAG laser at a different wavelength, as described in the following section. It can be assumed that PAHs are precursors to soot formation [8] and references therein. The current LII measurements are also conducted in order to characterize the sooting tendency of the sprays. High-temperature soot is also probed by recording natural luminosity [12].

The second stage of ignition is visualized by line-of-sight OH^* chemiluminescence measurements, as described in more detail in [13]. Excited-state OH^* is formed in near-stoichiometric high-temperature combustion [14].

Soot formation is also considered in this article, based on both LII and luminosity measurements. As demonstrated in [12, 22, 24, 25, 26, 27, 28, 29, 30]. The air/fuel ratio of the mixture at the lift-off position is crucial for soot formation. For short injection durations, it is generally affected by the temporal evolution of injection and high-temperature combustion. Thus, the temporal and spatial overlap of the liquid-phase distribution and the high-temperature flame, i.e. the lift-off length, is sometimes used as a measure of the relevant mixture composition [22, 24, 25, 26, 27]. Other important parameters, such as the ambient gas temperature [33], are discussed in Sec. 3.

2. EXPERIMENTAL

Figure 1 depicts a sketch of the optical set-up used for the formaldehyde LIF, LII, the soot luminosity, as well as for imaging OH^* chemiluminescence. The combustion vessel is described in detail in [13]. The constant-volume vessel is purged by a constant air flow of $20 \text{ m}^3/\text{h}$. The corresponding gas velocity without injection is about 0.1 m/s inside the vessel. Thus, approximately quiescent conditions are established. The compressed, filtered air is guided through

two heating cartridges (7.5 kW) before it enters the vessel. In the present study, it is operated at an ambient temperature of $(800 \pm 5) \text{ K}$ and an ambient pressure of $(50 \pm 0.5) \text{ bar}$. Exhaust gas recirculation is not used. For fuel injection, a solenoid common-rail injector (Bosch Crip 1.3) equipped with a three-hole nozzle (bore diameter = $100 \mu\text{m}$, $k_s = 1.3$) is used. The fuel-rail pressure is varied in the range of 600–1000 bar. The injection is split into two parts, a pilot and a main injection with a mass of about 6.0 mg each. The energizing time (ET) for each of the two injections is $630 \mu\text{s}$. However, the fuel mass of the second injection may be slightly affected by rail dynamics. The injection timing is depicted in Fig. 2. The actual fuel injection is determined by optical jet visualization. The dwell time (t_d), which is the delay between the injections in terms of injector current, is varied and investigated at 500, 750, 1000, 1250, 1500, and 1750 μs in the present study. For instance, a t_d of 750 μs and 1250 μs is shown in Fig. 2. In this figure, fuel injection and injector current are only schematically illustrated. For instance, a relatively high pulling current of 17 A is applied to the injector for the first 300 μs of the injection event. Afterwards, a holding current of 12 A is used. More details are given in [15].

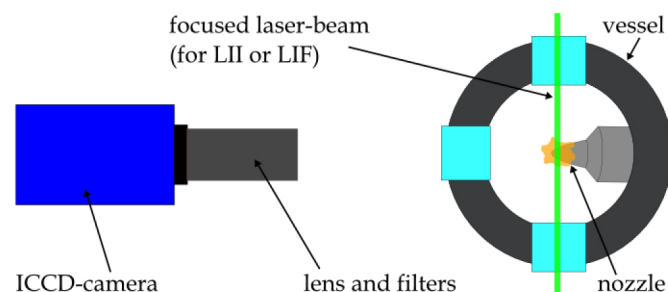


Figure 1. Experimental set-up. Formaldehyde LIF and LII measurements are conducted in separate experiments, using the same laser and camera.

N-decane is used as fuel, because it is a commonly used surrogate for standard diesel fuel with high cetane number and heating value [24].

All images are acquired by an intensified double-frame ICCD-camera (LaVision, 1280×1024 pixels) that is equipped with an UV lens (Nikon, $f = 105 \text{ mm}$, $f_\# = 4.5$). The formaldehyde measurements are described first.

For the LIF measurements, the flame is illuminated using the third harmonic of a Nd:YAG laser ($\lambda = 355 \text{ nm}$) formed to a sheet of 40 mm height and about 1 mm width [11]. The duration and the energy of the laser pulse are 10 ns and approximately 60 mJ, respectively. Thus, the energy flux in the probe volume of $75 \text{ mJ}/\text{cm}^2$ is close to the LII threshold [16]. For this reason, LII is a minor source of interfering signals during LIF measurements. In order to suppress the stray light and to select a certain range of the formaldehyde fluorescence spectrum, a long pass filter (transmission band 363.2 nm - 800.8 nm) combined with a band pass filter ($(395 \pm 5.5) \text{ nm}$) is used. The exposure time of the two images of

the combined formaldehyde LIF and luminosity measurements are $1\text{ }\mu\text{s}$ and $0.1\text{ }\mu\text{s}$, respectively, with a delay of $2\text{ }\mu\text{s}$ between the images. The laser pulse occurs during the second exposure time. Thus, in the first image flame luminosity, dominated by soot radiation in the observed wavelength range of the flame, and in the second image the LIF signal of formaldehyde are measured quasi-simultaneously. The second image contains LIF signals, and also weak signals from the natural radiation. The first image is subtracted from the second image (corrected for the different gating times) to get the pure LIF signal.

The double-frame camera is also used as follows. The OH^* chemiluminescence is measured in a second experiment. For this, a filter combination with a maximum transmission around 313 nm and a bandwidth of about 30 nm is placed in front of the camera to suppress emissions from soot and other species [13]. Two images with an exposure time of each image of $10\text{ }\mu\text{s}$ are recorded per injection by the double-frame camera. The delay with regard to the end of the first exposure time is $50\text{ }\mu\text{s}$.

The probing of the soot volume fraction by two-dimensional LII is described in the following. The double-frame camera is applied again. The narrowband band pass filter with a center wavelength of 395 nm is used to separate the LII signal from the natural soot radiation. In addition a notch filter is used to suppress scattered laser light. Overall the elastically scattered laser light is suppressed by approximately twelve orders of magnitude (six for each of the filters). Both signals, soot luminosity and LII, are filtered in the same way, because a double frame ICCD is used. A pulsed Nd:YAG laser with a second harmonic generator at 532 nm is used to heat up the soot nearly to its sublimation temperature. The laser light is formed to a thin sheet in the probe volume (height of 42 mm , thickness of 0.3 mm). The probe volume starts 5 mm above the nozzle. Below 5 mm , droplets are present which cause strong Mie scattered light. These strong signals may damage the intensifier of the camera. Thus, this area is not investigated.

The LII signal is nearly independent of the local laser pulse intensity for a wide range, but a minimum of 0.2 J/cm^2 must be reached to heat the soot up to its sublimation temperature [16]. The intensity in this application is approximately 1 J/cm^2 while the pulse duration is 10 ns . The laser intensity is permanently controlled using an energy meter head positioned behind the chamber. Decreasing laser energy due to window fouling is detected, but the variations are so small that their influence on the LII signal can be neglected.

The first image of the double-frame ICCD is taken shortly before the laser pulse with a gate width of $1\text{ }\mu\text{s}$. So only soot luminosity is measured. After a delay of $2\text{ }\mu\text{s}$ the second image is taken simultaneously with the laser pulse and a gate width of 100 ns . This image contains LII signals, and also weak signals from the natural radiation. The first image is

subtracted from the second image (corrected for the different gating times) to get the pure LII signal.

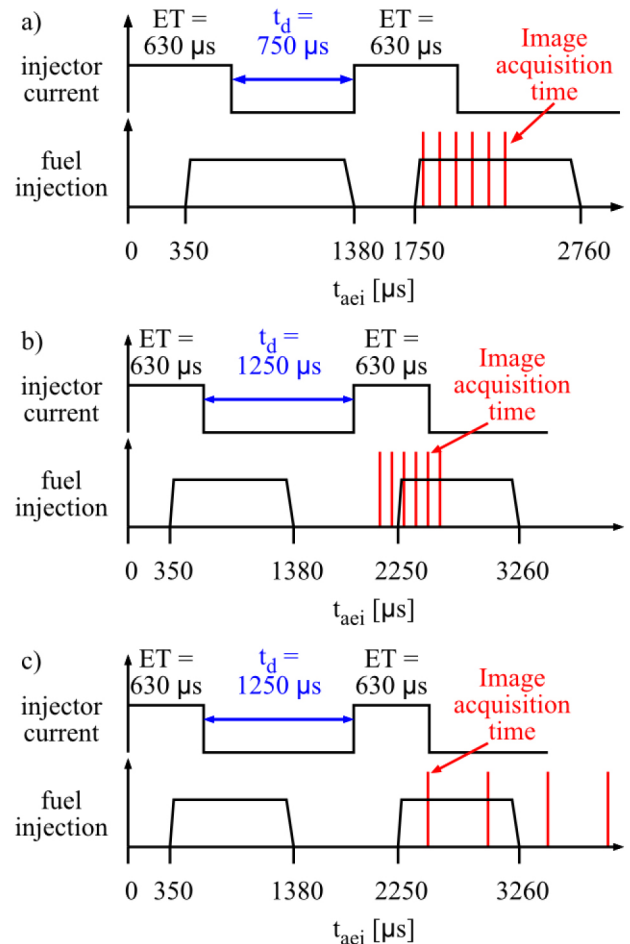


Figure 2. Schematically illustrated injection and measurement timing. Panels a), b), and c) correspond to the data presented in Figs. 7/8, 9, and 10, respectively.

3. RESULTS AND DISCUSSION

3.1. Pilot Injection

The pilot injection is first studied without the main injection, i.e., single-pulse measurements are conducted. The current n-decane jets were previously characterized in terms of near-nozzle droplet velocity by laser flow tagging (LFT) [17] and in terms of air/fuel ratio and temperature by spontaneous Raman scattering (SRS) [18]. Very similar jets were also visualized by Mie scattering and shadowgraphy [19]. Thus, jet formation is only briefly discussed here. Fuel injection actually starts at about $350\text{ }\mu\text{s}$ after energizing the injector (t_{aei}), as illustrated in Fig. 2. The dynamic behavior of the jet after a t_{aei} of $600\text{ }\mu\text{s}$ is depicted in the formaldehyde LIF images in Fig. 3a). In these images, the nozzle orifice is located at $x = y = 0$. The laser sheet covers approximately a distance between 8 mm and 45 mm to the nozzle. The liquid phase of the jet is observed in Fig. 3a) due to very strong Mie

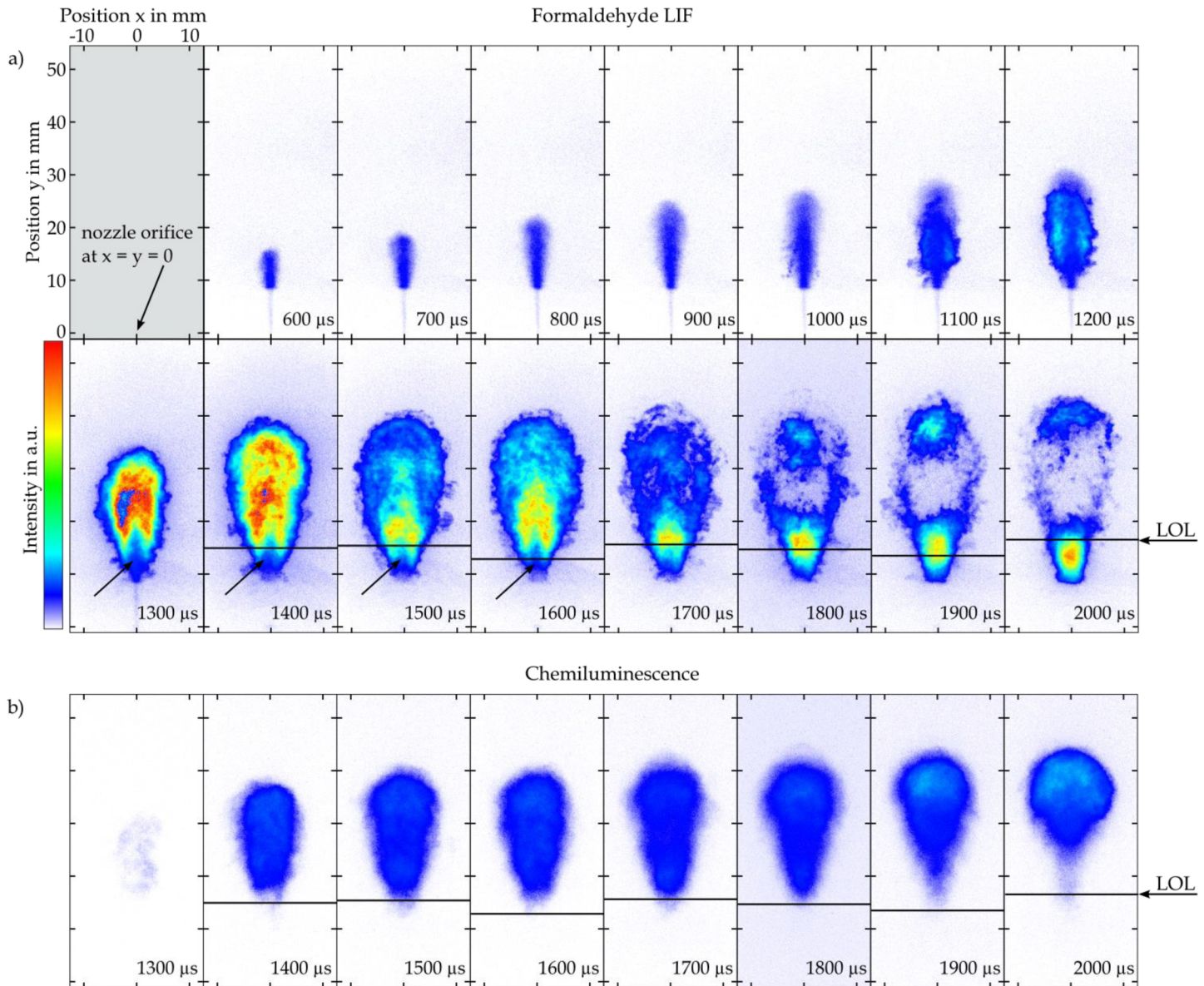


Figure 3. Ensemble-averaged formaldehyde LIF images of the pilot injection (without main injection) at a p_{rail} of 600 bar (a); quasi-simultaneously measured natural luminosity images (b). Measurement times, t_{aeb} are given in each image. LOL values are indicated by horizontal lines in the images measured at 1400 - 2000 μs .

scattering, although elastically scattered laser light is suppressed by twelve orders of magnitude by the used filter combination.

However, the images also show that an approximately uniform formaldehyde distribution is found in the leading portion of the jet in the early phase. The observed occurrence of formaldehyde (starting at a t_{aei} of 600 μs) is consistent with chemical kinetics of n-decane under the current conditions. According to [34, 35], a relatively large amount of formaldehyde is first formed about 100 μs after start of injection, i.e. at a t_{aei} of about 450 μs , corresponding to the first stage of ignition. It is also unlikely that the detected LIF signal in the jet was predominantly caused by fluorescent fuel

impurities, because such components would have been likely observed in spectrally resolved Raman and LIF measurements in the same jets [18]. Thus, the early LIF signal presented in Fig. 3 is indeed basically attributed to formaldehyde. This is also essentially consistent with previous formaldehyde measurements by LIF [8]. Formaldehyde was also detected shortly after the start of injection by spectrally resolved chemiluminescence measurements in a diesel engine [10]. The jet penetration length shown in Fig. 3a) is consistent with previous data in [15, 18, 19]. However, the observed uniformity of the formaldehyde distribution in the early phase is also partly caused by ensemble averaging over 25 injections. Thus,

turbulent fluctuations are greatly reduced. Note also that the ensemble-averaged stoichiometric ratio, λ , and temperature in the inner region of the early formaldehyde distribution were found to be about 0.5 ± 0.05 and $650 \text{ K} \pm 65 \text{ K}$, respectively (the given standard deviations of the single-shot measurements arise from both measurement errors and real fluctuations of the measured quantities from injection to injection) [18]. The stoichiometric ratio, λ , is defined as follows:

$$\lambda = \frac{[O_2]}{[O_2]_{sto}} \quad (1)$$

where $[O_2]$ is the local oxygen concentration, and $[O_2]_{sto}$ is the oxygen concentration required for stoichiometric combustion of the local fuel concentration.

The images in Fig. 3a) also show that the early formaldehyde LIF distribution becomes less uniform after a t_{aei} of 1100 μs . (However, this is partly caused by temperature effects as discussed below.) In this phase, the total formaldehyde LIF intensity also increases substantially, as shown in Fig. 4. These findings were not reported in [8]. It may be caused by slightly different mixture formation in the present work. The formaldehyde LIF intensity may also be affected by the heat release of the flame and also by vaporization cooling.

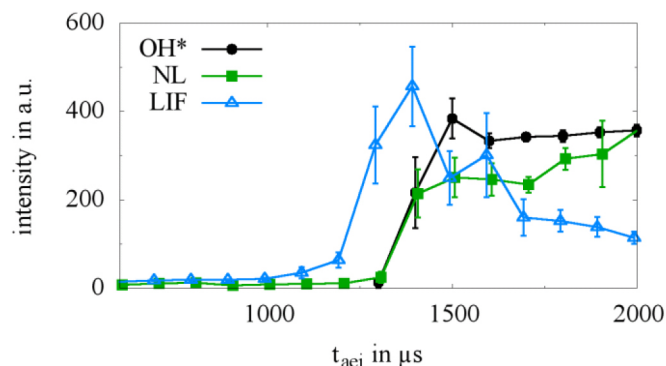


Figure 4. Total formaldehyde LIF, OH* chemiluminescence and luminosity (NL) traces corresponding to Figs. 3 and 5. The variations (standard deviation) of the data from injection to injection are shown by bars.

According to [20], the LIF quantum yield decreases gradually with increasing temperature, but this is overcompensated by the formation rate of formaldehyde, which increases strongly with increasing temperature. Consequently, the temperature dependence of the LIF is not the dominating factor and the LIF images rather show real formaldehyde density variations. (Thus, the LIF intensity is likely reduced on the jet axis by vaporization cooling.) One might also think that the formaldehyde signal is affected by interfering PAH LIF and/or LII, as noted in Sec. 1. (LIF and LII measurements are intentionally not conducted

simultaneously, so that there is not any cross-talk, but unwanted interfering LII and PAH-LIF signals may occur in the formaldehyde LIF images.) However, quasi-simultaneously recorded soot luminosity intensities shown in Fig. 4 demonstrate that they are very low prior to 1300 μs . Thus, the corresponding luminosity images are not shown in Fig. 3b). This indicates that not any (“hot”) soot is formed in the cool flame as expected [21]. The recorded luminescence signal prior to $t_{aei} = 1300 \mu\text{s}$ can be explained by cool-flame chemiluminescence from formaldehyde and possibly other species [10]. Note also that PAH-LIF measurements were previously conducted by using a much more efficient detection system based on a focused high-power laser at 248 nm in the same jets [18]. It turned out that PAH-LIF signals were very low prior to the second stage of ignition. Thus, PAH LIF is presumably a negligible source of error prior to $t_{aei} = 1300 \mu\text{s}$ in the present formaldehyde measurements. Recall also that LII is a minor source of interfering signals, as discussed in the previous section.

The formaldehyde data in Fig. 3a) and 4 also show that the LIF signal decreases after a t_{aei} of 1400 μs , starting at the periphery of the plume. This indicates that formaldehyde is consumed after the onset of high temperature combustion [8]. Accordingly, the second stage of ignition is detected by OH* chemiluminescence images starting at a t_{aei} of 1300 μs , which are depicted in Fig. 5. The corresponding total OH* chemiluminescence trace in Fig. 4 confirms this finding.

Furthermore, Fig. 3a) shows that the LIF signal distribution is changed drastically after a t_{aei} of 1600 μs , due to high-temperature combustion. On the jet axis, the LIF decreases strongly close to the lift-off length (LOL), which is indicated by the OH* images. (The LOL is defined as the distance between the nozzle exit and the location of flame lift-off, [13] and references therein). However, increased LIF signal is found further downstream, starting at a nozzle distance of about 30mm, which can be basically explained by PAH LIF, as discussed in the following. The images in Fig. 3a) and 5 implicate that there is a certain spatial overlap of the two components in the t_{aei} range from 1800 to 2000 μs . However, formaldehyde is not completely enclosed within the high-temperature reaction zone, i.e., formaldehyde is present upstream of the LOL. This particular flame structure was previously found under so-called “no-soot” and “low-soot” ambient conditions in [9]. These two conditions can be distinguished by the appearance of PAH LIF in the images of the H₂CO measurements [9]. Detectable PAH forms downstream of the H₂CO region only in the case of the “low-soot” condition. Indeed, the LIF signal in the images of Fig. 3a) 35 mm downstream from the nozzle tip can be explained by the formation of PAHs [9]. The presence of soot in this region is also demonstrated by the soot luminosity and LII measurements depicted in Figs. 3b) and 6a/b). However, LII is a minor source of interfering signals as noted previously.

Fig. 2 shows that pilot injection ends at a t_{aei} of 1380 μs . This is confirmed by the Mie scattering depicted in Fig. 3a).