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Transient Flame Development in a Constant-Volume Vessel using a Split-Scheme Injection Strategy

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Abstract

Multiple-injection strategies are characterized by a complex and transient interplay between high- and low-temperature reactions. Tracking low-temperature reaction products such as formaldehyde (CH_2O) is particularly important to understand ignition phenomena and the so-called “combustion recession” that is observed in experiments. Experimentally, it is often difficult to discriminate between formaldehyde and other species such as poly-aromatic hydrocarbons, which is why a selective excitation approach is used in this work. Simultaneous high-speed imaging of the chemically-excited hydroxyl radical (OH^*) is used to improve indication of flame location and second stage ignition. During experiments in a constant-volume vessel, two 0.5-ms injections of n-dodecane, separated by 0.5-ms dwell time, are injected into a 900-K ambient. The global flame development is characterized based on high-speed diagnostics, followed by an investigation into the spatial distribution of formaldehyde at four different times after start-of-injection (aSOI). Results show significant influence of the first injection on characteristics of the second. Ignition delay and lift-off location of the second injection are prominently reduced, while flame penetration is greatly enhanced by the wake of the first injection. Formaldehyde structure is observed during both end-of-injection transients, reaching as far upstream as 6 mm from the nozzle. Even after the second injection, the flame structure still appears to be influenced by the first, with a shorter lift-off length and compressed formaldehyde structure. Based on the selective excitation procedure, it becomes clear that the interpretation of laser-induced fluorescence (LIF) images obtained by 355-nm excitation alone is prone to ambiguity.

Introduction

In an effort to reduce engine-out noise and pollutant emissions from compression-ignition engines, contemporary injection strategies frequently employ multiple consecutive fuel injections. With an optimized configuration of injection and dwell timing, injection of small quantities prior to the principal fuel delivery has been proven capable of reducing fuel consumption, particulate matter, and CO and NO_x emissions in different load regimes [1-5]. Supplementary injections after the main delivery, known as post-injections, may significantly reduce engine-out soot and unburnt hydrocarbon (UHC) emissions [3,6], but the reported efficacies of this differ significantly [7].

Added to the complexity of a multi-parameter system, the scheduling of multiple injections has a profound influence on the characteristics of emission formation, and potentially fuel consumption, through the interplay between mixing and combustion [8,9]. An explanation for the largely different optimization schemes and resulting emissions from the previous studies can be found in the aforementioned interaction, combined with the impact of boundary conditions (e.g. combustion regime, nozzle geometry, combustion chamber size, and a temporally varying ambient environment upon fuel injection). Without providing an exhaustive review, some of the effects of consecutive injections can be summarized as follows:

1. During early pilot injections, density and temperature can be relatively low, which increases liquid penetration and thus the risk of fuel impinging on the cylinder wall. Additionally, ignition delays are expected to be relatively long because of the relatively low ambient temperature and density [10]. Generally, an increase in unburnt hydrocarbons can be expected.
2. During main injection, flame penetration of shorter injection durations may be reduced compared to a single, long injection. Effectively, using multiple injections can aid in limiting the contact duration between flame and wall or bowl, which could reduce heat losses. Simultaneously, combustion noise is lowered due to a lower pressure rise rate. Ignition delay and initial lift-off may be markedly shorter when the injection takes place into the combustion products of a pilot injection. This lack of mixing will alter the spray morphology.
3. Post-injections can (re-)introduce high-temperature reactions in a region near the injector or increase local mixing again, promoting complete oxidation of the soot formed earlier [11]. The scheduling of post-injections is particularly important and seems to be hardware dependent, but reduced engine-out soot levels have been reported, without necessarily compromising on fuel economy [7].
4. Two end-of-injection (EOI) effects have an impact on subsequent injections. Locally low densities (through temperature) and the wake of a previous injection increase spray velocities (slip-streaming effect) [9,12-14]. Additionally, the end-of-injection entrainment wave can cause the fuel-air mixture to rapidly lean out [12]. If specific regions after injection become too lean, incomplete combustion with high unburnt emissions can be expected [12,15].

The importance of understanding ignition, and combustion recession transients is clear given the aforementioned considerations. Hence, visualization of low- and high-temperature reactions is used to study transients in a multiple-injection strategy by tracking formaldehyde (CH_2O) and the chemically-excited hydroxyl radical (OH^*).

Both quiescent vessels and optical engines have been used in several previous studies for formaldehyde imaging in Diesel sprays using a tripled Nd:YAG laser at 354.82 nm (generally simply referred to as 355 nm) [8,16-23]. Although considered a well-established method to visualize CH_2O , the technique is known to suffer from interference by fluorescing Poly-Aromatic Hydrocarbons (PAH) and Laser-Induced Incandescence (LII) from soot. Based on spectral imaging, spatiotemporal analysis, and trends obtained by variations in boundary conditions, formaldehyde has been distinguished from PAH fluorescence, provided that they do not overlap [17,21,22].

Alternative excitation methods are available, but do not necessarily prove valuable. For example, to distinguish PAH from CH_2O in a heavy-duty Diesel engine, Donkerbroek et al. used an on- and off-resonance approach at 339.017 nm and 348.6 nm, respectively [18]. The on- and off-resonant wavelengths were created by a Nd:YAG laser and a frequency-doubled dye laser. At relatively low-temperature conditions (855 ± 20 K, with a top-dead center in-cylinder pressure of 45 bar, approximately), they observed that the total fluorescence in the off-resonant experiments reaches approximately 55% of the total fluorescence from on-resonant experiments, indicative of a distinct contribution of other species. Compared to the conventional 355-nm wavelength, and based on spectral simulations, the use of 339.017 nm for excitation was predicted to provide a factor 3.5 larger excitation efficiency. Experimentally, however, only a 10% increase was found. For this reason, Donkerbroek et al. decided to use 355-nm excitation in future work.

Several planar laser-induced fluorescence (PLIF) studies, imaging after the EOI transient in both single and double injection schemes, ascribe fluorescence in the near-injector region to CH_2O [8,9,19,22]: late-introduced fuel should somehow be converted as well. Adequate reactive conditions cause the high-temperature reaction zone to propagate towards the injector, which is commonly termed “combustion recession” [15].

Lachaux et al. used spectrally-resolved LIF measurements to identify formaldehyde in a heavy-duty Diesel engine operated in the low-temperature combustion regime [17]. In the experiments, it was observed that laser-induced signal in the upstream region of the spray after EOI featured certain bands corresponding to formaldehyde, but less distinct from the broadband background compared to earlier in the cycle. This indicates that apart from CH_2O , other species are definitely contributing to the obtained signal in the near-nozzle region. As background contributions to the CH_2O PLIF results are generally ascribed to PAH and LII, formation of PAH in this region after EOI needs to be considered.

For operating conditions with a reduced injection pressure and increasing reactivity compared to the current work (e.g., high-temperature ambient or high oxygen concentration), Knox et al. suggest the occurrence of soot recession after EOI [24]. Similar to combustion recession, the term refers to soot formation upstream of a lifted Diesel flame after EOI. Although the conditions studied in the present work do not seem to favor soot production in the near-nozzle region, it indicates that locally-rich mixtures may readily produce detectable amounts of PAH.

In this work we substantiate the identification of CH_2O and PAH in various different phases of a split-injection scheme using the on- and off-resonant strategy applied by Bakker et al. [25]. Using a frequency-doubled Nd:YAG laser in combination with a frequency-doubled dye laser allows for a more selective approach to identify CH_2O fluorescence. The on- and off-resonance wavelengths used were 353.16 and 350.00 nm, respectively. We illustrated how the method can successfully eliminate PAH-PLIF for both the ECN Spray A baseline condition [26], and a more sooting variation with 21 vol% oxygen, enabling substantiated identification of CH_2O [25]. The very same excitation strategy will be applied here.

The combustion vessel conditions are identical to a previous study in which Schlieren and formaldehyde PLIF using 355-nm excitation were applied to visualize ignition processes [9]. Rather than combining these two techniques, high-speed chemiluminescence imaging of OH^* is selected here, in order to evaluate the high-temperature reactions.

Experimental Setup

Pre-Burn Combustion Vessel and Injection Strategy

Experiments were conducted in an optically-accessible, high-pressure, high-temperature, constant-volume vessel, capable of reaching ambient conditions characteristic for current generations of compression-ignition engines [27,28]. The ambient environment in the current study targets the Spray A condition of the Engine Combustion Network (ECN), with a local gas temperature of 900 K, oxygen concentration of 15 vol%, and a density of 22.8 kg/m^3 [26]. Both in-vessel pressure and common rail pressure were monitored using high-speed pressure transducers (Kistler model 6041A and model 4067E3000, respectively).

A single-orifice common-rail injector (ECN #306.22 [29]) was centrally mounted in one of the faces of the cubical combustion vessel. A multiple-injection scheme was applied, involving two 0.5-ms injections of high-purity n-dodecane ($\text{C}_{12}\text{H}_{26}$) at 1500 bar, separated by a 0.5-ms dwell period. This injection scheme is recommended by the ECN, and similar to what has been used in previous ECN publications [9,30]. The injection durations were experimentally tailored by altering the energizing time. With the present injector the energizing schedule was set to 0.311 ms / 0.660-ms dwell / 0.340 ms, which is notably different from the 0.355 ms / 0.645-ms dwell / 0.365 ms reported by Skeen et al. [9].

Optical Arrangement

The cubical vessel can be equipped with up to five sapphire and/or fused-silica windows, permitting the use of multiple optical diagnostic techniques for visualizing (non-)reacting fuel sprays. In this case, simultaneous high-speed OH^* chemiluminescence and PLIF of formaldehyde was set up, as depicted in Figure 1. Unless stated otherwise, results presented in this work consist of ensemble averages based on 10 to 30 experiments.

Figure 1. Schematic overview of the high-pressure vessel and simultaneous formaldehyde PLIF and high-speed OH* chemiluminescence detection. The laser light sheet is entering from the top and is aligned with the spray axis.

Formaldehyde PLIF

Formaldehyde was excited using a frequency-doubled, tunable dye laser (Sirah PrecisionScan) operated on Pyridine 1. The dye laser was pumped by a frequency-doubled Nd:YAG laser (Spectra Physics Quanta-Ray Pro 270-10). The output wavelength of the dye laser was monitored using a HighFinesse WS6 wave meter. On- and off-resonant excitation was performed at wavelengths of 353.16 and 350.00 nm, respectively. This strategy has been chosen based on a detailed excitation-emission scan, illustrated in Figure 2. This spectrum was recorded on heated formaldehyde (90 °C and 1 atm) by evaporating formalin in the high-pressure vessel. Additional off-resonant experiments have been conducted using a wavelength of 351.00 nm. Using two cylindrical lenses, a light sheet of 30 x 0.5 mm was formed, with a typical energy of 20 mJ/pulse before entering the combustion vessel. Fluorescence was recorded using an ICCD camera (PI-MAX 3 with Unigen II photocathode) equipped with a 50-mm Nikkor AF-D f/1.4 objective. A 500-nm short-pass filter was used to capture the most significant part of the formaldehyde spectrum, in combination with a Schott WG360 filter to further reject elastically-scattered laser light.

Figure 2. Excitation-emission scan of the 4_0 band of the $A^1A_2 - X^1A_1$ system. Note the increase in fluorescence yield around 353 nm compared to 355-nm excitation. The arrowheads with dashed vertical lines indicate the two off-resonant wavelengths, the on-resonant wavelength and the common 3rd harmonic of a Nd:YAG laser (at 354.82 nm).

High-Speed OH* Chemiluminescence

OH* chemiluminescence represents the flame front location in the upstream region, making it suitable for determining ignition delay and flame lift-off length [31,32]. The consecutive injections applied in this study, however, result in transients which would not be captured with a traditional quasi-steady lift-off length determination. A high-speed camera (Photron SA-Z) was lens-coupled to a high-speed intensifier (LaVision IRO, S20 photocathode) to record OH* chemiluminescence at a frequency of 70 kHz, with a gate time of 13.28 μ s. The intensifier was equipped with a 100-mm f/2 Bernhard Halle Nachfl. UV objective. Light was collected through a filter set consisting of a 315-nm (15 nm FWHM) narrow-band filter centered near the peak emission of OH*, combined with a 300-nm (80 nm FWHM) band filter to suppress incandescent soot radiation at longer wavelengths.

High-Speed Natural Luminosity

A number of natural luminosity movies were recorded using the same high-speed camera without the image intensifier. A Sigma 105-mm f/2.8 EX lens replaces the UV objective. It has been equipped with a 600-nm short-pass filter to suppress part of the soot incandescence. The camera frame rate was identical to that used in the high-speed OH* chemiluminescence movies (70 kHz), but now with an exposure time of only 0.25 μ s to prevent over-exposure and motion blur. The natural luminosity movies are intended to aid in understanding the contribution of soot to the OH* chemiluminescence images.

Pressure Analysis

The in-vessel pressure was measured at a sampling rate of 50 kHz using a pressure transducer placed in one of the upper corners of the vessel, opposite the injector. After the pre-burn event, temperature (and thus vessel pressure) gradually decays due to heat transfer to the walls. To limit the pressure analysis to spray-induced changes, a pressure correction is applied which takes into account this decay. The correction is based on exponential fitting of the vessel pressure during 100 ms before ignition and after combustion. The correction is constantly adjusted during the spray event. Furthermore, a speed-of-sound correction is applied based on the lift-off location obtained from the high-speed chemiluminescence images. Based on a local speed of sound of 578 m/s, the used correction amounts to 0.19 ms. This approach is similar to what was used by Higgins et al. who used the liquid length as an estimate for ignition location [33]. Filtering of the pressure signal is performed using a low-order smoothing procedure (Savitzky-Golay). Apparent Heat Release Rate (AHRR) is calculated as described by Heywood [34]. Additional filtering of the AHRR is applied after the first- and second ignition events to reduce large pressure oscillations. The use of additional filtering between the SOI and ignition, for both injections, is avoided to prevent artificial rise of the AHRR signal. Usage of different filtering regions will be justified in more detail when discussing the AHRR curve.

Ignition of the primary injection is based on an in-vessel pressure increase of 30 mbar. A 20% increase in AHRR for detection of the second ignition is proposed by Skeen et al. [9]. In this work, however, the superposition of pressure waves caused by the first- and second injection prohibited reliable determination of the timing of the second ignition. Similar to the detection of the first ignition, a pressure increase with a fixed threshold, starting from the second start of injection is applied.

Results and Discussion

Global Flame Developments

Whereas only a single PLIF image is obtained for each experiment, the pressure and chemiluminescence data can aid in interpreting transients during the full event. To ease interpretation, OH* chemiluminescence data (I) can be integrated in the direction perpendicular to the spray axis (y) to find the temporal evolution of the intensity along the spray axis (x), according to Equation 1,

$$I(x, t) = \int_{y_{min}}^{y_{max}} I(x, y, t) dy. \quad (1)$$

Following this approach, the temporal evolution of OH* intensity along the spray axis can be constructed, which is commonly known as an I_{xt} -plot [21]. The top panel of Figure 3 depicts such an I_{xt} -plot for the injection schedule under study. The columns in this I_{xt} -plot give a false color representation of the total intensity as a function of axial distance (vertical axis) at any time (horizontal axis). The bottom panel of Figure 3 provides the AHRR and net pressure increase during the corresponding period (solid black and red lines, respectively). The dashed grey line corresponds to the unfiltered AHRR curve, which is used in the periods between injection and ignition for both events. Similarly, the dotted grey line shows the additionally-filtered AHRR which is used for the final part of the analysis. Additional filtering of the curve is applied between 0.5 and 1.0 ms to capture global trends and neglect pressure waves originating from the pre-mixed burn.

The ignition delay times determined in the subsequent analysis are listed in Table 1. In addition the ignition delay is determined from the ensemble-averaged I_{xt} -plot of Figure 3, a fitting algorithm was applied to the individual experiments, which is more similar to the procedure used based on natural luminosity with a dynamic range of the camera focused on ignition [35]. In the procedure applied here, a line is fit through the increasing intensity in the ignition region, and the inception with the time axis is used to determine the ignition delay. Although giving more realistic uncertainty values, the use of filtered chemiluminescence significantly raises the detection limit (also discussed by Bardi et al. [35]), so that such defined ignition delay values cannot be directly compared to other definitions. Moreover, the procedure does not allow for detection of the second ignition. The impact of selected threshold on eventual ignition delay values cannot be ignored.

Table 1. Ignition delay times (ID) for both injections based on chemiluminescence and pressure data. The uncertainty values for the ignition delay based on the average I_{xt} -plot correspond to the camera frame-rate. For the OH* fitting procedure and pressure based values, 95% confidence intervals are given using a t-distribution.

	1 st injection	2 nd injection	
ID _{OH* Ixt}	0.40 ± 0.02	0.11 ± 0.02	ms
ID _{pressure}	0.37 ± 0.02	0.11 ± 0.02	ms
ID _{OH* fit}	0.54 ± 0.07	-	ms

Figure 3. Direct comparison between ensemble averaged, time-resolved chemiluminescence (top) and pressure analysis (bottom). Features which are discussed in the text are indicated in both panels. A gamma-corrected scaling has been applied to enhance visibility in the upstream region of the spray.

First Injection

The primary indication of combustion is found in the pressure data, showing a steep increase in AHRR starting around 0.25 ms. Earliest detection of OH* chemiluminescence occurs around 0.4 ms after SOI, when a threshold of 2% of the maximum intensity is reached. This is only 0.03 ms after the pressure-based ignition delay, corresponding to a 30 mbar net increase. Compared to the I_{xt} -plot of a single injection with longer injection duration (e.g. [21]), a region with two bright spots can be identified between 0.5 and 0.7 ms after SOI. Note that the relatively intense, but narrow column located exactly at 0.7 ms corresponds to the first PLIF timing, which was studied simultaneously for the displayed results. Fundamentally, there should be no difference between the early combustion phase of single-injection Spray A and the first injection of a split-scheme. Nonetheless, a small discrepancy is found with respect to the baseline case. Given the identical thermodynamic conditions (900 K at 22.8 kg/m³) the difference can only originate from the injector. Despite the lack of momentum or mass flux measurements for the injector used and energizing schedule, results can only be compared to the readily available information. Based on the work of Kastengren et al. [36], maximum needle lift is by far not reached for the short injection durations applied in this work, although mass-flow stabilizes. When

translating their findings for a 1.5 ms injection to a 0.5 ms case, this implies that the closing motion of the needle starts at the latest 0.25 ms after SOI for the work presented here. Altered (i.e. fully transient) fluid dynamics will then have an effect on the local equivalence ratio and temperature, which may eventually impact combustion. Therefore, it is expected that high-temperature reactions after the end of injection are promoted by the injection ramp-down and the end-of-injection entrainment wave [12,13].

After 0.8 ms combustion recession occurs, as observed in the single-injection Spray A case [15]. Based on the I_{kl} -plot, the minimum distance of the flame closely coincides with the start of the second injection. With respect to possible variations in injection schedules, this indicates that temperatures are most likely approaching a maximum in the near-nozzle region for a 0.5-ms dwell. In turn, hot products of combustion recession are expected to result in a minimum ignition delay and lift-off length for the second injection.

Second Injection

Effects of the remaining combustion products in the near-nozzle region of the I_{kl} -plot are observed shortly after the second start of injection. Ignition delay is significantly shortened, and ignition location has moved upstream accordingly. Using the threshold of 2% intensity increase in this region gives an ignition delay of 0.11 ms for the second injection. The subsequent flame penetration is similar to typical spray penetration results obtained from Schlieren images (see e.g., [9]). This indicates how ignition occurs near the periphery of the jet, rather than the premixed combustion as observed for the first injection. Halfway during the second fuel delivery (at 1.25 ms), the head of this second spray reaches the retreating tail (in downstream direction) of the first injection. In the upstream region, a much shorter lift-off is observed, owing to the axial ignition location. Up until 1.6 ms aSOI, the lift-off location steadily progresses downstream, although evidently much slower compared to the local spray velocities. This observation is consistent with results by Pickett et al. [37], where forced laser ignition was used to decrease the lift-off length.

Compared to the intense premixed peak in the heat release for the first injection, the AHRR during the second injection is less vigorous. The peak AHRR is about 50% closer to SOI than for the first injection. To find the source of heat released (or pressure) increase after 1 ms is more challenging. It could either be burn-out of the first injection or ignition of the second, even further complicated by the inevitable filtering. Nevertheless, based on this indirect observation of half the available mixing time compared to the first injection, a pressure increase of only 15 mbar is used here to determine ignition delay of the second injection. After the premixed peak of the second injection, additional filtering is applied to smooth the superimposed pressure oscillations of both ignition events. Note that using this amount of filtering ahead of the second ignition (illustrated by the dotted grey line), would give the false impression that AHRR is already increasing before the start of the second injection, making the signal more prone to incorrect determination of ignition. Whereas the first heat release hump suggests premixed burn only (followed by a burn-out phase), the second hump shows evidence of a small premixed peak followed by some spray-driven phase [34]. After 1.5 ms, second fuel delivery has ceased and consumption of the total

amount of injected fuel follows, characterized by a slowly decreasing AHRR.

After 1.8 ms, combustion recession occurs in a similar fashion to the first injection, although less pronounced. Again, combustion continues moving upstream until about 2.0 ms (0.5 ms after EOI for both injections). At that time, the head of the second spray catches up with the flame penetration originating from the first injection. As shown by Skeen et al., this point is reached only after 3 ms for a non-reacting spray. Analogous to their analysis, this can be explained by the decreased local density in which the second injection is introduced. Effectively, this so-called slip-streaming behavior considerably increases spray and flame propagation.

Low-Temperature Reaction Trends in Transients

PLIF images of formaldehyde, using the on- and off-resonant detection strategy, were recorded at four different time intervals after SOI, corresponding to some of the cases where formaldehyde was identified by Skeen et al. [9].

1. 0.7 ms aSOI. The first injection event has just ended and the entrainment wave has spread-out the late fuel of the first pulse.
2. 1.2 ms aSOI. The second injection has ignited and remainders of the first injection have traveled further downstream.
3. 1.5 ms aSOI. The momentum of the second injection is about to recede, and the second and first injections have started to interact. (Just a single on- and off-resonant image have been acquired at this instance.)
4. 1.7 ms aSOI. The second injection has just ended and the question arises as to whether it behaves the same as the preceding event, given the altered upstream conditions (in terms of density and temperature) or not.

Results from the PLIF recordings are collected in the left column of Figure 4. With exception of the 1.5 ms case, the ensemble average of off-resonant recordings is subtracted from the on-resonant ones. Laser sheet locations were aligned with regions in which formaldehyde signal was expected. A laser sheet intensity distribution, included in the top of each PLIF image, is used to normalize the detected fluorescence. These distributions were recorded similar to the procedure used to obtain the spectrum depicted in Fig. 2. Such a procedure tends to amplify noise in regions of low laser-light intensity. Therefore, signal that exceeds more than twice the original maximum value within the image is treated as an artefact from this correction, and thus set to zero.

Time is indicated next to the vertical axis, and supplementary results from the high-speed techniques are provided in the central and right-most column, respectively, to show the evolution of high-temperature reactions. Each set of CH₂O PLIF results will be discussed separately below, and the accompanying high-speed OH* and natural luminosity data is used to aid interpretation. White contours at 15% of the displayed OH* intensity are superimposed on the PLIF figures. Similarly, red contours from natural luminosity recordings are overlaid on the OH* data to identify regions which are most likely to be influenced by soot incandescence.

Figure 4. Left: time evolution of formaldehyde PLIF after off-resonant subtraction and excitation intensity correction for nominally identical ambient conditions. Center and right column: movie stills from high-speed OH* chemiluminescence and natural luminosity, respectively. The OH* image at 0.7 ms is substituted by the preceding frame at 0.686 ms to prevent the slight increase in overall intensity due to the laser. On- and off-resonant PLIF results at 1.5 ms aSOI are single-shot results. The white contour in the PLIF results represent a 15% contour from the OH* images, whereas a red contour in the OH* images represents a 15% contour from the natural luminosity images. Intensity during ignition of the first- and second injection have been amplified within a region identified by a dashed white rectangle. See text for additional details.

After the First Injection (0.7 ms)

Just after end-of-injection an entrainment wave quickly dilutes late-introduced fuel. Combustion recession might not occur (completely), if the mixture becomes overly-lean, or if temperature declines too rapidly [15]. At 0.7 ms aSOI, combustion recession is not visible in the OH* data, but low-temperature reactions are expected to take

place upstream of OH* regions. The result indicates the presence of a distinct formaldehyde tail that covers the region from 6 to 25 mm, approximately. Further downstream, i.e., around 30 mm, there is some evidence of formaldehyde, although the relative signal strength is rather low and the spatial distribution is irregular. It could rather be a residual of the “on-off” subtraction, which is further amplified by the laser correction, given the peak illumination being located around 20 mm. Still further downstream (around 35 mm), the same

observation holds. Given that injection-induced momentum diminishes upon end-of-injection, the presence of formaldehyde closer to the nozzle (up to 6 mm) seems reasonable, particularly when qualitatively compared to single-injection quasi-steady Spray A results [21,22,25]. The maximum intensity is observed between 11 and 15 mm. Further downstream, formaldehyde is consumed upon approaching the high-temperature diffusion flame or mixes and interacts with high-temperature products in the central region of the spray [21]. This presumption is consistent with the OH* chemiluminescence distribution.

After the Second Ignition (1.2 ms)

As observed in the I_{xt} -plot, ignition of the second injection is already becoming visible in the OH* recordings as soon as 0.1 ms after SOI of the second injection. In Figure 4 this is illustrated by the amplified signal within the dashed white rectangle at 1.1 ms. Skeen et al. [9] observed natural luminosity signal in their experiments around this time as well. Apparently, high-temperature chemistry is already occurring this early, which is attributed to the relatively hot end gas in the vicinity of the nozzle. Subsequently, the entrainment of fresh ambient gas (of around 900 K) causes some downstream travel of the flame lift-off. A time of 1.2 ms aSOI is still at the beginning of that phase and the chemiluminescence figure shows that the typical spray structure is starting to develop (e.g. at 0.9 ms). Based on these observations, the resulting formaldehyde structure is expected to resemble that of the igniting Spray A baseline in a previous publication by Skeen et al. [22]. Indeed, Figure 4 shows how the typical spatial CH₂O structure with distinct lobes above and below the spray axis is present in conjunction with OH*, indicating pre-mixed auto-ignition of most of the fuel present in that region. Formaldehyde is undoubtedly not present in the wake of the first injection, downstream of 25 mm. The remainder of signal of the primary spray in the OH* recording at this time nearly fully coincides with the natural luminosity, indicating a significant contribution of soot over the downstream region during the burn-out phase.

The Second End of Injection (1.5 ms)

Near the end of the injection sequence only one couple of single-shot PLIF images were taken. The upper half of the on-resonant recording is placed in the top of the image. The upper half of the off-resonant recording is mirrored along the spray axis and displayed in the lower half; this minimizes any effects of laser sheet attenuation. Although these are only single-shot results, the results seem to confirm the analysis by Skeen et al. [9], who argue that signal downstream from 20 mm of the injector most likely corresponds to PAH fluorescence. Whereas in their case the analysis is based on the estimated location of PAH at a later time instance, our off-resonant result directly shows strong similarity of the downstream structure compared to that of the on-resonant image. Only upstream of 20 mm there is evidence for CH₂O being present.

After the Second Injection (1.7 ms)

Analogous to the situation at 0.7 ms an entrainment wave is rapidly dispersing the late fuel at 1.7 ms aSOI. For the second injection, however, flow conditions are slightly different compared to the quiescent conditions just before the first injection. Both spray and flame penetration have been vastly increased due to the reduced local density, as discussed above. Based on the OH* contours, and with respect to the first injection, formaldehyde is expected to be located

closer to the nozzle as well. The red contour from the natural luminosity recording reaches upstream to 30 mm from the injector for the first time. In the upstream direction, however, the spatial extent of the CH₂O-PLIF signal seems to be limited by the laser light sheet. The downstream structure, when compared to the result at 0.7 ms, remains relatively close to the spray axis in radial direction. This observation is expected to find its origin in the elevated local ambient temperature again, where the rapid upstream transition to high-temperature reactions is limiting the radial extent of the formaldehyde distribution, similar to high-temperature variations of Spray A, as studied by Maes et al. [21].

Formaldehyde Signal Ratio

By quantitatively comparing the signal strength of off-resonant images to the corresponding on-resonant recordings, the contribution of fluorescence from other sources than formaldehyde can be estimated. For the single-shot PLIF results at 1.5 ms, shown in Fig. 4, it was clearly observed how negligible signal was present in the CH₂O region around 15 mm for the off-resonant case, compared to the on-resonant image. This observation, however, does not hold for all the results shown in Figure 4. To illustrate this difference, the average signal strength in a region from 15 to 20 mm downstream of the injector and spanning a radial direction of 3 mm above and below the spray axis is determined for all cases. This region-of-interest has been selected on the basis of the presence of formaldehyde signal after off-resonant correction, for each time interval. Individual backgrounds are subtracted by selecting a similar square starting on a 7 mm distance from the spray axis. Subsequently, the background contribution to on-resonant signal strength is computed; results are listed in Table 2. Both cases after the end of injection (0.7 ms and 1.7 ms) show a background contribution of 46%, indicating that the background fluorescence makes up for nearly half of the detected signal. On the other hand, for the case which is most comparable to a quasi-steady situation, the background only reaches about 21% of the detected signal. Note, however, that this is based only on single on- and off-resonant resonant images. When computing the value for quasi-steady spray results with a long injection duration (presented in Ref. [25]), likewise a relatively low background contribution of 33% is found. Although it is not exclusively proven by the results presented here; we presume that the fuel-rich regions, going through first-stage ignition before combustion recession occurs, produce soot precursors. Such behavior would be consistent with the increased broadband signal in the formaldehyde spectrum after EOI in the near nozzle region shown by Lachaux et al. [17]. If the hypothesis is correct, the presence of precursors might give rise to the soot-recession discussed by Knox et al. [24], when considering conditions with more soot. The signal ratio at 1.2 ms after SOI is still slightly higher compared to the value obtained at 1.5 ms, possibly due to the limited mixing time available for the second injection. Such a highly non-premixed situation might result in noticeable PAH presence.

Table 2. Background contribution of non-formaldehyde signal to on-resonant PLIF recordings. Uncertainty values are based on shifting the region used for computing the background contribution 1 mm up- and downstream. The second 0.7 ms case (identified by an asterisk) corresponds to a second off-resonant wavelength.

	0.7 ms	1.2 ms	1.5 ms	1.7 ms	0.7 ms*	
Background contribution	46 ± 1	37 ± 2	21 ± 4	46 ± 6	51 ± 1	%

To substantiate the findings listed above, and justify the applied off-resonant correction, the off-resonant wavelength was varied for the 0.7 ms case. This is studied since increased pressure will cause the excitation spectrum to broaden, while increased temperature might simultaneously populate more rotational levels, and thus unexpected formaldehyde excitation might occur. Although an apparent band head is present near 352 nm (see Figure 2), high-temperature, high-density spectra are difficult to obtain under engine-like conditions. The upper panel of Figure 5 shows a direct comparison between the ensemble-averaged on- and off-resonant results corresponding to the 0.7 ms PLIF panel in Fig. 4. The method of display is identical to the 1.5 ms PLIF result presented in Figure 4, with exception of a laser sheet intensity distribution correction to prevent noise amplification. Note that subtraction of the off-resonant results applied in Fig. 4 resulted in an improved signal-to-noise ratio, and that the most upstream locations where formaldehyde PLIF signal is found in the 0.7 ms case corresponds to the limit of the laser sheet. The lower panel represents a second set of on- and off-resonant experiments taken with a slightly different laser-sheet location, using an off-resonant wavelength of 351.00 nm (indicated by “off 2” in Figure 2). Apart from the apparent shift in intensity distribution originating from the laser illumination, the structure above and below the spray axis is very alike. This is confirmed by the quite similar second background contribution at this time after SOI (identified by an asterisk in Table 2). Note that a slight increase in ratio for the 351.00 nm comparison might also indicate that moving closer to the band head is reducing the efficacy of the off-resonant correction.

Figure 5. Comparison between off-resonant correction using a wavelength of 350.00 nm and 351.00 nm, respectively. Note that the laser sheet correction is not applied in this case, which accounts for the apparent upstream shift of formaldehyde in the lower panel (see text for more details). The ensemble averages in the lower panel consist out of 10 and 7 individual recordings for on- and off-resonant, respectively. Dashed white rectangles represent the area which has been used for determining the background contribution values presented in Table 2. The reader should particularly focus on the relative signal intensities present in the indicated region of interest.

Conclusions

A split-injection strategy (0.5 ms/0.5 ms dwell/0.5 ms) was investigated in a constant-volume pre-burn vessel at boundary conditions relevant to internal combustion engines (900 K, 15 vol% O₂ and 22.8 kg/m³). Using pressure analysis, a combination of on- and off-resonant formaldehyde PLIF, and high-speed OH* chemiluminescence, and natural luminosity recordings, the ignition behavior and combustion recession were studied. Particular emphasis was put on the differences between the first and second injections. The main findings are listed below.

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- Even though thermodynamic conditions are identical to those of the Spray A baseline with a long injection duration, a more intermittent combustion during the premixed burn of the first injection has been attributed to injector dynamics. With shorter energizing times the start of needle closure and the after EOI entrainment wave seem to influence combustion in the described region.
- Hot end gas of the preceding combustion event increases velocities and mixing of the second injection and reduces the ignition delay down to 0.11 ms, which is shorter compared to the values found by Skeen et al. (0.17 ms, [9]).
- The lift-off length of the second injection, although not reaching a quasi-steady state, is also located closer to the injector orifice. The entrainment of cooler air causes the lift-off length to slowly progress further downstream after ignition of the second fuel jet. This process continues until the lift-off starts progressing upstream with a subsequent combustion recession event.
- The time evolution of the formaldehyde PLIF distribution further illustrates the differences between the first and second injection event. For the initial injection a pronounced, but little-structured formaldehyde distribution is found at 0.7 ms, which is just after end-of-injection. On the other hand, the subsequent second fuel delivery experiences fast ignition and presumably rapid transition towards high-temperature reactions that consume formaldehyde. For this reason, the resulting structure at 1.7 ms is significantly smaller and less intense compared to the corresponding structure after the first pulse.
- Potentially more important is that during the second injection, no remnants of CH₂O from the first injection are found. This finding implies that left-overs are either located far downstream, or are not present at all. The eventual formaldehyde structure of the second injection at 1.2 ms resembles that of the quasi-steady spray-driven phase, as shown in earlier works [25]. A similar axial distribution is found: from 12 mm to 24 mm, approximately.
- Using the off-resonant subtraction, PAH fluorescence is (at least partially) removed from the PLIF images. This approach suggests that significant amounts of PAH are found in the near-nozzle region during the onset of combustion recession as well. This observation is based on the increased background contribution in the on-resonant PLIF images obtained during the onset of combustion recession, with respect to the results obtained during the quasi-steady period of Spray A experiments.

Recommendations

Some recommendations for future (ECN) work have originated from the results presented here. They are listed in order of decreasing priority, according to the authors.

1. Because of the difference in premixed burn of the first injection compared to the baseline Spray A case, also remarked by Skeen et al. [9], the effect of energizing duration and thus injection duration must be studied in more detail. Apart from the effect on combustion, different requirements in energizing time have been noticed. It is recommended to sweep injection duration until the differences disappear. The timing window around 0.5 ms injection duration seems to be the region of interest. The other proposed ECN double-injection case (0.3 ms / 0.5

ms dwell / 1.2 ms) could suffer from injector effects even more.

2. Another interesting variable is dwell time. The authors have run experiments with 0.3 and 0.7 ms of dwell (not presented here). The specific reason to vary dwell lies in the ignition behavior of the second injection and as such, the interaction between end gas of the preceding combustion and ignition of the second injection can be studied. Additionally, numerical work can benefit from such experiments, given the fact that capturing ignition properly remains challenging [38,39]. More efforts should be put in studying the interplay between dwell time and ignition of the second injection.
3. In spite of the Schlieren data presented by Skeen et al. [9], the local flow fields during spray-spray interaction at Spray A boundary conditions have never been resolved using particle image velocimetry (PIV), or equivalent. Such experiments could not only shed light on the “slip-streaming” effect, but also on species transport in the flame.

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