

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.

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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 NOx emissions in different load regimes [1, 2, 3, 4, 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 (high temperature) and the wake of a previous injection increase spray

velocities (slip-streaming effect) [9,12, 13, 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, 17, 18, 19, 20, 21, 22, 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 6045A 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 [31].

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.

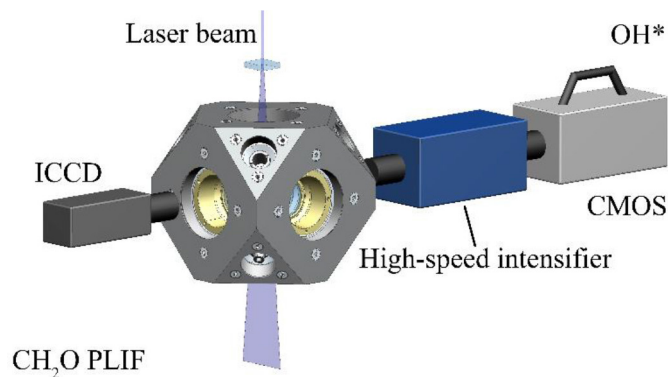


Figure 1. Schematic overview of the high-pressure vessel and simultaneous formaldehyde PLIF and high-speed OH* chemiluminescence detection. The laser light sheet is entering from the top and is aligned with the spray axis.

Formaldehyde PLIF

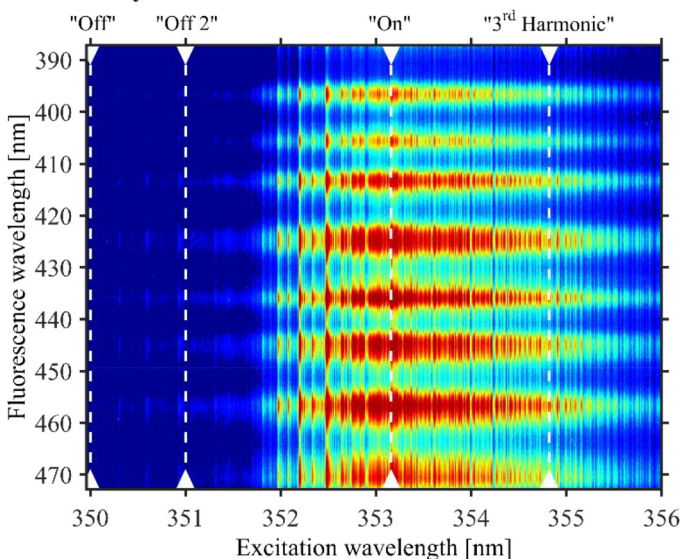


Figure 2. Excitation-emission scan of the 4^1_0 band of the $A^1A_2 - X^1A_1$ system. Note the increase in fluorescence yield around 353 nm compared to 355-nm excitation. The arrowheads with dashed vertical lines indicate the two off-resonant wavelengths, the on-resonant wavelength and the common 3rd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

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.

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 μs. 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 μs 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.
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