

Visualization of Ignition Processes in High-Pressure Sprays with Multiple Injections of n-Dodecane

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ABSTRACT

We investigate the mixing, penetration, and ignition characteristics of high-pressure n-dodecane sprays having a split injection schedule (0.5/0.5 dwell/0.5 ms) in a pre-burn combustion vessel at ambient temperatures of 750 K, 800 K and 900 K. High-speed imaging techniques provide a time-resolved measure of vapor penetration and the timing and progression of the first- and second-stage ignition events. Simultaneous single-shot planar laser-induced fluorescence (PLIF) imaging identifies the timing and location where formaldehyde (CH_2O) is produced from first-stage ignition and consumed following second-stage ignition. At the 900-K condition, the second injection penetrates into high-temperature combustion products remaining in the near-nozzle region from the first injection. Consequently, the ignition delay for the second injection is shorter than that of the first injection (by a factor of two) and the second injection ignites at a more upstream location near the liquid length. At the 750 K and 800 K conditions, high-temperature ignition does not occur in the near-nozzle region after the end of the first injection, though formaldehyde remains from first-stage reactions. Under these conditions, the second injection penetrates into cool-flame products that are slightly elevated in temperature (~ 100 K) relative to the ambient. This modest temperature increase and the availability of reactive cool-flame products reduces the first- and second-stage ignition delay of the second injection by a factor of approximately two relative to the first injection. At the 750-K ambient condition, high-temperature ignition of the first injection does not occur until the second injection enriches the very fuel-lean downstream regions.

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INTRODUCTION

Multiple injection strategies are now commonly used in direct-injection compression-ignition engines as a means to improve emissions and noise while maximizing fuel economy. The advent of fuel injector hardware with greater flexibility and repeatability for injection duration and dwell between injections permits new opportunities for engine optimization, but it also creates a new degree of complexity to find these optima through development and calibration. An improved understanding of multiple injection combustion, and advancements in computational tools describing the process, are therefore needed to focus engine and injector development in the most advantageous areas.

Multiple injections have shown many benefits, and some offsetting weaknesses, with regards to engine-out emissions and engine noise. Pre- and pilot-injections are usually intended to reduce the ignition delay and fuel-air mixing of the main injection, which can reduce NO_x , CO, and UHC emissions [1, 2] while also distributing heat release more evenly to reduce engine noise [3, 4]. The reduced fuel-air mixing of the main injection typically increases PM (soot) emissions [2], but this drawback (caused by the pilot injection) can be countered by the addition of yet another "post" injection to actually reduce PM emissions [5,6,7].

Simultaneous to the emissions benefits, multiple injections offer increased flexibility for optimization of the heat-release timing, which can improve fuel economy. Reductions in CO, UHC, or soot emissions clearly correlate with improved fuel economy through better combustion efficiency as well as the energy saved by avoidance of aftertreatment. Nonetheless, in addition to heat-release phasing and combustion efficiency, researchers have shown that multiple injections offer the potential to improve fuel economy through a reduction in heat transfer to combustion chamber walls [8]. Injections are tailored in such a way that the hottest gases, and strongest velocities with high convective heat transfer potential, remain distant from the wall [8].

Observations of multiple-injection combustion at conventional diesel conditions must be reevaluated and optimized when applied to low-temperature combustion (LTC) engines or operating conditions that use higher EGR, lower compression ratio, or even a different fuel type (e.g., gasoline compression-ignition). A pilot injection to reduce ignition delay may not be desirable because it prevents premixing, while the need to slow heat-release rates with a pilot is somewhat mitigated by the high EGR [9]. At the same time, LTC suffers from increased UHC and CO emissions [10] that have been improved with late or post injection [11]. In addition, multiple early injections [12, 13, 14], or multiple late/post injections [15], have been shown to be effective in reducing liquid impingement on

in-cylinder walls, which is a concern for emissions and efficiency. Other concerns about multiple injections at LTC conditions include pilot injections that fail to ignite [16] or the general loss of control of heat-release timing as injection timing becomes increasingly separated from ignition and combustion.

With so many factors and tradeoffs affecting multiple-injection combustion, it is imperative that the fundamental in-cylinder processes are understood, and that CFD models accurately represent them. Key aspects of the problem include the dynamic rate shape of each injection, the spray mixing and evaporation, the first- and second-stage ignition position and timing, local combustion efficiency, NO_x formation and reburning, soot formation and oxidation, interaction with the engine flow field and neighboring plumes, and so forth.

The rate of injection profile for each injection deserves special attention in typical common rail systems because the minimization of injection duration and dwell between injections and the accompanying hydraulic pressure waves in the system can easily modify each injection profile [17, 18] and the resulting mass per injection. The rate of injection for short injections falls below that of a single, long injection because of throttled opening and closing effects. Characterization of the rate of injection is required but caution in interpretation should be exercised because rate meters with liquid injected into liquid do not perfectly match engine conditions with liquid injected into gas [19].

Fundamental studies characterizing the velocity and mixing of subsequent injections at well-characterized conditions have shown marked differences compared to single injections [20, 21]. In high-temperature, high-pressure conditions typical of an engine, but in inert, quiescent chambers, the second injection mixes with a cooler, vaporized fuel-ambient mixture produced by the first injection and its liquid-phase penetration is longer than that of a first injection of the same duration [14, 22]. In addition, the rate of penetration of the second injection is faster than that of the first injection. Velocity measurements show that the second injection enters a “slipstream” produced by the first injection [21]. Rather than forming a stagnation plane at the head of the spray, as is the case for the first injection, the fluid ahead of the second injection is already moving downstream. Mixing measurements and CFD predictions actually show that there is an increased mixing rate at the head of the second injection because of the enhanced velocity and turbulence produced from the first injection [20, 21, 23]. While these findings are simplified because the experiments were performed in quiescent chambers, there is no question that the interaction of the first injection with the engine flow field [24] will influence mixing of the second injection.

The progression of reaction of earlier injections is obviously critical to the mixing, ignition, combustion, and soot formation of subsequent injections. Possible scenarios for combustion of the earlier injection include: (1) vaporization but no reaction, (2) first-stage (cool-flame) ignition, (3) second-stage, high-temperature ignition and combustion without soot formation, or (4) high-temperature, fuel-rich combustion with soot formation. In reality, (1)-(4) occur at different timings and spatial positions, thereby making the dwell between injections and the movement (e.g. swirl motion) of earlier injections critical. In a

detailed investigation of double injections of equal injection duration, but different dwell time, Bruneaux and Maligne [21] found that the dwell between injections significantly changed the combustion structure of the second injection. Using planar laser-induced fluorescence imaging of formaldehyde (CH₂O) to indicate first-stage ignition, and of hydroxyl (OH) to indicate high-temperature combustion, they quantified the combustion structure of the first injection beginning at the time of the second injection. At a short dwell timing, the first injection produces a pattern of upstream first-stage (cool flame) ignition products and downstream high-temperature combustion products as documented extensively for LTC conditions by Musculus et al. [10]. The second injection ignites and burns close to the position of the high-temperature combustion products. With a longer dwell, both the cool flame and high-temperature combustion products recede closer to the injector. Ignition and combustion of the second injection occurs much closer to the injector in this case, producing a shorter ignition delay and more fuel-rich mixture. After the end of the second injection, high-temperature combustion products extend all of the way to the injector, suggesting minimal UHC.

Results of Bruneaux and Maligne [21] may be compared to the high-speed visualization of multiple injections shown by Pickett et al. (see Fig. 13 of [25]), where each injection also had an equal injection duration but the ambient and injector conditions were not the same as Bruneaux and Maligne [21]. Not surprisingly, the sequence of combustion events is different. The first injection presents only cool-flame combustion products at the beginning of the second injection. High-temperature ignition then occurs in the downstream region of the first injection shortly before the second injection head arrives at this position. The second injection ignites only when it reaches the high-temperature combustion products from the first injection. Mixing with fuel vapor or cool flame products from the first injection was not sufficient to cause ignition on its own before reaching the hottest products from the first injection. With ample premixing upstream, the second injection did not form soot. The high-temperature combustion region advanced slightly towards the injector during the second injection, but the second injection did not consume fuel vapor or cool flame products left in the near-nozzle region, as would be desired in order to reduce UHC in low-temperature combustion.

What emerges from the comparison of these detailed studies of multiple injections is that many questions remain unanswered regarding the interaction of spray mixing and the various stages of ignition and combustion. Remaining questions include:

- How does the first injection affect mixing and penetration of the second injection?
- What determines whether cool-flame or high-temperature combustion products are produced from the first injection?
- What is the role of mixing with cool-flame and high-temperature combustion products, potentially in a non-uniform distribution, on the ignition and combustion of the second injection?
- Will reaction and lift-off length always be advanced towards the injector with subsequent injections?



- What parameters determine if the last injection produces high-temperature combustion products very near the injector signifying complete combustion?

Addressing these questions requires a detailed understanding of spray mixing as well as the reaction state of each injection with individual multiple-injection sequences, all of which are highly transient phenomena that are difficult to fully quantify. Nevertheless, aspects of these questions may be addressed with a careful experimental and modeling approach. For this study, we apply a recently developed simultaneous high-speed, line-of-sight, and planar diagnostic to relate the entire time sequence of injection and combustion events to a more quantitative planar image at a particular time in the sequence [26]. High-speed (150-kHz) schlieren imaging is used to visualize the temporal progression of the multiple injection penetration and mixing as well as the low- and high-temperature ignition events, while CH_2O fluorescence in a planar laser sheet provides details of combustion state at a specific time during, after, or between injections. Interpretation of results is also aided by pressure and heat-release analysis and direct high-speed chemiluminescence imaging obtained at the same conditions.

As mentioned above, a desired outcome of this research is that CFD models will accurately predict multiple-injection combustion thereby addressing the questions listed above. The process of model improvement, including identification of current weaknesses, is facilitated if the injector and ambient conditions for the multiple-injections study are already well known and well characterized. Accordingly, we have chosen to focus on the “Spray A” conditions of the Engine Combustion Network (ECN) [27] where dozens of experimentalists and modelers have already contributed data and understanding. The selected multiple injection condition for the present work consists of an equal split injection, already identified as preferred target operating points by the ECN with active modeling and experimental research by a number of institutions. For example, in subsequent studies, we will address the transient soot formation and oxidation dynamics with this same injection sequence.

EXPERIMENTAL SETUP

Ambient and Injector Conditions

Sprays of n-dodecane ($\text{C}_{12}\text{H}_{26}$) were injected into a high-pressure (up to 35 MPa), high-temperature (up to 1400 K) pre-burn combustion vessel that simulates the thermodynamic conditions of modern compression-ignition engines [28]. The vessel is nearly cubical with a volume of approximately 1 liter. The fuel injector is mounted at the center of a metal side-port such that the fuel spray is directed into the center of the chamber, while four transparent windows provide line-of-sight and orthogonal optical access to the spray event.

A common-rail single-hole diesel fuel injector (# 210370, 90- μm orifice) belonging to the family of Spray A injectors of the Engine Combustion Network (ECN) [27] injected fuel at 1500 bar. The standard Spray A condition is a single injection case corresponding to a 1.5-ms duration and approximately 3.7 mg. For multiple injection experiments, the ECN has advertised a split-injection schedule with equal 0.5-ms injection duration, and a 0.5-ms dwell between

injections. This split-injection condition will be the target for this study. A different “pilot-main” schedule with 0.3 ms / 0.5-ms dwell / 1.2 ms is also recommended by the ECN, and experiments have been performed, but will not be presented here. To add relevant information about mixing and combustion before the second injection arrives, we have also used a single 0.5-ms injection for this study.

The injection duration, and estimates for the mass injected during each injection, were made using a force sensor positioned in front of the spray, along with total mass collection as detailed in [19]. Results are shown in Figure 1 and the electronic injection schedule is given in the caption. As discussed in Ref. [19], the measured momentum of the spray is subject to experimental artifacts due to inertia of the sensor and mass accumulation of the spray before impacting the sensor, which appears as fluctuations during injection, lack of a complete decay to zero after injection, and so forth.

In an effort to remove experimental artifacts, and to standardize the rate of injection used in CFD modeling, CMT-Motores Térmicos has provided a model for the rate of injection. This model was specifically derived for Spray A operating conditions and the relevant coefficients are given in the caption of Figure 1. The modeled ROI curve given in the figure is from two separate single-injection initializations of this model, spaced in time and duration to match that of the experiment. Through experimental trimming of the commanded electronic durations, the duration of each injection is closely matched. The modeled ramp-up and ramp-down shapes are reasonable compared to the experiment, while the fluctuations in the model during the steady portion are intentionally dampened to avoid reproducing the experimental artifacts. The modeled mass of the first injection is 1.18 mg, and the second is 1.16 mg. Because of the ramp-up and ramp-down in ROI, where the mass flow rate is restricted, the total mass from the two 0.5-ms injections is slightly less than two-thirds of the single 1.5-ms injection. The model ROI, which is recommended for CFD modeling of these conditions, may be downloaded at [29].

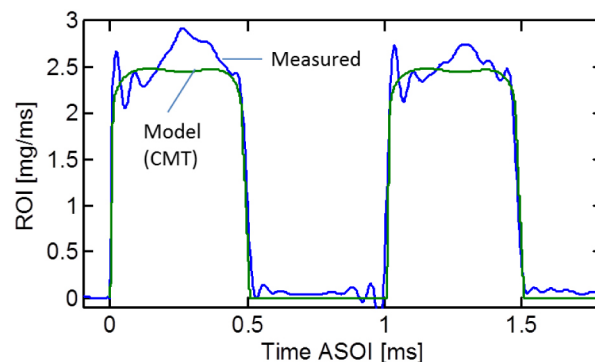


Figure 1. Measured and modeled rate of injection for the 0.5 ms equal split injection. The electronic injection commands were 0.355 ms (@18A), 0.645 ms dwell (delay), 0.365 ms (@18A). Model parameters for Injector # 210370 were: $d = 0.0908$ mm, $\rho_{\text{fuel}} = 698$ kg/m³, $C_d = 0.888$.

Experimental ambient gas conditions were chosen to mimic engine conditions and also follow the ECN Spray A conditions. Ambient gas temperatures of 750 K, 800 K and 900 K along with 15 vol% oxygen were investigated to vary the time sequences of ignition of the first

and second injection. Non-reacting cases using 0% ambient oxygen were also considered to characterize mixing and vapor penetration without effects of heat release.

Optical Diagnostics

Simultaneous planar laser-induced fluorescence (PLIF) and schlieren imaging of the combustion event from the same perspective was accomplished using a 200-mm $\times$ 250-mm 30/70 beam splitter (Edmund Optics #43-362) as shown in Figure 2. Images captured from the same perspective allow for a direct comparison of flame structures observed from both diagnostics. Details of the formaldehyde PLIF setup and high-speed schlieren setup are provided below. In addition to the optical diagnostics, the constant volume vessel is equipped with high speed pressure transducers permitting the determination of pressure-based ignition delay times.

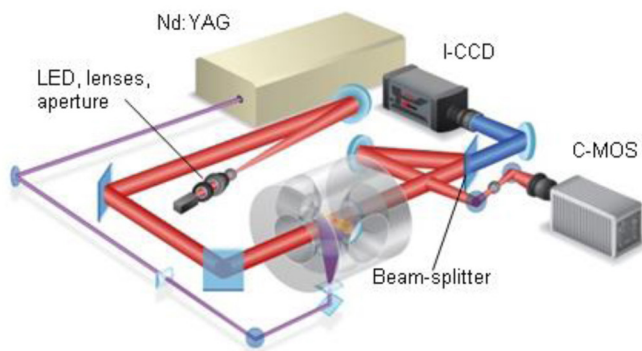


Figure 2. Schematic diagram of the high-pressure combustion vessel and optical arrangement for simultaneous high-speed schlieren imaging and formaldehyde PLIF. Not shown is a second high-speed C-MOS camera interchanged with the I-CCD camera for visualization of the flame luminosity.

Formaldehyde PLIF Imaging

Images of formaldehyde along a thin plane of the fuel jet were made with PLIF. Radiation at 355 nm (100 mJ/pulse), produced by a 10-Hz (7-ns pulse) Quanta-Ray Nd:YAG laser and formed into an 80-mm $\times$ 0.3-mm sheet, excited the formaldehyde fluorescence. The laser sheet intersected the fuel jet from the bottom of the vessel and passed through the jet centerline as shown in Figure 2. A flat field correction for the laser intensity profile along the spray axis, which would result in a more even representation of the fluorescence signal, was not made; however, we do not believe this affects the qualitative comparisons of the PLIF signal at different timings ASOI. An intensified CCD camera (Princeton Instruments, PI-MAX3) with a 250-ns gate time imaged the PLIF signal. The camera was equipped with a 50-mm f/1.2 Nikkor glass lens along with a 450-nm short-pass filter and a 385-nm long-pass filter to block flame luminosity, elastically scattered light, and reflections from the 355-nm excitation, while transmitting over the strongest resulting fluorescence bands of formaldehyde [30].

Formaldehyde PLIF as described above can potentially suffer from interference due to polycyclic aromatic hydrocarbon (PAH) fluorescence as well as laser-induced incandescence (LII) from soot; however, optical engine and spray vessel experiments have leveraged formaldehyde's characteristic spectral features to demonstrate that

formaldehyde fluorescence can be distinguished from PAH and soot interference both temporally and spatially [31, 32]. O'Connor and Musculus [5] also concluded that fluorescence from formaldehyde and PAH in a diesel spray flame could be distinguished by considering their relative intensities, with the formaldehyde fluorescence yield notably smaller than that attributed to PAH. This simplified approach is valid provided that the laser fluence is below the saturation threshold for PAH-LIF [33].

With the above considerations, we note that the 750-K and 800-K operating conditions in the present work appear free of soot formation. For the 900-K condition, both temporal and spatial separation of the formaldehyde LIF from PAH-LIF and soot-LII for the first injection is observed. For the second injection, the temporal and spatial separation is less pronounced.

High-Speed Schlieren Imaging

High-speed imaging of the vapor penetration, cool-flame ignition, and high-temperature ignition were made using a Z-type schlieren setup [34] in an arrangement similar to Ref. [14]. A high-speed CMOS camera (Photron SA-X2) imaged the spray at 150,000 frames per second (fps) with a 2- μ s exposure time. An 85-mm f/1.8 Nikkor glass lens resulted in a projected pixel size of 0.213 mm/pixel and a 628-nm (32-nm FWHM) band-pass filter was mounted on the lens to reject flame luminosity. A custom LED, emitting 3.5-W of 635-nm (15-nm FWHM) radiation in 1- μ s pulses, was synchronized with the high-speed camera to provide illumination for the schlieren setup. Using a short LED pulse further enhanced temporal resolution. A 50-mm condensing lens collected the LED emission and directed it through a 3-mm aperture prior to collimation by a 115-mm diameter, f/8 parabolic mirror. After passing through the combustion vessel, the collimated beam was re-focused using a second parabolic mirror and a series of flat folding mirrors. The light was imaged by the high-speed camera approximately 100 mm after the focal point, where a schlieren stop aperture of 12-mm diameter was placed to yield the desired contrast to density gradients. The 3-mm aperture at the light source and the 12-mm schlieren stop aperture were selected by trial and error to reduce the intensity of unwanted background schlieren caused by temperature gradients at the windows, while maximizing the contrast of softening gradients during the low-temperature ignition event similar to Pastor et al. [35]. To further reduce the appearance of background schlieren structures, the schlieren images were processed by normalizing the images by a frame just prior to the beginning of injection or by a time-differencing technique.

High-Speed Luminosity Imaging

Though not depicted in Figure 2, for select cases we measured ignition delay times using a high-speed camera running at 30,000 fps. The camera was equipped with a 600-nm short-pass filter to suppress the high intensity soot luminosity and take advantage of the camera's dynamic range. The high-speed luminosity imaging is particularly helpful in situations where the high-temperature ignition of the second injection is obscured in the high-speed schlieren imaging.

Pressure Trace and Apparent Heat Release Rate

The vessel is equipped with high-speed pressure transducers to permit the determination of a speed-of-sound corrected, pressure-based ignition delay time. In many instances, the pressure trace and corresponding apparent heat release rate curve can aid in the interpretation of the high-speed schlieren imaging and PLIF data, provided the speed-of-sound correction has been applied. The speed-of-sound correction assumes that heat release occurs near the anticipated penetration distance of the vapor along the spray axis. Along with the fixed distance from the pressure transducer to the spray axis, the time required for the pressure wave to reach the transducer can be computed for the speed-of-sound correction. Additional details are available in Lillo et al. [36].

The initial pressure signal is smoothed using a low-order filter to remove the relatively small noise observed before high-temperature ignition. Following ignition, larger oscillations are observed that can be attributed to pressure waves propagating throughout the vessel. This signal is smoothed using a Fourier filter as described in detail in Ref. [27]. For a split injection event, the pressure-based ignition delay time for the first injection corresponds to the time at which the smoothed vessel pressure exceeds a specified threshold. For the second injection, a 20% increase in the apparent heat release rate (AHRR) curve after the start of the second injection defines the ignition delay.

RESULTS AND DISCUSSION

Non-Reacting Vapor Penetration

A time sequence of the non-reacting vapor penetration acquired by the high-speed schlieren imaging diagnostic is presented in Figure 3 for the double injection case (0.5 ms/0.5-ms hold/0.5 ms). The images were processed based on the normalized absolute difference between sequential images to highlight fast temporal changes while neglecting the slow-moving background schlieren caused by temperature gradients in the boundaries near the vessel walls. With this technique, the progress of the vapor boundary can be readily distinguished. Raw schlieren movies available online [29] show that during the 0.5-ms hold time between injections, the schlieren effect attributed to the first injection has diminished in the near injector region. Consequently, the second injection is clearly visible when it begins, as shown in the image frame corresponding to 1025 μ s ASOI in Figure 3.

It is interesting to compare the penetration distance of the two injections at similar timings relative to the first appearance of liquid at the injector tip. As such, the images shown for the second injection in Figure 3 (frames 6 through 8) were selected such that the time steps correspond as closely as possible to those of the first injection. For example, the second frame (145 μ s ASOI) is 127 μ s after the first frame in which the liquid has penetrated approximately 4 mm from the injector tip. The sixth frame (1152 μ s ASOI) also falls 127 μ s after liquid from the second injection has penetrated approximately 4 mm. For illustrative purposes, the bottom three frames of Figure 3 include an outline indicating the boundary of the first penetrating jet depicted in the second through fourth frames. The three bottom frames of Figure 3 clearly show that the second injection penetrates

faster along the spray axis than the first injection. As discussed above, this can be attributed to the second injection entering the slipstream of the first injection. The faster penetration of the second injection and higher turbulence also enhances the rate of mixing [20, 21, 23].

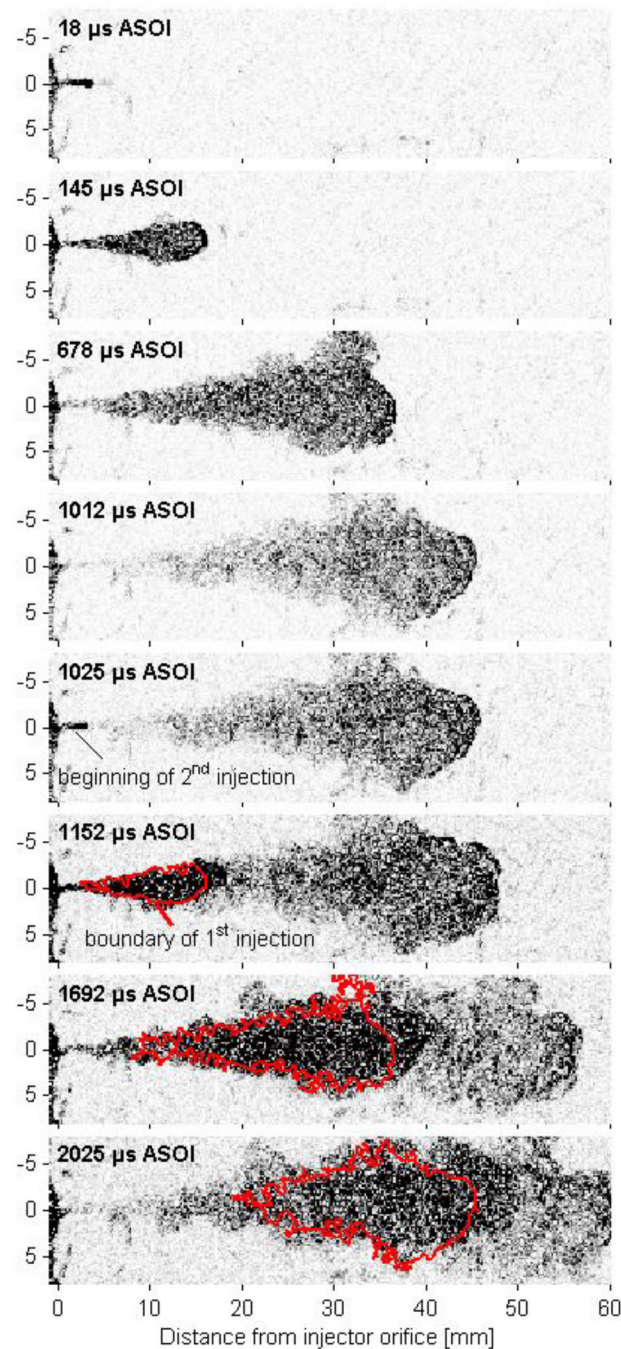


Figure 3. Time sequence of schlieren images showing non-reacting vapor penetration for double injection (0.5 ms/0.5-ms hold/0.5 ms). The ambient temperature, density, and oxygen concentration were 900 K, 22.8 kg/m³, and 0%, respectively. Red lines overlaid show the vapor boundary of the first injection.

A comparison of the measured vapor penetration under a range of conditions is provided in Figure 4. We observe that the penetration of the single and double injections diverge near 1.5 ms ASOI; however, the second injection does not reach the axial position of

the first injection until approximately 3 ms ASOI. The data therefore suggest that the second injection slightly increases the penetration of the first. The penetration of the reacting double injection into a 900-K ambient also increases relative to the non-reacting case. This can be attributed to the higher temperature, and thus lower density, environment near the injector as high-temperature ignition occurs in this region after the end of the first injection. This will be discussed in more detail later.

The penetration of the non-reacting second injection is also displayed in Figure 4 with a temporal shift to better visualize a comparison with the first injection. We note that the second injection only begins to penetrate faster than the first after it reaches an axial distance of 30 mm, which is well beyond the typical liquid length measured under these conditions (10 mm). The faster penetration and mixing of the second injection must be considered when trying to understand its ignition behavior.

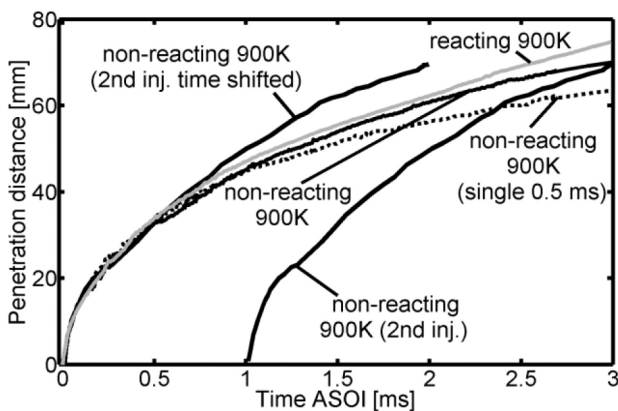


Figure 4. Vapor penetration as a function of time ASOI for single (0.5 ms) and multiple injection (0.5/0.5(hold)/0.5 ms) schedules under reacting and non-reacting conditions.

Though not shown here, at ambient temperatures of 750 K and 800 K, the reacting penetration of the double injection is identical to that of the non-reacting case. At these lower temperatures, high-temperature ignition of the first injection occurs at later timings and farther away from the injector orifice. More important to the penetration, high-temperature ignition in the near injector region after the end of the first injection is not observed in these lower temperature cases.

First- and Second-Stage Ignition Characterization for Double Injections

Skeen et al. [26] demonstrated that first-stage (low-temperature or cool-flame) ignition first occurs in the radial periphery of the spray head under the Spray A standard condition. This was followed by a volumetric first-stage ignition event throughout most of the spray head just prior to second-stage or high-temperature ignition. In the present work, we examine the cool-flame ignition event at lower ambient temperatures (750 K and 800 K) as well as the Spray A standard (900 K) to understand potential differences in the progression of low- and high-temperature ignition when comparing the first and second injections in a split-injection scenario. On an individual basis, the diagnostics implemented in the present work

can provide only a limited level of detail on the progression of first- and second-stage ignition; however, as we will show, the combination of pressure data, high-speed schlieren imaging, single-shot PLIF, and high-speed chemiluminescence imaging reveal a wealth of valuable information.

We begin by providing the average ignition delay times of the first and second injections based on the high-speed imaging and pressure data in Table 1. For reference, ignition delay times measured previously that are available on the ECN database for longer injections (1.5 to 4.0 ms) [27] are also shown in the shaded region. The pressure-based ignition delay times measured in the present work for the first injection are somewhat shorter than those measured previously at 800 K and 900 K. While changes in ignition delay are expected for different injection schedules, a slight drift to shorter ignition delays was also noticed for longer injections during this study. Based upon our analysis, the most likely factors contributing to the shorter ignition delay times measured here include: (1) a systematic drift in the ambient temperature or a different temperature distribution in the core of the vessel (2) variation in the initial pre-burn mixture leading to a higher oxygen concentration, or (3) the build-up of peroxides in the n-dodecane during storage [37]. An evaluation of all of the factors potentially contributing to these shorter ignition delays must be performed in a future study. As the present study focuses on the temporal evolution of the mixing field and combustion dynamics during multiple injections, the slightly shorter ignition delays measured for the first injection relative to archival data do not confound the purposes of this work.

Table 1. Average ignition delay times for the first and second injection

T_{amb} [K]	$\tau_{1,pressure}$ [ms]	$\tau_{1,schlieren}$ [ms]	$\tau_{ECN,pressure}$ [ms]	$\tau_{2,pressure}$ [ms]	$\tau_{2,lum/schlieren}$ [ms]
902 ± 2	0.33 ± 0.03	0.35 ± 0.01	0.39 ± 0.01	0.17 ± 0.01	[†] 0.15 ± 0.02
803 ± 2	0.88 ± 0.09	0.92 ± 0.04	0.94 ± 0.02	0.34 ± 0.06	[†] 0.4
752 ± 2	[‡] 2.0 ± 0.05	[‡] 2.0 ± 0.05	2.3 ± 0.07	[‡] 1.0 ± 0.05	[‡] 1.0 ± 0.06

[†]Ignition of second injection was obscured by schlieren from first-injection combustion products. Second injection ignition timing for the 900 K ambient case was evaluated to be 1.15 ± 0.02 ms by high-speed luminosity imaging during separate injection events having a mean ambient temperature of 903 ± 2 K. High-speed luminosity imaging was only available for a single 800 K case.

[‡]Cases at 750 K ambient did not exhibit distinct high-temperature ignition events for the first injection in the pressure trace or AHRR curve. Schlieren imaging suggests that the first injection only proceeds through first-stage ignition before the second injection undergoes high-temperature ignition. See text for more details.

In Table 1, the high-temperature ignition delay of the second injection is provided as the time after the start of the second injection. Typical raw and filtered pressure traces as well as the AHRR curves for the three ambient temperature conditions of this study are provided in Figure 5. For the 800-K and 900-K ambient conditions, two distinct peaks in the AHRR can be observed corresponding to heat release from the first and second injections. The peak AHRR for the first injection is consistently larger for the 800-K cases relative to the 900-K cases. This is attributed to the additional mixing that occurs because of the longer ignition delay time for the 800-K case. The additional mixing time results in a larger volume of uniform mixture that undergoes high-temperature ignition leading to a more rapid pressure rise. Under the 800-K and 900-K conditions, schlieren from the first-injection combustion obscure the second injection schlieren preventing an evaluation of the ignition delay time for the second