

Effects of End-of-Injection Transients on Combustion Recession in Diesel Sprays

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ABSTRACT

End-of-injection transients have recently been shown to be important for combustion and emissions outcomes in diesel engines. The objective of this work is to develop an understanding of the coupling between end-of-injection transients and the propensity for second-stage ignition in mixtures upstream of the lifted diesel flame, or combustion recession. An injection system capable of varying the end-of-injection transient was developed to study single fuel sprays in a newly commissioned optically-accessible spray chamber under a range of ambient conditions. Simultaneous high-speed optical diagnostics, namely schlieren, OH* chemiluminescence, and broadband luminosity, were used to characterize the spatial and temporal development of combustion recession after the end of injection. As ambient conditions become cooler or contain less oxygen (i.e. less reactive), combustion recession transitions from strong sequential ignition, to weak separated pockets of ignition, and finally to the absence of combustion recession altogether. At ambient conditions that do not favor combustion recession, increasing the end-of-injection transient duration promotes combustion recession. At high temperatures and/or oxygen concentrations, and also with longer end-of-injection transients, soot recession was observed, suggesting a trade-off in the emissions impact of combustion recession. Combustion recession under relatively lean conditions can help to reduce unburned hydrocarbons, but if mixtures are too rich, combustion recession can promote increased soot emissions. A previously developed reduced-order model was also used to provide further insight. The model shows that the shape of the end-of-injection transient is important. In particular, the minimum pressure at time of needle closing has a strong impact on combustion recession.

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INTRODUCTION

The importance of end-of-injection processes on engine-out emissions in modern compression ignition engines is becoming clearer as researchers continue to probe the physical mechanisms underlying common emissions metrics, e.g. soot, nitrogen oxides (NO_x), unburned hydrocarbons (UHC), and carbon monoxide (CO). End-of-injection processes have been found to enhance ambient gas entrainment into the fuel spray [1, 2], which alters soot formation/oxidation processes [3], as well as ignition (UHC) [1] and CO oxidation kinetics [4, 5] compared to steady injection processes. While specific combustion or injection timing strategies can result in different emissions challenges, e.g. high soot and NO_x emissions for conventional diesel combustion strategies or high UHC and CO emissions for Low-Temperature Combustion (LTC) strategies, end-of-injection processes appear to play an important supporting role in all emissions outcomes, regardless of the injection strategy.

Different end-of-injection phenomena are being discovered as modeling and diagnostics become more advanced. Phenomena that accompany or contribute to end-of-injection processes include poorly atomized fuel dribble, enhanced probability of cavitation [6, 7], or even ambient gas ingestion [8]. For example, researchers at Argonne National Laboratory have used x-ray phase contrast imaging to observe end-of-injection processes within a single-hole common rail injector nozzle and found ambient gas ingestion into the nozzle sac following an injection event [8]. Gas ingestion from the previous

injection event has been used to explain the observation that liquid penetration is shorter during start-of-injection [9, 10]. The impact of these phenomena on global combustion behavior and engine-out emissions is still an open research question.

Other end-of-injection processes that have been more clearly linked to combustion and emissions outcomes include the rate at which fuel flow is decreased through the nozzles, often referred to as injection ramp-down. Musculus and coworkers have demonstrated that the injection ramp-down contributes to enhanced ambient gas entrainment and mixing such that fuel-air mixtures near the nozzle may become over-mixed beyond the flammability limit under LTC conditions [11]. This process of enhanced entrainment after the end of injection has been termed an "entrainment wave." After the entrainment wave passes through near-nozzle mixtures, the resulting overly fuel-lean mixtures may reach first-stage ignition, forming formaldehyde and other partially-oxidized species, but they never reach second-stage ignition and are thus considered a contributing source of hydrocarbon emissions under LTC conditions. Musculus and co-workers have primarily demonstrated the importance of these phenomena for combustion strategies with a positive ignition dwell, where ignition occurs after end-of-injection and well after the passage of the entrainment wave through near-nozzle mixtures, leading to very lean conditions in the near nozzle region that do not reach second-stage ignition. However, these phenomena are also likely to

be important for highly dilute negative ignition dwell conditions where a conventional lifted-flame stabilizes well downstream of the injector nozzle (i.e., long lift-off lengths). Under such conditions, mixtures upstream of the lift-off length will experience rapid leaning during passage of the entrainment wave after end-of-injection and may not reach second-stage ignition. Under this scenario, exploratory modeling work performed by the authors has demonstrated that UHC emissions can be reduced to negligible values by employing a longer injection ramp-down duration [12]. The mechanism for UHC emissions reduction was a process termed combustion recession, where the high-temperature reaction zone (lifted flame) propagates back towards the injector nozzle after end-of-injection [13].

In an effort to better understand the conditions that contribute to combustion recession, previous work by the authors compiled a large experimental dataset of high-speed diesel spray combustion images at a wide range of ambient conditions (temperature, oxygen concentration, and density), injector parameters (injection pressure, nozzle diameter) and fuel [13]. All were shown to have an important influence on the existence of combustion recession as well as the time required for the overall process. The experimental data was supplemented by a reduced-order model to infer the effect of injection ramp-down duration, which was used to develop a regime diagram for the propensity of combustion recession. At the time, no validation data existed for the effect of ramp-down duration on combustion recession, in part because of the difficulty in controlling ramp-down for typical injectors.

Concurrently with our work in Ref. [13], Koci et al. [14] used a modified Hydraulic Electric Unit Injector (HEUI) to investigate the effects of ramp-down duration on combustion recession experimentally. They presented results on the effects of ramp-down duration that ranged from ~ 100 -1000 μ s, in conjunction with a range of ambient conditions from 860-915 K and 18.5-20.9% O_2 . From imaging of OH*, they found that combustion recession was promoted at higher ambient temperatures and oxygen concentrations, as well as with longer ramp-down durations. Similar to their OH* imaging, their CH*/soot luminosity images indicated that soot recession was also promoted. However, at intermediate conditions, they found that combustion recession could exist without soot recession. Finally, at low ambient temperatures and/or oxygen concentrations with a short ramp-down duration, they found that neither signal retreated back towards the nozzle after end-of-injection, indicating the absence of combustion recession. While this study demonstrated a transition between soot recession, combustion recession, and the absence of both as ambient conditions and injection rate-shape were varied, the spatial and temporal development of these igniting and/or soot-producing near-nozzle mixtures was unclear. For example, are combustion and soot recession binary or can they be in partial existence? Moreover, is soot-producing dribble present and if so, when and where does it form and under what conditions?

This work seeks to extend our understanding of combustion and soot recession and potential interactions with soot-producing dribble under a larger range of ambient conditions and end-of-injection transients than what is currently available in the literature. The goals of this work are threefold: i) create an injection apparatus that can control the end-of-injection transient to mimic the ramp-down behavior of a

wide variety of current and future injectors, ii) develop a diagnostic portfolio that focuses on end-of-injection combustion observables, iii) validate previous model predictions, and iv) identify difficulties and challenges for control of combustion recession with advanced injection strategies.

EXPERIMENTS

Spray Chamber

Experiments were performed in an optically-accessible high-temperature, high-pressure spray chamber that mimics in-cylinder thermodynamic conditions. Capabilities of the spray chamber include a maximum temperature and pressure of 950 K and 100 bar, as well as approximately 100 mm of optical access at the front, sides, and the top of the chamber. The spray chamber was designed by Advanced Combustion GmbH and is similar to other continuous flow-through spray chambers in the literature [15]. An evaluation of the performance of the spray chamber, including the measured temperature distribution within the test section and the ability of the chamber to replicate key spray combustion experiments from the Engine Combustion Network (ECN) database, is given in the [Appendix](#).

Optical Diagnostics

Three simultaneous optical diagnostics were employed to study the effects of end-of-injection transients on combustion recession. High-speed schlieren, OH* chemiluminescence, and broadband chemiluminescence/soot luminosity were performed for each test case. The three cameras were positioned to capture images from the side of the vessel. Due to physical constraints, each camera was positioned at a slight angle (<10 deg.) off-axis. A calibration grid was used to determine the projective transformation matrix for each camera, which was then used to correct the images.

To identify regions of fuel vapor and combustion products, which will be used to characterize combustion recession, the following equipment and settings are used. Illumination is provided by a 150-W tungsten-halogen lamp, where light is passed through an f/1 aspheric condenser lens, 600 grit ground glass diffuser, and then a 9-mm iris to emulate an "extended light source." Light is then collimated by an f/8 parabolic mirror, passed through the measurement volume and focused back down by another f/8 parabolic mirror in a typical Z-shaped arrangement. A 3-mm iris is used as the schlieren stop, located at the focal point of the second mirror, to enable adequate schlieren sensitivity. Light is passed through a 600 nm short-pass filter to reduce soot incandescence and then collected by an f/1.2, $f = 50$ mm Nikkor lens and Photron SA-X2 CMOS camera to provide a projected pixel size of 0.1058 mm/pixel. Images were captured at 81 kfps with a shutter duration of 11 μ s.

Evidence of second-stage ignition, which will also be used to characterize combustion recession, was found by detecting OH* and CO2* (if any) chemiluminescence. To collect light from the relaxation of these excited-state species back to ground, a narrow band-pass interference filter centered at 310 nm is placed in front of an f/1.8, $f = 45$ mm UV-VIS lens and coupled to a Hi-C 250 mag intensifier and Photron SA-1 CMOS camera. The projected pixel size

for this optical arrangement is 0.1389 mm/pixel. Images were captured at 30 kfps with intensifier exposure duration and voltage of 5 μ s and 700 V. The boundary of OH* chemiluminescence was defined as 3% of the maximum counts during quasi-steady injection.

Because ignition in diesel sprays can occur over a range of equivalence ratios, imaging in both the visible and ultra-violet range may be necessary. To ensure adequate detection of ignition for combustion recession, collection of CH*, HCO*, CH₂O*, CO₂* and C₂* (if any) was achieved with a BG40 Schott glass filter (transmission range of 335–610 nm) and is coupled directly to an f/1.8, f = 85 mm visible lens and Photron SA-3 camera without the need for intensification. The projected pixel size for the setup is 0.1088 mm/pixel. Images were captured at 30 kfps with fully-open shutter duration of 33 μ s. Note that soot luminosity is spectrally broad and could have a significant contribution to the overall signal under some conditions even with the employed filter. However, soot is typically discernable by its higher signal compared to chemiluminescence (by orders of magnitude) [16]. Therefore, these images will provide a measurement of chemiluminescence but also a qualitative indication of soot.

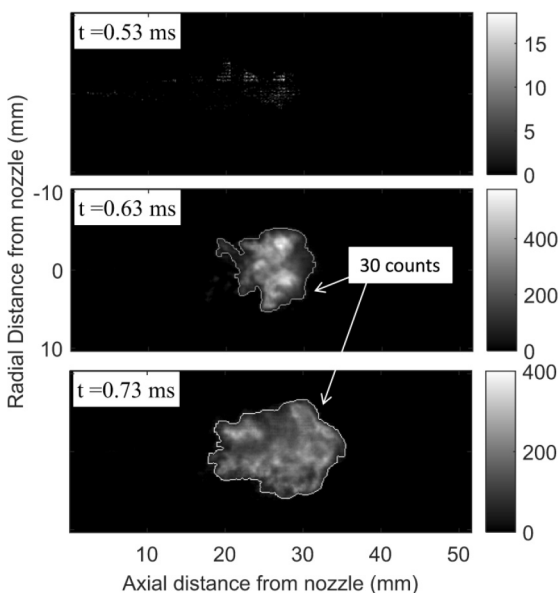


Figure 1. Time sequence showing progression from first to second-stage ignition and the measured intensity of each. Images were acquired with the broadband/soot luminosity camera under the Spray A condition with injection pressure = 1000 bar.

Guided by Engine Combustion Network recommendations, the border of second-stage ignition was defined by the intensity count in the broadband chemiluminescence/soot luminosity images such that the threshold is above first-stage ignition and is sufficiently low to capture the boundary. Figure 1 shows a time sequence of ignition at the Spray A condition, but with an injection pressure of 1000 bar. First stage ignition is evident at $t = 0.53$ ms after the start of injection (ASI), where the intensity count is approximately 15. Prior to this time instance, the maximum intensity count was ~ 1 –2. By 0.63 ms ASI, second-stage ignition is evident where the maximum intensity count is ~ 500 . Based on these findings, the boundary for second-stage

ignition was chosen to be 30 counts. Images were captured with 12-bit resolution, or 4096 counts full scale.

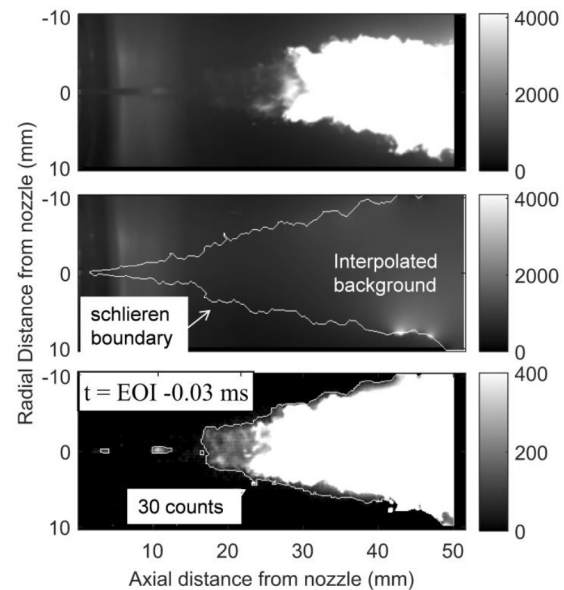


Figure 2. Dynamic background correction procedure. The top image is the raw broadband chemiluminescence/soot luminosity image, the middle is an estimated background image and the bottom image is after applying the background subtraction.

After the initial ignition sequence, soot luminosity creates a bright background that is non-uniform in space and time and complicates interpretation of the broadband chemiluminescence signal. To overcome this difficulty and improve signal-to-noise ratio, a dynamic background correction was performed. In Figure 2, the top image displays raw chemiluminescence/soot luminosity during quasi-steady state. The simultaneously acquired schlieren image was then used to define the boundary of the jet and to mask the broadband chemiluminescence/soot luminosity image. After applying the mask to the chemiluminescence/soot luminosity image, inward interpolation was performed to create an estimate of the background inside of the jet boundary, shown in the middle of Figure 2. Finally, the bottom image of Figure 2 was created by subtracting out this estimated background from the raw image at the top. A threshold of 30 counts again defined the border for second-stage ignition. Note that the quality of this methodology is dependent on the schlieren image and threshold for jet boundary detection, and uncertainties in the jet border can lead to inconsistencies in the estimated background level near the jet edge (see bottom right edge of center image in Figure 2). However, the method enables extraction of broadband chemiluminescence information for combustion recession that might otherwise be obscured with other background subtraction techniques. Unfortunately though, even with this method of dynamic background correction, we are unable to identify the very low intensity of first-stage ignition as is commonly done prior to start of combustion. Further work will be focused on other ways to minimize the unwanted background signal within the vessel rather than with post-processing. Lastly, this methodology does not remove other interference sources like mie scatter from liquid droplets, which will be present in these images up to the point of end of injection.

Injection Rate-Shaping Apparatus

To study end-of-injection effects on combustion recession, a fully-flexible injection rate-shaping apparatus was developed, as shown in Figure 3. This system controls the pressure supplied to the experimental injector (located within the spray chamber) by charging or discharging the fuel supply lines. Common rail injectors were used as ultra-high-pressure, fast-acting valves that can operate at pressures up to 200 MPa and fully open/close in approximately 100 μ s. Fuel was fed to the common rail by a high-pressure pump, which was then routed to the charging injector. A custom coupling block provided a unique seal for the charging injector to the rest of the system. Fuel can travel to the experimental injector, discharging injector, or is stopped by a check valve. A low-pressure fuel pump supplied fuel through the check valve when the pressure in the system decreases below a pre-defined minimum. The pressure supplied to the experimental injector must remain above some minimum in order to prevent air in the high temperature, high pressure spray chamber from escaping back through the injector.

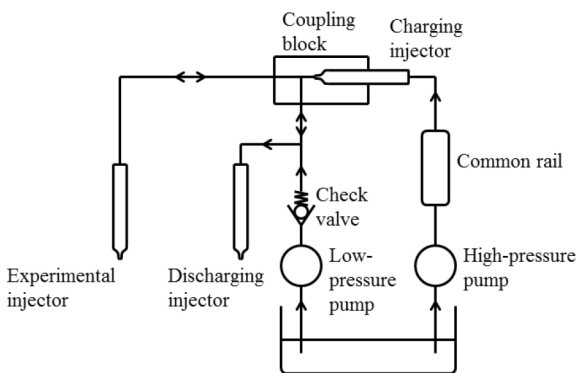


Figure 3. Schematic of experimental rate-shaping system.

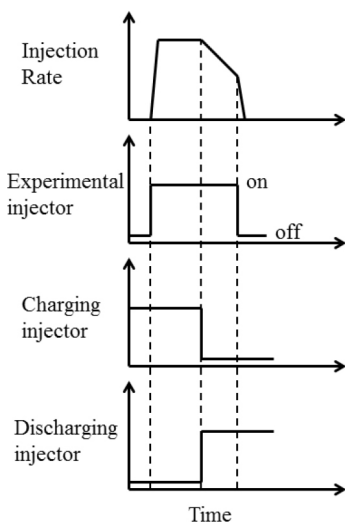


Figure 4. Sample control strategy to achieve variable ramp down injection rates.

Nearly any injection rate shape desired is possible with this injection system offering a unique opportunity to explore the effects of end-of-injection transients on combustion and emissions. A sample control strategy for varying the ramp-down at the end of injection is shown in Figure 4. The charging injector opens well before the experimental injector in order to provide a constant high-pressure

source upstream. Then, the experimental injector is energized and the flow rate of fuel through this injector resembles the initial portion of a conventional injection rate shape. Shortly thereafter, the charging injector is deenergized at nearly the same instance as the discharging injector is energized. The fuel pressure that supplies the experimental injector quickly decays as the volume upstream empties. A custom LabVIEW program simultaneously controls each injector and further data acquisition needs.

Injection Profile Measurements

Existing measurements of the rate-of-injection for diesel fuel injectors have indicated that the ramp-down duration of typical injectors may last anywhere from $\sim 100 \mu$ s to in excess of 400μ s [17]. The ramp-down duration, in addition to the overall injection profile, are controlled by the injector design, i.e. method for needle actuation (hydraulic vs. mechanical), needle closing speed, sac volume, number of holes, among other injector design features. For instance, slower needle closing speed or larger sac volume creates a longer end-of-injection transient. In order to study the effects of ramp-down duration and shape, systematic control of the end-of-injection transient is required to effectively evaluate their impact on combustion metrics under a range of ambient thermodynamic conditions.

Therefore, simultaneous rate-of-momentum and injection pressure measurements were conducted to quantify the injection rate shape and, in particular, the end-of-injection transient. Rate-of-momentum measurements were conducted using an impingement technique, where fuel (dodecane) is sprayed onto the face of a transducer. Simultaneous injection pressure measurements were taken with a piezoresistive pressure transducer located within the fuel line 7 cm from the inlet to the experimental injector. To match the nozzle boundary conditions of the high temperature, high pressure spray chamber, rate-of-momentum measurements were conducted with the injector body heated to 90°C . The injector used in this study is an ECN Spray A injector (#211020), which is a single-hole Bosch solenoid-actuated Gen 2.4 injector with a nominal nozzle outlet diameter of $90 \mu\text{m}$. For brevity, further details on the experimental setup, nozzle flow coefficients, and uncertainties are outlined in Ref. [18].

As previously discussed, to generate a controlled ramp-down of the fuel injection rate with this fuel system, the discharging injector is opened, allowing the pressure behind the experimental injector to rapidly decay. The transient pressure history within the volume that supplies the experimental injector is shown at the top of Figure 5. Two observations regarding the pressure decay are worth noting. First, the pressure decay features two distinct slopes from 1000 bar to 250 bar. Specifically, a steeper slope is observed between ~ 1.5 and 2.5 ms (1000 and 500 bar) than between ~ 2.5 and 3.5 ms (500 and 250 bar). Second, the discharging injector was forced shut at ~ 250 bar even though the solenoid was still energized. This closing event is evident by the abrupt stop in pressure decay at ~ 250 bar and ~ 3.5 ms and the oscillations that are seen afterward. The injector was forced shut at a low pressure because the spring force that drives the needle to the closed position overcame the pressure that keeps the needle in the open position. This type of needle

slowly and may explain the shallower slope between ~ 2.5 and 3.5 ms (500 and 250 bar). Acoustic oscillations that are a function of the internal geometry may also help explain the shallower slope.

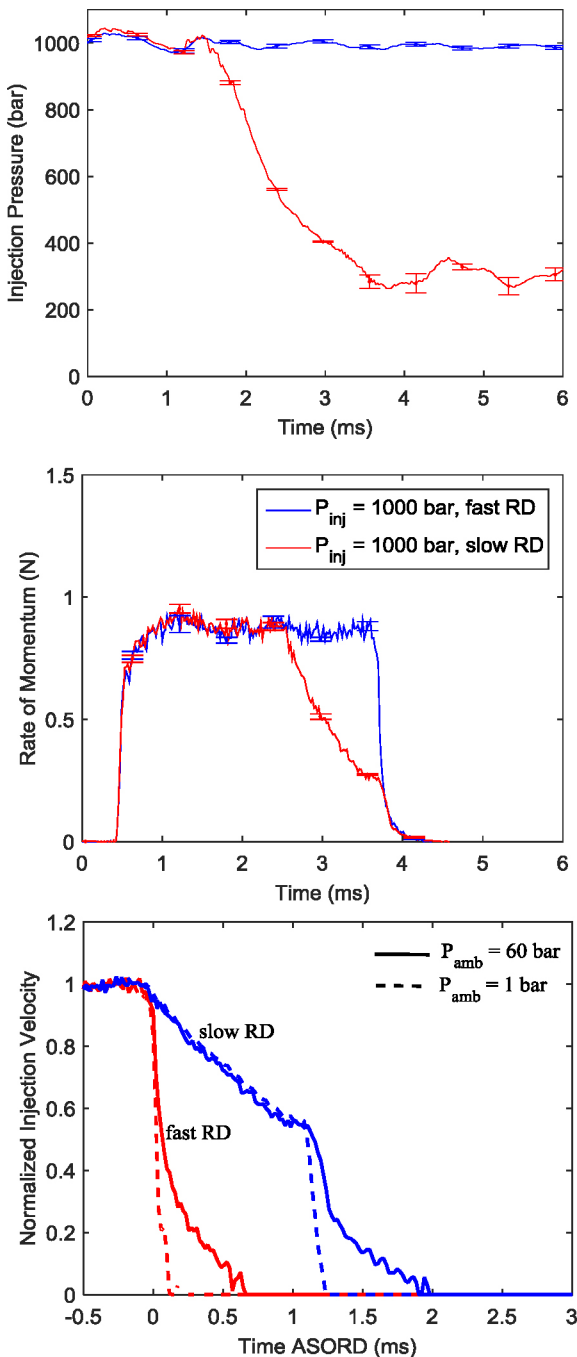


Figure 5. Fuel pressure (top) and rate-of-momentum (middle) measurements for two different end-of-injection transients. Bottom: measured injection velocities normalized by their steady-state values. Steady-state injection velocity = 542 m/s for $P_{amb} = 1$ bar and 465 m/s for $P_{amb} = 60$ bar.

For the present experiments, a fast ramp-down and a slow ramp-down injection profile are generated. In an effort to produce a simple ramped end-of-injection transient free of oscillations or needle dynamics effects, the experimental injector was commanded to close when the pressure reached 500 bar for the slow ramp-down (RD)

profile shown in the middle of Figure 5. Both the fast RD and slow RD injection profiles are nearly identical for ~ 2 ms before the different end-of-injection transients.

The bottom of Figure 5 highlights some of the difficulties and uncertainties in measuring the end-of-injection transient. Using a constant area contraction coefficient of 0.90 and a liquid fuel density of 699 kg/m^3 , rate-of-momentum is converted to injection velocity and is shown with respect to the time after start of ramp-down (ASORD). For measurements of the rate-of-momentum under high backpressures (60 bar), the end-of-injection transient appears to be much longer than at atmospheric backpressure. This is suggested to be an artifact of the measurement technique [19]. Therefore, the end-of-injection transient durations are taken as those measured at atmospheric backpressure.

Combustion Recession Test Conditions

Test conditions were chosen to sample a range of ambient thermodynamic conditions and determine their influence on combustion recession for different end-of-injection transients. As a first step towards characterization of combustion recession, injection durations were chosen such that the spray ignited before start-of-ramp-down for all conditions shown. As such, all test cases are classified as negative ignition dwell. While the relevance of combustion recession to LTC conditions has been given some treatment [13], and LTC conditions often exhibit a positive ignition dwell, the injection durations were chosen to ensure negative ignition dwell for several reasons. First, interaction between the entrainment wave and the head vortex is unclear and likely adds another unknown variable to characterization of combustion recession. Second, the injection duration may need to be extremely short under more reactive conditions to enable positive ignition dwell. Under such conditions, needle dynamics may alter the injection rate more than just the intended ramp down duration. To control these additional transient effects in the current experiments, a quasi-steady spray flame is established prior to changes in the injection rate.

As previously discussed, the goal of this work is to better understand the coupling between chemical and end-of-injection mixing time scales. As such, test conditions were chosen to modulate the balance of mixing and chemistry timescales. The range of conditions explored in the measurements is shown below in Table 1. Chemical kinetics timescales were modulated by varying the ambient temperature and oxygen concentration, while changes in ambient gas entrainment and mixing rates were modulated via the end-of-injection transient duration.

Table 1. Test conditions for effects on combustion recession

Ambient Temperature	800, 825, 850, and 900 K
Ambient Oxygen Concentration	10, 15, and 21 %
End-Of-Injection Transient Duration	100 μs , 1300 μs
Ambient Density	22.8 kg/m^3
Injection Pressure	1000 bar
Fuel	dodecane
Nozzle diameter	Nominally 50 μm

COMBUSTION RECESSION MEASUREMENTS

Diagnostics Interpretation

An example of a single combustion recession event is shown in [Figures 6, 7, and 8](#) to highlight the utility of the simultaneous diagnostics employed. This event is an example of separated combustion recession, where ignition occurs in pockets upstream of the lift-off length. This example is at the nominal Spray A condition, but with an injection pressure of 1000 bar and the fast RD injection profile shown in [Figure 5](#). The time evolution of the combustion recession process will be described and the reader is referred to [Figures 6, 7, and 8](#) for references to imaging of schlieren, OH* chemiluminescence, and broadband chemiluminescence/soot luminosity, respectively.

The first frame ($t = \text{EOI} - 0.030$ ms) of each image sequence in [Figures 6, 7, and 8](#) is just prior to the end-of-injection when fuel is still being injected. In addition to the intended signals, the broadband chemiluminescence/soot luminosity image also exhibits Mie scattering from the interaction between soot incandescence and liquid droplets up to ~ 14 mm from the nozzle. The instantaneous lift-off length is indicated by the chemiluminescence boundary ~ 16 mm downstream of the injector and by the rapid radial expansion in the schlieren image. No Mie scatter was measured in the broadband chemiluminescence/soot luminosity images 100 μs after end of injection (not shown). Kook et al. have shown that complete vaporization occurs in less than 100 μs after end-of-injection for the range of conditions in this work [17].

By $t = \text{EOI} + 0.2$ ms, portions of the jet in the schlieren image have begun to disappear, particularly just upstream of the lift-off length. Mixtures in this region have likely undergone first stage ignition where the small amount of heat released during this phase of ignition brought local temperatures close to that of the ambient, hence the lack of refractive index gradients. Somewhat surprising is that even the core of the jet has disappeared, suggesting a nearly uniform radial distribution of reactivity. This disappearance is unlikely to be attributed to vaporization because even very fuel-lean gas-phase mixtures at the edges of a non-reacting jet, which are closer in composition and density to the ambient gases, are identifiable in the schlieren images. Moreover, this region is expected to be reasonably fuel-rich and thus colder and denser than the ambient gases, which would exhibit substantial refractive index gradients. By $t = \text{EOI} + 0.3$ ms, the entire jet upstream of the lift-off length has disappeared and the lift-off length remains at the same axial location.

The lift-off length recedes to ~ 12 mm from the nozzle by 0.47 ms after the end-of-injection in both the schlieren and OH* chemiluminescence images. At this time, a small ignition kernel is evident ~ 7 mm downstream of the nozzle in the schlieren image. This kernel does not appear to register in either of the chemiluminescence images until shortly after when the kernel grows to appreciable size, suggesting that the schlieren imaging is more sensitive to the onset of second-stage ignition than chemiluminescence. Indeed, the schlieren signal requires only a mild density (temperature) gradient anywhere along the illumination path while the chemiluminescence signal

requires sufficiently high local temperatures to electronically excite radical species and thus emit a photon. This may also be in part due to the higher spatial resolution of the schlieren setup than either of the chemiluminescence setups. As time progresses past this point, schlieren imaging indicates that this separated region of hot combustion products merges with the slightly-recessed lift-off length to nearly fill the entire jet area. By $t = 0.9$ ms after the end of injection, soot-producing dribble is evident very close (~ 5 mm) to the injector in the broadband chemiluminescence/soot luminosity image. Evidence that this signal is indeed soot is provided by the fact that the signal is bright (saturating the pixels), small, and short-lived (lasting only one frame).

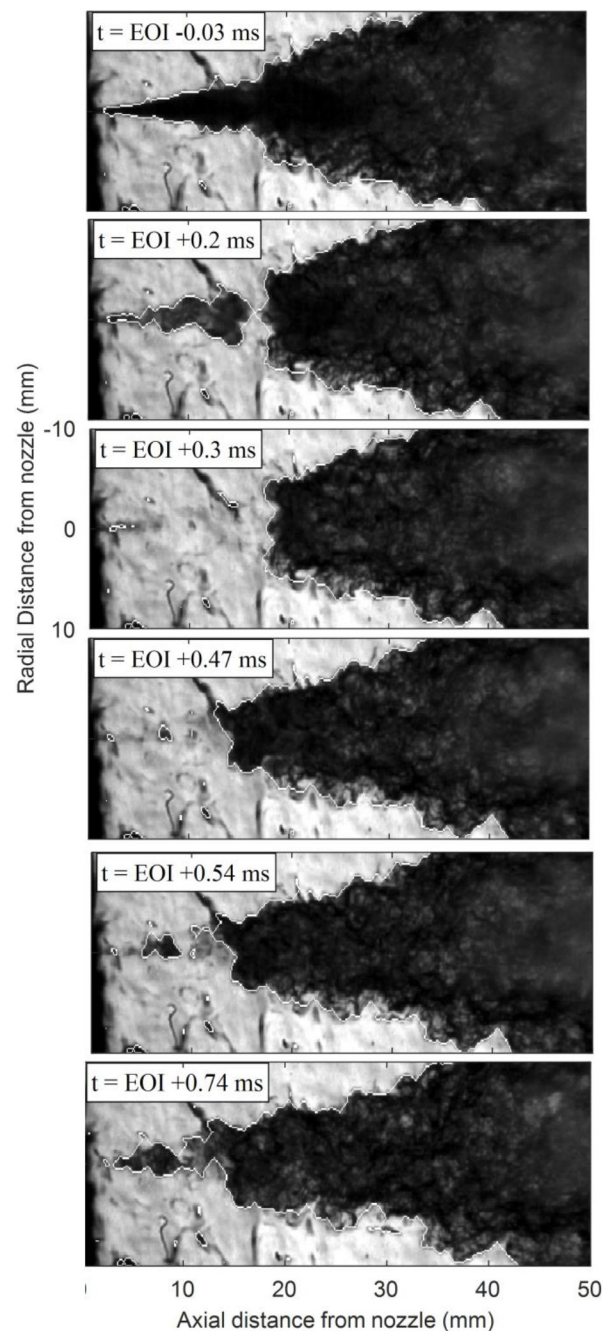


Figure 6. Sequence of schlieren images demonstrating separated combustion recession for the Spray A, 1000 bar, fast RD operating condition.