

In-Cylinder Mechanisms of Soot Reduction by Close-Coupled Post-Injections as Revealed by Imaging of Soot Luminosity and Planar Laser-Induced Soot Incandescence in a Heavy-Duty Diesel Engine

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ABSTRACT

Post injections have been shown to reduce engine-out soot emissions in a variety of engine architectures and at a range of operating points. In this study, measurements of the engine-out soot from a heavy-duty optical diesel engine have conclusively shown that interaction between the post-injection jet and soot from the main injection must be, at least in part, responsible for the reduction in engine-out soot. Extensive measurements of the spatial and temporal evolution of soot using high-speed imaging of soot natural luminosity (soot-NL) and planar-laser induced incandescence of soot (soot-PLII) at four vertical elevations in the piston bowl at a range of crank angle timings provide definitive optical evidence of these interactions.

The soot-PLII images provide some of the most conclusive evidence to date that the addition of a post injection dramatically changes the topology and quantity of in-cylinder soot. As the post jet penetrates toward the bowl wall, it carves out regions from the main-injection soot structures, either through displacement of the soot or through rapid and progressive oxidation of the soot. Later in the cycle, the regions of main-injection soot on either side of the jet centerline, clearly present in the main-injection-only case, have all but disappeared when the post-injection is added - only the soot in the post-injection pathway remains. Evidence of this apparent late-cycle oxidation of main-injection soot appears in both the soot-PLII and soot-NL images, providing substantial support for the mixing mechanism of soot reduction with post injections. Implications of these findings and future work are also discussed.

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INTRODUCTION

Modern heavy-duty diesel engines can meet pollutant emissions targets using a variety of strategies [1, 2]. Approaches include multi-stage aftertreatment systems [3], modification to the combustion mode to achieve various degrees of low-temperature combustion (LTC) [4], and advanced fuel-injection schemes [5, 6], including multiple-injection schedules and injection rate-shaping. In this study, we address the use of multiple injections, post-injections in particular, to control particulate emissions from heavy-duty diesel engines.

Post injections can be an effective way to reduce engine-out soot emissions for a variety of engine sizes and at a wide range of operating conditions. Measurements of post-injection efficacy have been published in numerous studies; for a more

detailed review, see O'Connor and Musculus [7]. These studies have shown that post-injection efficacy is sensitive to several key operating parameters, including injection timing, load, exhaust gas recirculation (EGR), speed, and fuel-spray targeting.

Proposed mechanisms for engine-out soot reduction with post injections generally fall into three categories. First, several studies [5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20] have identified an enhanced mixing mechanism as the driver of engine-out soot reduction. Some authors have attributed the engine-out soot reductions to enhanced mixing of the main-injection soot with air entrained by the post injection, which increases oxidation rates of main-injection soot [8, 9, 12, 17, 19]. Alternatively, other authors [14] have indicated that the post injection enhances mixing of ambient air with fuel and/or

combustion intermediates, from both the main and post injection, thereby reducing the local equivalence ratio and suppressing local soot formation.

Second, several authors have proposed a thermal mechanism by which the combustion of the post injection increases local temperatures, thereby enhancing oxidation of main-injection soot and reducing overall soot emissions [5, 8, 21, 22, 23, 24, 25, 26]. Temperature effects on soot oxidation are difficult to verify experimentally, but two-color pyrometry measurements [27] and predictive simulations [12] have indicated increased soot temperatures with post injections, which is consistent with the proposed thermal mechanism.

Finally, a small number of studies have indicated that engine-out soot may be a function of injection duration and not simply total mass of fuel injected [19, 28, 29, 30, 31]. According to these studies, soot formation during an injection is a non-linear function of the duration of the injection. Consequently, a given quantity of fuel will form less soot if it is delivered in several short injections instead of a single large injection. Sometimes referred to as the "split-flame" concept [29, 30], this hypothesis has mostly been proposed for multiple-injection schedules with a very short dwell between injections. Other studies refer to the fundamental mechanism behind duration-dependent soot formation as "jet replenishment" [28].

Despite the prevalence of these three explanations in the literature, there are few studies that provide direct experimental or computational evidence of these mechanisms or quantify the relative importance of each fundamental mechanism by which post injections reduce engine-out soot. This lack of data is driven by the complexity of the problem; not only are in-cylinder mixing fields and temperatures difficult to measure, the mechanism by which soot is reduced by post injections may vary with operating condition [32], creating a virtually endless experimental design space.

In particular, the extent of the interaction between the post jet and the main-injection mixture is difficult to quantitatively measure in engine environments. Several spray-vessel experiments have used scalar mixing and front-tracking techniques to quantitatively measure the interaction between multiple injections [33, 34, 35]. While these studies provide valuable information about the freely-propagating regime of the spray, the boundary conditions of these experiments do not faithfully represent those in an engine environment. In particular, the lack of jet impingement and subsequent roll-up at the bowl wall makes it difficult to extrapolate these results to an engine geometry. Indeed, in current production engines that use post-injections, soot-reduction efficacy is known to be strongly dependent on spray targeting and/or piston geometry [7, 36]. Further, two of the three theories of soot reduction using post injections - the enhanced mixing and thermal mechanisms - are dependent on the interaction between the post jet and the main-injection products. Hence, interactions of both the main jet and post jet with the engine geometry are key to understanding the mixing field. For the mixing mechanism,

the post injection transports oxygen to oxidizer-starved regions, either suppressing soot formation as the main-injection fuel is burning, or enhancing soot oxidation after soot has formed from the main-injection fuel. For the thermal mechanism, interaction of the reacting post jet with the main-injection products raises local temperatures, enhancing oxidation of soot from the main- and/or post-injection combustion. In either case, the details of the interaction between the post jet and the main-injection mixture clearly are important, but are difficult to measure.

In our previous work [32, 37], we have made an initial attempt to understand the interaction between the post jet and the main-injection soot in a heavy-duty optical diesel engine using high-speed soot natural luminosity imaging (soot-NL) and phase-resolved (one image per cycle at a selected crank angle) soot planar laser-induced incandescence (soot-PLII) along the spray axis. From these data, it was clear that the post jet interacted with the main-injection mixture, where interactions appeared to include displacement of the main-injection mixture by the post jet, entrainment of some of the residual main-injection jet by the post jet, and merging of the post-injection mixture with the main-injection mixture in the rotating soot structures on either side of the jet centerline. The magnitude of these effects varied with main-injection duration and post-injection duration. These effects may have also changed with intake-oxygen level; however, as discussed in Ref. [32], we were unable to track fluid motion and mixing using soot-NL imaging at very low intake-oxygen levels (12.6%-15%).

While the observations in these studies confirmed that interaction between the post jet and the main-injection products was associated with engine-out soot reduction, both the spatial and temporal details of the interaction were difficult to discern as a result of the limited data available. While the soot-NL videos provided a fast frame rate that allowed visualization of the evolving soot structures, this line-of-sight integrated data did not resolve the vertical location of the soot and fluid structures that drive the interaction between the post jet and main-injection products. Although complementary soot-PLII data helped to unravel some of the line-of-sight issues, data were only available within one plane, and soot distributions within the full three-dimensional field not intersected by the laser sheet could be quite important during these interactions. The goal of the current study is to acquire soot-PLII data at multiple elevations from the firedeck to map the evolution of soot in both space and time over a greater extent of the combustion chamber.

In this study, we have limited the operational space to low-load, conventional diesel operation with 18% intake-oxygen (20-30% EGR) at a single speed and boost. In our previous studies [32, 37], we mapped the injection-timing space with variations in main-injection duration, post-injection duration, and dwell between the two injections; we also varied load and EGR level. In this study, we have chosen two operating points: one where

the post-injection is most effective for reducing soot at 18% intake oxygen for a given main-injection duration, and one that is the corresponding main-injection-only case.

For the optical diagnostics, we applied soot-PLII at multiple elevations from the firedeck to provide data about both the horizontal and vertical displacements of the soot from the main and post injections throughout the cycle. The soot-PLII data are acquired in one plane at a time, and are phase resolved. In the ensemble, this dataset provides much more spatially and temporally resolved data than our previous experiments and many of those like it. This multi-plane view of the soot field has provided us with more concrete evidence about the mechanism by which post injections reduce soot.

Simultaneously with the acquisition of soot-PLII data, we also used high-speed cinematography to observe the temporal evolution of soot-NL. The high frame rate available with the soot-NL technique provides evidence of the temporal evolution of soot structures in a single cycle that is not available from phase-resolved soot-PLII data. However, the soot-NL technique suffers from several limitations, including a signal bias to hotter soot and, in particular, a lack of spatial resolution along the line of sight. That is, the soot-NL images are two-dimensional projections of complex three-dimensional soot distributions. Hence, it is difficult from the soot-NL data alone to determine if soot structures are merging together, or passing over or under each other from the perspective of the camera. This of course makes it even more difficult to understand the nature of the interaction between the post injection and the main-injection soot. Our recent work [32, 37] made some steps toward interpreting soot-NL data and providing information about the nature of the interaction between the post injection and main-injection soot. In the current study, the multi-plane soot-PLII technique provides information about soot distribution along the soot-NL line of sight so that the two-dimensional projection issues can be more fully resolved. Furthermore, the soot-PLII technique is nearly insensitive to the combustion-heated soot temperature, so comparisons of images from the two techniques also help to resolve the potential temperature bias in soot-NL images. These optical data will also serve well for validation of and comparison with modeling efforts. For more details on the first phase of this multi-year companion modeling effort, see Hessel *et al.* [38].

The remainder of this paper is organized as follows. First is an overview of the experimental facility with a detailed discussion of the soot-NL and soot-PLII diagnostics. Next, the engine-out emissions data at the conditions of interest are summarized, along with a discussion of the high-speed soot-NL images. The soot-PLII images are presented next, and are compared to the soot-NL images. Finally, the important findings and possible next steps are reviewed.

Table 1. Optical engine and fuel system specifications.

Engine base type	Cummins N-14, DI diesel
Number of cylinders	1
Cycle	4-stroke
Number of intake valves	2
Number of exhaust valves	1*
Intake valve opening	703 CAD [‡]
Intake valve closing	195 CAD [‡]
Exhaust valve opening	485 CAD [‡]
Exhaust valve closing	27 CAD [‡]
Combustion chamber	Quiescent, direct injection
Swirl ratio	0.5 (approx.)
Bore	139.7 mm [5.5 in]
Stroke	152.4 mm [6.0 in]
Bowl width	97.8 mm [3.85 in]
Displacement	2.34 liters [142 in ³]
Connecting rod length	304.8 mm [12.0 in]
Piston pin offset	None
Geometric compression ratio	11.2:1
Replicated compression ratio	16:1
Fuel Injector	Delphi DFI-1.5 (light duty)
Fuel injector type	Common-rail, solenoid actuated
Cup (tip) type	Mini-sac
Number of holes & arrangement	8, equally-spaced
Spray pattern included angle	156°
Nominal orifice diameter	0.131 mm

*In this optically accessible diesel engine, one of the two exhaust valves of the production cylinder head was replaced by a window and periscope (see Fig. 1).

[‡]All valve timings correspond to the crank angle of the first detectable movement from fully closed.

EXPERIMENTAL SETUP

Optical Engine Experiment

The optical engine is a single-cylinder version of the heavy-duty diesel Cummins N-series (139.7/152.4 mm bore/stroke). The engine is equipped with a Bowditch piston with a right-cylindrical bowl and a flat piston-crown window providing imaging access to the bowl, viewing from below. A flat, round window is also installed in place of one of the exhaust valves for imaging access to a portion of the squish region above the piston (view not used in the current study). A 30-mm wide curved window matching the contour of the bowl-wall allows laser access into the bowl. Flat rectangular windows installed in a ring at the top of the cylinder provide additional laser access through the cylinder wall. Information about engine geometry is in Table 1 and a schematic of the experiment is in Fig. 1. Further details about this engine can be found in Refs. [39, 40].

The fuel is n-heptane, which was selected for its low fluorescence upon illumination by ultraviolet (UV) laser-light. In optical engine studies that use laser diagnostics, n-heptane is commonly used as an approximation for diesel fuels; compared to U.S. diesel fuel, its cetane number of 56 [41] is slightly higher than the value of 44 typical of U.S. diesel fuel [42], a lower density, a much lower boiling point, and zero aromatics. With only a slightly higher cetane number, the autoignition characteristics of these two fuels are similar. The lower boiling point means that the liquid-to-vapor transition in the fuel jet will occur sooner. While the absence of aromatics will affect soot formation, the general in-cylinder mechanisms of post-injection interactions with in-cylinder soot formation and oxidation should be similar [43].

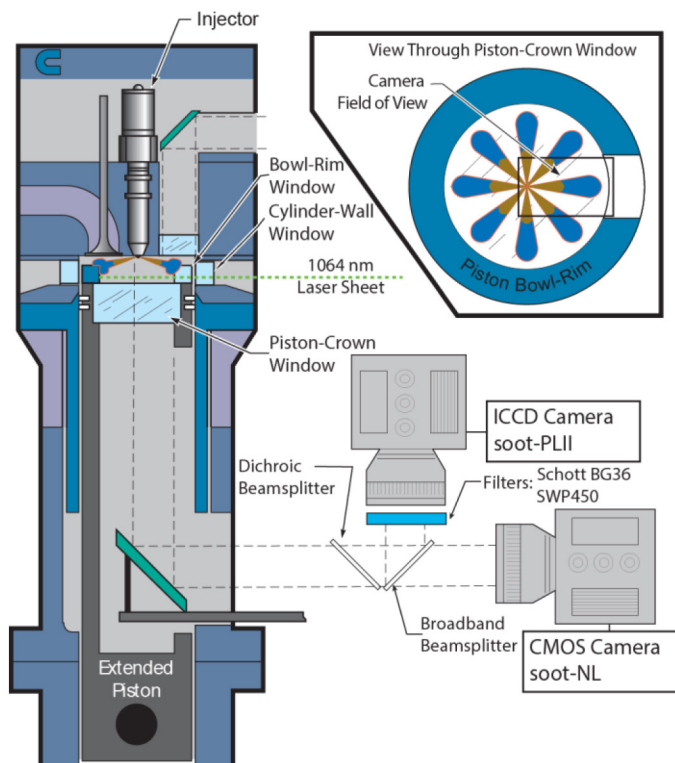


Figure 1. Experimental setup of the single-cylinder engine, laser configuration, and two-camera optical system. The camera field-of-view is shown in the upper right.

The injector is a centrally mounted solenoid-actuated common-rail Delphi DFI 1.5 with eight 131-micron orifices, equally spaced with an included angle of 156°. The heavy-duty injector used in previous studies was replaced by this light-duty injector for its fast response time and its ability to deliver close-coupled, short-duration post injections over a range of injection schedules. Because of the low lubricity and low viscosity of special fuels (such as n-heptane) selected for optical research, the production common-rail fuel pump could not be utilized. Instead, a custom high-pressure diaphragm pump specially designed for low-lubricity fuels pressurizes the fuel rail at up to 2000 bar. The delivery rate of the diaphragm pump is limited, however, and as a result it could only sustainably pressurize the fuel rail to 1200 bar at the static back-leak rate of this particular injector.

Engine Diagnostics

Measurements of cylinder pressure, rate of fuel injection, and engine-out emissions, along with two simultaneous imaging diagnostics, provide data to better understand the mechanism of soot reduction with post injections. Cylinder pressure was measured with an AVL QC34D pressure transducer with a one-quarter crank angle degree (CAD) resolution. The apparent heat release rate (AHRR) was calculated from the measured cylinder pressure using standard techniques [44].

The rate of fuel injection for the two operating conditions was derived from spray momentum measurements. Spray impingement (momentum) was measured by a Kistler 9215 force transducer connected to a Kistler 5004 charge amplifier. Data for each injection schedule were collected at 140 kHz over the span of 200 injections in a collection unit at atmospheric back-pressure [45]. The mass rate-of-injection profiles were derived from the momentum data [46]. The profiles were ensemble averaged and low-pass filtered (Gaussian roll-off at 10 kHz) to remove ringing at the natural frequency of the transducer assembly. While this filtering technique is effective to remove the high-frequency resonance at the natural frequency of the detector, it does introduce small filtering artifacts, such as apparent ringing ahead of the start of injection (also see Fig. 3, discussed later). For more details in the injection rate measurements and injector dynamics, see O'Connor and Musculus [32].

Fuel rate of injection measurements were obtained to measure start of injection and ignition delay timing, but were not used to calculate fuel consumption. In this single-cylinder engine where runs are skip fired and run times are very short, the uncertainties of fuel delivery per cycle are too great to calculate a meaningful fuel consumption metric or measure the effect of post injections on fuel consumption. Some studies have noted that post injections can reduce fuel consumption [5], a possible result of "accelerated combustion" from the post injection [30], although more evidence is needed to understand this mechanism further.

Engine-out smoke was measured using an AVL 415S smoke meter. This device draws a known sample volume of engine exhaust through a filter and measures the change in reflectance (blackening) of the white filter due to accumulated smoke. One potential concern about smoke meter measurements is the response of the meter to adsorbed hydrocarbons. For some LTC conditions that have high adsorbed hydrocarbons, the filter can become tinted with color [47, 48], which could conceivably bias the reflectivity measurement. However, comparisons with other soot and adsorbed hydrocarbon measurement techniques show that even with adsorbed hydrocarbons, the reflectivity strongly correlates with the elemental carbon [47]. Furthermore, no color tinting by adsorbed hydrocarbons is discernible from visual inspection of the loaded filter paper from the current study. Hence, we expect that the reflectivity measurements in the current study are indicative of elemental carbon (C), which

is treated here as synonymous with engine-out soot. We have discussed the use of filter-paper methods for measurement of elemental carbon in this engine in previous works [32].

In this work, we report engine-out soot in milligrams of carbon per cubic meter, which is derived from a correlation computation as follows. The smoke meter quantifies the change in reflectance for a given volume of sample gas as a filter smoke number (FSN) [49]. In this study, FSN was then converted to elemental carbon volume-fraction using a standard correlation from AVL [49]. In each test, sampling commenced before the first fired cycle and continued well after the last fired cycle so that all the exhaust soot for each run was sampled; this amounted to a sampling time of 65 seconds, or approximately 12000 ml of exhaust gas. Although the engine was skip fired, all data reported in this paper have been corrected to the value that would have been measured for continuously fired operation (as if the engine were not skip-fired) by correcting for the intake volume to the smoke meter, referred to as the “effective length” in the AVL calculations. The actual effective length was multiplied by a factor of the ratio of fired time to sample time, where sample time is 65 seconds and fired time is the number of fired cycles divided by engine cycles per second [50]. Repeatability of this measurement was tested at several injection schedules; the standard deviation of the carbon volume-fraction measurements at each of these repeated conditions was approximately 0.05 mg/m³.

Two complementary imaging techniques were used simultaneously: high-speed natural luminosity imaging and phase-resolved planar laser-induced incandescence of soot. The two techniques shared the same perspective, viewing through the piston-crown window as shown in Fig. 1. A dichroic beam splitter with a cutoff near 485 nm spectrally separated light emitted from the combustion chamber, with long-wavelength light directed to the soot natural-luminosity imaging system, and short-wavelength light directed to the laser-induced-incandescence imaging system. These two techniques, and some of the nuances of using them together, are discussed below.

High-Speed Natural Luminosity Imaging (Soot-NL)

A high-speed (high frame-rate) Phantom 7.1 complementary metal oxide semiconductor (CMOS) camera equipped with a Nikon 105-mm focal-length, f/2.8 glass lens imaged the soot-NL. Previous optical engine studies at similar conditions have shown that soot luminosity is several times brighter than any other source of light during combustion; as a result, we expect that the light from this imaging technique represents soot [46, 51]. The lens aperture was set to f/11. Images with a resolution of 256 × 512 pixels were acquired at half crank-angle intervals (70 microseconds at 1200 RPM). The exposure time was 2 microseconds. The high-speed imaging allows for high frame rates over a long data set; in this study, the entire combustion event during each fired cycle was imaged using this technique.

Planar Laser-Induced Incandescence of Soot (Soot-PLII)

The fundamental output (1064 nm) of a Spectra-Physics Quanta-Ray single-cavity Nd:YAG laser was attenuated to 130 mJ/pulse and formed into a 30-mm wide, approximately 1-mm thick sheet for planar laser-induced incandescence of soot within the engine cylinder. As described in the Optical Engine Experiment section, the sheet was oriented to probe soot horizontally across the width of the bowl, parallel to the firedeck. Using the fundamental output at 1064 nm avoids fluorescence of large poly-cyclic aromatic hydrocarbons (PAH) species, so that only solid soot particles are imaged [52].

As described in previous studies [40], the laser-heated soot emits more strongly at shorter wavelengths than the cooler combustion-heated soot, so the soot-PLII emission was spectrally filtered to shorter wavelengths to improve the signal-to noise ratio of laser-heated to combustion-heated soot. Soot-PLII emission was imaged with an intensified Princeton Instruments PI-MAX 3 camera with a resolution of 1024×1024, a gate time of 15 ns, and at 50% of maximum gain. Two filters, Schott BG36 and SWP450, rejected emission at wavelengths longer than approximately 450 nm. PLII data were limited to one frame per cycle, due to repetition-rate constraints of both the laser and camera systems.

A schematic of the laser imaging planes is provided in Fig. 2. The soot-PLII data were collected along four horizontal planes. One plane elevation was utilized for each engine run, and the sheet elevation was adjusted between runs (the laser sheets were not simultaneous). For each run, the laser sheet was oriented at either 9, 11.5, 14, or 19 mm below the firedeck. The distances from the firedeck were constrained by physical aspects of the engine across the range of crank angles of interest. An elevation 9 mm below the firedeck was the highest sheet position accessible, as constrained by the upper side of the cylinder-wall window. At all heights and at all crank angles, the laser must not be obstructed by the upper surface of the bowl-rim window; this also limited the achievable range of sheet elevations and image crank-angle timings. Note that the position of the piston with respect to these planes changed at each crank angle, but the position of each plane with respect to the firedeck was fixed across all crank angles. For more details on the position of the sheets relative to the piston throughout the range of image acquisition, see Fig. A1 in the Appendix.

The horizontal laser sheet at a given elevation entered from the right of the schematic in Fig. 2, passing through both the cylinder-wall window and the bowl-rim window. While the cylinder-wall window is not curved, the bowl-rim window is curved, with concentric surfaces, so that it is a negative cylindrical lens. Hence, when the laser sheet passes through the bowl-rim window, its divergence in the horizontal plane increases somewhat. Also, the laser sheets were oriented parallel to the firedeck, while the nominal jet axis is declined 12° from the firedeck. Hence, the sheet intersected the jet at a

12 degree angle relative to the jet axis (see Fig. 2) so that the soot-PLII images are not on a nominal symmetry plane of the jet.

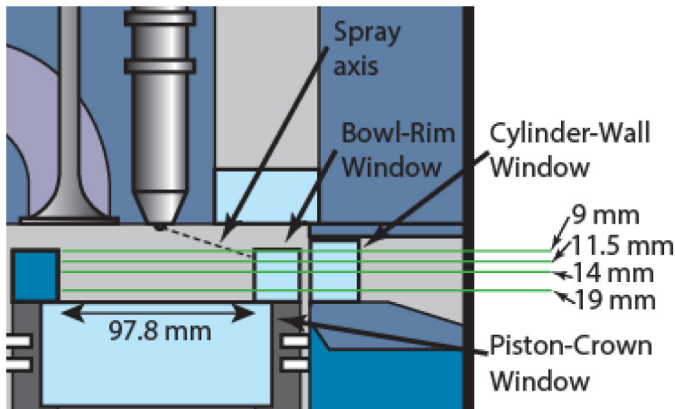


Figure 2. Schematic of four soot-PLII imaging planes at 9, 11.5, 14, and 19 mm from the firedeck.

At each vertical location in the engine and at each crank angle of interest, 40 images were acquired from 40 different cycles to form the ensemble average. Visual inspection of the soot-PLII images shows no significant signal attenuation due to soot deposited on the piston crown window in the first 40 fired cycles. Signal attenuation becomes apparent after 40 fired cycles, so the engine was stopped and windows were cleaned after every 40 cycles. The instantaneous images in each set presented here are from the early cycles of several engine runs. Even though soot accumulation on the piston-crown window could affect the signal collection, soot deposits did not affect the signal creation through laser-induced incandescence - the laser fluence was high enough to ablate nearly all of the soot deposits on the cylinder-wall and bowl-rim windows between fired cycles.

Finally, the instantaneous images shown in this paper are statistically and objectively the “most representative” of the ensemble; to select the most representative image, each image was correlated with every other image in the ensemble, and the image with the highest average correlation coefficient was chosen as the most representative. For more discussion of this image selection technique, see the Ph.D. dissertation by Genzale [36].

Engine Operating Conditions

Table 2 provides an overview of the engine operating conditions. The intake pressure and temperature are elevated from what they would be for a production engine to account for the low compression ratio of the optical engine. While the production engine has a compression ratio of approximately 16:1, the compression ratio of the optical engine is only 11.22:1. The compression ratio is lower in the optical engine primarily because of an increased squish-volume due to the absence of valve pockets in the top of the piston, the absence of the central pip in the piston, an increased ring land crevice, and increased crevices from the flat cylinder-wall windows that

do not match the contour of the cylinder bore. To compensate for the lower compression ratio, the engine was operated to replicate the thermodynamic state at top-dead center (TDC) of the piston stroke for a 16:1 compression ratio engine by using a preheated, boosted intake stream [39]. Additionally, this engine was run in skip-fired mode; for every ten cycles, nine were motored using a dynamometer and one was fired. This was done to reduce thermal loads on the optical components.

Table 2. Engine operating conditions.

Engine Speed	1200 RPM
Main-Injection-Only Engine Load	405 kPa gIMEP [†]
Main- Plus Post-Injection Engine Load	523 kPa gIMEP
Intake O ₂	18%
Equivalent EGR	25%
Fuel Pressure	1200 bar
TDC Motored Density	16.6 kg/m ³
TDC Motored Temperature	900 K
Intake Pressure	161 kPa
Intake Temperature	108° C
(16:1 Compression Ratio BDC Pressure)	(99 kPa abs)
(16:1 Compression Ratio BDC Temperature)	(41° C)
Commanded Main Start of Injection (SOI1 _c)	347 CAD
Actual Main Start of Injection	350 CAD
Commanded Main Duration of Injection (DOI1 _c)	1550 microseconds
Actual Main Duration of Injection	13 °CA
Main-Injection Fuel Quantity	57.3 mg/injection
Commanded Post Start of Injection (SOI2 _c)	366 CAD
Actual Post Start of Injection	369 CAD
Commanded Post Duration of Injection (DOI2 _c)	500 microseconds
Actual Post Duration of Injection	3.5 °CA
Post-Injection Fuel Quantity	13.8 mg/injection

[†]gIMEP = Gross Indicated Mean Effective Pressure, calculated using indicated work done during compression and expansion strokes only.

The operating condition is typical for modern low-load heavy-duty diesel operation - 18% intake-oxygen, 523 kPa gross indicated mean effective pressure (gIMEP), and a speed of 1200 RPM. The choice of 18% for the intake-oxygen fraction was guided by industry practice with regard to EGR levels commonly used to meet emissions regulations. 18% O₂ was chosen because the corresponding range of EGR (20-30%) is commonly used to meet 2010 US on-road heavy-duty diesel-engine particulate and NO_x regulations [52] with the use of both urea-based selective catalytic reduction (SCR) and diesel particulate filter (DPF) after-treatment systems [3].

The selected post-injection schedule is the minimum-soot condition from previous work [32] with a main- plus post-injection schedule at a main-injection command duration of 1550 microseconds. As will be shown later in the paper (see Fig. 4, we chose this point from a sweep in the post-injection

duration where the *main-injection duration is held constant throughout the post-injection duration sweep*. This kind of test was done intentionally so that with each different post-injection duration, even though the load is not held constant, the conditions of the main-injection would stay the same, creating a constant in-cylinder “initial condition” for the post-injection tests. A more detailed discussion of this experimental design approach can be found in our previous work [32, 37].

RESULTS

Operating Point Characterization

The measured cylinder pressure, rate of injection, and AHRR for both the main-injection-only and the main- plus post-injection operating conditions are in Fig. 3. For both conditions, the AHRR profile contains the characteristic premixed combustion spike (from the start of combustion near 354 CAD to about 360 CAD) followed by a longer mixing-controlled combustion period (starting near 360 CAD). In the main- plus post-injection schedule test, combustion from the post injection is manifest during the mixing-controlled combustion portion as an additional rise in AHRR starting near 370 CAD. The AHRR and injection-rate measurements in Fig. 3 show three important aspects of the ignition delays and combustion characteristics for the two injections.

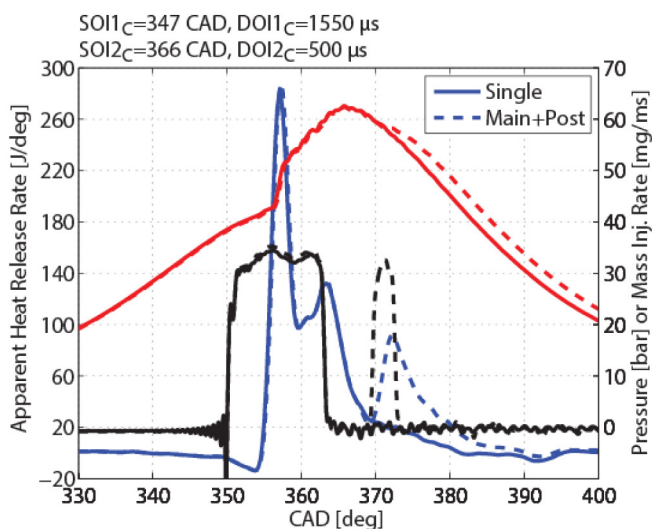


Figure 3. Cylinder pressure (red), rate of fuel injection (black), and AHRR (blue), for main-injection operation (solid) with $SOI1_c=347$ CAD and $DOI1_c=1550$ microseconds; and main- plus post-injection operation (dashed) with $SOI1_c=347$ CAD, $DOI1_c=1550$ microseconds, $SOI2_c=366$ CAD, and $DOI2_c=500$ microseconds.

First, the actual main-injection duration is 13 °CA, while the main ignition delay is only approximately 4 °CA. As a result, the ignition dwell for the main injection, from the end of the main injection near 363 CAD, to the start of main combustion near 354 CAD, is negative. A negative ignition dwell is typical for conventional diesel conditions. (Advanced low-temperature combustion modes, by contrast, typically have a positive ignition dwell). Second, the relatively low level of the mixing-controlled AHRR peak compared to the premixed burn peak is

typical of a low-load condition. Much of the fuel from the main injection is consumed in the premixed burn, but the relatively short main-injection duration means that the net heat release from mixing-controlled combustion is relatively small compared to higher-load conditions.

Third, the ignition delay of the post injection is only 1 °CA, which is much shorter than the main injection ignition delay (4 °CA). This difference is likely driven by the higher in-cylinder ambient density and local temperatures encountered by the post-injection fuel. With such a short ignition delay, the post-injection combustion does not exhibit the same two-stage burning characteristics of the main injection, but instead burns as a single heat-release event. The relatively short post-injection ignition-delay does not provide as much time for fuel/air premixing before ignition, meaning that combustion of the post-injection fuel should be more mixing-controlled.

Engine-Out Soot Measurements

Engine-out soot measurements for both a single-injection duration sweep and a main- plus post-injection sweep are shown in Fig. 4. These data were obtained through two separate sets of tests. The single-injection baseline (closed squares) was collected by varying the commanded duration of the single injection ($DOI1_c$) from 1350 to 2750 microseconds, corresponding to engine loads from 350 to 750 kPa gIMEP, while holding the command start of the single injection ($SOI1_c$) constant at 347 CAD. For the post-injection sweep (open symbols), a post injection of increasing commanded duration ($DOI2_c$) from 300 to 1200 microseconds was added to one main-injection duration, $DOI1_c=1550$ microseconds. The commanded start of injection for the post injection ($SOI2_c$) was held constant at 366 CAD.*

The engine-out soot data in Fig. 4 clearly show that the post injection reduces engine-out soot compared to a single injection at the same load over a wide range of post-injection durations, from $DOI2_c=300$ microseconds to 800 microseconds. At the condition considered in this paper, $DOI2_c=500$ microseconds, the post injection reduces engine-out soot by 40% compared to a single injection at the same load of 523 kPa gIMEP. At longer post-injection durations, the engine-out soot at a given load is lower than for a single injection at the same load, but the magnitude of the post-injection soot reduction decreases as the post injection duration increases. Eventually, the engine-out soot with a long post-injection is larger than for a single injection at the same load. For this particular condition, the cross-over point, where the addition of a post injection is detrimental to engine-out soot

*. Compared to previous data [32] at the same injector command conditions, the absolute magnitudes of both the loads and exhaust soot are slightly different. For example, the load at the $DOI1_c=1550$ microseconds, $DOI2_c=500$ microseconds condition is approximately 7% higher than in the previous tests. The difference is most likely due to slight changes in injector performance as the new injector “breaks in.” Even with the slight differences in an absolute sense, the trends are the same as data from previous tests at the same conditions, and the emissions data at a given load are nearly identical.