

Effects of Post-Injection Strategies on Near-Injector Over-Lean Mixtures and Unburned Hydrocarbon Emission in a Heavy-Duty Optical Diesel Engine

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ABSTRACT

Post-injection strategies aimed at reducing engine-out emissions of unburned hydrocarbons (UHC) were investigated in an optical heavy-duty diesel engine operating at a low-load, low-temperature combustion (LTC) condition with high dilution (12.7% intake oxygen) where UHC emissions are problematic. Exhaust gas measurements showed that a carefully selected post injection reduced engine-out load-specific UHC emissions by 20% compared to operation with a single injection in the same load range. High-speed in-cylinder chemiluminescence imaging revealed that without a post injection, most of the chemiluminescence emission occurs close to the bowl wall, with no significant chemiluminescence signal within 27 mm of the injector. Previous studies have shown that over-leaning in this near-injector region after the end of injection causes the local equivalence ratio to fall below the ignitability limit. With a carefully selected post-injection, mixtures close to the injector show significant chemiluminescence emission, indicating more complete combustion of those regions, likely due to increased local equivalence ratios.

Simultaneous planar laser-induced fluorescence (PLIF) of OH with 284-nm excitation and PLIF of combined formaldehyde and poly aromatic hydrocarbons (PAH) with 355-nm excitation were employed to identify the regions of first- and second-stage ignition, as well as providing some indication of local equivalence ratios. The laser

diagnostics show that without a post injection, regions close to the injector show formaldehyde fluorescence late in the cycle without detectable OH fluorescence, indicating that these regions do not achieve second-stage ignition, and therefore likely contribute to UHC emissions. Persistence of formaldehyde fluorescence late in the cycle is also consistent with fuel-lean mixtures. With a carefully selected post injection, strong OH fluorescence appears in the near-injector regions, indicating that they are likely enriched by the post-injection such that they reach second-stage ignition and more complete oxidation. The reduction observed in the exhaust UHC emission is therefore attributed to the enrichment mechanism of the near-injector regions by the close-coupled post-injection.

INTRODUCTION

The past decade has seen tremendous development in diesel engine technology and performance in response to ever more stringent emissions legislations. Heavy-duty diesel engines have significantly reduced their emissions of nitrous oxides (NO_x) and particulate matter (PM). Low temperature combustion (LTC) is one way of improving the NO_x /PM tradeoff by dilution of the charge with large amounts of cooled exhaust gas recirculation (EGR). The dilution with EGR keeps the adiabatic flame temperature below the thermal NO_x formation temperature region and decreases soot formation [1]. In the lower load range, ignition typically occurs after the end of injection (EOI), so that the ignition dwell, which is the time from EOI to the start of combustion, is positive. The ignition dwell is

usually longer at lower loads, in part because the injection duration is shorter.

Conventional diesel combustion typically has a negative ignition dwell and therefore a significant quasi-steady period [2], where much of the heat release occurs through mixing-controlled combustion during the spray-driven diffusion flame phase. By contrast, for LTC conditions with positive ignition dwells, heat release does not overlap with the fuel injection event, so the quasi-steady jet is not an adequate model for combustion. Instead, as more mixing of air and fuel takes place prior to ignition, more of the heat release is premixed.

The evolution of the local equivalence ratios prior to combustion was investigated in a previous study [3] for a case of LTC combustion. The local fuel concentration within and between two neighboring jets was measured using planar laser-induced fluorescence (PLIF) of a fuel tracer (toluene) under non-reactive conditions. The three images presented in Fig. 1 show equivalence ratio contours corresponding to 12.7% intake oxygen concentration, which were derived from the fuel vapor concentration measurements under non-reacting conditions. The nozzle is located on the left side of the frames and the two studied jets are directed up and to the right and down and to the right of each image.

The first frame presents the results at the end of injection (EOI). The highest local equivalence ratios are located close to the nozzle, as for a quasi-steady jet. 2 crank angle degrees (CAD) after the end of injection (AEI), in the middle image, the mixtures are becoming leaner and close to stoichiometric in the upstream regions. The downstream regions are also becoming leaner but they are now richer relative to the near-nozzle region, which is contrary to the situation at EOI. This leaning trend continues in the bottom frame at 5 CAD AEI, where the mixture close to the nozzle is now below stoichiometric conditions. Formaldehyde imaging has shown that lean mixtures remain stagnant close to the nozzle late in the expansion stroke [4]. At equivalence ratios below 0.5, mixtures are unlikely to ignite or achieve complete combustion. Therefore, very lean mixtures in the near-nozzle region have been identified as potential sources of unburned hydrocarbons (UHC) emissions [3, 4, 5]. Also other studies have pointed out that over-lean mixtures could contribute to explaining the correlation between highly diluted LTC cases and engine-out UHC emissions [6, 7, 8].

The mixtures close to the nozzle shown in Fig. 1 become leaner very quickly after EOI. The air-entrainment rate in the jet after EOI can be compared to a steady jet case. The circled numbers in the top image represent the time needed in CAD for a fuel particle exiting the nozzle to reach the indicated locations in a steady-jet at the measured jet penetration rate. At the position of the second circle, the local equivalence-ratios are in the range 5 to 7. At the same

location, i.e. 25 mm from the injector, the equivalence-ratios in the middle frame (2 AEI) are significantly lower, between 2 and 3. In the bottom image (5 AEI) mixtures become closer to stoichiometric in the downstream regions. These observations indicate a faster air-entrainment mechanism after the end of injection compared to a steady-jet.

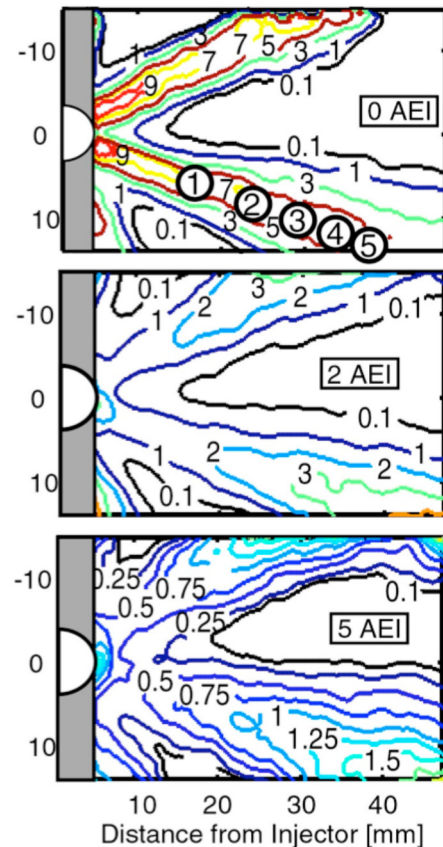


Figure 1. Equivalence ratio contour lines for a portion of the combustion chamber obtained by fuel tracer fluorescence measurements [3]. The nozzle is located on the left side of the frames and two jets are directed up and to the right and down and to the right in the image. The equivalence ratios correspond to 12.7% inlet oxygen. The circled numbers in the top image represent the time needed in CAD for a fuel particle exiting the nozzle to reach the indicated locations at the jet penetration rate.

Previous work also indicates that part of the UHC emissions during low-load LTC operations are caused by stagnant lean mixtures close to the injector after EOI [3]. The goal of this study is to investigate the potential to increase the upstream local equivalence ratios in the jet above the ignitability threshold by a post injection, and thereby reduce UHC emissions.

Toluene fluorescence is strongly affected by collisional quenching due to oxygen, so the technique is typically applied under non-reacting conditions. Non-reactive conditions can be seen as representative until ignition occurs. After ignition, combustion can significantly affect

mixing. To investigate the effects of post-injections on the near-injector equivalence ratios and UHC emissions when ignition occurs near the post-injection event, it is more relevant to study reactive conditions. Therefore, the present investigation of post-injections uses other laser diagnostics for more indirect measurements of mixing.

Imaging of certain combustion intermediates can indicate the progression of two-stage ignition, and may even provide bounds on the local equivalence ratios. For example, Collin *et al.* used combined laser diagnostics to measure the distribution of OH and formaldehyde for HCCI combustion [9]. It was shown that formaldehyde is formed during the first-stage ignition and fills the measurement region in the studied case. When second-stage ignition occurs, OH is detected in small pockets within the formaldehyde region without overlapping. As second-stage ignition continues, OH regions grow and merge while formaldehyde regions are consumed. Therefore, OH- and formaldehyde-PLIF can indicate the ignition-stage that a region of interest goes through.

Similar combined laser diagnostics were employed by Genzale *et al.* on LTC combustion [7]. Observations of the OH and formaldehyde distributions relative to the first- or second-stage ignition were similar to the ones reported previously. Furthermore, toluene-PLIF was used under non-combusting conditions to obtain quantitative information about local equivalence ratios. The comparison between LIF images of OH, formaldehyde, and PAH under reacting conditions with and toluene fluorescence under non-reacting conditions showed how the spatial distribution and temporal evolution of the combustion intermediates can provide boundaries on the local equivalence ratio. Firstly, formaldehyde first appears in regions ranging from fuel-lean to fuel rich, but it persists late in the cycle only in fuel-lean regions, for which the delay to second-stage ignition is very long. Second, OH concentrations are highest in regions of intermediate stoichiometry, and the OH fluorescence signal should be roughly proportional to its concentration [10], so that OH fluorescence during its initial appearance is strongest in regions that are likely of intermediate stoichiometry. Finally, PAH fluorescence arises in regions that are fuel-rich and later may proceed to soot formation.

In a similar manner, combustion intermediates are used as quantitative indicators of local stoichiometry in the present investigation. Two different post-injection strategies are presented and compared to a single injection in terms of engine-out UHC level, and estimated distributions of near-stoichiometric, lean and potentially rich mixtures derived from laser-induced fluorescence imaging of OH and formaldehyde/PAH. One of the injection strategies is shown to rapidly render the mixture in the upstream regions combustible and thereby decrease load-specific UHC emissions by 20% at approximately the same load as a single injection condition. Rate of injection measurements

and sensitivity of the post-injection parameters on UHC reduction are also discussed.

EXPERIMENTAL SETUP AND DIAGNOSTICS

OPTICAL ENGINE

The optical engine is a single cylinder version of a Cummins N-series heavy-duty diesel engine having a bore of 139.7 mm, a displacement of 2.34 liters, and a swirl ratio of 0.5. Other specifications are listed in Table 1. Figure 3 is a schematic showing the extended Bowditch piston with a large flat piston-crown window, small rectangular windows located at the top of the cylinder liner providing cross-optical access for laser-based diagnostics. It has also a small cylinder head window in place of one of the exhaust valves. The piston bowl-rim has a cut-out to allow laser-sheet access to the combustion bowl near top dead center (TDC), see Fig. 2. More details about the optical engine can be found in [2, 11, 12].

The engine is equipped with a Cummins XPI high-pressure, electronically controlled common-rail fuel injector. This injector uses a solenoid-actuated pilot valve and a pressure-balanced needle to control fuel delivery. It is capable of multiple injections at up to 2000 bar fuel-rail pressure. For the experiments presented here, an eight-hole mini-sac injector cup (tip) was employed, having an included angle of 152°. The eight orifices are equally spaced and have a nominal diameter of 0.15 mm.

Exhaust UHC emissions were measured using a 600 series UHC analyzer from California Analytical Instruments. Under skip-fired conditions where the exhaust is significantly diluted, measurement of UHCs can be challenging due to low species concentrations and possible condensation in the exhaust system and sample lines due to the low mean exhaust temperatures. For the conditions tested, UHC emissions were quite high, well above the detection limit of the analyzer, even with skip-firing. To avoid condensation in the exhaust system, the sampling point was located as close to the exhaust valve as possible, in the exhaust manifold. Furthermore, heated sample lines helped to prevent condensation during extraction. The system responded rapidly to transients from fired to non-fired operation, indicating that heavy hydrocarbons had not condensed in the exhaust pipe and released later. Furthermore, a steady level of UHC was reached after a few combustion cycles only and evaluation is based on the steady part of the UHC curve obtained. Although the UHC measurements are reliable, many compromises to the combustion chamber geometry for optical access, such as greatly increased crevice volumes, likely affect UHC emissions. As such, the absolute levels of UHC presented here for the optical engine are not meant to be taken as a quantitative measurement for a practical engine, but rather to indicate the trends and comparisons between different combustion cases.

Table 1. Engine and injector 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*
Combustion chamber	Quiescent, direct injection
Swirl ratio	0.5 (approx.)
Bore	139.7 mm
Stroke	152.4 mm
Bowl width	97.8 mm
Displacement	2.34 liters
Connecting rod length	304.8 mm
Piston pin offset	None
Geometric compression ratio	11.2:1
Simulated compression ratio	16:1
Fuel injector type	Common-rail, solenoid actuated
Cup type	Mini-sac
Number of hole	8, equally spaced
Spray pattern included angle	152°
Rail pressure	1600 bar
Orifice treatment	None (square edged)
Nominal orifice diameter	0.15 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.

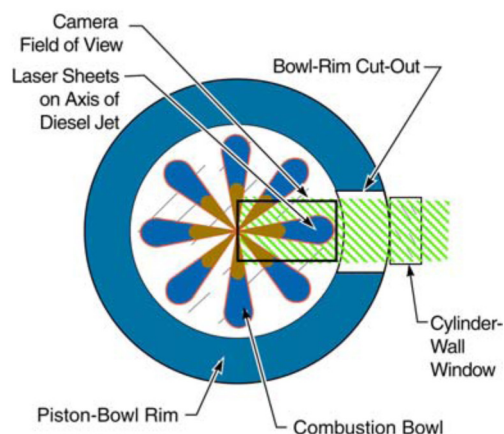


Figure 2. Schematic of the piston with eight-hole injector.
The laser sheets enter the combustion chamber from the right side through a cut-out in the bowl rim and follow the jet axis towards the injector nozzle.

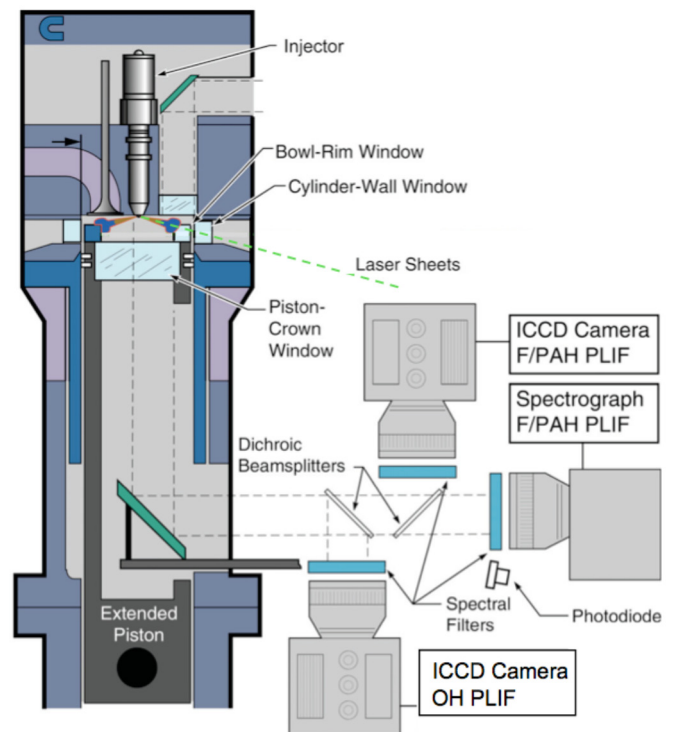


Figure 3. Schematic of the optical heavy-duty diesel engine and layout for the combined laser induced diagnostics.

OPERATING CONDITIONS

The engine operating conditions are summarized in Table 2. To achieve LTC conditions, the oxygen concentration was reduced to 12.7% in the inlet flow. Because the engine is a single-cylinder, and skip-fired for thermal loading reasons, EGR was not available for dilution. Rather, a metered flow of nitrogen was added to the intake stream to dilute the oxygen concentration to the desired level. At the chosen dilution of 12.7% O₂, the adiabatic flame temperature for a stoichiometric mixture at peak pressure is 2170 K, compared to 2680 K for pure air. Ojeda *et al.* have shown that this level of dilution can comply with the NO_x limit of the US 2010 heavy-duty on-road legislation without NO_x after-treatment for a wide load range by adjusting the injection strategy [13].

The injection parameters are given for the different injection strategies in Table 3. The values for actual start and duration of injection are extracted from injection rate measurements for each strategy. For each of the low load LTC cases investigated, the start of the main injection is -5° ATDC. This particular timing of the main injection gives both a positive ignition dwell (essential for LTC) and a practical combustion phasing for fuel efficiency. Also, for more fundamental reasons, injection starting at -5 ATDC is attractive because the density remains nearly constant before and after injection (little piston motion), so that the data are more easily compared with nearly constant-density constant-volume combustion chamber experiments. The

fuel mass delivered in the post-injection is discussed together with rate of injection results in a later section.

Table 2. Engine operating conditions.

Engine speed	1200 rpm
Intake O ₂	12.7%
Common-rail fuel pressure	1600 bar
TDC Motored Density	22.1 kg/m ³
TDC Motored Temperature	837 K
TDC Motored Pressure	54.9 bar
Intake Pressure	214 kPa (abs)
Intake Temperature	78°C

Table 3. Injection parameters for the different strategies.

	Single Main Injection	Main + Small Post Injection	Main + Large Post Injection
Actual Start of Main Injection	-5° ATDC	-5° ATDC	-5° ATDC
Actual Duration of Main	~980 µs	~970 µs	~830 µs
Actual Start of Post Injection	-	3° ATDC	4° ATDC
Actual Duration of Post Injection	-	~200 µs	~560 µs
Total Fuel Injected	39.2 mg	41 mg	44.7 mg
Post-injected fuel	-	1.8 mg	14.6 mg
IMEP _g	270 kPa	287 kPa	327 kPa
Indicated efficiency	37.7%	38.3%	40.1%

For all operating conditions, cylinder pressure and fuel rail pressure were digitized and recorded at quarter CAD increments, simultaneously with the acquisition of the optical data. The apparent heat release rate (AHRR) was calculated from ensemble-averaged pressure data using an air-standard first-law analysis (see e.g. [14]). A regular schedule is maintained during these experiments where the engine is motored for 90 seconds before the injecting fuel to minimize variability of results due to transients.

A diesel primary-reference fuel (PRF) mixture was used to avoid unwanted fluorescence interferences from aromatic components in diesel fuel. The PRF mixture is 32.3% n-hexadecane (cetane) and 67.7% heptamethylnonane by volume, giving a defined cetane number of 42.5, which is typical of U.S. diesel fuel [15].

Rate of injection analysis

Multiple injection strategies can possibly affect the dynamics in the injector due to pressure waves in the common rail system. To understand the effects of pressure waves on post injections, the rates of injection for the strategies in Table 3 were measured using a spray-impingement meter [16]. Fig. 4 shows the derived mass rate of injection for all three cases. The rail pressure in the fuel line upstream of the injector is also indicated on the plot. Both parameters are averaged over 100 injections and low-pass filtered using a Butterworth filter with a normalized cutoff frequency of 0.1. The rate of injection was measured with atmospheric back-pressure and the nozzle was heated to 90°C, which corresponds to the nominal temperature of the coolant in the engine cylinder head. The low pressure of the injector test chamber compared to the in-cylinder pressure close to TDC could influence the injection rate measurements. The spray velocity is proportional to the square root value of the pressure difference between the nozzle-sac and the surrounding air. However, Klein-Dowel *et al.* showed that for fully cavitating flows in similar injectors, the mass flow rate was independent of the chamber pressure [17]. Cavitating flow is estimated to occur above 200 bar injection pressure.

It appears clearly on the figure that the delayed post-injection strategy, i.e. actual start of post injection at 4° ATDC, shows a much larger fuel mass in the post-injection compared to the strategy with an earlier post-injection at 3° ATDC. It is important to note that both post-injection strategies had the same energizing time from the injector control system. The two strategies only differ by a delay of 1 CAD in the start of injection command. The main injection duration was reduced in the large post-injection strategy to maintain roughly constant load with the increased post-injected fuel mass. The start of the main-injection was kept unchanged. The results gave 39.2 mg of fuel per injection with a standard deviation of 0.9 mg for the single injection only and 41.0 mg for the main and small post-injection together. The large post-injection strategy resulted in 44.7 mg of fuel per cycle. Analysis of the rate of injection results shows that 14.6 mg of the 44.7 mg are injected in the large post injection with a standard deviation of 0.6 mg. On the other hand, only 1.8 mg of 41.0 mg are post-injected in the small post-injection strategy. The standard deviation for this post injection is 0.4 mg. These values are determined from 100 cycles.