

Early Direct-Injection, Low-Temperature Combustion of Diesel Fuel in an Optical Engine Utilizing a 15-Hole, Dual-Row, Narrow-Included-Angle Nozzle

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ABSTRACT

Low-temperature combustion of diesel fuel was studied in a heavy-duty, single-cylinder, optical engine employing a 15-hole, dual-row, narrow-included-angle nozzle (10 holes x 70° and 5 holes x 35°) with 103- μ m-diameter orifices. This nozzle configuration provided the spray targeting necessary to contain the direct-injected diesel fuel within the piston bowl for injection timings as early as 70° before top dead center. Spray-visualization movies, acquired using a high-speed camera, show that impingement of liquid fuel on the piston surface can result when the in-cylinder temperature and density at the time of injection are sufficiently low.

Seven single- and two-parameter sweeps around a 4.82-bar gross indicated mean effective pressure load point were performed to map the sensitivity of the combustion and emissions to variations in injection timing, injection pressure, equivalence ratio, simulated exhaust-gas recirculation, intake temperature, intake boost pressure, and load. High-speed movies of natural luminosity were acquired by viewing through a window in the cylinder wall and through a window in the piston to provide quasi-3D information about the combustion process. These movies revealed that advanced combustion phasing resulted in intense pool fires within the piston bowl, after the end of significant heat release. These pool fires are a result of fuel-films created when the injected fuel impinged on the piston surface. The emissions results showed a strong correlation with pool-fire activity. Smoke and NO_x emissions rose steadily as pool-fire intensity increased, whereas HC and CO showed a dramatic increase with near-zero pool-fire activity.

INTRODUCTION

Early direct-injection, low-temperature combustion of an ultra-low-sulfur, 46-cetane, #2 diesel fuel was studied in the Sandia compression-ignition optical research engine (SCORE) in collaboration with Caterpillar as part of the US Department of Energy sponsored high efficiency clean combustion (HECC) program. This project was aimed at better understanding the feasibility of utilizing premixed-charge compression-ignition (PCCI) strategies to meet the stringent 2010 emissions standards for on-highway, heavy-duty diesel engines while simultaneously improving fuel efficiency.

The near-constant-volume, premixed combustion of a fuel-lean mixture that results from homogenous-charge compression-ignition (HCCI) or PCCI operation offers the possibility of high thermal efficiency coupled with low emissions of nitrogen oxides (NO_x) and particulate matter (PM). However, producing this mixture, especially with a higher-boiling-range fuel like diesel, presents many challenges including fuel films, pool fires, oil dilution, and high emissions of HC and CO [1-5]. Several methods of fuel delivery have been studied in an attempt to understand and perhaps limit these negative effects of liquid-fuel impingement on in-cylinder surfaces.

Kashdan *et al.* utilized a wall-guided re-entrant bowl geometry along with a 60°-included-angle, 6-orifice nozzle to direct the liquid fuel toward the center of the cylinder, thereby containing the fuel-air mixture within the piston bowl [1]. Laser induced fluorescence (LIF) measurements of the narrow angle direct injection (NADITM) system showed the formation of liquid fuel-films, especially for injection timings that targeted the base of the piston bowl. The LIF measurements also provided evidence that the fuel-films may flash boil during the expansion stroke leading to the high HC emissions observed.

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Fang, *et al.* utilized a 70°, narrow-included-angle orifice configuration to study smokeless combustion in a small-bore, direct-injection diesel engine [2]. Early, late, and multiple-injection strategies were employed. The early-injection strategy led to fuel impingement on the bowl wall and subsequent pool fires, the late post-TDC injection strategy led to smokeless combustion, and the multiple-injection strategy led to low-smoke, low-NO_x combustion.

Iwabuchi *et al.* utilized multi-row orifice nozzles with the included angles chosen such that the inner- and outer-row fuel jets impinged upon each other and were thereby able to significantly reduce the liquid penetration length while providing a high level of fuel dispersion [3]. This provided for premixed compression ignition (PCI) combustion with ultra-low NO_x and low smoke emissions.

Hardy and Reitz studied PCCI combustion with a more standard included-angle nozzle through the application of high EGR rates. The large included angle led to significant cylinder-wall wetting and high HC emissions while achieving low NO_x and smoke at part-load operation [4].

Takeda *et al.* studied several injector configurations including a centrally located injector with a conventional-diesel included angle (155°); a pair of injectors mounted near the edge of the bore-diameter in the head, with sprays directed toward the center of the cylinder; and a three-row nozzle design incorporating 155°, 105°, and 55° included-angle orifices [5]. The PREmixed lean Diesel Combustion (PREDIC) produced dramatic reductions in NO_x emissions, but these were accompanied by increased HC and CO levels.

In the current study, a dual-row, narrow-included-angle nozzle is utilized to enable early direct-injection, low-temperature combustion of diesel fuel. The narrow-included-angle nozzle provides the spray targeting necessary to contain the fuel mixture within the piston bowl, and the dual-row orifices allow for better air utilization.

EXPERIMENTAL SETUP

The SCORE is a single-cylinder version of a Caterpillar® 3176/C-10 heavy-duty diesel engine that has been modified to provide extensive optical access into the cylinder. A schematic of the engine showing the optical-access modifications is provided in Fig. 1, and its basic hardware parameters are shown in Table 1. The piston bowl is centered on the axis of the cylinder bore; it has vertical sidewalls and a flat bottom to simplify imaging. More detailed specifications of the optical engine are provided in Ref. [6].

The engine is equipped with a hydraulically-actuated electronically-controlled unit injector (HEUI). The general

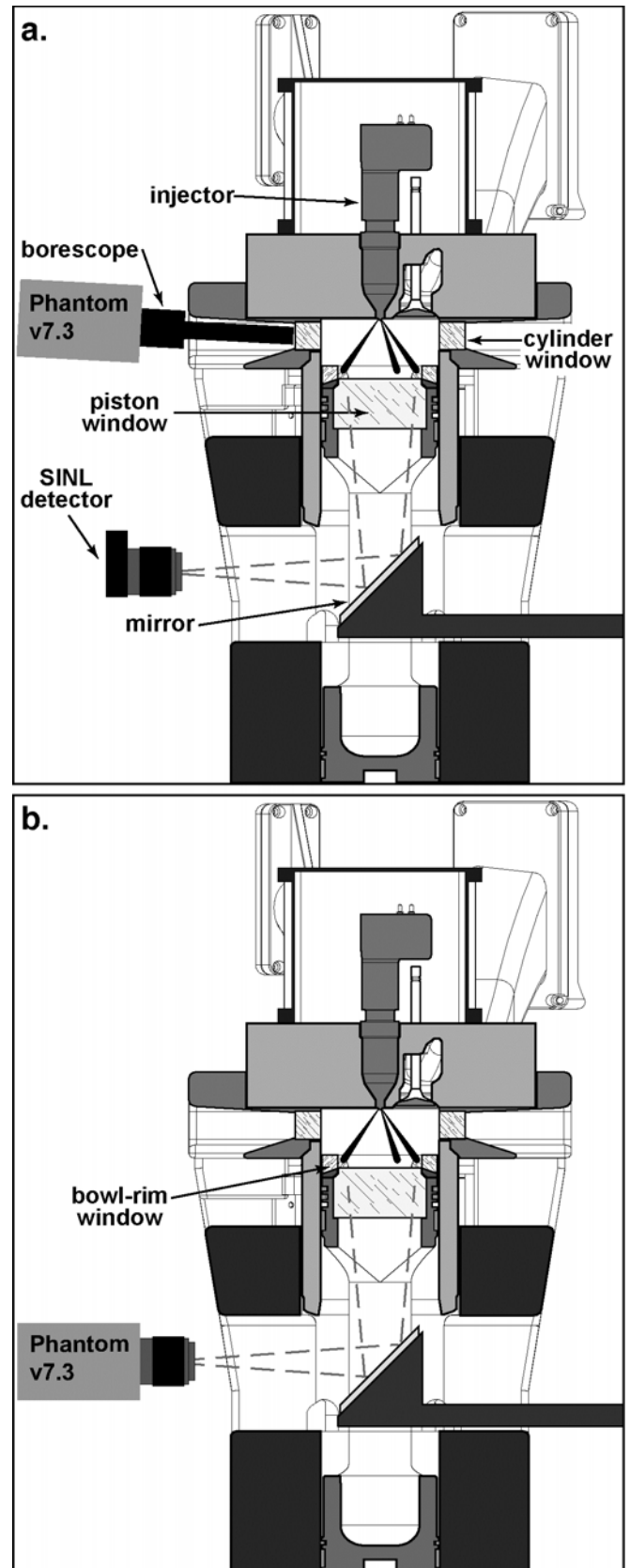


Figure 1. Cross-sectional schematics of SCORE as configured for collecting SINL data and high-speed movies. **a.** Setup for high-speed imaging through the cylinder window. **b.** Setup for high-speed imaging through the piston window. Only one inner-cone jet is visible in each cross-section plane because the inner-cone jets are aligned with every other outer-cone jet.

Table 1: SCORE Specifications

Research engine type	1-cyl. version of C-10/3176
Cycle	4-stroke CIDI
Valves per cylinder	4
Bore	125 mm
Stroke	140 mm
IVO ^a	32° BTDC exhaust
IVC ^a	153° BTDC comp.
EVO ^a	116° ATDC comp.
EVC ^a	11° ATDC exhaust
Connecting rod length	225 mm
Connecting rod offset	None
Piston bowl diameter	90 mm
Piston bowl depth	16.4 mm
Squish height	1.5 mm
Swirl ratio ^b	0.59
Displacement per cyl.	1.72 liters
Compression ratio	11.8:1

^aAll valve timings are for 0.03 mm lift

^bMeasured at the Caterpillar Technical Center using an AVL swirl meter

specifications of the fuel-injection system are provided in Table 2. For this study, the injector was equipped with a 15-hole, dual-row, narrow-included-angle nozzle (10 holes x 70° and 5 holes x 35°) with 103- μ m orifices. Figure 1 shows an axial slice through the center of the cylinder bore indicating the alignment of one inner-row and two outer-row fuel sprays. The injector axis is the same as the cylinder-bore axis. The 70° included angle of the outer row of 10 evenly spaced orifices was chosen such that liquid fuel would impinge fully within the piston bowl when the engine was less than 65 crank angle degrees (CAD) from top dead center (TDC). Accounting for the jet penetration rate allows actual start of injection (SOI_a) as early as -70° after TDC (ATDC)¹. The inner row of 5 evenly spaced orifices was aligned such that the axis of every other outer-row jet was co-planar with the axis of an inner-row jet and the cylinder-bore axis.

An ultra-low-sulfur, #2 diesel fuel typical of that commonly available in the United States was used for this work. Selected fuel properties are provided in Table 3.

OPTICAL MEASUREMENTS

In-cylinder spray-visualization and natural-luminosity (NL) movies were acquired using a Phantom V7.3, 14-bit, high-speed camera. Two camera views were utilized to provide quasi-3D information about the in-cylinder fuel penetration, mixing, and combustion. The first camera view images through a cylinder-wall window, see Fig. 1a. This setup utilizes a 20-mm-diameter variable-focal-length borescope with a 115° field of view that was built by Abakus Ltd. This

¹ All CAD timings are given in terms of degrees ATDC to simplify the in-cylinder imaging figure labels.

Table 2: SCORE Fuel-Injection System Specifications

Injector type	Caterpillar® HEUI™ A
Injector model	HIA-450
Nozzle style	Single-guided
Outer row	10 x 103 μ m x 70° VCO
Inner row	5 x 103 μ m x 35° minisac
Oil rail pressure	20.8 MPa (3000 psig)
Max. injection pressure	142 MPa (20600 psia)
Intensification ratio	6.85:1
Valve opening pressure	31 MPa (4500 psig)

Table 3: Ultra-Low-Sulfur #2 Diesel Fuel Properties

Parameter	ASTM Test Method	Value
Density (15.6°C)	D 4052-1	838.8 kg/m ³
Cetane Number (CN)	D 613	45.9
Derived CN	D 6890	45.0
Distillation	D 86	
	<i>Initial</i>	194°C
	<i>5%</i>	209°C
	<i>10%</i>	213°C
	<i>20%</i>	222°C
	<i>30%</i>	230°C
	<i>40%</i>	238°C
	<i>50%</i>	244°C
	<i>60%</i>	249°C
	<i>70%</i>	256°C
	<i>80%</i>	267°C
	<i>90%</i>	308°C
	<i>95%</i>	343°C
	<i>End</i>	351°C
SFC Aromatics	D 5186	
	<i>1-ring</i>	23.1 wt%
	<i>2 or more rings</i>	11.7 wt%
	<i>Total</i>	34.8 wt%
Sulfur	D 2622	11 mg/kg
Nitrogen	M 1208	6 mg/kg
Hydrogen	M 1252-1	12.99 wt%
Carbon	100%-H-S-N	87.01 wt%
Kin. Viscosity (40°C)	D 445-3	2.02 mm ² /s
Heat of Combustion	D 4809	
	<i>Gross</i>	45.5 MJ/kg
	<i>Net</i>	42.8 MJ/kg

borescope enables in-cylinder imaging with a clear view from the surface of the head down to the bottom of the piston bowl from approximately -90° to +90° ATDC with a single optical setup.

For spray-visualization imaging, two high-intensity discharge (HID) lamps enclosed in parabolic reflectors replace the spatially integrated natural luminosity (SINL) detector shown in Fig. 1a. These HID lamps are directed



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through the piston window to illuminate the fuel jets with diffuse, white light. The sequence of events for spray-visualization imaging is as follows. First, at the desired crank angle a trigger signal is sent to the electronics that fire the fuel injector. This time is called the indicated start of injection and is denoted SOI_i . At a known delay after SOI_i , the high-speed camera is triggered to start acquiring images with 15- μs exposure duration at a rate of 50 kHz. Next, fuel begins to enter the combustion chamber. The time when fuel begins to enter the combustion chamber is called the actual start of injection and is denoted SOI_a . The difference between SOI_a and SOI_i is called the injector lag, and it can be calculated from these experiments. A total of 200 images were acquired from each cycle at 50 kHz to capture the evolution of individual injection events. To date, only limited spray-visualization imaging through the piston window has been accomplished (see Fig. 1b). Therefore, only cylinder-window spray-visualization results will be discussed.

High-speed NL imaging was accomplished for both camera views shown in Fig. 1. For high-speed NL imaging through the cylinder window, simultaneous SINL measurements were made through the piston window. SINL is a measure of the time history of natural luminosity integrated across the view through the piston window; this is accomplished with a single-element, silicon photodetector (New Focus, Model 2031) and lens set to view through the piston window [7]. The SINL detector can be configured to provide a linear signal level even for the brightest cycles. This configuration allowed for the high-speed camera to be set up to improve low-light collection at the cost of allowing the peak NL levels to significantly saturate the camera. Because of the camera saturation and non-linear grayscale map applied to the NL images, it is best to compare the relative areas of peak NL signal in the images and utilize the SINL data to compare relative intensities.

SIMULATED EXHAUST GAS RECIRCULATION

The SCORE used a simulated exhaust gas recirculation (EGR) system capable of supplying up to 140 g/s of air, 45 g/s of N_2 , and 20 g/s of CO_2 at up to 3.0 bar absolute intake pressure. 4.0 bar intake pressure is possible with reduced N_2 flow rates. The mixture is supplied by computer-controlled regulators based on model calculations to match the intake oxygen mole fraction as well as the constant-pressure specific heat capacity of the in-cylinder mixture at -30° ATDC in a metal engine utilizing real EGR. The mole fraction of CO_2 is higher in the simulated-EGR mixture than it would be in a comparable mixture of real EGR because the simulated-EGR mixture lacks H_2O .

Throughout this paper, the terms EGR and simulated EGR are used to refer to the simulated-EGR mixture of air, N_2 , and CO_2 used in the SCORE. This is different

than the clean gas induction (CGI) used in Caterpillar® engines with ACERT® Technology. CGI draws clean inert gas from downstream of the particulate filter and then introduces this clean gas into the intake-air system.

EMISSIONS MEASUREMENTS

In addition to the optical diagnostics, the engine is equipped with exhaust-gas emissions analyzers including: 1. a heated flame-ionization detector (California Analytical Instruments, Inc. (CAI) Model 600 HFID) for unburned hydrocarbons (HC); 2. a non-dispersive infra-red absorption and paramagnetic detector (CAI Model 602-P NDIR/ O_2) for CO , CO_2 , and O_2 ; 3. a heated chemiluminescence detector (CAI Model 600 HCLD) for NO_x ; and 4. a smoke meter (AVL Model 415S). Because the SCORE is operated in a skip-fired mode where the injector is only fired once every 12 engine cycles, it is necessary to scale the emissions values to represent continuous-fired operation [8]. Skip-fired operation is used to reduce thermal loading and fouling (from soot and other combustion-generated residues) of the fused-silica windows. Because the optical engine is skip-fired and utilizes simulated EGR, any combustion products or unburned fuel will have 11 motored engine cycles to be convected out of the cylinder and into the emissions analyzers. Therefore, it is likely that the optical engine HC emissions are greater than would be expected from a continuously firing metal engine using actual EGR. The scaled emissions concentrations are then converted into indicated specific emission values based on the known intake mass flow rates of air, simulated EGR, and fuel, as well as the measured gross indicated mean effective pressure (gIMEP) calculated from the cylinder-pressure data. The emissions results were not scaled to brake-specific values because the pumping and frictional work in the SCORE are not representative of those in a production engine.

OPERATING CONDITIONS

A 1200-rpm, light-load, 50% simulated-EGR operating condition was roughly identified using results from metal-engine testing performed at the Caterpillar Technical Center for a similar-sized engine. The exact parameters for the SCORE baseline operating condition were selected to minimize emissions of smoke, NO_x , HC and CO resulting from single-parameter sweeps of injection timing and injection pressure. The baseline parameter values are provided in Table 4. A total of seven single- and two-parameter sweeps were performed to test the sensitivity of the baseline operating condition to changes of injection timing, injection pressure, equivalence ratio, simulated EGR, intake temperature, intake boost, and load. Details of the parameter limits for each sweep are provided in Table 5.

Careful examination of Table 5 shows that all seven parameter sweeps are actually two-parameter sweeps.



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Table 4: Baseline Operating Condition

Load, gIMEP	4.82 bar
Boost	1.418 bar
IMT	42° C
simulated EGR	50%
Equivalence ratio	0.39
Max. fuel-injection pressure	142 MPa
SOI _a	-39.5° ATDC
Intake O ₂ mole fraction	15.0 %
Intake CO ₂ mole fraction	5.0 %
Simulated compression ratio	12.0:1
Speed	1200 rpm

For the injection-timing sweep it was necessary to inject additional fuel to maintain the load as the injection timing was advanced. Because the intake mixture composition was maintained while the quantity of injected fuel was increased, the effective simulated-EGR level decreased slightly as injection timing was advanced. However, this variation in EGR is small enough that the injection-timing sweep will still be treated as a single-parameter sweep. Similarly, the SOI_a timing was retarded toward TDC by approximately 3.3 CAD due to the increased injector lag at lower injection pressures. To first order, this effect is small and the results can also be treated as a single-parameter sweep. Further details of both single-parameter sweeps are provided below.

In addition to the single-parameter sweeps, several two-parameter sweeps were tested. Most of the two-parameter sweeps were chosen such that the second varied parameter was boost pressure. Boost was chosen as the second parameter in most sweeps to

allow load, equivalence ratio, percent EGR, and intake manifold temperature (IMT) to be varied one at a time, independently of each other. However, diesel fuel is a two-stage ignition fuel and shows significant changes in cool-flame chemistry with increased cylinder pressure [9]. Therefore, a sweep of IMT and equivalence ratio was chosen to separate some of the effects of increased IMT from those of increased boost. Most of the sweeps consist of five steps; the injection-pressure sweep has only three and the equivalence-ratio-and-boost sweep has seven steps.

The performance, emissions, and optical data of these seven parameter sweeps are presented below, starting with the single-parameter sweeps.

INJECTION-TIMING SWEEP

An injection-timing sweep at constant injection pressure was accomplished to determine the effects of spray targeting and in-cylinder fuel-air mixing on engine performance and emissions. Figure 2 presents the average in-cylinder pressure, apparent heat release rate (AHRR), and SINL data for SOI_a from -69.5° to -29.5° ATDC. Detailed operating parameter values are presented in Table 5.

The injection-timing limits were chosen to allow some time between the end of injection and the start of combustion for the most retarded case, and to contain the fuel within the piston bowl for the most advanced case. At the 142-MPa injection pressure, the injector has a lag of approximately 1462 μs (or ~10.5 CAD at 1200 rpm). Spray-visualization of the SOI_a = -29.5°

Table 5: Operating Conditions for the Parameter Sweeps

	SOI _a Timing [°ATDC]	Injection Pressure [MPa]	Φ [-]	EGR [%]	Intake Temp. [°C]	Load gIMEP [bar]	Boost [bar]
Baseline Condition	-39.5	142	0.39	50	42	4.82	1.418
Injection Timing	-69.5 to -29.5	142	0.39	46.6 to 50.2	42	4.82	1.418
Injection Pressure	-36.3 to -39.5	47, 95, 142	0.39	50	42	4.82	1.418
Equivalence Ratio and Boost	-39.5	142	0.24 to 0.58	50	42	4.82	2.060 to 1.132
EGR and Boost	-39.5	142	0.39	30 to 70	42	4.82	1.188 to 1.949
Intake Temperature and Boost	-39.5	142	0.39	50	32 to 62	4.82	1.373 to 1.508
Intake Temperature and Equivalence Ratio	-39.5	142	0.39 to 0.41	50	32 to 62	4.82	1.418
Load and Boost	-39.5	142	0.39	50	42	3.82 to 5.83	1.203 to 1.629

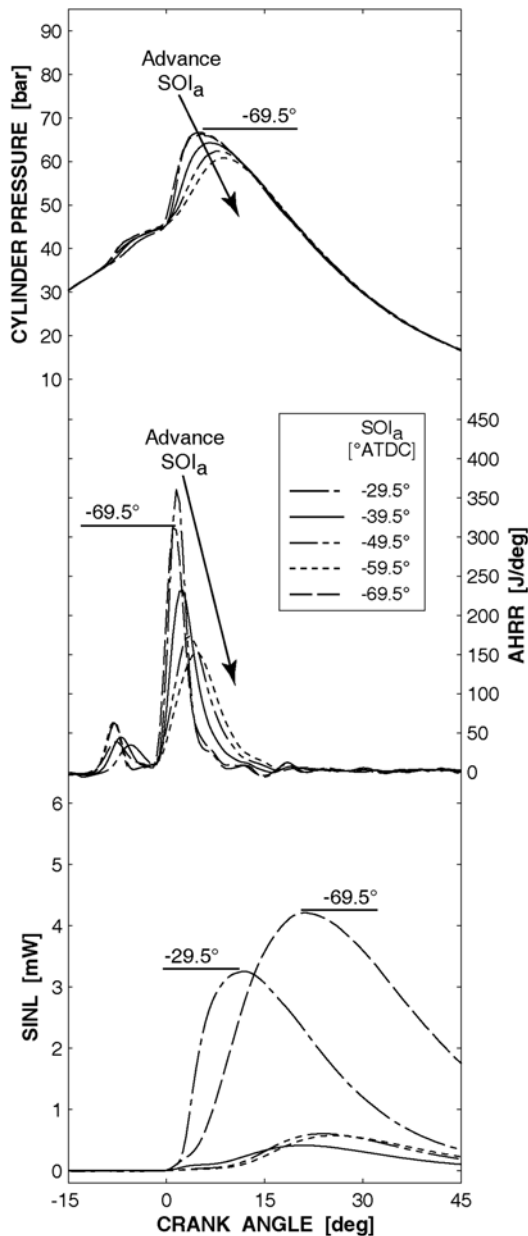


Figure 2. Injection-timing sweep plots of average cylinder pressure, AHRR, and SINL for $SOI_a = -29.5^\circ$ to -69.5° . All traces have been averaged over 75 fired engine cycles. Note that the PCP and max. AHRR levels for the most advanced ($SOI_a = -69.5^\circ$) injection-timing case do not follow the trend of decreasing values observed for advancing SOI_a from -29.5° to -59.5° .

injection-timing case showed that the fuel jets finish penetrating into the piston bowl at approximately -15° ATDC, and AHRR data shows that the cool-flame combustion phase begins at approximately -10° ATDC. Hence, this case is near the limit of retarding the injection timing toward TDC while still allowing time for the fuel to premix. Similarly, the $SOI_a = -69.5^\circ$ injection timing case represents the most advanced injection timing where the outer row of fuel jets is fully contained within the piston bowl. As a result, this timing represents the limit of advancing the injection without cylinder-wall wetting. While it is possible to inject at slightly earlier

timings and allow the liquid fuel to impinge on the top outer rim of the piston, this surface is flat and the resulting fuel-films will likely enter the crevice between the piston and the cylinder. Preliminary test results showed that HC emissions rise sharply if the outer-row of fuel jets is targeted outside of the bowl.

As seen in Fig. 2, the peak value of the AHRR trace decreases and the total duration of heat release increases as the SOI_a timing advances from -29.5° to -59.5° ATDC. The more-advanced injection timings produce a more homogeneous, locally fuel-lean in-cylinder mixture at the time of ignition, and are therefore expected to show the observed trends [10]. However, at the most-advanced injection timing, $SOI_a = -69.5^\circ$, the peak value of the AHRR trace dramatically increases back to nearly the same level as the -29.5° case. Spray-visualization movies show that the outer row of fuel jets impinges on the flat piston window for injection timings from $SOI_a = -59.5^\circ$ to -29.5° ATDC (*i.e.*, all fuel jets impinge on the bottom of the piston bowl). However, at the earliest injection timing, $SOI_a = -69.5^\circ$, the outer-row of fuel jets impinges upon the vertical surface of the piston bowl. This change in spray targeting may result in a locally fuel-rich region near the vertical piston bowl wall, thus changing the combustion characteristics of this earliest injection timing.

Careful examination of the AHRR and SINL plots in Fig. 2 shows that most of the intense NL occurs after the AHRR trace has returned to near-zero levels, *i.e.*, the latest significant AHRR levels occur from $\sim 8^\circ$ to 15° ATDC depending on the SOI_a timing, while the peak averaged SINL levels occur between 10° and 25° ATDC. The high-speed NL movies, discussed below, revealed that this intense SINL signal after the end of significant AHRR is associated with regions of high-temperature soot from pool fires that result from the liquid-fuel films created by impingement of the early direct-injection diesel jets. It was observed that both the earliest and latest injection timings resulted in a significantly larger SINL signal than the three intermediate injection timings.

In addition to the average SINL traces presented in Fig. 2, Fig. 3 presents the 75 individual fired-cycle SINL traces for a given run at each SOI_a timing, with the averaged SINL traces overlaid as a thick line in each plot. From these data it is evident that the peak SINL varies greatly from one cycle to the next. The data also show that the peak of the individual-cycle SINL values have little or no correlation to cycle order, peak cylinder pressure (PCP), timing of PCP, gIMEP, AHRR maximum, nor location of AHRR maximum. This result suggests that the large variation of peak SINL that can be observed from one cycle to the next may be related to local in-cylinder mixing and heat transfer acting on the liquid-fuel films. Therefore, high-speed spray-visualization and NL movies were acquired to provide more insight into the nature of the mechanisms underlying the observed trends.

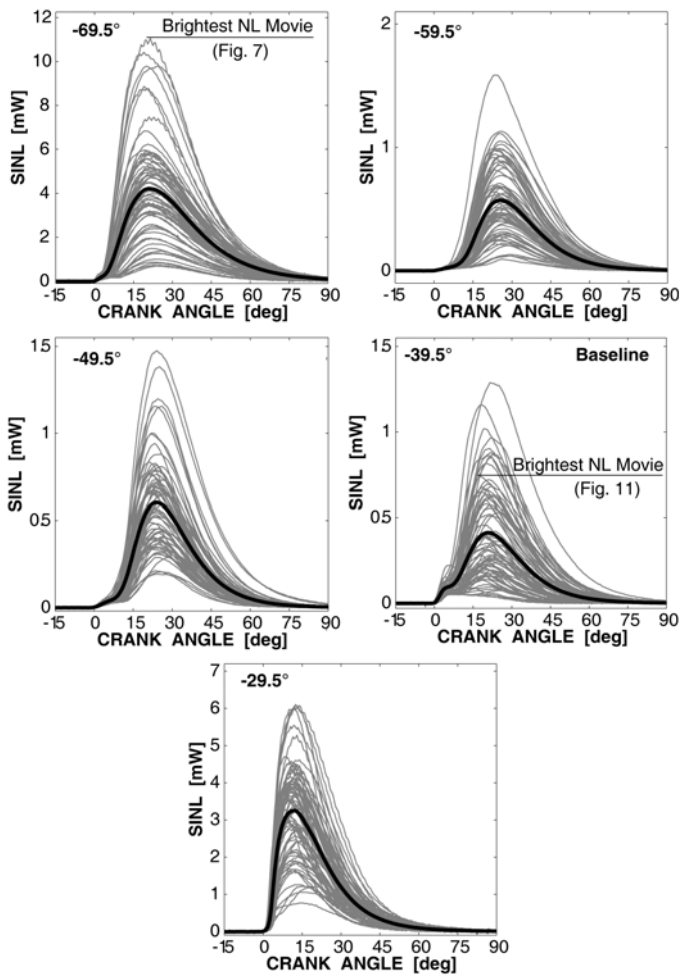


Figure 3. Single-cycle SINL traces for each injection timing plotted with overlay of averaged SINL trace from Fig. 2 (average SINL trace is the thick black line). The “Brightest NL Movie” labels in the $SOI_a = -69.5^\circ$ and -39.5° SINL plots refer to the brightest of the first 20 fired engine cycles for each run and were selected for display in Figs. 7 and 11, respectively.

HIGH-SPEED SPRAY-VISUALIZATION IMAGING

High-speed spray-visualization movies were acquired for all timings of the injection-timing sweep. Figures 4 and 5 show selected images from the $SOI_a = -69.5^\circ$ and -39.5° injection-timing spray-visualization movies, respectively. As mentioned earlier, the high-speed spray-visualization movies were acquired by imaging through the cylinder window as shown in Fig. 1a. Because of the high velocity of the fuel jets and the need to use a 15- μ s (0.11-CAD) exposure duration, each individual frame is unable to freeze the jet motion as well as laser-pulse illuminated spray visualization where the exposure is limited by the sub-microsecond duration of the laser pulse. Still, the temporal resolution is adequate, and the high-speed camera allows for imaging the complete injection event from a single engine cycle. Before discussing the results of the spray visualization experiments, a brief description of the camera field of view will be provided to better orient the reader with the in-cylinder view.

Thin white lines have been added to Figs. 4 and 5 to help highlight various edges within the cylinder when viewing through the cylinder window. In each selected image frame of Fig. 4, a downward curving arc is provided about $\frac{1}{4}$ of the way down from the top of the image. This line marks the corner between the surface of the head and the cylinder wall. It is only possible to see this corner on the far side of the cylinder, away from the camera and borescope (see Fig. 1a). Above this line it is possible to see the injector tip and parts of three of the four valves. The valve farthest from the camera is hidden by fuel sprays. In all images of Fig. 4, the piston is below the level of the cylinder window. Therefore it is possible to see over the top of the piston, down into the piston bowl. The three images in the top row have both the top and bottom edges of the vertical piston-bowl wall marked with white lines. In the last three rows of Fig. 4 only the top edge of the vertical piston-bowl wall is marked.

The injection timing of Fig. 5 is significantly retarded from that of Fig. 4; therefore the piston is significantly closer to TDC at the time of spray-visualization imaging. Similar to Fig. 4, a downward curving arc is provided about $\frac{1}{4}$ of the way down from the top of the image. This line marks the corner between the surface of the head and the cylinder wall. This line is omitted from the last two images of the last row in Fig. 5 because the piston is close enough to TDC that it is no longer possible to see the corner between the surface of the head and the cylinder wall.

Two additional white lines are provided in all images of Fig. 5. The first is an ellipse that marks the bottom edge of the vertical piston-bowl wall. This is the bottom of the piston bowl and is viewed through both the cylinder window and the bowl-rim window. This ellipse shortens in the vertical direction as the piston moves closer to TDC and the bottom of the piston bowl becomes nearly even with the borescope. The other white line in all images of Fig. 5 marks the top outer edge of the piston (*i.e.* the line follows the 125-mm-diameter outer edge of the piston top). In the 1562- to 1982- μ s images, this line curves downward because the piston is below the height of the borescope. It is possible to see reflections in the top of the piston-bowl-rim window just above this line in the 1562- to 1982- μ s images. In the 2262- μ s image, the top edge of the piston is almost even with the height of the borescope and therefore becomes nearly straight. In the 2542- to 3382- μ s images this white line starts to curve upwards as the piston continues to move toward TDC. Now the reflections in the piston-bowl-rim window originate from the bottom side of the top surface. This results in the reflections showing up just below the now upward-curving line. In the 2822- μ s image, from the perspective of the camera, the top edge of the piston is even with the corner between the surface of the head and the cylinder wall. Therefore, the camera is unable to image the corner between the surface of the head and the cylinder wall in the final two images of Fig. 5 and the

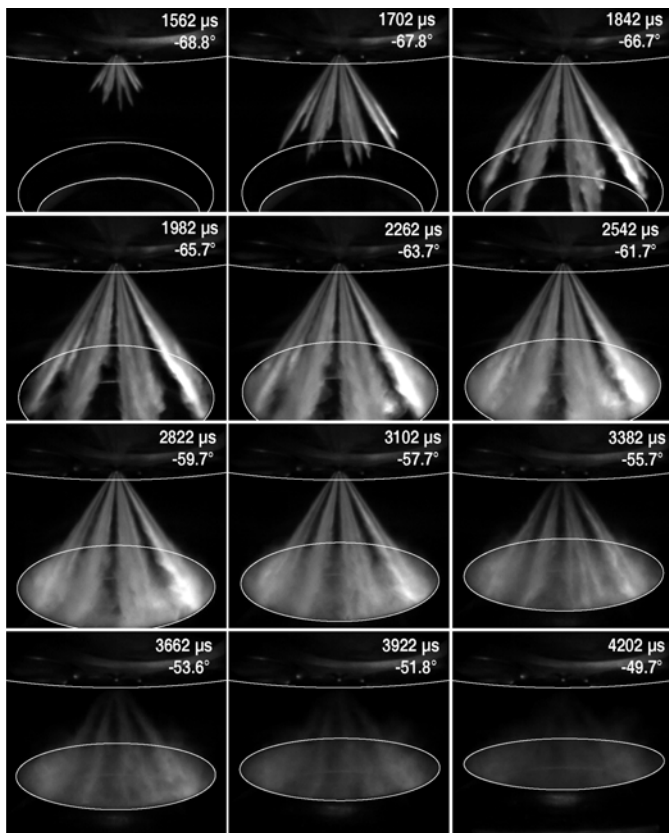


Figure 4. Selected spray visualization images from the high-speed camera for the $SOI_a = -69.5^\circ$ injection timing. The images were collected through the cylinder window, as shown in Fig. 1a. The timing from the indicated start of injection ($SOI_i = -80^\circ$) to halfway through the 15- μs image exposure is provided in the upper-right corner of each image frame. The crank angle labels are approximate, since the camera was synchronized with the injector in the time domain. The interaction of liquid fuel with the piston bowl can be observed in the second and third rows of images. The end of injection occurs between the 3102- and 3382- μs images.

white line is omitted. Now that the field of view has been explained, the results of the spray-visualization experiments will be discussed.

High-Speed Spray-Visualization Results

The first row of images in Fig. 4 ($SOI_a = -69.5^\circ$) shows the fuel jets penetrating from the surface of the head toward the piston. Jets from both the outer- and inner-row orifices can be seen, but the inner-row jets are often obscured by outer-row jets. By the 2262- μs image, the outer-row of fuel jets can be observed impinging on the vertical wall of the piston bowl. The inner-row of fuel jets impinges directly on the flat surface of the piston window that makes up the bottom of the piston bowl. As the piston ascends toward TDC, the targeting of the outer-row of fuel jets moves toward the bottom of the piston bowl. The end of injection occurs between the 3102- and 3382- μs images. In the bottom row of images, a significant amount of non-vaporized fuel remains in a

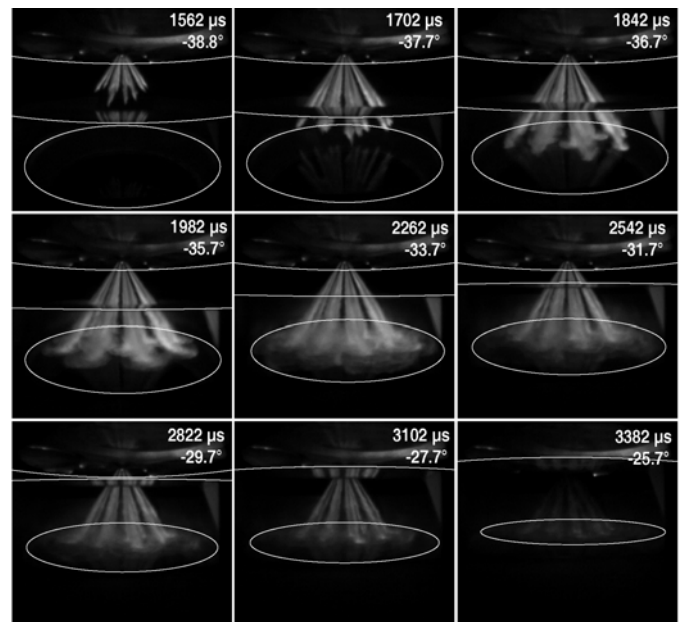


Figure 5. Spray visualization for the $SOI_a = -39.5^\circ$ injection timing. The image timing is again given in time since indicated SOI ($SOI_i = -50^\circ$) and in approximate crank angle. This retarded injection timing provides a slightly different view within the cylinder. Starting in the 1702- μs image, the spray visualization shows the jets entering the piston bowl, and there is a reflection of the fuel jets that originates from the top surface of the piston bowl-rim window, approximately 2/3 down the length of the fuel jets. By 1842 μs and more obviously in the 1982- μs image, the fuel jets have impinged on the surface of the piston bowl and started to spread out radially. By 2822 μs the piston has moved significantly closer to TDC and there is a reflection of the fuel jets on the bottom side of the top surface of the piston bowl-rim window. The end of injection occurs between the 3102- and 3382- μs images.

cloud filling the piston bowl, significantly after the end of injection. This cloud is still visible at -49.7° , after the end of injection. Later images from the $SOI_a = -69.5^\circ$ spray-visualization movie show that the remaining atomized liquid fuel has either vaporized or collected into the liquid-fuel film on the surface of the piston by $\approx -40^\circ$ ATDC.

Figure 5 shows selected spray-visualization images for the $SOI_a = -39.5^\circ$ case. This injection timing was chosen as the baseline condition. For injection timings from $SOI_a = -59.5^\circ$ to -29.5° , both the inner- and outer-row jets impinge directly on the surface of the piston window, unlike the $SOI_a = -69.5^\circ$ case where the outer-row jets impinge on the vertical bowl wall. As the injection timing is retarded, the impingement points move radially inward because the piston is closer to TDC. At this more-retarded injection timing ($SOI_a = -39.5^\circ$), the fuel jets enter the piston bowl in the 1702- μs image. In the middle of this image the top surface of the bowl-rim window obstructs the view of fuel jets, with the leading part of the individual fuel jets penetrating down into the piston bowl. By the 1842- μs image and more obviously in 1982- μs