

The Visualization of Soot Late in the Diesel Combustion Process by Laser Induced Incandescence with a Vertical Laser Sheet

Gregory K. Lilik, Charles J. Mueller, and Cosmin E. Dumitrescu
Sandia National Laboratories

Christopher R. Gehrke
Caterpillar Inc.

ABSTRACT

Although soot-formation processes in diesel engines have been well characterized during the mixing-controlled burn, little is known about the distribution of soot throughout the combustion chamber after the end of appreciable heat release during the expansion and exhaust strokes. Hence, the laser-induced incandescence (LII) diagnostic was developed to visualize the distribution of soot within an optically accessible single-cylinder direct-injection diesel engine during this period. The developed LII diagnostic is semi-quantitative; i.e., if certain conditions (listed in the [Appendix](#)) are true, it accurately captures spatial and temporal trends in the in-cylinder soot field. The diagnostic features a vertically oriented and vertically propagating laser sheet that can be translated across the combustion chamber, where “vertical” refers to a direction parallel to the axis of the cylinder bore. The diagnostic allows soot visualization in almost the entire region above the piston bowl late in the cycle (until the piston descends below the imaged field of view). It also enables estimation of the total in-cylinder soot mass as a function of crank angle. These attributes of the diagnostic allow it to provide unique insights into the production, oxidation, and distribution of soot within the combustion chamber. This manuscript reports on the development of the diagnostic and results from its initial application, in which 21-, 18-, and 16-mol% intake-oxygen conditions were examined.

CITATION: Lilik, G., Mueller, C., Dumitrescu, C., and Gehrke, C., "The Visualization of Soot Late in the Diesel Combustion Process by Laser Induced Incandescence with a Vertical Laser Sheet," *SAE Int. J. Engines* 8(2):2015, doi:10.4271/2015-01-0801.

INTRODUCTION

New and forthcoming diesel emissions standards demand lower tailpipe-out soot emissions. To meet these standards, various exhaust-aftertreatment strategies have been adopted by diesel-engine manufacturers, at the expense of both increased hardware cost and reduced brake thermal efficiency. Hence, a direct benefit could be realized if soot concentrations could be lowered within the cylinder, lessening the need for aftertreatment.

A detailed understanding of in-cylinder soot formation and oxidation processes is helpful for lowering in-cylinder soot levels through modification of the combustion process. The Dec conceptual model of conventional diesel combustion [1] describes soot formation during the mixing-controlled combustion process when the burning jet reaches a quasi-steady phase. In contrast, this study examines the temporal evolution of the in-cylinder soot distribution late in the combustion process.

Laser-based optical techniques can provide direct measurements of combustion intermediates, including soot. Such techniques often require signal acquisition nearly orthogonal to the axis of the laser sheet (or beam) used to measure the parameter of interest. As such, optically accessible engines generally provide a bottom view of the

combustion process with visual access through the piston window and laser access through a side window of the engine. Conversely, a side cylinder window can provide a view of the combustion chamber with laser access through the piston window or another side window.

Many optical techniques have been developed to both qualitatively and quantitatively measure in-situ soot. Laser-induced incandescence (LII) is the measurement technique of primary interest in this study, and it is employed to detect soot well into the expansion stroke. Initially, natural luminosity (NL) measurements of soot incandescence are presented to assist the reader in visualizing the in-cylinder soot cloud and its orientation and location with respect to the planar LII laser sheets.

NL signal is produced by the combustion process, where the main sources of NL are soot incandescence and chemiluminescence [2]. Soot incandescence is the dominant source of NL under typical mixing-controlled diesel-combustion conditions (such as those studied herein), and it occurs due to hot soot particles emitting broadband thermal radiation [3]. The broadband spectrum of soot incandescence is temperature dependent, such that the peak emitted intensity decreases and the spectral location of this peak shifts to longer wavelengths as the soot cools. In contrast to soot

incandescence, chemiluminescence is a faint source of NL that occurs as excited gas-phase molecules relax to their ground states by emitting photons. NL due to chemiluminescence is emitted over relatively narrow spectral ranges that are particular to various intermediate combustion species [4].

NL measurements have two shortcomings when used to determine the location of soot. First, NL measurements are line-of-sight measurements, which results in difficulty spatially resolving soot that is distributed along the optical axis for each pixel. Second, soot temperature has a strong influence on NL signal; as a result, the signal is biased toward soot particles with higher temperatures and may not adequately indicate regions of cooler soot, particularly when a camera that is not sensitive to infra-red wavelengths is used [2].

LII is accomplished by heating soot particles with a laser and measuring the subsequent radiative emission from the particles. As a result, LII can be used to detect soot regardless of its temperature. Wavelengths of 532 nm and 1064 nm have been used often in LII engine studies, but 532-nm LII has been shown to suffer from interference from the fluorescence of large poly-aromatic hydrocarbons (PAH) and C_2 or C_3 emissions [5]. In the present study, an excitation wavelength of 1064 nm was chosen because it has been shown to avoid interferences by non-soot species [5]. Quantification of the soot volume fraction and soot particle size has been attempted by correlating the magnitude of the LII signal with the volume fraction of the particles [6], such that the LII signal is proportional to the particle diameter to the third power [7]. In an optical engine, quantitative LII measurements require laser-extinction measurements to calibrate the LII measurement to soot volume fraction [8]. In the laser-extinction measurement, a beam must travel along the same path as the LII laser-sheet and pass outside the engine to be collected in an integrating sphere. At the time of this study, the optical-engine setup did not provide the optical access required for the LII measurement to be calibrated against an extinction measurement. Nonetheless, the resultant LII signal can provide a semi-quantitative indication of relative soot concentrations within the combustion chamber. For the purposes of this paper, “semi-quantitative” means that if certain conditions (listed in the Appendix) are true, the diagnostic accurately captures spatial and temporal trends in the in-cylinder soot field.

LII has been used to measure the location and quantity of soot in diesel engines with optical access. Dec and coworkers [9,10] were the first to utilize planar LII to determine where and when soot occurs in a diesel engine. Later Dec utilized LII among other techniques to develop his conceptual model of the mixing-controlled burn of a diesel fuel jet. Dec and Kelly-Zion [11] examined parametric effects on late-combustion soot burnout (well after exhaust-valve opening, EVO) using planar LII along with planar laser induced fluorescence (PLIF) to image OH.

The aforementioned studies by Dec [1] and Dec et al. [9,11] were conducted with the laser sheets horizontally oriented and horizontally propagating with imaging occurring either through the piston window or an exhaust-valve window. For the purposes of this paper, “horizontal” refers to a direction perpendicular to the axis of the cylinder bore, whereas “vertical” refers to a direction parallel to it. A

study conducted by Pires da Cruz et al. [8] employed planar LII of soot using a vertically oriented and horizontally propagating laser sheet with visualization through a side cylinder window. Bladh et al. [12] conducted LII with a vertically oriented and vertically propagating sheet, with imaging occurring through a side cylinder window. They examined the effects of pilot-injection timings at early crank angles from 1 to 21 crank-angle degrees ($^\circ$ or CAD) after top-dead-center (ATDC) at a single laser-sheet position.

In contrast, this study was conducted with multiple vertically oriented and vertically propagating laser-sheet positions, with imaging occurring through a side cylinder window. The advantage of LII with a vertically oriented and vertically propagating sheet with multiple sheet positions is that it allows soot visualization in almost the entire region above the piston bowl late in the cycle (until the piston descends below the imaged field of view, at which point the bottom of the soot field cannot be seen). This approach enables more-comprehensive visualization of the soot within the combustion chamber, particularly later in the cycle. The focus of this study is on the development of this modified LII diagnostic and its application to estimate the total in-cylinder soot mass as a function of crank angle during and after combustion.

EXPERIMENTAL SETUP

Engine and Fuel System

The experiments were performed in a single-cylinder version of a heavy-duty engine modified to provide optical access to the combustion chamber. A schematic and the primary specifications of this optical engine are provided in Fig. 1 and Table 1, respectively.

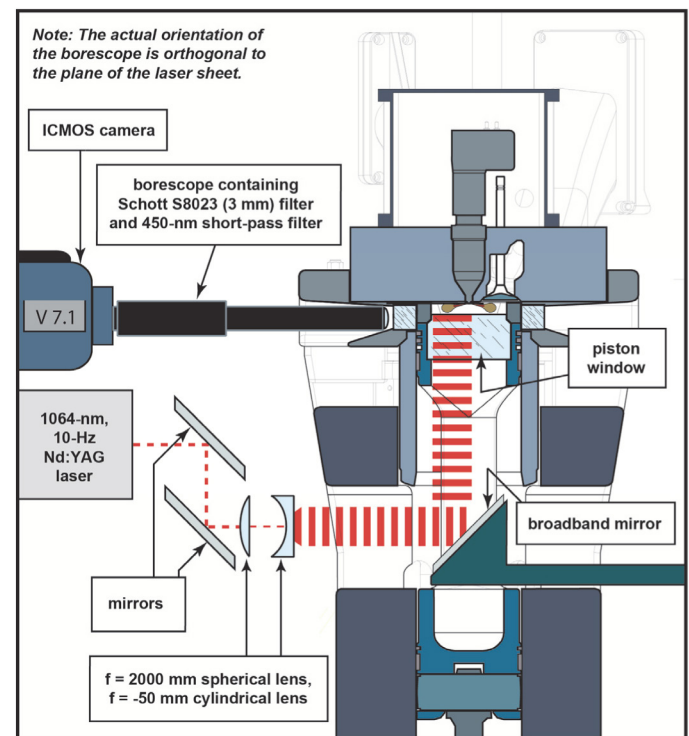


Figure 1. Optical setup for vertical-sheet laser-induced incandescence (LII) imaging experiments.

Table 1. Optical-engine specifications.

Research engine type	Single-cylinder
Cycle	4-stroke CIDI
Valves per cylinder	4
Bore	125 mm
Stroke	140 mm
Intake valve open ^a	32° BTDC exhaust
Intake valve close ^a	153° BTDC comp.
Exhaust valve open ^a	116° ATDC comp.
Exhaust valve closed ^a	11° ATDC exhaust
Connecting-rod length	225 mm
Piston-pin offset	None
Piston-bowl diameter	90 mm
Piston-bowl depth	16.4 mm
Squish height	1.5 mm
Swirl ratio ^b	0.59
Displacement	1.72 liters
Compression ratio (geometric)	12.3:1

^aAll valve timings are for 0.03 mm lift^bMeasured at the Caterpillar Technical Center using an AVL swirl meter

The major differences between the optical engine and a comparable production engine relate to the piston bowl, which has a flat bottom, vertical walls, and a larger land above the top compression ring. The larger top-ring land allows optical access through a notch in the bowl-rim and prevents the rings from riding over the cylinder-wall windows. The above differences lead to a lower geometric compression ratio (CR) of 12.3:1 for the optical engine versus ~16:1 for a comparable production engine. To compensate for the lower CR, the intake temperature and pressure in the optical-engine experiments are elevated to closely match the conditions in the production engine over the crank-angle range during which combustion occurs [13].

The optical engine was skip-fired with one injection event every 5 engine cycles in these experiments. This approach was used to reduce the rate of soot accumulation on the combustion-chamber windows and to lower the risk of window failure due to the thermal and mechanical stresses generated when switching between motored and fired operation. Using this approach, the residual exhaust gas that remains trapped in the combustion chamber after a fired cycle is replaced with fresh intake charge, i.e., air, nitrogen (N₂), and/or carbon dioxide (CO₂), during the subsequent motored cycles. The heat rejection from the combustion chamber to the coolant is lower due to the skip-fired operation, which requires the optical engine to use a heater to maintain a constant coolant temperature.

Fuel delivery was accomplished using a high-pressure common-rail fuel-injection system, the principal components of which include two diaphragm pumps (Newport Scientific, Model 46-16060) modified at Sandia for improved durability at injection pressures > 150 MPa, and a near-production Caterpillar electronically actuated solenoidoperated

fuel injector. The fuel-wetted internals of the pumps are fabricated from stainless steel, Kalrez, and Teflon, making the system suitable for handling a wide range of conventional and unconventional fuels having high corrosivities, low viscosities, or other properties that can cause conventional piston-type pumps to fail.

Fuel-injector specifications are provided in Table 2. X-ray tomography was used to confirm the orifice diameter, length-to-diameter ratio, and included spray angle listed in Table 2. While the injection duration and pressure used in this work are representative of those employed in modern diesel engines, an injector tip with only two orifices was used. The 2-hole injector tip was selected for several reasons: 1) to allow unobstructed imaging of a fuel-jet of interest through the cylinder-wall window, 2) to make the results more independent of engine-geometry effects by effectively precluding jet-jet interactions [14], and 3) to maintain consistency with conditions employed in parametric fuel-effects studies in the same facility (e.g., [15]). The quantity of fuel injected by the 2-hole tip is of course lower than from a 6- or 8-hole tip in a typical production engine (at equivalent injection pressure, duration, and orifice diameter), so bulk-gas-averaged in-cylinder temperatures, global in-cylinder equivalence ratios, and quasi-steady heat-release rates in the present study will be lower as well. The interested reader is referred to [15] for emissions, efficiency, and other combustion-related results at conditions identical to those employed in the present study.

Table 2. Common-rail fuel-injector specifications.

Injector type	Cat CR350
Injector tip style	Mini-sac
Number of injector orifices	2
Orifice diameter (nom.)	110 µm
Orifice length-to-diameter ratio	8
Hydro-erosion	20 ± 2%
Included spray angle	140°

A flush-mounted, water-cooled pressure transducer (AVL Model QC32C) was used to measure cylinder pressure every 0.5 CAD. To ensure good data repeatability, 540 engine cycles of pressure-based data were recorded at each operating condition, during three separate engine runs that generally occurred on different days.

Gas analyzers (California Analytical Instruments, Series 600) measured carbon monoxide (CO), CO₂, oxygen (O₂), nitrogen oxides (NO_x), and hydrocarbon (HC) emissions. Engine-out smoke emissions were measured using both a smoke meter (AVL Model 415S) and a prototype laser-induced incandescence instrument (see Figure 5 of [16] and [17]). Reference [18] describes in detail the procedures used for cylinder-pressure data acquisition and how the skip-fired exhaust-gas measurements were converted to values similar to those that would be obtained if the engine was operated in a continuous-fired mode. Further details of the experimental setup and procedures are available in [13,14].

Fuel

A #2 ultra-low-sulfur diesel certification fuel (CF) was used in this study. Selected properties of the CF are given in Table 3. References [19] and [15] give further details regarding the composition and combustion behavior, respectively, of this fuel.

Table 3. Tested fuel properties [15,19].

Parameter	ASTM Method	Cert Fuel ULSD #2
Specific gravity [g/ml]	D4052	0.848
Cetane number	D613	43.3
Derived cetane number	D6890	43.7
Distillation temperature [°C]	D86	
T10		211
T50		253
T90		310
Carbon [mass %]	D5291	87.04
Hydrogen [mass %]	D5291	13.03
Molar C/H ratio		0.561
Sulfur [ppm]	D5453	14.4
Aromatics (by SFC)	D5186	
1-ring [mass %]		20.7
2 or more rings [mass %]		9.0
Total [mass %]		29.7
Net heat of combustion [MJ/kg]	D240	42.9
Kinematic viscosity @ 40°C [cSt]	D445	2.3

Engine Operating Conditions

Table 4 presents the engine operating parameters that were held constant during the experiments. The intake charge, cylinder liner, and head were maintained at the same temperature to minimize the uncertainty in charge-gas temperature at the beginning of the compression stroke due to heat transfer among these elements of the system. The start of injection (SOI) was adjusted to maintain the constant start of combustion (SOC) timing. For the purposes of this study, SOC is defined as the crank angle where the high-temperature heat release (HTHR) first becomes positive after SOI. This choice was made because, as shown in Fig. 3, a distinct low-temperature heat-release event does not occur for the operating conditions investigated herein.

Table 4. Engine operating parameters that were held constant.

Speed	1500 rpm
Intake manifold absolute pressure	2.50 bar
Intake manifold temperature	95.0 °C
Coolant temperature	95 °C
Load (gross indicated mean effective pressure)	1.72 ± 0.03 bar
Injection pressure	80 MPa
Start of combustion	-5.0° ATDC

Three dilution levels were studied in this work. Table 5 shows the mole fractions of O₂, N₂, CO₂, and argon (Ar) in each intake mixture, as well as the intake-mixture densities (ρ) at -10° ATDC. Because the skip-fired operating mode that was employed in these experiments affects the exhaust-gas composition, real exhaust-gas recirculation (EGR) was not used to achieve these dilution levels. Instead, the mole fraction of oxygen in the intake mixture (X_{O_2}) was varied by adding N₂ and CO₂ to the dry intake air. The experiment was designed such that the specific heat (c_p), temperature (T), and pressure (P) of each charge-gas mixture were held constant at -10° ATDC under motored conditions at 32.1 J/mol/K, 850 K, and 63.3 bar, respectively. This approach was used: 1) to isolate the effects of X_{O_2} variation on the results (independent of c_p variation); 2) to enable liquid-phase fuel penetration lengths measured under the same in-cylinder thermodynamic conditions (but without appreciable heat release at 2 mol% X_{O_2}) to be applicable to the present study [13,20]; and 3) to reduce the rate of consumption of bottled CO₂ during the experiments.

Table 5. Species mole fractions and densities of the studied charge-gas mixtures.

	21-mol% O ₂ (dry air)	18-mol% O ₂	16-mol% O ₂
X_{O_2} [mol%]	20.947	18.000	16.000
X_{N_2} [mol%]	78.084	80.899	82.811
X_{CO_2} [mol%]	0.035	0.298	0.476
X_{Ar} [mol%]	0.934	0.803	0.713
ρ (-10° ATDC) [kg/m ³]	26.0	25.9	25.8

Optical Measurements

Vertical Laser-Induced Incandescence (VLII)

LII was produced using a 1064-nm laser-sheet from an Nd:YAG laser (Spectra Physics PRO-270) firing at 10 Hz. The 1064-nm wavelength was chosen over 532 nm to mitigate non-soot interference caused by 532-nm excitation [5]. A mean fluence of ~0.4 J/cm² was targeted so that the LII signal would be independent of the excitation fluence [21]. The fluence was measured with a combination of a beam profiler (DataRay, Inc. WinCamD-LCM4) and a power meter (Ophir Model F100A-HE-SH). The laser sheet was formed by the optics shown in Fig. 1. The laser-sheet thickness was ~1.5 mm, and the sheet width was adjusted according to its position in the cylinder (see Fig. 4). The 2-hole injector tip was the center reference point for the laser-sheet position. At this center position, the laser sheet was focused along the axis of one of the jets spanning from the injector tip to the bowl rim. The laser sheet was repositioned by translating the broadband mirror directly below the piston in five 10-mm increments. The laser-sheet positions were defined as 0, 10, 20, 30, and 40 mm, with 0 mm being on the injector tip and increasing values moving away from the camera.

A Phantom v7.1 high-speed camera was used to acquire both VLII and vertical natural luminosity (VNL) images through the side piston window at a resolution of 600 × 320 pixels. Interference from NL in

the VLII images was minimized by using a 40-ns intensifier gate with a spectral filter pack (450-nm short-pass filter plus 3-mm-thick Schott S8023 filter, the latter for blocking near-infra-red wavelengths). At each operating condition and laser-sheet position, VLII images were acquired from -5° to 200° ATDC, in 5° increments. Twelve image replicates were taken at every crank angle. The 10-Hz repetition rate of the excitation laser only allowed for one VLII image per combustion cycle.

Figure 2 shows the optical piston with a notch in the bowl-rim. The notch allowed visualization along the top of the piston-window early in the expansion stroke. The camera was positioned to allow visibility of the piston top until the latest possible crank angle, $\sim 80^\circ$ ATDC, providing soot visualization in almost the entire region above the piston bowl late into the cycle. The piston partially obscured the LII signal on the piston-window surface at the early crank angles of -5° to 20° ATDC with this camera positioning.

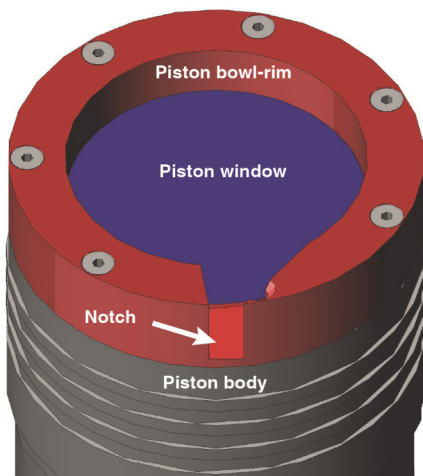


Figure 2. Optical piston with a notch in the bowl-rim for optical access.

Horizontal Natural Luminosity (HNL) and Horizontal Chemiluminescence (HCL)

In this work, HNL and HCL are defined as NL and CL where the images were acquired with the high-speed cameras viewing through the piston window. Dumitrescu et al. [15] provides imaging-diagnostic and setup details for both the HNL and HCL measured at the same operational conditions as used in this study. The HNL and HCL are provided to help orient the reader to the evolution of the in-cylinder combustion process and the positions of the VLII laser sheets. HNL provides a line-of-sight indication of locations where hot soot is present, while HCL provides an indication of locations where significant oxidation is likely occurring.

RESULTS

Combustion Phasing

SOI, SOC, EOI (end of injection), and EOC (end of combustion) values for the three X_{O_2} levels studied in this work are provided in Table 6. The SOI and EOI values are actual (rather than electronic-

command) timings determined from injection-rate measurements, and EOC is the crank angle at which 95% of the energy release of the combustion event has occurred. As X_{O_2} decreased, SOI was advanced to maintain SOC at -5.0° ATDC. Nevertheless, EOC retarded with decreasing X_{O_2} , presumably because more time is required for the fuel-air mixing required to complete combustion at lower X_{O_2} levels. For reference, the peak bulk-gas-averaged in-cylinder temperature and the peak cylinder pressure were 900 ± 5 K and 72.8 ± 0.3 bar, respectively, under fired conditions regardless of the X_{O_2} level.

Table 6. Fuel-injection and combustion-phasing parameters for the studied charge-gas mixtures.

X_{O_2} [mol %]	21	18	16
Start of injection, SOI [$^\circ$ ATDC]	-8.2	-9.0	-9.6
Start of combustion, SOC [$^\circ$ ATDC]	-5.0	-5.0	-5.0
End of injection, EOI [$^\circ$ ATDC]	23.3	22.4	21.9
End of combustion, EOC [$^\circ$ ATDC]	32.9	34.6	35.3

Apparent heat-release rate (AHRR) data for the three X_{O_2} conditions of this study are presented in Fig. 3. The AHRR curves are very similar for the three X_{O_2} conditions because SOC and load were matched for all conditions. Each AHRR curve exhibits a premixed-burn spike followed by mixing-controlled heat release, characteristic of conventional diesel combustion.

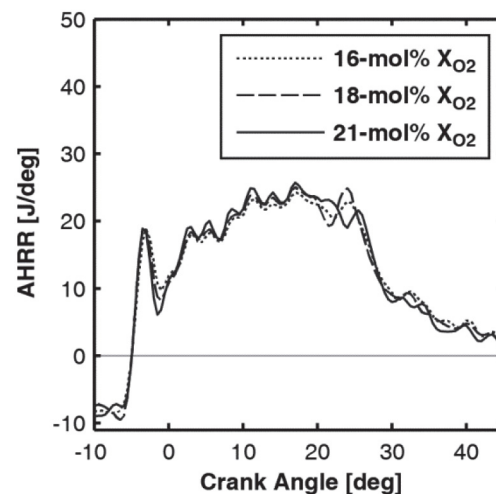


Figure 3. AHRR for the three different X_{O_2} conditions.

Smoke and Gaseous Emissions

Smoke and gaseous emissions from the engine are provided in Table 7. Engine-out smoke emissions are shown to increase with a decrease in X_{O_2} . Adiabatic flame temperatures (see Fig. 14 of [15]) are lower for conditions with lower X_{O_2} . Presumably, the reduction in local temperatures and reduced availability of O_2 reduces the rate of soot oxidation, leading to elevated smoke emissions in the exhaust. An increase of incomplete combustion in the form of increased indicated-specific hydrocarbon (ISHC) and indicated-specific carbon monoxide (ISCO) emissions is evident with lower X_{O_2} levels and could also be

due to lower local temperatures and lower availability of O_2 . A classic diesel combustion NO_x -soot trade-off occurs, with an increase of $ISNO_x$ at higher X_{O_2} levels.

Table 7. Smoke and gaseous emissions.

X_{O_2} [mol%]	21	18	16
Smoke [FSN]	0.06	0.17	0.53
$ISNO_x$ [g/kW-h]	6.73	2.05	0.85
ISHC [g/kW-h]	0.95	1.21	1.65
ISCO [g/kW-h]	1.42	2.33	4.29

Natural Luminosity and Chemiluminescence

As shown in Fig. 4, HNL and HCL images can provide a frame of reference for the VLII images acquired at laser-sheet locations of 0, 10, 20, 30, and 40 mm from the injector axis and parallel to the plane containing the axis of the diesel jet of interest. HNL and HCL images were acquired during different engine runs than the VLII images. The HNL and HCL images were obtained simultaneously with two separate cameras and subsequently superimposed by converting the grayscale color map of the HNL to red and the grayscale color map of the HCL to cyan. Regions of the image where HNL and HCL are both present hence become dirty red or dirty cyan, depending on whether the local HNL or HCL signal is larger, respectively. Regions where HNL and HCL signal levels are equal will appear gray, and if both HNL and HCL were saturated at a given location, that location would appear black. The HNL signal is indicative of hot soot, and the HCL signal is indicative of electronically excited OH radicals (and the oxidation associated with the presence of OH). Cool soot and ground-state OH are not detected by HNL and HCL imaging, respectively.

The relative intensities of HNL and HCL images at different X_{O_2} conditions should not be directly compared due to: 1) unquantified NL and CL signal non-linearities (including effects of local and line-of-sight temperature and species distributions), 2) the use of different image-acquisition parameters, and 3) the use of non-linear color maps to display the image data, i.e., γ correction. In γ correction, each measured pixel value in an image is normalized by the maximum possible pixel value for the given camera, and the result is raised to the power γ . When γ is less than unity, this has the effect of preferentially enhancing the brightness of lower-signal regions relative to higher-signal regions. The γ -values used to display the HNL and HCL images in Fig. 4 are 0.2 and 0.6, respectively. These γ -values were chosen to enhance diminishing signal levels at later crank angles. Figure 4 shows HNL and HCL images from the 21-, 18-, and 16-mol% X_{O_2} conditions at 0°, 25°, 50°, and 55° ATDC. The HNL and HCL images are shown at these particular crank angles to emphasize the locations of hot soot and the subsequent signal decay of NL.

At 0° ATDC, the two combusting fuel jets of the 16-mol% X_{O_2} condition are shown to have HNL impinging at the edge of the piston bowl-rim. In contrast, the 18- and 21-mol% X_{O_2} images at 0° ATDC indicate that their respective combusting fuel jets have not reached the piston bowl-rim. The difference in combusting jet penetration is due to the earlier SOI timing used for the diluted conditions to obtain an SOC of -5.0° ATDC (see Table 4). At 0° ATDC the combusting fuel jet at all three conditions is concentrated in the region of the 0-mm VLII laser sheet, which contains the jet axis. The jets at the 16- and 18-mol% X_{O_2} conditions have expanded sufficiently to intersect the 10-mm VLII sheet. The less-developed 21-mol% X_{O_2} jet is shown in Fig. 4 to nearly touch the 10-mm laser-sheet position. The faint blue haze around the jets at 0° ATDC (and to a lesser extent at 25° ATDC) is likely CL that has been reflected back to the camera, primarily from the firedeck. Its signal level is low, but it is visible due to the low image γ used to display the data.

At 25° ATDC, the combusting jets have impinged on the piston bowl-rim and split into two lobes, each traveling away from the jet axis in opposite directions along the circumference of the piston bowl. The lobes have a slight clockwise offset corresponding to the direction of flow swirl. At 25° ATDC, the HNL signal indicates the hot soot has extended to the 30-mm VLII laser-sheet position. Although the soot distributions are similar for all three X_{O_2} conditions, the illuminated outlines of the intake and exhaust valves can be used as reference features to show that the hot soot from the 21-mol% X_{O_2} condition covers a smaller area than the 16-mol% X_{O_2} condition. This is likely due to the higher rate of soot oxidation and later SOI timings under higher- X_{O_2} conditions. A cyan tip of HCL is evident near the upstream centerline of each jet, which becomes a gray region where the HCL and HNL signals overlap.

At 50° ATDC, significant HCL is no longer visible at any of the conditions, and the HNL signal indicates that the lobes of the two jets have intersected along the periphery of the piston bowl. With the aid of the swirl, hot soot from the upper lobe of the left-hand jet is observed to intersect the 40-mm VLII sheet position on the other side of the cylinder. The HNL signal indicates that little hot soot is present near the jet axes (though cool soot could be present). The 21-mol% followed by the 18-mol% X_{O_2} conditions exhibit a significant decline in HNL signal, while substantial HNL signal remains for the 16-mol% X_{O_2} condition. This also points to attenuated soot formation and/or enhanced oxidation under the higher- X_{O_2} conditions because fuel injection starts later but the HNL signal disappears earlier under such conditions, even though flame temperatures (and hence NL signal levels for a constant soot concentration [2]) are likely higher.

At 55° ATDC, virtually all the HNL signal has diminished at the 21- and 18-mol% X_{O_2} conditions, while larger patches of HNL signal still remain for the 16-mol% X_{O_2} condition. The HNL signal indicates that the hot soot sequentially intersected the five VLII laser-sheet positions. According to the HNL images at 50° and 55° ATDC, little hot soot should occupy the region along the jet axis (i.e., the 0-mm laser-sheet position).