

Effects of Piston Bowl Geometry on Mixture Development and Late-Injection Low-Temperature Combustion in a Heavy-Duty Diesel Engine

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ABSTRACT

Low-temperature combustion (LTC) strategies for diesel engines are of increasing interest because of their potential to significantly reduce particulate matter (PM) and nitrogen oxide (NO_x) emissions. LTC with late fuel injection further offers the benefit of combustion phasing control because ignition is closely coupled to the fuel injection event. But with a short ignition-delay, fuel jet mixing processes must be rapid to achieve adequate premixing before ignition. In the current study, mixing and pollutant formation of late-injection LTC are studied in a single-cylinder, direct-injection, optically accessible heavy-duty diesel engine using three laser-based imaging diagnostics. Simultaneous planar laser-induced fluorescence of the hydroxyl radical (OH) and combined formaldehyde (H₂CO) and polycyclic aromatic hydrocarbons (PAH) are compared with vapor-fuel concentration measurements from a non-combusting condition. Through comparative analysis of OH, H₂CO, and PAH fluorescence, mixtures are identified as either fuel-lean, fuel-rich, or of intermediate stoichiometries.

The impacts of combustion chamber design on in-cylinder mixing processes are explored by comparing three piston bowl diameters of 60%, 70% and 80% of the cylinder bore. The data show that piston-bowl diameter influences in-cylinder mixing and pollutant formation processes by altering jet-jet and jet-wall interactions. When the fuel jets impinge on the bowl wall prior to ignition, adjacent jets merge, forming fuel-rich regions where soot formation occurs. By using a larger diameter bowl, wall impingement prior to ignition is reduced and delayed, and mixtures are leaner throughout the jet. However, a greater fraction of the jet becomes too lean for complete combustion. By using a smaller diameter bowl, a strong jet-wall interaction pushes the fuel-rich jet-jet interaction regions into the center of the chamber, where mixtures are predominantly lean. This reduces net soot formation and displaces fuel-lean regions of otherwise incomplete combustion into the combusting regions near the bowl wall.

INTRODUCTION

As emissions regulations for diesel engines are becoming more stringent worldwide, diesel combustion research is focusing on low-temperature combustion (LTC) strategies [e.g., 1-6]. LTC achieves a simultaneous reduction of nitrogen oxides (NO_x) and particulate matter (PM) emissions by suppressing combustion temperatures and by premixing fuel with the in-cylinder charge prior to ignition. In one class of LTC strategies, which includes premixed charge compression ignition (PCCI), fuel is mixed with the intake charge early in the compression stroke [4-6]. Alternatively, fuel may be mixed with the air charge after compression, using a relatively late fuel injection with a large amount of exhaust gas recirculation and typically high swirl (e.g., Nissan's "MK" combustion concept [1,2]). The latter alternative is attractive because combustion is more closely coupled to the injection event, thereby offering more direct control over the combustion phasing than with premixing prior to compression. However, due to the short ignition-delay for fuel injection near top dead center (TDC), the injected fuel may not mix rapidly enough with the in-cylinder gases to avoid the rich regions that form soot after ignition.

Indeed, recent studies have shown that some portions of the in-cylinder mixtures of late-injection LTC strategies were likely fuel-rich at ignition, based on soot luminosity distributions observed after ignition [7]. In another study, very fuel-lean regions were observed near the injector between the end of injection and the start of combustion [8]. The amount of fuel in these overly lean regions correlated well with trends in unburned hydrocarbon (UHC) emissions. These two observations suggest that late-injection LTC strategies can create both fuel-rich and fuel-lean regions that are problematic for emissions. As a result, while increasing mixing prior to ignition is desirable to reduce fuel-rich regions that may form soot, it may at the same time increase overly fuel-lean regions, resulting in higher UHC emissions. Therefore, to comply with emissions regulations, it is

PM and UHC, late-injection LTC strategies will need to address emissions problems arising from both fuel-rich and fuel-lean regions.

The ultimate fate and emissions formation in the rich and lean mixtures depends on the mixing and combustion processes of diesel fuel jets. Investigations in optical engines have revealed that mixture development and combustion in LTC diesel jets are significantly different than in conventional high-temperature combustion (HTC) diesel jets. Recently, we found that jet mixing processes in EGR-diluted LTC diesel jets change dramatically as the ignition dwell period (i.e., the time between the end of injection and autoignition) becomes positive [8].

HTC diesel jets typically have a negative ignition dwell (due to a short ignition delay). Consequently, ignition and combustion overlap with the fuel injection process, and mixtures near the injector are fuel-rich for these “quasi-steady” jets [9]. Optical diagnostics show OH fluorescence in a thin region at the periphery of the combusting fuel jet, marking a stoichiometric reaction zone at the diffusion flame. Laser-induced incandescence of soot reveals that the stoichiometric diffusion flame surrounds a fuel-rich, soot-producing core [9].

By contrast, LTC diesel jets typically have a positive ignition dwell (due to a long ignition delay), so the jet does not display a quasi-steady period with combustion occurring during injection. Furthermore, mixtures do not remain fuel-rich near the injector. Instead, the mixtures near the injector can rapidly become fuel-lean between the end of injection and the start of combustion [8]. In fact, when ignition occurs, equivalence ratios throughout much of the jet are more fuel-lean than in conventional diesel jets. As a result, the initial distribution of OH in LTC jets is markedly different than in HTC jets. Rather than forming in a thin diffusion flame on the periphery of the jet, OH fills the jet cross-section under LTC conditions, indicating mixtures of intermediate stoichiometries in the core region in the jet [10]. Furthermore, soot is nearly absent from the central cross-section of LTC fuel jets, and is primarily shifted downstream to the head of the jet [10-12]. The presence of OH and the absence of soot in the jet core indicate that LTC jets, with a positive ignition dwell, are significantly leaner than HTC jets.

While the mixing processes of conventional HTC diesel fuel jets have been extensively studied under conditions with negative ignition dwells [e.g., 9,13], a conceptual picture of LTC combustion with positive ignition dwell is just beginning to emerge from recent investigations [8, 10-12]. A positive ignition dwell is essential for most LTC regimes to provide time for premixing and in-cylinder mixing and combustion processes must be properly controlled to optimize LTC strategies.

One important tool available to engine developers for controlling in-cylinder mixture preparation and combustion processes is combustion chamber design. For example, squish-generated flows and the matching of piston bowl geometries with fuel spray targeting can be important for fuel oxidation processes under LTC regimes [14]. Furthermore, late-injection LTC heat release rates indicate that the latter half of combustion is mixing controlled [7], so that the heat release rate may be influenced by combustion chamber design. While some limited information about the impact of combustion chamber design on in-cylinder LTC processes is available, additional in-cylinder optical data are needed to further complete the picture.

The objective of the current study is to gain a better understanding of mixing and combustion processes for an EGR-diluted late-injection LTC strategy and to assess the potential impact of combustion chamber design on these processes. Direct measurements of fuel-vapor concentration by fuel-tracer fluorescence are compared to simultaneous hydroxyl radical (OH) imaging and combined formaldehyde (H₂CO) and polycyclic aromatic hydrocarbon (PAH) fluorescence imaging to evaluate mixing, combustion, and pollutant formation. The optical diagnostics are applied in a low-swirl, heavy-duty optical engine using simulated EGR (12.7% intake O₂) with three different piston designs having bowl diameters of 60%, 70%, and 80% of the cylinder bore.

EXPERIMENTAL SETUP

OPTICAL ENGINE

The optical engine is a single-cylinder version of a Cummins N-series direct-injection (DI), 4-stroke diesel engine, extensively modified for optical access. Figure 1 shows a schematic of the engine, and Table 1 summarizes specifications of the engine. A complete description of the engine is available in Refs. [9,15,16].

The engine has a bore of 140 mm and a stroke of 152 mm, yielding a displacement of 2.34 liters per cylinder. The intake-port geometry of the production cylinder head, which has a steady-state swirl ratio of 0.5 on a flow bench, is preserved in the optical engine.

As shown in Fig. 1, the engine is equipped with an extended piston and flat piston-crown window. Windows located around the top of the cylinder-wall provide cross-optical access for the laser-based imaging diagnostics. A window replaces one of the two exhaust valves to provide imaging access to the squish region, although it is not used in the current study. The current investigation used three piston designs with piston bowl diameters of 60%, 70% and 80% of the cylinder bore (exact dimensions are given in Table 1). The 70% piston bowl maintains the standard dimensions used in previous research on this engine [9,15,16]. The bowl depths of the 60% and 80% pistons are also shown in the

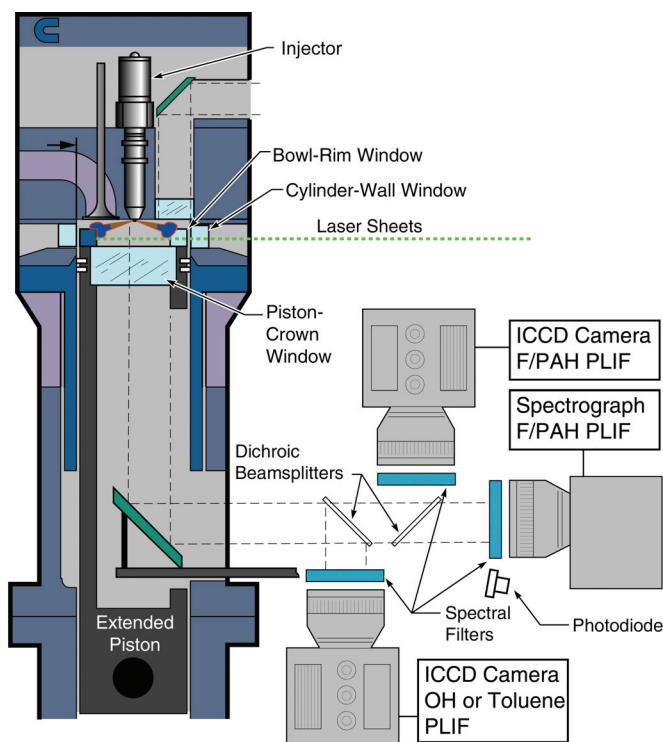


Figure 1. Schematic diagram of the optically accessible DI diesel engine and optical setup.

the compression ratio is the same as for the 70% piston (11.2:1), while the squish height is held constant.

OPERATING CONDITION AND FUEL SELECTION

The engine was operated at a single late-injection LTC operating condition with fuel injection starting at 0° after top dead center (ATDC). The fuel injection duration was approximately 0.94 ms, or 6.75 crank angle degrees (CAD) at 1200 RPM, and the fuel rail pressure was 1600 bar (see Table 2). This injection delivered approximately 56 mg of fuel and yielded a nominal gross indicated mean effective pressure (GIMEP) of 400 kPa. This low-load condition was chosen to avoid damaging the large piston-crown window by limiting the maximum energy release during combustion. Finally, to simulate EGR, the intake air stream was diluted with nitrogen to an oxygen concentration of 12.7% oxygen (by volume).

While some of the optical diagnostics can be applied under normal combusting conditions, the fuel tracer diagnostic required an environment free of oxygen, so that the tracer would not break down during combustion and oxygen quenching of the fluorescence could be avoided. The non-combusting condition presented in Table 2 replicates the estimated in-cylinder TDC conditions of the combusting condition, but with a 100% N₂ intake stream. In this manner, fuel is injected into the same temperature and density environment as in the combusting condition.

Table 1. Engine, Injector, and Fuel 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 [5.50 in]
Stroke.....	152.4 mm [6.00 in]
Displacement	2.34 liters [142 in ³]
Squish Height.....	5.5 mm [0.22 in]
Connecting rod length	304.8 mm [12.00 in]
Piston pin offset	None
Geometric compression ratio	11.2:1
Simulated compression ratio	16:1
60% Bowl diameter	83.8 mm [3.30 in]
60% Bowl depth	21.9 mm [0.86 in]
70% Bowl diameter	97.8 mm [3.85 in]
70% Bowl depth	16.0 mm [0.63 in]
80% Bowl diameter	111.8 mm [4.40 in]
80% Bowl depth	12.3 mm [0.49 in]
Fuel Injector Type	Common-rail, solenoid actuated
Cup (Tip) Type	mini-sac
Number of Holes & Arrangement	8, equally-spaced
Spray Pattern Included Angle	160°, 152°, or 140°
Rail Pressure	1600 bar
Orifice Treatment	None (square-edged)
Nominal Orifice Diameter	0.196 mm
Orifice L/D	5
Base Fuel (by volume)	71% n-heptane, 29% iso-octane
Fuel Tracer (by weight)	1.0 % Toluene

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

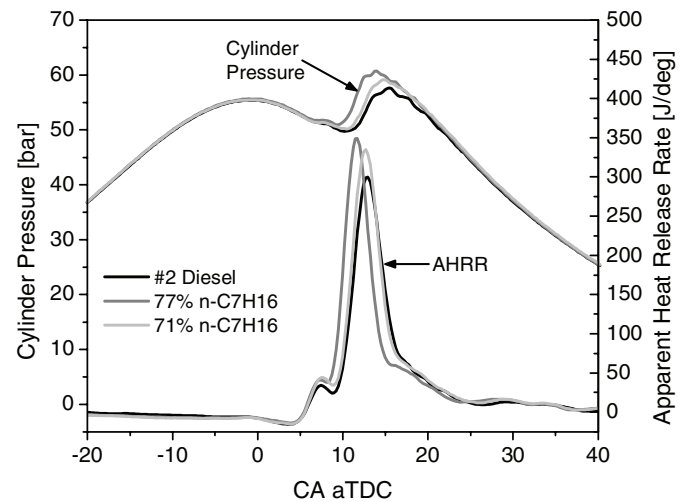
The engine charge conditions at TDC were estimated using a classical polytropic compression calculation starting from the intake manifold conditions, using the geometric compression ratio and a polytropic exponent of 1.36. As shown in Table 2, the estimated motored TDC temperature and density were 838 K and 22.2 kg/m³, respectively. This is typical of lightly boosted diesel operation in a 16:1 compression ratio engine with BDC conditions of 49 °C and 129 kPa, with cooled EGR dilution to 12.7% oxygen (polytropic exponent approx. 1.345). Note that the intake temperature and pressure are higher than typical for production engines because of the low compression ratio of the optical engine. Due to compromises necessary to implement optical access in the engine, the geometric compression ratio is about 11.2:1, compared to 16:1 in the production version of this engine. As a result, elevated intake-air temperatures and pressures are required to yield charge conditions at TDC typical of a production engine.

Table 2. Engine Operating Conditions

Parameter	Combusting	Non-Combusting
Engine Speed, RPM	1200	
Nominal GIMEP, kPa	400	-
Quantity of injected fuel, mg	56	
Injection duration, ms (CAD)	0.94 (6.75)	
Actual SOI, °ATDC	0	
Intake oxygen, % (by volume)	12.7	0
Equivalent EGR rate, %	60	-
Global equivalence ratio	0.27	-
Estimated motored TDC density, kg/m ³	22.2	22.2
Estimated, motored TDC temp., K	838	838
Intake temperature, °C	70	72
Intake pressure, kPa abs.	202	206
BDC temperature, °C	78	79
16:1 BDC temperature, °C	49	49
16:1 BDC pressure, kPa abs	129	129

As presented in Table 1, the fuel chosen for both the combusting and non-combusting experiments was a gasoline primary reference fuel (PRF) blend of 71% (by volume) HPLC-grade n-heptane (C_7H_{16}) and 29% (by volume) HPLC-grade iso-octane (C_8H_{18}), or PRF29, to which 1% (by mass) toluene (C_7H_8) was added. This fuel choice was motivated by the need for an optically clean fuel. Like most pure alkanes, n-heptane and iso-octane display very little fluorescence under UV excitation [17]. This is beneficial for the measurement of combustion species like OH and formaldehyde, which require excitation at UV wavelengths. Diesel fuel, on the other hand, contains many absorbing and fluorescing species, which can obscure these measurements. The addition of 1% toluene provided a tracer for the direct measurement of fuel concentration.

This blend of n-heptane and iso-octane was determined to best represent the ignition and heat release characteristics of a typical U.S. diesel fuel. With the engine operating under the late-injection LTC operating condition of Table 2, several n-heptane/iso-octane fuel blends were evaluated and compared to a 2007 emissions certification grade number 2 ultra-low sulfur diesel (ULSD) fuel. The resulting in-cylinder pressure and apparent heat release rates (AHRR) for two of the PRF fuel blends are compared to ULSD in Fig. 2. Both conditions show a prominent first-stage ignition peak near 8° ATDC and a large second-stage premixed burn peak near 12° ATDC, which accounts for about 80% of the heat release. The 71% n-heptane blend (*i.e.*, PRF29) most faithfully represents the ignition and heat release characteristics of the ULSD fuel, though the peak heat release is slightly higher with the PRF29 fuel. The addition of 1% toluene to the fuel did not noticeably

**Figure 2:** Measured cylinder pressure and AHRR under late-injection LTC operating with n-heptane/iso-octane fuel blends and #2 Diesel.

affect the ignition characteristics of the PRF29 fuel blend.

The low boiling points of the PRF29 components also facilitate calibration of the toluene fuel-tracer fluorescence diagnostic, as described in the Optical Diagnostics section. However, the low boiling points also affect in-cylinder vaporization processes, so that the fate of liquid fuel for the PRF29 mixture is likely different than that of typical diesel fuel. However, previous optical experiments under similar conditions have shown that even standard diesel fuel vaporizes rapidly after the end of injection [10]. Since we expect the fuel to be well vaporized prior to combustion and the ignition timing is matched between the two fuels, it is reasonable to deduce that the mixture distributions are likely similar at the time of combustion. Most of the ignition and combustion processes examined in this study occur after the end of injection, so we do not expect significant differences between the PRF29 fuel and standard diesel fuel.

FUEL INJECTOR

The engine is equipped with a Cummins XPI, common-rail fuel injector. Table 1 includes specifications for the high-pressure, electronically-controlled fuel injector. A solenoid-actuated pilot valve and a pressure-balanced needle control fuel delivery in the injector.

The experiments presented here use several 8-hole, mini-sac injection cups (tips), depending on the bowl design. For each bowl design, the injector spray angle was selected so that the nominal spray axis intersected the vertical midpoint of the bowl wall with the piston at TDC. For the 60%, 70%, and 80% piston bowls, the spray angles were 140°, 152°, and 160°, respectively (see Table 1). The eight fuel orifices in each tip were equally spaced and had a nominal diameter of 0.196 mm with no edge treatment (*i.e.*, they are sharp-edged). The rate of injection was measured using a momentum

based meter [18]. To minimize thermal loading on the optical engine, the injector was fired one out of ten cycles and an electric dynamometer maintained constant engine speed.

ENGINE PERFORMANCE DIAGNOSTICS

Cylinder pressure and fuel-rail pressure were acquired simultaneously with the optical data, at quarter crank-angle-degree increments. To thermally stabilize the engine, it was motored for approximately 1 minute and fired for 60 skip-fired cycles before acquiring each set of cylinder pressure data. The AHRR was calculated from ensemble-averaged pressure data using an air-standard first-law analysis (e.g., see Heywood [19]). Prior to calculating the AHRR, the pressure data were smoothed using a Fourier series low-pass filter with a Gaussian roll-off function having a transmission of 100% from 0 to 800 Hz and dropping to 1% at 3360 Hz. These cut-off frequencies were selected to remove acoustic ringing in the cylinder pressure data, while retaining the general features of the AHRR. Using these filter parameters, the apparent start of combustion (first zero-crossing of the AHRR) was generally advanced by about 0.5 CAD compared to the unfiltered data. The delay due to the pressure wave transit time from the combusting jets to the pressure transducer is of comparable magnitude, so that the effects essentially cancel [20]. Additionally, the peak of the premixed burn spike in the filtered AHRR was generally reduced by about a factor of 2, while its width was increased by a factor of 2. As a result, the apparent energy released during the premixed burn (area under the AHRR curve) is virtually unchanged.

LASER SHEETS AND CAMERA SETUP

Three different laser systems generated pulsed illumination for the three planar optical diagnostics, which are described in the Optical Diagnostics section below. First, an optical parametric oscillator (OPO), pumped by the 355-nm third harmonic of an Nd:YAG laser, generated 10-Hz, 10-ns pulsed laser radiation near 568 nm. This 568-nm fundamental output of the OPO was frequency-doubled to near 284 nm with 17 mJ per pulse for the OH fluorescence diagnostic. Second, a 10-Hz frequency-tripled Nd:YAG laser generated 10-ns pulses at 355 nm with 60 mJ per pulse for the combined formaldehyde and PAH fluorescence diagnostic. The 284-nm and 355-nm pulses were separated by less than 1 microsecond, so that the fluorescence images from the two diagnostics were essentially simultaneous compared to relevant engine time scales. Third, the same 10-Hz Nd:YAG laser was reconfigured so that it operated in frequency-quadrupled mode, generating 10-ns pulses at 266 nm with 80 mJ per pulse for the toluene fluorescence fuel tracer diagnostic under non-combusting conditions.

All three beams were converted into thin (less than 1 mm thick) sheets using a combination of cylindrical

and spherical lenses. For the simultaneous OH and formaldehyde/PAH fluorescence diagnostics, the 284 nm and 355 nm beams were combined and overlapped using dichroic mirrors. For the toluene fluorescence diagnostic, a single 266-nm beam was used, without any other beams. As shown in Fig. 1, the sheets entered the cylinder horizontally, parallel to the firedeck (i.e., the bottom surface of the cylinder head). The laser sheets passed through a window in the cylinder wall to illuminate one of the fuel jets that was in-line with the cylinder-wall and piston bowl-rim windows, as depicted in Fig. 3. After being clipped by the window apertures, the sheet was about 35 mm wide inside the combustion chamber.

As shown in Fig. 1, the fluorescence signals were chromatically separated by a 450-nm cut-off dichroic beamsplitter, which reflected short-wavelength ultraviolet (UV) light and transmitted visible light. The UV light was directed to an intensified CCD camera equipped with a UV-Nikkor 105-mm f/4.5 camera lens. A second beam splitter further separated the visible light, directing 10% of the signal to a second intensified camera that was equipped with a Nikkor 105-mm f/2.5 glass camera lens. An intensified 1/8-meter imaging spectrograph received the remainder of the visible light signal, as described in the formaldehyde and PAH fluorescence diagnostic subsection.

The field of view for the cameras is shown in Fig. 3. For the 60% and 70% piston bowls, the field of view is bounded on the left by the fuel injector and on the right by the edge of the piston bowl. For the 80% bowl, the field of view is limited by the size of the piston crown window, which was smaller in diameter than the bowl. As a result, the right side boundary of the field of view was approximately 6 mm short of the piston bowl radius, which has implications for interpretation of the images, as described in the results section.

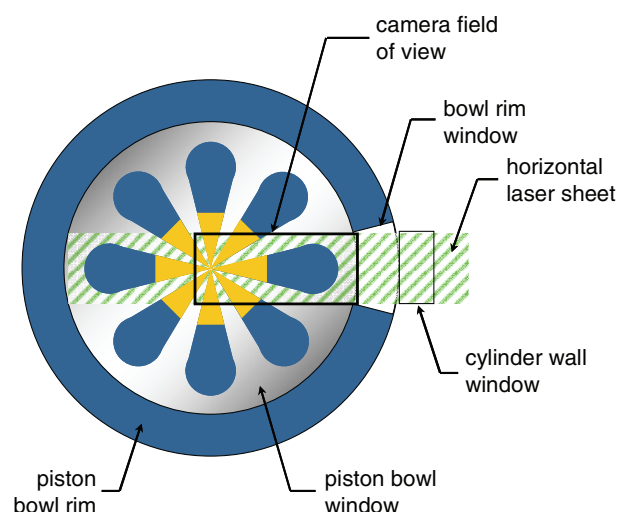


Figure 3. View through piston-crown window, showing bowl-rim window, laser sheet illumination, diesel jet orientation, and camera field of view.

OPTICAL DIAGNOSTICS

Mixing, ignition, combustion, and pollutant formation processes were studied using three different optical diagnostics. Under combustive conditions, planar laser-induced fluorescence of OH was imaged simultaneously with a second diagnostic that recorded formaldehyde and PAH fluorescence in the same image and discriminated the fluorescence using emission spectroscopy. To study the mixture development of the fuel jets, the equivalence ratio was quantitatively measured using toluene fuel tracer fluorescence under non-combustive conditions. Brief descriptions of these diagnostic techniques follow.

OH Planar Laser Induced Fluorescence (OH-PLIF) - OH fluorescence was excited by pumping the overlapping $Q_1(9)$ and $Q_2(8)$ lines of the (1,0) band of the $A \leftrightarrow X$ transition near 284 nm. The UV camera in Fig. 1 imaged the resulting fluorescence emission from multiple rotational transitions in both the (0,0) and (1,1) vibrational bands from 308 to 320 nm range. A set of three filters helped to isolate the OH fluorescence and reject elastic scatter: (i) a 16 nm wide unblocked bandpass filter (BPF) centered at 312 nm isolated the OH fluorescence, (ii) a 358-nm short-pass filter rejected fluorescence from other species and other interference, and (iii) a 2 mm thick WG 305 long-wave-pass colored-glass filter helped to remove elastically scattered laser-light. This technique is essentially the same as that employed previously in this engine, and more details, including the filter selection criteria, can be found in [21].

Interference from broadband fluorescence of other species, including the toluene fuel tracer, formaldehyde, and PAHs, as well as other emission sources (e.g., laser-induced soot incandescence) may occur within the same 308-320 nm band as the OH fluorescence. Fortunately, OH displays a unique, well-defined fine-scale ro-vibrational structure in its fluorescence excitation spectrum. As a result, the OH fluorescence decreases drastically as the laser wavelength is tuned off any of the narrow excitation lines. Therefore, to identify the extent and spatial location of the interference, the OH-PLIF images were acquired from different engine cycles with excitation at two different wavelengths: online, near 284 nm, and offline, near 283.9 nm. A strong contrast between online and offline images indicates that the fluorescence is dominated by OH, while weaker contrast indicates that other sources contribute to the signal. Throughout all image acquisition timings with the low-fluorescing fuel of the current study, interference in the OH fluorescence signal is insignificant, and all of the fluorescence signal may be interpreted as solely due to OH fluorescence. Prior to ignition, the toluene tracer contributed very weak background fluorescence (4.5 % of peak OH) that was absent without the tracer. Because it was so weak, the toluene fluorescence excited by the 284-nm beam was easily distinguished from the much stronger OH

fluorescence. Note that this “clean” fluorescence behavior is in contrast to previous studies using diesel fuel, for which the fluorescence signal is more difficult to interpret because of strong broadband interference [22, 23].

Combined Formaldehyde and PAH Planar Laser Induced Fluorescence (F/PAH-PLIF) - Formaldehyde fluorescence was excited by the 355-nm beam of the frequency-tripled Nd:YAG laser. The resulting fluorescence was imaged by the visible-light camera in Fig. 1, equipped with two filters: (i) a CG385 long-pass colored glass filter, and (ii) a 40-nm wide blocked BPF centered at 408 nm. These filters helped to isolate the formaldehyde fluorescence from other sources of interference, including elastic scattering of the laser light, fluorescence from other species, and laser-induced soot incandescence. Although the filters removed much of the interference, some interference remained within the spectral band of the formaldehyde fluorescence emission. Because of the temporal and spatial location of the interference (as shown in the results), the most likely source is fluorescence from PAHs, and potentially some laser-induced incandescence from soot late in the cycle. Thus, the technique reveals both formaldehyde and PAH fluorescence (F/PAH-PLIF).

Unlike OH, formaldehyde does not display a well-defined fine-scale ro-vibrational structure, especially at the high in-cylinder pressures of engines, which cause significant broadening of its closely spaced lines. As a result, small adjustments to the laser wavelength will not tune off the fluorescence excitation lines for formaldehyde, and therefore formaldehyde fluorescence cannot be verified in the excitation spectrum. Instead, the fluorescence is verified from the emission spectrum, along the jet axis. In diesel jets, the primary gradient in the temporal evolution of the fluorescing species is streamwise, along the jet axis. To detect the changing fluorescence emission signature in the streamwise direction, the jet axis was imaged onto the entrance slit of a Oriel 1/8-meter spectrometer using a 105-mm f/2.5 glass lens. A CG375 long-pass colored glass filter was placed in front of the lens to help reject strong elastic scatter from the laser. The entrance slit width was set to 0.6 mm, and with a 1200 line/mm grating blazed at 350 nm, the nominal spectral resolution was 4 nm. The fluorescence spectrum was imaged onto an intensified CCD array at the exit of the spectrometer, capturing emission from 380 nm to 450 nm.

Formaldehyde displays a distinct emission spectrum, with 7 broad peaks within the spectral range captured by the spectrometer [24,25]. The peaks have nearly uniform spacing in wavelength space, and the Fourier transform of the emission spectrum displays a characteristic two-peak structure near a wavenumber of seven [26]. In a previous study using the same equipment, correlation of the observed fluorescence spectra with a reference formaldehyde spectrum

successfully distinguished formaldehyde fluorescence from other more broadband sources [26]. A similar approach is adopted here. In this study, the reference formaldehyde spectrum, shown in Fig. 4a, is taken from the average of 20 emission spectra acquired shortly after the initial appearance of formaldehyde fluorescence, when the formaldehyde fluorescence was particularly strong and clean (formaldehyde fluorescence peaks were strong). This spectrum, with several peaks rising above an apparent broad background, is typical of formaldehyde fluorescence in engines [27]. By comparison, a typical spectrum recorded shortly after peak heat release, with strong PAH fluorescence, is also shown in Fig. 4a. The spectra emitted by fluorescence of broadband sources like PAH (dashed black line in Fig. 4a) do not display significant spectral structure.

The Fourier transforms of the reference formaldehyde and PAH spectra in Fig. 4a, are shown in Fig. 4b. The formaldehyde spectrum exhibits two distinct peaks at wavenumbers 6 and 8, which correspond to the 7 peaks in the spectrum in Fig. 4a, while the PAH spectrum exhibits no significant structure in this range. The

similarity of the Fourier transforms of other measured spectra, to the reference formaldehyde spectrum are quantified by calculating the statistical correlation to the reference spectrum (see Appendix for details). Spectral signals that exhibit prominent peaks at wavenumbers 6 and 8, similar to the reference signal, have a high correlation value while those that do not (such as the PAH spectrum in Fig. 4b) have a low correlation value. This quantitative comparison of the fluorescence signals offers a simplified and direct method to distinguish between formaldehyde and PAH fluorescence. In the results section, the correlation calculation is applied to discrete sections of the fluorescence images along the jet axis, and a color scale along the axis indicates the strength of the correlation.

Toluene Fuel-Tracer Planar Laser-Induced Fluorescence (T-PLIF)

- The vapor-fuel equivalence ratio was measured by exciting planar laser-induced fluorescence of the toluene fuel tracer (T-PLIF) in a reference-fuel mixture of n-heptane and iso-octane. As previously discussed, we chose a reference-fuel mixture in part because toluene is not a suitable tracer for standard diesel fuel due to the low boiling point of toluene relative to the diesel-fuel distillation temperatures. The boiling points of n-heptane (98 °C) and iso-octane (99 °C) are much more similar to that of toluene (110 °C) than is standard diesel fuel, so that toluene vapor should track fuel vapor reasonably well. As previously discussed, the toluene tracer concentration was selected at 1% (by volume). This concentration balanced signal strength against undue attenuation of the laser light. In a previous study, insignificant attenuation was observed at 0.5% toluene [8]. To help boost signal strength, we increased the concentration to 1.0% in the current study, which still caused minimal attenuation of the excitation beam. Indeed, this tracer concentration is significantly less than the 10% level that showed observable, but not excessive attenuation in other studies in HCCI engines [28].

T-PLIF has a strong dependence on collisional quenching, primarily by oxygen. Because of the non-uniform distribution of oxygen that can occur in the heterogeneous mixtures of diesel jets, corrections for oxygen quenching are quite difficult. Further, ignition and combustion chemistry in the presence of oxygen can consume the toluene tracer, affecting the equivalence ratio measurements. To avoid the oxygen quenching corrections and to study mixing in the absence of combustion, the engine was operated with pure nitrogen in the intake stream. Even in a nitrogen environment, several corrections are required for quantitative measurements, including for temperature and pressure dependence, reflections, and background fluorescence. A detailed description of the T-PLIF technique, including the corrections required for quantitative measurements, is provided in [8]. A brief description of the technique is provided in the following paragraphs.

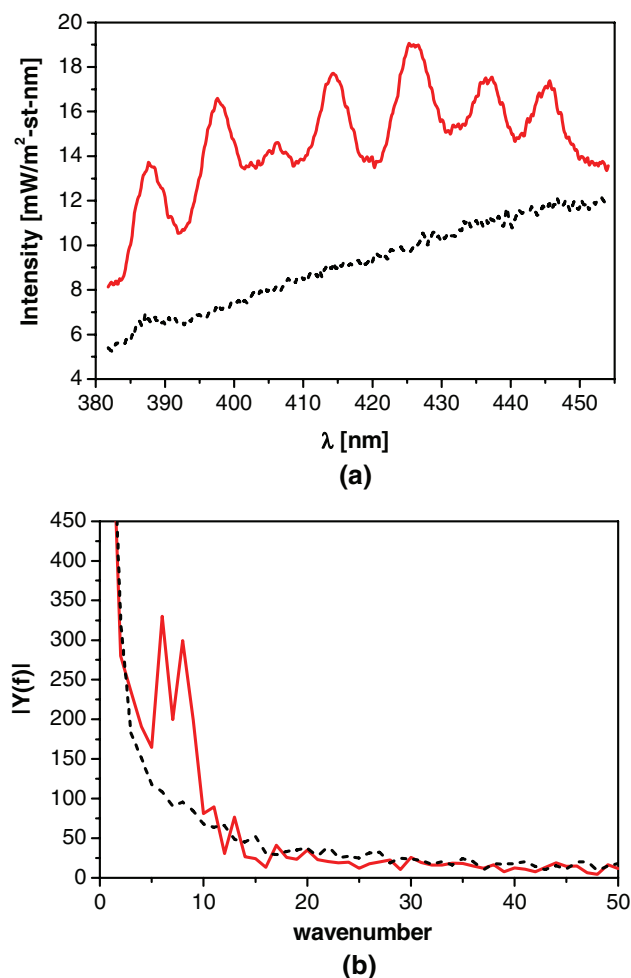


Figure 4. Top: Measured fluorescence spectra of formaldehyde at peak heat release of first-stage ignition (solid, red) and PAH after second-stage ignition (dashed, black). Bottom: Fourier transforms of the spectra.

The 266-nm laser sheet excited the T-PLIF, which was imaged by the UV-camera in Fig. 1. Two spectral filters isolated the T-PLIF signal from laser elastic scatter and other interference: (i) a WG295 long-wave-pass filter and (ii) a 25-nm wide blocked BPF centered at 300-nm.

Quantitative equivalence ratio measurements require calibration of the T-PLIF signals. As described in [8], a relatively uniform mixture of fuel with a known concentration for calibration was generated by injecting fuel very early, during the intake stroke. Because the in-cylinder density and temperature are low during the intake stroke, significant wall wetting would occur with typical diesel fuels. However, the boiling points of the fuel components in the current study (98 to 110 °C) are much lower than diesel fuel components. Furthermore, the fuel component boiling points are comparable to the relatively hot wall temperatures (95 °C or more). As a result, the early injection produces a vaporized, well-mixed charge for calibration [8]. The T-PLIF signals at the standard timing are calibrated against the known, uniform fuel quantity in the early injection, after accounting for temperature and pressure dependencies [8]. For the T-PLIF diagnostic, sets of 50 images were acquired at each desired crankshaft position, from 50 separate cycles with fuel injection. The fuel injection timing alternated from early in the intake stroke (for calibration) to the standard diesel timing near the end of the compression stroke (for diesel injection measurements) to no fuel injection, with the laser on (for background measurements).

Soot Luminosity - In addition to the imaging techniques, combustion luminosity was also directed to a large-area (1 cm²) photodiode, as shown in Fig. 1. A neutral density filter with an optical density of 3 (0.1% transmission) attenuated the light reaching the photodiode so that it would not saturate. For conventional diesel combustion, soot luminosity is typically orders of magnitude brighter than chemiluminescence [20,29]. At LTC conditions, soot and soot luminosity are much lower, but they are still much stronger than chemiluminescence. Thus, the signal from the filtered photodiode represents primarily soot luminosity (non-sooting combustion yields essentially zero signal). The photodiode collected light from the entire combustion bowl, and its signal therefore represents a time-record of the overall combustion luminosity. Note that because the imaging diagnostics only view a portion of the combustion bowl, the photodiode signal may not be representative of combustion processes within the camera field of view. Instead, the photodiode signal provides a general temporal progression of the overall in-cylinder soot luminosity.

Selection of Representative Instantaneous Images - Due to speed limitations of the pulsed lasers (10 Hz), only one image or image pair could be acquired for each engine cycle. Accordingly, to generate a statistical

dataset, images of OH- and F/PAH-PLIF were acquired at each crank-angle of interest in sets of 20, from 20 different engine cycles. A representative image was selected from each set using a correlation technique similar to that used for the formaldehyde spectrum correlation. A two-dimensional normalized cross-correlation coefficient was calculated for each image.

$$r_{2d,xy} = \frac{\sum_i \sum_j (x_{i,j} - \bar{x})(y_{i,j} - \bar{y})}{\sqrt{\sum_i \sum_j (x_{i,j} - \bar{x})^2 \sum_i \sum_j (y_{i,j} - \bar{y})^2}} \quad (1)$$

In Eq. 1, x represents the ensemble-averaged image for a set of 20 images and y represents an instantaneous image, while i and j represent each row and column pixel in the images, respectively. By applying Eq. 1 to each image in the set, the instantaneous image most resembling the ensemble-averaged has the highest correlation coefficient. To compile images of fluorescence measured simultaneously from more than one camera (i.e. simultaneous OH and formaldehyde/PAH), correlation coefficients were calculated for images from each camera separately. The products of the resulting set of coefficients yielded a combined correlation value. Images with the highest combined correlation were compiled into the temporal sequences presented in the Results section.

RESULTS: BASELINE 70% PISTON BOWL

The results are presented in two parts. The first section describes our interpretation of OH, formaldehyde and PAH PLIF under combusting conditions versus T-PLIF under non-combusting conditions for the baseline 70% piston bowl geometry. The second section introduces results from the 60% and 80% bowls to illustrate some effects of piston bowl size on in-cylinder mixture preparation, combustion, and pollutant formation processes.

CYLINDER PRESSURE AND HEAT RELEASE

Figure 5 shows the measured cylinder pressure, AHRR, and soot luminosity with the baseline 70% piston bowl. The pressure data are ensemble-averaged over approximately 360-400 fired cycles. Three main periods of the AHRR that correlate with important events in the fluorescence images are identified in Fig. 5.

1. **Ignition Dwell:** The first important period is the ignition dwell, which is from the end of injection (at 7° ATDC) to the start of second-stage ignition near 8° ATDC. Starting prior to the end of injection, the first-stage or “cool-flame” ignition reactions cause the first bump in the AHRR, which accounts for approximately 5% of the total heat release.