

Measurements of Liquid Length, Vapor Penetration, Ignition Delay, and Flame Lift-Off Length for the Engine Combustion Network ‘Spray B’ in a 2.34 L Heavy-Duty Optical Diesel Engine

W. Ethan Eagle
Sandia National Laboratories

Louis-Marie Malbec
IFPEN

Mark PB Musculus
Sandia National Laboratories

ABSTRACT

This paper presents new measurements of liquid and liftoff lengths, vapor penetration, and ignition delay using the Engine Combustion Network (ECN) ‘Spray B’ injector in a 2.34 L skip-fired heavy-duty optical engine. The data from the Spray B injector, having three 90-micron holes, are compared with previously existing constant-volume vessel data using both the Spray B injector as well as the ECN Spray A injector, which has a single 90-micron axial hole. The new data were acquired using Mie scattering, OH* chemiluminescence imaging, schlieren imaging, and incylinder pressure measurements. This paper presents data from estimated isentropic-core top-dead-center conditions with ambient densities of 15.2 and 22.8 kg/m³, temperatures of 800, 900, and 1000 K, and for both non-reacting (0% and 7.5% O₂) and reacting (13, 15, and 21% O₂) injections of n-dodecane at fuel-rail pressures of 500, 1000, and 1500 bar. Particular attention is given to the data analysis process during transient injection, and boundary condition uncertainty. In addition to the hole of interest (#3), measurements from all three Spray B holes demonstrate that the hole-to-hole variations are small, but may indicate that the influence of internal sac flows, as well as orifice geometry, are important. In addition to the ensemble-averaged data presented here, the full dataset including cycle-to-cycle variability has also been published to an online-database available at <https://ecn.sandia.gov> for computer model validation. A companion paper makes a preliminary comparison of these data to Reynolds-averaged Navier Stokes solutions using Lib-ICE to simulate Spray B with a sector mesh.

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INTRODUCTION

The Engine Combustion Network (ECN) is an international consortium of universities, research labs, and industrial partners that was founded at Sandia National Laboratories in 2009 in response to repeated requests for access to data generated in the Sandia constant-volume spray-combustion vessel [1]. Beginning with Sandia (US), IFPEN (France), Bosch (US), Caterpillar (US), and CMT-Motores Térmicos (Spain), the network has grown to over 30 participating groups. To better understand direct injection internal combustion engine spray combustion, the group’s mission has been to perform and replicate experiments using the same hardware across many different facilities. A collected list of the more than 100 publications generated on spray combustion from group participants can be found at www.sandia.gov/ecn/refs.php. In one example, many contributions from constant-volume combustion vessels were compared, and

recommendations for standardized measurement and analysis best-practices in constant-volume vessels were established [2] and differences in their boundary conditions were assessed [3].

What has been missing from the ECN until now is data from more realistic engine geometries with a moving piston, rather than in a constant-volume chamber or rapid compression facility. The data presented here begins to fill in this gap and is the first of several forthcoming experimental datasets to be made available on the ECN taken in a skip-fired optical engine. One question is the impact that the moving, and more confined geometry has on the spray dynamics and combustion and their comparisons with models developed from data gathered in vessels. Care is taken to ensure that target parametric variations are met with acceptable accuracy, and that any limitations or uncertainties are well documented. Only when these preconditions are met can we make fair and valid comparisons of engine design quantities of interest, such as liquid length, vapor penetration, ignition

delay, and flame lift-off-length (see the companion paper to this work [4].) The measurement of these parameters can be directly related to combustion efficiency and pollutant emissions, as described below.

The liquid length is the distance from the injector that fuel remains in liquid phase (droplets) in the combustion chamber. One practical concern liquid length measurements address is the potential for wall wetting, particularly in small bore engines [5]. Simple scaling arguments related to mixing have been proposed to account for how the liquid length varies with ambient temperature and density, nozzle geometry, and fuel volatility [5, 6]. Under subcritical ambient-pressure conditions, the liquid length of a spray has been shown to depend on primary and secondary breakup mechanisms, and the break-up length can be estimated based on shear-layer scaling arguments [7]. The rocket engine community have efforts in parallel to understand the concept of the break-up length of a jet potential core, a mixing concept related to liquid length, most often in the context of co-axial jets [8, 9]. Though the concept of a liquid length implies multi-phase flow, which is how sprays are typically modeled, there currently exists some uncertainty regarding whether the concept of a liquid-vapor interface remains valid at the super-critical pressures encountered in engines [10].

There are many examples of liquid length correlations in the literature. Their forms vary depending on the presence of cavitation and other factors [11]. Payri [12] considers a power law form for liquid length, LL , as:

$$LL = A_1 d_o^{A_2} C_a^{A_3} \rho_a^{A_4} T_a^{A_5} \Delta P^{A_6} \quad (1)$$

In the equation, A_1 to A_6 are constants, with A_1 to account for units, d_o is the orifice diameter, C_a is the area contraction coefficient, ρ_a is the ambient-gas density, T_a is the ambient-gas temperature, and ΔP is the pressure drop from the fuel rail to the ambient gas. This correlation was developed for injection pressures from 300 to 1600 bar, at top dead-center (TDC) temperatures of 800 and 950 K, and at ambient densities 18, 22, 26, and 30 kg/m³. The nozzle diameter in the experiments varied from hole to hole: 175 μ m, 160 μ m and 155 μ m.

Vapor penetration is an important indicator of the temporal evolution in the general spatial distribution of fuel within the combustion chamber. The two main parameters of interest are the jet tip penetration and the jet spreading angle. Naber and Siebers proposed a mixing model based on a gas-jet analogy that has proved to be a robust method for estimating important mixing phenomena [13, 5]. Measurements of the mixing state compare favorably to this simple model during injection [14], such that information about mixing can be inferred from vapor-penetration measurements. The gas-jet analog has been further extended in recent work to include the influence of real-gas effects and end-of-injection processes on both mixing and ignition [15, 16, 17]. Other methods to predict vapor penetration rely more heavily on empiricism or are only valid during certain periods of injection [6]. A critical piece in these models is an accurate estimate for the spreading angle. Entrainment has been identified as the link between penetration and spreading angle, but only recently have time-resolved measurements of entrainment, penetration and

spreading angle become available [18, 19, 20]. Because of optical diagnostic limitations in this optical engine, only the jet penetration is measured.

Hiroyasu and Arai [6] proposed a correlation based on a physical model for steady jet penetration, $S(t)$, as a function of time into an infinite quiescent environment:

$$S(t) = B_1 d_o^{B_2} \rho_a^{B_3} t^{B_4} \Delta P^{B_5} \quad (2)$$

In the equation, B_1 to B_5 are constants, with B_1 to manage units, and t is the time after the start of injection. This form of the jet penetration correlation is only valid after the establishment of the steady liquid length. Details on this and other models for jet penetration are available elsewhere [21].

Ignition delay is one of the most widely reported metrics of compression-ignition engine combustion. In addition to the influences on ignition delay of fuel chemical and physical properties, spray behavior, interactions with engine geometry, and ambient gas composition, temperature, density, the value of the ignition delay is also sensitive to the analytical method of quantifying it from the raw data [22, 23]. That is, although a general concept of ignition delay can be simply stated as the time between the start of fuel injection and the start of combustion, there are several ways to detect or define the 'start' of fuel injection and the 'start' of combustion. Additionally, the choice of averaging or filtering of the in-cylinder pressure data can result in a significant shift in the ignition delay. Murphy and Rothamer showed that their choice of ignition delay criteria could increase or decrease the ignition delay by roughly ± 0.1 ms across a range of density from 15 to 40 kg/m³, while the use of filtered pressure causes an additional 0.2 ms advancement in ignition delay [22]. This uncertainty is 10 to 20 times higher than the cycle-to-cycle repeatability of ignition delay (0.01 ms) reported here. Nevertheless, the trends in ignition delay for ambient-gas temperatures from 900 K to 1100 K, and for ambient-gas densities of 15, 25 and 40 kg/m³ among various processing methodologies remain consistent and/or identical [22]. Hence, while ignition-delay trends for a given facility are relatively insensitive to methodology, absolute comparison of ignition delays from one facility to another can be highly uncertain due to methodology differences, most typically including different filtering of the pressure data.

Malbec et al. [17] cite a correlation for ignition delay, ID , built on the Arrhenius approximation for the chemical kinetics:

$$ID = C_1 \exp(C_2/T_a) d_o^{C_3} \rho_a^{C_4} P_{rail}^{C_5} O_2^{C_6} \quad (3)$$

In the equation, C_1 to C_6 are constants, with C_1 to manage units, P_{rail} is the fuel-rail pressure, and O_2 is the ambient oxygen volume fraction.

Following ignition, an important combustion metric is the flame lift-off length, which is the distance from the injector to the most upstream extent of the diffusion flame. The lift-off length is typically indicated by the presence of electronically excited hydroxyl radicals (OH*) emitting strongly in the ultraviolet (UV) flame lift-off

length is also an indirect indicator of the ambient-air entrainment that has occurred prior to local combustion that affects soot formation [24]. Increasing the lift-off length is one potential method to achieve soot-free combustion (a so-called leaner lifted-flame) [25, 26]. However, particularly under heavy load, or with injectors with many orifices and therefore close inter-nozzle spacing, the flame lift-off length becomes transient, leading to larger cycle-to-cycle variability [27]. After the end of injection, the lean flammability limit may be reached more rapidly than the flame is able to consume the fuel. Therefore, controlling the fuel injector ramp-down, and/or controlling mixture preparation, is critical to avoiding unburned hydrocarbon emission and maximizing fuel efficiency with long lift-off lengths [28].

Siebers et al. [29] proposed a correlation for the lift-off length, H , as:

$$H = D_1 T_a^{D_2} \rho_a^{D_3} d_0^{D_4} \Delta P^{D_5} O_2^{D_6} \quad (4)$$

In the equation, D_1 to D_6 are constants, with D_1 a constant to manage units. Equation 4 is built on an extensive database of ignition data for ambient-gas temperatures ranging from 800 to 1300 K and for ambient-gas densities between 7.3 and 58.5 kg/m³.

Specific Aims

This paper provides detailed experimental methods and associated measurements of liquid length, vapor penetration, ignition delay, and lift-off length of ECN Spray B taken from the optical heavy-duty diesel engine at Sandia. All data are available for download at <https://ecn.sandia.gov>. Engine measurements of each hole enable a comparison of the target hole #3 with the other two holes of this injector.

Quantification of boundary conditions is one of the core aspects of the ECN community. This paper quantifies the experimental uncertainties of input boundary conditions and TDC variation in ambient-gas pressure, temperature, and density, as well as estimates the impact of moving piston during the injection event. Injector fuel pressure and ambient-gas oxygen concentration are also monitored for variations about their nominal targets. These data represent a first step toward comprehensive characterization, though it is not yet complete; additional boundary condition measurements, including in-cylinder flows, wall temperatures, and exhaust-gas characterization are left as a subject of future work.

The role of experimental uncertainty is highlighted by anticipated future use of Spray B in a variety of engine facilities, where the presence of uncontrollable bias might otherwise prevent fruitful comparisons.

EXPERIMENTAL METHODS

Optical Engine

The Sandia single-cylinder 2.34 L heavy-duty optical diesel engine is based on the Cummins N-series production line. Selected details of the geometry for the engine appear in Table 1, and more detailed specifications have already been published [30]. The Cummins

N-series engine is typical of heavy-duty diesel engines, with a bore of 140 mm and a stroke of 152 mm. These dimensions are retained in the single-cylinder, optically accessible engine. The intake-port geometry of the production cylinder head also is preserved, yielding a quiescent (low swirl) combustion chamber. The optical engine is designed so that the upper cylinder liner separates and drops down from the head without engine disassembly, allowing rapid cleaning of in-cylinder optical surfaces. To provide optical access, the engine is equipped with an extended piston and flat piston-crown window. One of the two exhaust valves has also been replaced with a window, which provides optical access down through the cylinder head and piston-crown windows.

Table 1. Sandia heavy-duty optical engine specifications [30]

Intake valves	2
Exhaust valves	1 ^a
Swirl ratio	0.5
Bore × Stroke	139.7 × 152.4 mm
Bowl width × depth	97.8 × 15.5 mm
Displacement	2.34 L
Compression ratio	11.22:1 ^b
Connecting rod length	304.8 mm

^a One exhaust valve has been replaced by an optical periscope.

^b TDC conditions typical of 16:1 compression ratio are met by boosting and heating the intake stream.

Fuel Injector

The fuel injector is from the ECN family [31], Spray B #211199, with specifications listed in Table 2. Although not used in practical engines, the three-hole Spray B injector has an included angle of 145° compared to 0° in the axial directed Spray A, and so is more representative of the flow turning and needle-sac dynamics of a production injector. Additionally, Spray B has widely spaced sprays compared to a production injector, which facilitates multi-directional optical measurements. Note that previous work shows that one of the strongest factors influencing in-cylinder (external spray) processes for multi-hole injectors is the proximity of other sprays [32]. These spray-interaction effects are purposefully minimized in the three-hole Spray B such that a comprehensive understanding of some aspects of the multi-hole problem is possible before adding other confounding factors.

In previous work with Spray B in vessels, the spray of interest issues from hole #3 (see ECN literature [31] for nomenclature of the holes). However, in the optical engine of this study, the schlieren imaging diagnostic is performed on hole #1 because it is the only hole that can be aligned with the cylinder-head window for vertical pass-through optical access required for schlieren imaging. Measurements indicate that the diameters of holes #3 and #1 are similar [33]. An approximately 300 mm long fuel line with an internal diameter of 2 mm connects the injector to the fuel rail, which has an internal volume of 200 mL and the rail-pressure transducer is 170 mm from the injector. The fuel is n-dodecane (Sigma Aldrich, lot #SHBD4471V, > 99.2% purity).

Table 2. Specifications for Spray B injector #211199 [31]

Common rail fuel injector	Bosch solenoid-activated, generation 2.4
Nominal nozzle outlet diameter	90 μm
Nozzle k-factor	1.5
Nozzle shaping	Smoothed by hydro-erosion
Mini-sac volume	0.2 mm^3
Discharge coefficient at 10MPa pressure drop	0.86
Number of holes	3
Holes #1,2,3 angular position	36.4, -62.3, 180°
Holes #1,2,3 exit diameter	90.9, 91.7, 90.9 μm
Hole pattern included angle	145°

Operating Conditions

To remain consistent with previous studies with this engine, we operate the engine in a skip-fired mode, with 9 motored cycles between each fired cycle. The nominal reference condition at 900 K, 22.8 kg/m^3 , 1500 bar rail pressure and 15% ambient O_2 (by volume) for Spray B is identical to previous work with Spray A. Mono-parametric variations are performed around this reference Spray B operating point. Injection configurations such as timing and duration are kept identical, but fuel-rail pressure and ambient-gas properties are changed, as shown in Table 3. Cases are named based on the variation relative to the base ‘Spray B’ case. At each condition, at least 30 injections are performed, and all reported measurements of liquid length, jet penetration, ignition delay and flame lift-off length are ensemble averages.

The targeted 800 K and 1000 K temperatures at TDC are achieved by adjusting the intake temperature. The 15.2 kg/m^3 density case is achieved by reducing the intake mass-flow (and hence pressure). In addition to the case at 21%, variations in ambient-gas oxygen volume-fraction (13% and 15%) are produced by dilution with a supplemental flow of nitrogen. Fuel-rail pressure is controlled by the set-point of a PID controller to the high-pressure fuel pump. Appropriate adjustments to the throttle position of the needle valve in the fuel pressure-relief return reduce the rail pressure variation to less than ± 10 bar.

To avoid confusion between the timing of the electrical drive pulse to the injector solenoid and the actual fuel-delivery response of the injector, the following nomenclature is adopted:

- Solenoid Energizing refers to the electric drive pulse for the injector solenoid. The start of solenoid energizing (SSE) is thus the start of the electrical current pulse to the solenoid, and the duration of solenoid energizing (DSE) is the time from the start to the end of the energizing pulse.
- Injection refers to the actual fuel-delivery response at the injector nozzle. The start of injection (SOI), i.e., when fuel first emerges from the nozzle, is delayed from SSE because of the electro-mechanical and hydraulic delays in the injector and fuel-rail system. The duration of injection (DOI) is evaluated from the start to the end of visible liquid fuel at the injector

orifice. In this study, the delay is determined from the 67.1 kHz optical Mie-scatter imaging. For this injector, DOI is *not* a linear function of DSE, which is likely due to transient pressure accumulation and needle dynamics and sac-volume effects internal to the injector.

- Hydraulic Delay refers to the time between SSE and SOI, measured to be $323 \pm 15 \mu\text{s}$ using the Mie-scatter setup at 1500 bar rail pressure. For this study, the hydraulic delay is assumed constant for all rail pressures.

The temperatures reported at TDC are estimated by an isentropic compression calculation using real air thermodynamic properties from the estimated bottom dead-center (BDC) temperature and pressure to the measured TDC pressure on a motoring cycle (with no fuel injection). This is intended to represent the temperature of the ‘core’ gases at TDC, for which heat transfer to the cylinder walls is negligible. Pressure at BDC is assumed to be equal to the average intake manifold pressure between 170 and 190 crank angle degrees (CAD), where TDC of the compression stroke is at 360 CAD. A previously developed empirical correlation [34] accounts for heat transfer during induction to estimate the BDC temperature relative to the measured gas temperature in the intake manifold:

$$T_{BDC}[^{\circ}\text{C}] = 0.68 \times (T_{\text{intake}} - 95[^{\circ}\text{C}]) + 95[^{\circ}\text{C}] \quad (5)$$

The TDC density is then computed with the perfect gas equation, taking into account a compressibility factor (Z_{fg}), which is about 1.01 at the considered TDC temperatures and pressures.

Diagnostics

Liquid Length

The ECN recommends diffused back-illumination (DBI) extinction imaging for liquid length measurements [35]. This technique has been selected among others [36] because it is self-calibrating and therefore enables comparison between different facilities without introducing differences based on threshold issues. However, the optical configuration of the engine in this study is not suited for the implementation of this DBI setup because vertical pass-through optical access is not available near the injector. Therefore, a more classical Mie-scattering setup for liquid length (e.g., [5]) is used. Recent evidence suggests that well-calibrated Mie scattering can perform very similarly to DBI [37]. A schematic of this setup is shown in Fig. 1. The sprays are illuminated by a pulsed high-power red light-emitting diode (LED)¹ through a fused-silica window on the side of the combustion chamber. The Miescattering signal is collected with a Phantom v611 color complementary metal oxide semiconductor (CMOS) camera at 67.1 kHz, corresponding to a captured image every 0.11 degrees crank angle (°CA) at 1200 crankshaft revolutions per minute (RPM). The camera is equipped with a 85 mm lens, f/1.4, focused on the firedeck and centered on the injector pip. The LED is triggered at the same frequency as the camera, and the illumination duration is 15 μs . The exposure duration of the camera is 14 μs , and the resolution is 128×128 pixels² in the red color channel², corresponding to $40 \times 40 \text{ mm}^2$ (i.e. 2.8 mm/pixel).

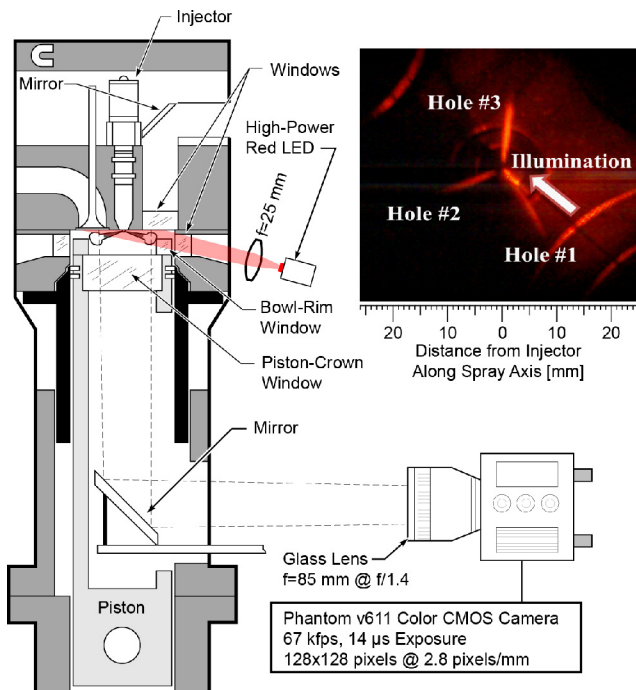


Figure 1. Left: Extended-piston optical imaging schematic with the Mie-scattering setup. Right: Example instantaneous image of Mie-scattering of red LED from liquid fuel from 0.363 ms after SOI at ambient-gas conditions of 800 K, 22.8 kg/m³, and 0% O₂, with 1500 bar injection pressure.

An example image acquired using the 45° mirror placed under the piston-crown window with this setup is shown in Fig. 1. Illumination from the LED is not uniform throughout the combustion chamber, but the total intensity per pulse is repeatable. In this optical arrangement, sprays #1 and #3 receive more light than spray #2. The camera is triggered at SSE, and 1675 images are recorded per cycle, corresponding to approximately 25 ms imaging duration per cycle (i.e., from 355 CAD to about 535 CAD). This long acquisition was

used to also record the eventual dribble occurring after the end of injection, though such data are not included in the current work; instead only the images corresponding to the first 2 ms after SSE are processed here.

The intensity profiles along the axes of the 3 sprays are computed from the images, and a threshold for liquid length is defined as 3% of the maximum value along each, similar to previously proposed methods [5]. The first pixel intensity lower than this threshold along the profile is defined as the liquid length. The distance measured on the image is then converted into a distance along the nominal spray axes, since the image collected on the sensor only gives *projected* distances, not taking into account the included angle of the injector. It is also important to highlight the fact that, because of facility limitations to achieving 22.8 kg/m³ ambient-gas density at TDC with pure N₂, images of the injector liquid length could not be acquired under fully non-reacting conditions with 0.0% O₂. The lowest achievable O₂ volume fraction to achieve the target density is 7.5% O₂ and is maintained across the temperature sweep and injection pressure variation. This decision is supported by a recent global sensitivity analysis for Spray A that did not show an influence of O₂ on liquid length [38].

Vapor Penetration

The vertical optical access through the cylinder-head window and the piston-crown window allows a schlieren diagnostic to image the penetrating vapor. The setup is shown schematically in Fig. 2. The field of view is the intersection of the cylinder-head and piston-crown windows, resulting in imaging of the downstream portion of jet #1, roughly 30 mm to 50 mm from the injector orifice, which passes below the cylinder-head window before impinging on the bowl wall. The configuration of the optical engine does not permit vertical imaging of vapor penetration of jet #3, but holes #1 and #3 have nearly the same orifice diameter as described previously and shown in Table 2.

Table 3. Target experimental conditions for Spray B engine tests

Case name	SprayB	800K	1000K	15.2	13%	21%	500b	1000b
Temperature @ TDC [K]	900	800	1000	900	900	900	500	1000
Density @ TDC [kg/m ³]	22.8	22.8	22.8	15.2	22.8	22.8	22.8	22.8
Non-Reacting O ₂ [% vol.]	7.5	7.5	7.5	0	-	-	-	-
Reacting O ₂ [% vol.]	15	15	15	15	13	21	15	15
Injector rail pressure [bar]	1500	1500	1500	1500	1500	1500	500	1000
Temperature @ IVC [K]	380	340	454	400	392	396	397	390
Pressure @ IVC [bar]	2.25	2.01	2.61	1.54	2.27	2.26	2.28	2.28
Injected liquid mass [mg/cycle]	3.68	3.68	3.68	3.68	3.68	3.68	2.06	2.98
Engine speed [RPM]				1200				
Start of Solenoid Energizing [CAD]				355				
Start of Injection [CAD]				357.25				
Duration of Solenoid Energizing [°CA], [μs]				5.86, 795				
Duration of Injection [°CA], [μs]				11, 1500				

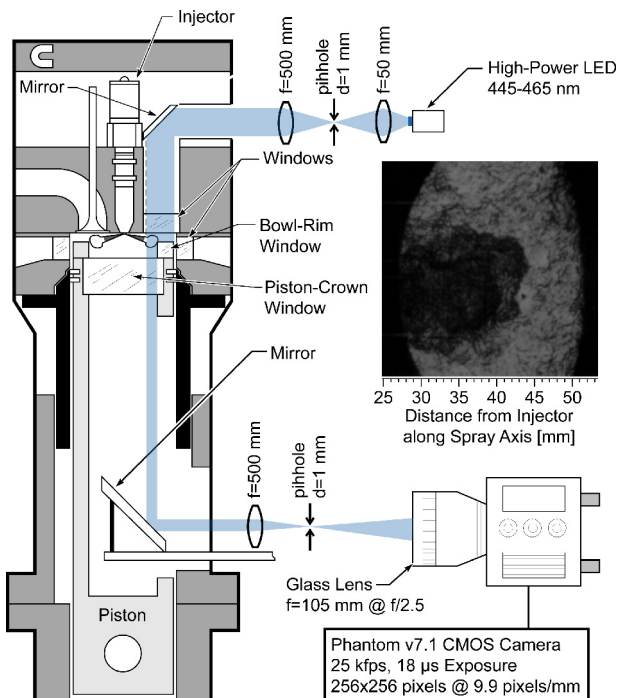


Figure 2. Left: Extended-piston optical imaging schematic with the schlieren setup. Right: Example instantaneous schlieren image at 364 CAD at ambient-gas conditions of 900 K, 15.2 kg/m³, and 0% O₂, with 1500 bar rail pressure.

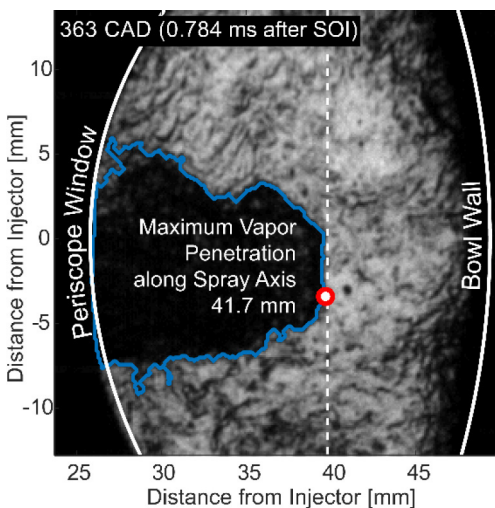


Figure 3. Example of a processed schlieren image at ambient-gas conditions of 900 K, 15.2 kg/m³, and 0% O₂, with 1500 bar rail pressure. The blue line defines the border of the fuel vapor. The red circle is the position of the maximum vapor penetration. The value of the vapor penetration is compensated for the viewing projection and presumed to be along the spray axis, as noted on the figure.

The schlieren light source is a blue LED (445 nm to 465 nm) producing pulses of 5 μ s duration at 25 kHz. The LED is driven in a burst mode and provides uniform illumination intensity. A shorter duty cycle and duration allows for instantaneous currents that temporarily ‘overdrive’ the LED and provide more incident light than it could tolerate at a 100% duty cycle. The LED source is imaged onto a 1 mm diameter pinhole by a 50 mm camera lens. The light

passing through the pinhole is collimated by a 500 mm focal-length spherical lens placed one focal length from the pinhole. The resulting collimated beam is directed through the engine, top to bottom, as depicted in Fig. 2. In front of the camera, another 500 mm focal-length spherical lens focuses the light transmitted through the engine to the bright-field schlieren stop, another 1 mm diameter pinhole.

The light is collected by a Phantom v7.1 CMOS camera at 25 kHz (corresponding to 1 one image each 0.29 °CA at 1200 RPM) with an exposure time of 18 μ s (though the effective exposure duration is set by the LED pulse duration of 5 μ s). The 105 mm camera lens object distance is set to infinity, and the f-stop is set to f/2.5. The camera resolution is 256×256, corresponding to 9.9 pixels/mm (approximately 26×26 mm²).

The processing of the vapor images requires an intensity threshold to separate the dark vapor from the bright background. This value depends on the intensity of the background light and the sensitivity of the schlieren setup. The same threshold is applied to all the images. Because the optical access only permits visualization of the jet between about 26 mm and 50 mm from the nozzle orifice, the processing method proposed by Naber and Siebers [13] cannot be applied. Instead, the vapor penetration is defined as the farthest point of the vapor border from the injector to the injector orifice.

An example of a processed schlieren image is presented in Fig. 3. The blue line is the border of the fuel vapor. The red circle represents the point of the border with the maximum distance to the orifice. Because the view is a projection of the jet into the horizontal plane, a correction for the hole-pattern included-angle of 145° has been applied to determine the true vapor penetration length, as annotated in Fig. 3 where the line at 40 mm indicates a penetration of 41.7 mm.

Flame Lift-Off Length

Using the setup in Fig. 4, the flame lift-off length is measured by collecting the UV emission near 310 nm from OH* radicals excited by combustion reactions returning to their ground states. OH* chemiluminescence is a marker of high temperature, near-stoichiometric combustion that occurs in diffusion flames [39], and OH* chemiluminescence imaging is the lift-off length methodology recommended in the ECN proceedings [40]. A Phantom v7.1 intensified CMOS camera outfitted with a 105 mm UV lens, f/4.5, collects light from OH* chemiluminescence at a frame rate of 7.2 kHz (1 image per °CA) through a 10 nm full-width at half-maximum (FWHM) bandpass filter centered at 310 nm. The images are centered on the injector pip and have a resolution of 512×512 pixels² corresponding to 8.5 pixels/mm (approximately 60×60 mm²).

A sample OH* chemiluminescence image is shown in Fig. 5. Each spray is processed individually. The axes of the jets are defined manually, and then the lift-off length computation is similar to previously proposed methods [41, 40]. The tabulated flame lift-off lengths presented in the results section are ensemble-averages from images acquired between 1.0 and 1.2 ms after SOI. This timing range is selected as representative of a quasi-steady jet after ignition and before the end of injection.

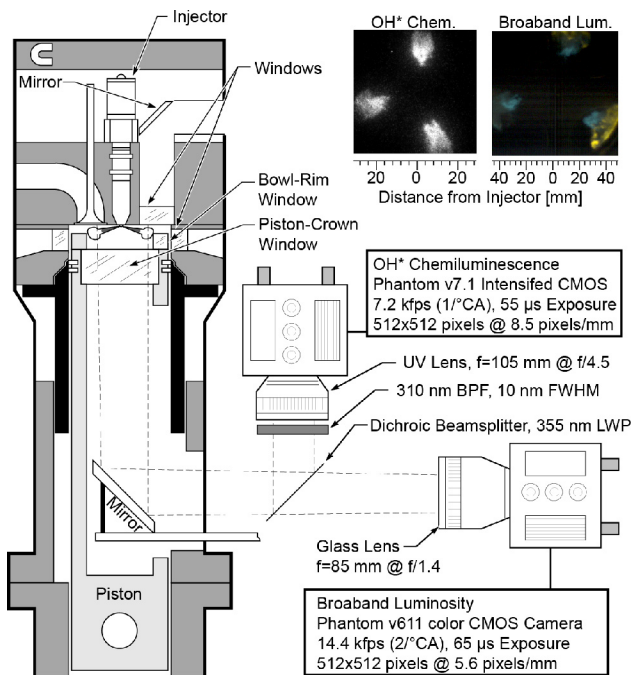


Figure 4. Left: Setup for simultaneous OH* chemiluminescence and broadband luminosity imaging. Top Right: Example images of OH* chemiluminescence (left) and broadband luminosity (right) at 900 K, 22.8 kg/m³, 13% O₂, and 1500 bar rail pressure conditions.

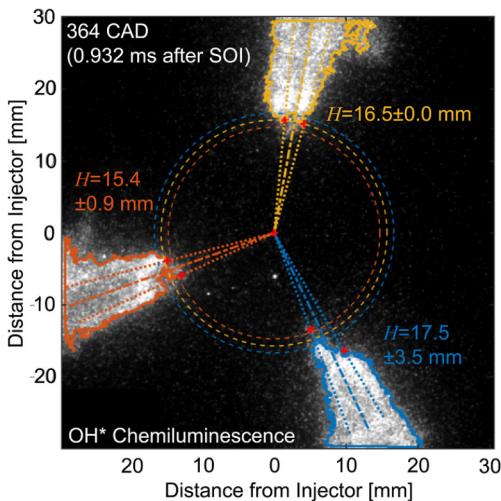


Figure 5. Example of a processed OH* chemiluminescence image, under 900 K, 22.8 kg/m³, 15% O₂, and 1500 bar rail pressure condition, 0.932 ms after SOI (i.e., 364 CAD). The lift-off length, H , of each jet (blue: jet #1, red: jet #2, yellow: jet #3) is processed independently. The dotted lines indicate a 5° angle on either side of the nominal spray axis.

In addition to the OH* chemiluminescence images, broadband combustion luminosity under reacting conditions is collected by the Phantom v611 high-speed color camera through a 85 mm lens, f/1.4, focused on the fire-deck. The field of view is centered on the injector pip and acquired at a frame rate of 14.4 kHz, providing one image at every 0.5°CA. The resolution of the images is 512×512 pixels² (the images are saved after an interpolation on the red, green

and blue pixels, to obtain this resolution), corresponding to 5.6 pixels/mm (approximately 90×90 mm²). The exposure time of the camera is 65 μs. A comparison of these images for lift-off length appears in the [Appendix](#).

Ignition Delay

For all operating conditions, cylinder pressure, fuel-rail pressure, and injector current are recorded at 0.25 °CA increments, simultaneously with the acquisition of the optical data. Other data including fuel return temperature after the injector, engine block coolant temperature, crankshaft RPM, and intake air temperature and mass flow rate, are separately recorded at 1.0 s intervals. The pressure data from each cycle are smoothed using a Fourier series low-pass filter having a transmission of 100% from 0 to 800 Hz that drops to 1% at 3360 Hz with a Gaussian roll-off function. We selected these cut-off frequencies to reduce acoustic ringing in the cylinder pressure data while retaining the general features of the AHRR. The apparent heat release rate (AHRR) is calculated from filtered pressure data using an air-standard first-law analysis (e.g. Heywood [42]).

Using these filter parameters, the apparent SOC, indicated by the first zero-crossing of AHRR, is advanced from the unfiltered data up to 70 μs depending on the magnitude of the pressure rise resulting from the premixed burn following ignition. The peak of the premixed burn spike in the filtered AHRR is typically reduced by about a factor of 2, while its width is typically increased by a factor of 2. The apparent energy released during the premixed burn (area under the AHRR curve), however, is virtually unchanged by this filtering technique. Examples of filtered and unfiltered AHRR are plotted in the Ignition Delay subsection of the results.

Boundary Condition Repeatability

Previous lessons learned from the ECN include the importance of a rigorous assessment and reporting of boundary condition variability [2]. Quantification of the boundary conditions is necessary for the error propagation approach used in the following sections. However, the standard deviation of a set of repeated measurements is only a measure of the repeatability, s_{xi} , of the measurement, and does not include potential bias. To facilitate a discussion of error propagation, the following bias estimates, b_{xi} , are introduced, based on our engineering judgement: 5 K on temperature, 0.2 kg/m³ on density, 0.1% ambient-gas O₂ volume fraction, and 10 bar on pressure. Although these estimates are somewhat arbitrary and actual bias errors may be higher, these values are used consistently across the data.

The resulting fractional uncertainties in the inputs, x_i , are shown in [Table 4](#). Absent column entries in [Table 4](#) indicate that the fluctuation in a value is below detectable limits. For every measurement condition, even using the somewhat optimistic biases assumed above, b_{xi} are always as large as or larger than the measured standard deviation s_{xi} . Thus total uncertainty may still be quite large, even with optimistic bias error estimates.