

Diesel Spray Ignition Detection and Spatial/Temporal Correction

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ABSTRACT

Methods for detection of the spatial position and timing of diesel ignition with improved accuracy are demonstrated in an optically accessible constant-volume chamber at engine-like pressure and temperature conditions. High-speed pressure measurement using multiple transducers, followed by triangulation correction for the speed of the pressure wave, permits identification of the autoignition spatial location and timing. Simultaneously, high-speed schlieren and broadband chemiluminescence imaging provides validation of the pressure-based triangulation technique. The combined optical imaging and corrected pressure measurement techniques offer improved understanding of diesel ignition phenomenon. Schlieren imaging shows the onset of low-temperature (first-stage) heat release prior to high-temperature (second-stage) ignition. High-temperature ignition is marked by more rapid pressure rise and broadband chemiluminescence. The use of multiple pressure sensors also permits charge-amplifier gain optimization tailored to characterize spray behavior rather than the global combustion chamber, thereby providing significantly improved pressure-rise measurement and derived heat-release rate for the fuel spray. Based on pressure data only, this study provides ignition measurement accuracy with temporal resolution below 20 μ s, and with spatial resolution below 5 mm, thereby fulfilling the need for better model validation data.

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INTRODUCTION

To meet current emissions regulations and fill the increasing demand for fuel efficiency, diesel engine researchers are working to develop advanced combustion strategies. The increasing variety and complexity of engine combustion strategies, coupled with an improved capability for predictive numerical modeling, has motivated researchers to look towards computational modeling for guidance. Modern spray combustion models typically combine multi-dimensional computational fluid dynamics (CFD) with chemical kinetics for prediction of combustion and emissions formation [1,2,3,4]. The quality of these numerical models is contingent upon the availability of high-fidelity experimental data for the purpose of validation and improvement [5].

Ignition processes have a strong impact on diesel engine efficiency and exhaust cleanliness [6]. Various parameters

affect ignition timing and heat-release rate, including fuel type, injection hardware, injection timing, and cylinder charge conditions. Therefore, a detailed understanding and ability to model these ignition processes is prerequisite to the control and development of advanced diesel engines.

Researchers have established that the basic sequences of ignition include fuel vaporization and air-fuel mixing, followed by low-temperature (first-stage) heat release and high-temperature (second-stage) heat release (e.g., [6,7,8,9,10,11,12]). Each of these stages is important, but the transition to high-temperature combustion is typically referenced as the ignition delay for diesel combustion because it represents the start of major heat release/combustion, a convention that we will follow in this study. Based on current modeling capability, however, there is still an incomplete understanding of ignition processes in sprays, particularly for many fuels and advanced combustion



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strategies. One level of model fidelity is to faithfully represent the time of ignition. But proper prediction of the spatial location of ignition, as well as the timing, requires much more complete understanding. Typically, the spatial location of ignition is not cross-checked with modeling results, primarily because the spatial location is not known experimentally. Nevertheless, the spatial location of ignition has pronounced effects on combustion and pollutant formation. Recent work has established a connection between the high-temperature ignition location and the flame lift-off length during the rest of combustion, which strongly affects soot formation within the spray [8,9].

Chemical heat-release events, whether within the low-temperature or high-temperature regime, create propagating pressure waves that are detectable by a sensor. The time delay between the creation of a pressure wave and its registration by a pressure transducer depends on the gas properties and the distance that lies between. With knowledge of these properties the time lag can be corrected for the speed-of-sound, provided that the spatial location of ignition is known. In-chamber pressure wave reflections can further complicate pressure signal analysis and obscure relevant heat-release data in noise. Several past publications have focused upon proper handling of pressure and heat-release data acquired in engine [13,14,15], but have neglected to focus on the need to make a speed-of-sound correction. Another study cites the existence of the speed-of-sound time lag for in-cylinder pressure data, but reports that filtering the acoustic waves artificially advances ignition timing, thereby partially compensating for the time lag [10].

In most engine research applications, pressure-based diagnostics are the primary source of information concerning heat release and ignition. Rectifying time-lag-induced errors in pressure data acquired from in-cylinder engine testing using a single pressure transducer is usually not possible. For this reason, the application of engine pressure data for model validation is problematic. Compared to engines with reciprocating pistons, combustion vessels offer a more controlled environment (gas temperature and pressure) that may be preferable for model validation experiments, particularly when equipped with optical access. However, combustion vessels present other difficulties when it comes to pressure and heat-release analysis. Some vessels are continuous-flow, open systems, designed to operate at constant pressure even with combustion. In contrast, pressure analysis is possible in constant-volume chambers, but these vessels typically utilize a large chamber volume for gas temperature boundary condition control, resulting in low rates of pressure rise and poor signal-to-noise ratio in pressure diagnostics. We will demonstrate how to use multiple pressure transducers to minimize signal-to-noise related issues.

Optical measurements are not limited by speed-of-sound concerns, and various chemiluminescence and laser-based diagnostics have documented the progression of ignition from cool-flame (first-stage) reactions to high-temperature

(second-stage) ignition and combustion (e.g., [6,7,10]). However, the lack of temporally correlated pressure measurements prohibits a deeper understanding of these optical measurements. A coupling of optical and pressure diagnostics is needed.

Higgins and Siebers coupled optical (chemiluminescence) diagnostics with measured pressure in a constant-volume chamber by applying a speed-of-sound correction to pressure data to report diesel ignition delays [6]. Their method relied on general knowledge of the ignition location based on a series of optical measurements, to calculate the distance from ignition site to the high-speed pressure transducer. Further definition of ignition location, and its impact on heat release derived from pressure was not warranted because of rather coarse data sampling resolution (28 μ s). Researchers working in all-metal engines have utilized multiple pressure transducers to determine ignition or knock location by triangulation of pressure data [16,17,18]. Without optical access, the ignition location derived from the triangulation routines is unconfirmed. Simultaneous optical and pressure measurements have been applied to understand knock in spark-ignition engines [19], but no attempts were made to determine if knock location could be derived from only the pressure measurement.

In this study we use dual pressure transducers with 5 μ s sampling resolution, together with knowledge of the spray penetration direction, to triangulate the ignition location. Simultaneously, we perform dual high-speed chemiluminescence and schlieren imaging to measure the ignition location timing and position directly. Our unique contribution is to use multiple pressure transducers to detect ignition location under diesel-like conditions, and to optically verify the pressure-based triangulation technique. In addition, we present a validation and demonstration on the usage of schlieren imaging for low-temperature heat release. Discussion is also provided on the proper temporal and spatial determination of diesel ignition events.

EXPERIMENTAL APPARATUS AND PROCEDURE

Experiments were performed in a constant-volume combustion vessel at Sandia National Laboratories. The vessel offers a well-characterized gas temperature and pressure environment, spanning diesel-like conditions, making it useful for fundamental spray studies and a source for model validation data. Detail beyond what is provided in this section can be found in references [6,7,8,20,21,22,23,24].

COMBUSTION VESSEL

The Sandia spray combustion vessel is a pre-burn type vessel designed to generate high in-chamber temperatures and pressures, similar to those of a diesel engine. A premixed charge is spark-ignited and then cooled to the pressure and temperature of interest. A simplified cross-sectional schematic of the combustion vessel is shown in Figure 1.

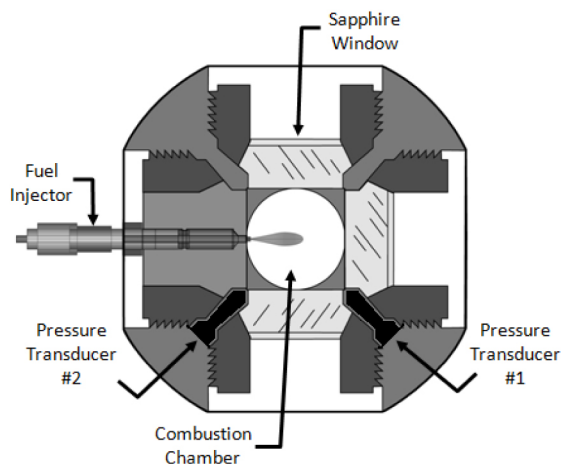


Figure 1. Cross-sectional schematic of the Sandia Spray Combustion Vessel.

The combustion chamber is cubic with six large access ports. For this study, four ports are equipped with sapphire windows and two others house the injector and spark plugs. [Figure 2](#) shows a photograph of the vessel. The photograph captures a diesel spray directed towards the viewer, also visible by mirrors at the left and bottom of the vessel. Notice that there are eight corner ports which are typically used for thermocouples, pressure transducers, intake/exhaust valves, and a mixing fan.

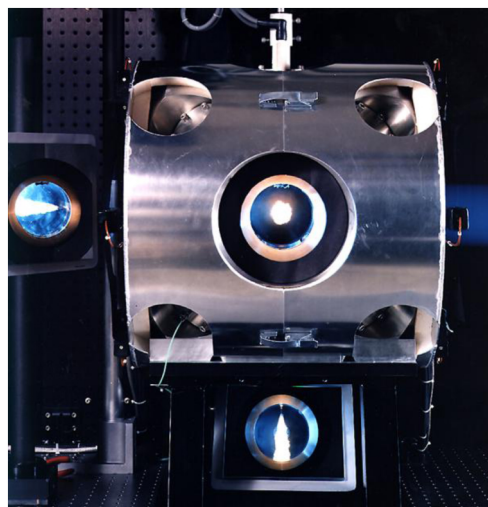


Figure 2. Photograph of the combustion vessel with mirrors showing a flame approaching towards viewer.

Two spark plugs are installed in the top window port of the vessel for pre-burn charge ignition. Much of this study focuses upon the signals acquired from the two pressure transducers which are both labeled in [Figure 1](#). The green wire in the lower left corner of [Figure 2](#) belongs to Pressure Transducer #1. Pressure Transducer #2 is not visible in this photograph, but is installed in the back, lower right corner, opposite the chamber from Transducer #1. As the jet

progresses away from the injector tip, its distance to Transducer #1 decreases, and from Transducer #2, increases. Some basic vessel characteristics are given in [Table 1](#), and more detailed chamber dimensions are discussed in the later section on ignition location triangulation.

Table 1. Basic characteristics of combustion vessel

Width of cube	108 mm
Window aperture	100 mm
Chamber volume	1150 cm ³
Injector mounting	Side window
Mixing fan location	Upper corner (opposite injector)
Fan speed	1000 rpm
Body temperature	461 K

For convenience, the test conditions and experimental setup were chosen to be similar to, or the same as, those specified for the Spray A condition by the Engine Combustion Network [\[20,28\]](#). The high-pressure common-rail fuel injection system is described in [Table 2](#). Additional details on the fuel delivery system and the n-dodecane fuel used can be found in Ref [\[20\]](#).

Table 2. Fuel system properties

Common rail fuel injector	Bosch solenoid-activated, generation 2.4
Injector serial number	210677
Nominal nozzle output diameter	90 μ m
Mini-sac volume	0.2 mm ³
Discharge coefficient*	0.86
Spray angle	0° (single axial hole)
Fuel Pressure	150 MPa
Fuel	n-dodecane
Fuel temperature at nozzle	90°C
Actual inject. duration	6.1 ms
Electr. inject. duration	4.45 ms

*using 10 MPa pressure drop and diesel fuel

Premixed fuel/oxidizer charges are prepared external to the combustion vessel. Hydraulically controlled intake and exhaust valves regulate the charge gas intake and exhausting process. A thermocouple installed in one of the corner ports monitors charge gas temperature prior to the pre-burn. The chamber is equipped with in-wall electronic heaters to maintain the prescribed wall temperature, and prevent spent charge condensation.

EXPERIMENTAL PROCEDURE

External to the combustion chamber a premixed gas charge is prepared composed of a combination of oxygen, hydrogen, nitrogen, and acetylene. The composition, temperature, and pressure of the charge is chosen so that, following its complete combustion, the product gas

composition is as desired for the start of the spray event. The initial reactant mixture may contain excess oxygen such that the product oxygen concentrations are typical of engine conditions (15-21% O₂ concentration). For non-reacting studies, a stoichiometric mixture is used so that the spent pre-burn mixture yields 0% O₂. Density is controlled via charge mass regulation.

At the start of an experiment, the chamber is charged and sealed. A premixed burn is initiated by the spark plugs, increasing both the temperature and pressure of the vessel. The temperature and pressure following the pre-burn are higher than those desired for the experimental spray burn, so the gas charge is allowed to cool via heat transfer to the chamber walls. A mixing fan helps to minimize thermal stratification and promote heat transfer during cool down. Injection is initiated when the in-chamber conditions match those prescribed for the experiment.

The injection duration is 6.1 ms for this study, creating a pressure increase of about 0.15 MPa. The injection duration is short relative to the cool-down time, but long in comparison to a typical diesel spray event. The long injection duration was chosen to allow adequate flame stabilization time over a wide range of test conditions. Figure 3 illustrates a typical pre-burn and injection event pressure history. The pressure increase of the diesel injection event is small in contrast to the peak ambient pressure during the pre-burn.

Following the injection event, the chamber is cooled and vented of the spent charge. A purging process is then initiated, clearing the chamber for the next experiment. Most of the experimental execution is performed electronically by a computer to increase accuracy, repeatability and safety. Detail about standard combustion vessel operation beyond what is provided in this section can be found in Ref. [20].

PRESSURE MEASUREMENT

The two piezoelectric pressure transducers for this study, referred to as pressure Transducer #1 and #2, are identical (Kistler model K-6001). Each transducer was coupled to a charge amplifier (Kistler model 5010) and sampled at 208 kHz with 12 bit A/D resolution. However, the gain setting of the charge amplifier was different for each transducer as described below.

While a large pressure vessel is convenient for well-controlled (near-uniform temperature and pressure) optical diagnostics, achieving detailed pressure information about a spray event is difficult because it only produces a small pressure rise. The spray-induced pressure rise is small because of the small mass of fuel injected compared to the large mass of ambient gas within the chamber. One pressure transducer is typically used in this type of facility, with a dynamic range that spans the pressure range of the entire experiment, in this case 0-12 MPa. The large dynamic range of the full-scale sensor, which for our experiments was Transducer #1, comes at the cost of reduced sensitivity and a

poor signal-to-noise ratio around the pressure event of interest, the ignition and combustion of the diesel spray.

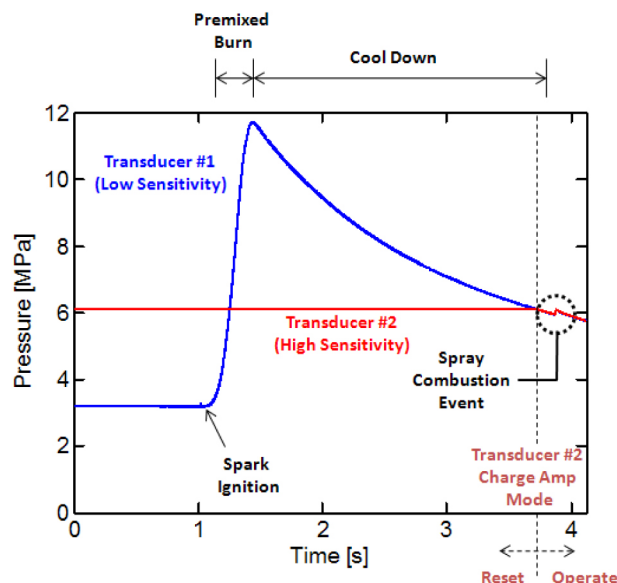


Figure 3. Pressure signals throughout an experiment.

At the expense of total range, the sensitivity of Transducer #2 was increased by setting its charge amplifier to 20 times the gain of Transducer #1. Experiments showed that the system noise was lower by adjustment of the charge amplifier gain compared to applying gain by the analog-to-digital convertor at the computer. With higher sensitivity to pressure, the charge amplifier would saturate and enter overload mode during the filling and pre-burn stages prior to the spray event. Therefore, the charge amplifier was kept in reset mode to continuously drain charge from the transducer until just prior to the spray event, as shown in Figure 3.

Figure 3 shows both pressure transducer signals during the pre-burn and the spray event. The high-sensitivity Transducer #2 is placed in “operate” mode at approximately 3.8 s, just prior to the spray event, and it therefore has no useful pressure measurement prior to this time. Meanwhile, the low-sensitivity Transducer #1 operates throughout the charging of the vessel as well as the pre-burn and cool down stages, avoiding saturation throughout the experiment. The low-sensitivity Transducer #1 also provides a needed reference (pegged pressure) for the high-sensitivity Transducer #2.

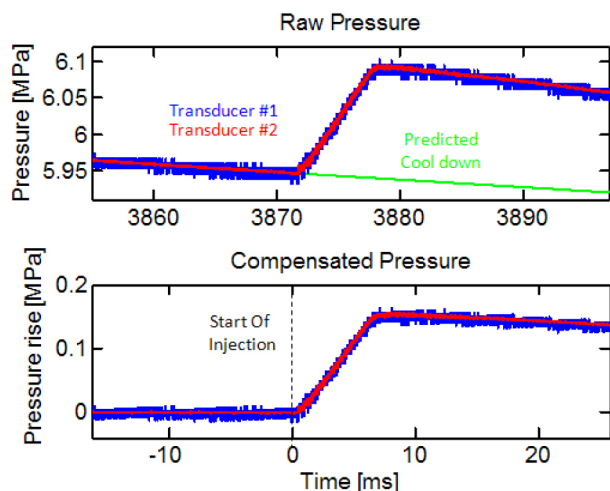


Figure 4. Comparison of pressure signals with and without compensation for heat-transfer and ambient pressure. The time base of the corrected signal has been adjusted relative to the measured start of injection.

During post-analysis, the measured pressure signal is corrected to isolate the spray event. This includes compensation for the rate of charge-to-vessel heat transfer [28]. A comparison between the compensated and uncompensated pressure signals is shown in Figure 4. The fall in pressure prior to injection apparent in the uncompensated pressure signal, is driven by convective heat loss through the chamber walls. The rate of pressure decrease from heat transfer is well characterized by an exponential curve fit, as shown by the green curve at the top of the figure. The compensated pressure rise at the bottom represents the original pressure subtracted by this green curve fit to the pressure decay trend. In this manner, the spray-induced pressure events are separated from the natural vessel pressure decay (heat transfer) prior to injection.

The actual start of injection is detected by monitoring the intensity of a 633 nm HeNe laser which was directed across the tip of the injector. The start of injection measurements were verified through high-speed optical imaging. The compensated pressure signal is adjusted as so that the origin of time reflects the measured start of injection, as can be seen in Figure 4. Since one of our purposes is to determine actual ignition delay, we will show time after the start of injection (ASI) throughout the paper.

We minimize signal smoothing for the bulk of our pressure analysis to avoid the loss of information. As discussed in detail by Musculus et al. [3], both the magnitude and duration of premixed burn may be dramatically altered by typical pressure smoothing techniques, such as Gaussian low-pass filtering. Higgins and Siebers suggested the usage of a cubic-spline fit for smoothing around the time of ignition, as to best preserve the shape of pressure rise [6]. For the limited pressure smoothing performed in this study, we used a cubic-spline type fit, as will be indicated.

Figure 4 also illustrates the dramatic difference in clarity and noise between Transducer #1 and #2. Transducer #1 clearly suffers from a low signal that is affected by A/D digitization resolution (0.005 MPa) and other electronic noise. In principle, a higher A/D bit resolution (e.g., 16 bit rather than 12 bit) would improve the quality of data acquisition for either transducer. As part of this study, we investigated the potential benefits of higher A/D resolution for Transducer #1 by applying additional gain and offset prior to the A/D converter such that digitization effects were not an issue. We discovered that sampling low pressure signals with higher bit resolution did not significantly improve signal quality-the signal quality was much better if gain was applied at the charge amplifier instrument, rather than before the A/D convertor. In other words, the dynamic range of our pressure sampling was limited by the charge amplifier at about 12-bit resolution. Consequently, sampling Transducer #1 with higher A/D resolution would have minimal benefits. Instead, the configuration of Transducer #2 (high charge amplifier gain with reset before the spray) is required. If space allows, a third pressure transducer could enable high-sensitivity pressure signals at multiple locations. However, as mentioned above, one must use a low-sensitivity transducer in at least one position to provide a reference pressure. In this way, the dynamic range of the system pressure measurement is extended to include fill and pre-burn (low-sensitivity) and spray (high-sensitivity) events.

OPTICAL MEASUREMENTS

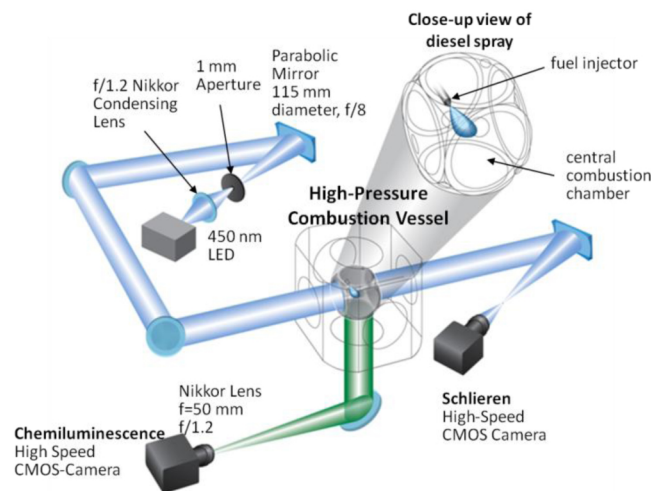


FIGURE 5. Optical setup of high-speed schlieren and chemiluminescence imaging.

Optical techniques were used to visualize ignition and flame progression. Broadband chemiluminescence was imaged at high speed to indicate high-temperature combustion. Simultaneously, high-speed schlieren imaging was acquired to determine the progression and timing of ignition in the vaporizing spray. The camera settings for all of the imaging techniques are listed in Table 3 and the setup is

Table 3. Camera Properties

	Schlieren	Broadband Chemiluminescence
Camera	Phantom v7.1 CMOS	Phantom v7.1 CMOS
Lens	Nikon 85 mm (f/2.8)	Nikon 50 mm (f/1.2)
Filter	450 nm band pass	600 nm low pass
Framing Period	26.25 μ s	50 μ s
Exposure	10 μ s	46 μ s
Resolution	400 x 112	512 x 128

shown in Figure 5. The essential elements of these diagnostics have been documented previously [7,22], therefore, only details specific to this experimental study will be discussed.

The purpose of the broadband imaging setup was to detect a large range of chemiluminescent species that appear at the onset of high-temperature chemiluminescence, as is described in Refs. [10,26,27]. The 600-nm low-pass filter was used to reject higher wavelength thermal emission from species and later soot incandescence, while permitting collection of other radicals (e.g. CH*, C2*). The broad wavelength collection permitted high-speed operation with a shorter camera gate (46 μ s) to temporally resolve the time of high-temperature ignition. Imaging was performed via a mirror at the bottom of the vessel as shown in Figure 5.

Schlieren imaging identifies refractive index gradients within the gas phase. Due to the presence of refractive index gradients, schlieren imaging is effective in revealing the jet/ambient gas boundaries, as well as gradients that exist within the diesel jet. The setup was a classic Z-type system described in Ref. [25]. Illumination was provided by a 450-nm-centered LED, spatially filtered, collimated with an f/8 mirror, and passed through the combustion chamber. On the other side of the chamber, the beam was re-focused by an f/8 mirror, yielding a focal point approximately 100 mm from the camera collection lens. A schlieren cutoff is typically set at the focal point to enable high-sensitivity to refractive index gradients. However, there is sufficient sensitivity at the conditions of this study (high pressure) such that it is preferable to use no schlieren stop [7,22]. This setup may also be called “focused shadowgraphy” [25]. More detail on this technique can be found in Ref. [7].

EXPERIMENTAL CONDITIONS

The experimental matrix consists of variables that intentionally change the location of ignition, thereby providing a test of the diagnostics and processing algorithms. Gas temperature has the most pronounced effect on ignition location and lift-off length, therefore, an ambient gas temperature sweep was performed. Three core gas temperatures are highlighted in this paper: 750 K, 900 K and 1200 K. The core gas temperature is defined as the unmixed temperature of the surrounding jet entrainment gases. The relationship between the bulk gas temperature, calculated

from the measured pressure, and the core gas temperature was determined via thermocouple measurement [20].

As will be shown, a low ambient gas temperature (750 K) highlights conditions with a long ignition delay and an extended lift-off length [6,8,21]. The intermediate core gas temperature (900 K) is more typical of engine operation and it has been identified as the “Spray A” condition of the Engine Combustion Network (ECN) working group. A core gas temperature of 1200 K produces a very short ignition delays and lift-off length. While this study highlights specific operating points as a way to succinctly describe the techniques, other diesel spray ignition delay data benefitting from our methodology and many other diagnostics is now available online [28]. In particular, Sandia and other laboratories have investigated a wider variety of ambient temperature, density, oxygen concentration, and fuel injection pressures as part of the ECN [20,28].

The ambient gas composition and density for this study is given in Table 4. An oxygen mole fraction of 15% corresponds to a diesel engine operating with EGR.

Table 4. Charge and injection gas composition and properties.

	prior to spark ignition [% vol]	at injection time [% vol]
O ₂ [% vol]	22.63	15.00
N ₂ [% vol]	73.82	75.10
CO ₂ [% vol]	0	6.20
H ₂ O [% vol]	0	3.60
H ₂ [% vol]	0.50	0
C ₂ H ₂ [% vol]	3.06	0
Average Molecular Weight [g/mol]	N/A	28.96
Ratio of Specific Heats [-]	N/A	1.319
Density [kg/m ³]	22.8	22.8

IGNITION DETECTION TECHNIQUES

Through a combination of schlieren and broadband chemiluminescence imaging and pressure-based techniques,



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