

Visualization of Diesel Spray Penetration, Cool-Flame, Ignition, High-Temperature Combustion, and Soot Formation Using High-Speed Imaging

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ABSTRACT

Shadowgraph/schlieren imaging techniques have often been used for flow visualization of reacting and non-reacting systems. In this paper we show that high-speed shadowgraph visualization in a high-pressure chamber can also be used to identify cool-flame and high-temperature combustion regions of diesel sprays, thereby providing insight into the time sequence of diesel ignition and combustion. When coupled to simultaneous high-speed Mie-scatter imaging, chemiluminescence imaging, pressure measurement, and spatially-integrated jet luminosity measurements by photodiode, the shadowgraph visualization provides further information about spray penetration after vaporization, spatial location of ignition and high-temperature combustion, and inactive combustion regions where problematic unburned hydrocarbons exist. Examples of the joint application of high-speed diagnostics include transient non-reacting and reacting injections, as well as multiple injections. Shadowgraph and schlieren image processing steps required to account for variations of refractive index within the high-temperature combustion vessel gases are also shown.

INTRODUCTION

High-speed imaging has been shown to be an essential diagnostic for understanding highly transient combustion phenomenon such as diesel spray injection and combustion. For example, shadowgraph/schlieren and natural luminosity imaging yield information about spray penetration, spreading angle, ignition delay time, ignition location, and soot formation (e.g., [1-5]). Such information is needed, and widely used, for improvement of multi-dimensional CFD codes developed for spray combustion. These CFD models are then applied for design optimization of the latest high-efficiency, low-emissions engines.

While early studies employed high-speed film photography that necessitated short image acquisition periods and long delays for film development [1-3], recent advances in highly sensitive digital cameras have made it possible to perform high-speed imaging with improved pixel resolution and framing rates (e.g., [6]). The improvement in technology allows high-speed imaging to be combined with other optical and conventional diagnostics, in a more routine manner, to better understand diesel spray mixing and combustion.

This combination of high-speed diagnostics is especially helpful to current research needs because the complexity of diesel injection and combustion has increased significantly. Modern diesel engines have adopted multiple injections per cycle to improve power output, noise and emissions performance. Fuel injection pressure has also increased. These changes lead to short injection events with little dwell between injections. Understanding the transient history of injection, vaporization, mixing and combustion that precedes a particular injection is therefore increasingly important. Arriving at this understanding by ensemble-averaged data, or by single images during the entire injection sequence, is also increasingly difficult. High-speed imaging diagnostics can help with this problem because they capture the time record leading up to the particular event.

In this paper, we discuss how various diagnostics may be combined with high-speed shadowgraph/schlieren imaging to elucidate the details of diesel spray combustion in an optically accessible combustion vessel. It is the combination of different high-speed diagnostics, along with some new post-processing methods, that are the uniqueness of this work. New insights about the interpretation of shadowgraph/schlieren imaging in reacting single- and multiple-injection diesel sprays are presented.

EXPERIMENTAL APPARATUS

COMBUSTION VESSEL- Experiments were conducted in a constant-volume combustion vessel under simulated, quiescent diesel engine conditions. Details about the combustion chamber geometry and operation may be found in [1]. Ambient and injector conditions were varied to determine how these changes affect diesel combustion. Sapphire windows located in four other ports permit line-of-sight and orthogonal optical access to the injected fuel jet as shown in Fig. 1.

INJECTION EQUIPMENT- A Bosch second-generation common-rail injector (CRIP 2.2) equipped with a single-spray, axial nozzle was used for this study. Results with different nozzle diameter typical of light and heavy-duty engines will be shown. The nozzles are all mini-sac-type, convergent ($K = (d_i - d_o)/10$), hydroground nozzles (KS1.5/86 specification by Bosch). Further details about the nozzles are found in [7].

FUELS- The properties for the certification-grade #2 diesel fuel used in this study are given in Table 1. Although many of the fuel properties are given at room temperature, the measured temperature of the injector tip was 373 K for these experiments. This increase in fuel temperature decreases fuel density and viscosity, as shown at the right of Table 1.

Table 1. #2 diesel fuel properties.

10% boiling point [K]	484	
90% boiling point [K]	588	
100% boiling point [K]	623	
Cetane Index	47	
Cetane Number	46	
Aromatics Vol. %	27.0	
H ₂ mass %	13.28	
Sulfur [ppm]	9	
Low. Heat. Value [MJ/kg]	42.975	
Density [kg/m ³]	843 (288K)	767* (373K)
Kin. Visc. [mm ² /s]	2.35 (313K)	0.95 (373K)
Flash Point [°C]	73	

*Estimated from relation in [3].

OPTICAL DIAGNOSTICS

SHADOWGRAPH AND SCHLIEREN IMAGING- Shadowgraph and schlieren imaging have been used for many years to identify refractive index gradients in various experiments [8]. For vaporizing diesel sprays, these techniques show the boundary between vaporized fuel and background ambient gases because (1) refractive index differences exist between the fuel and ambient gases and (2) density gradients are created in the ambient gases as the vaporized fuel spray cools the ambient [3]. Of course, strong density (and refractive index) gradients are also created at combustion interfaces where the high-temperature combustion creates low-density regions. Shadowgraph/schlieren techniques therefore provide important information about the temperature and composition of the system. In addition to high-speed shadowgraph/schlieren imaging

of diesel sprays [3-5], single-shot shadowgraph/schlieren imaging has been applied to diesel sprays using short-pulse light sources [9-12].

Laser-based techniques can provide more quantitative and spatially-resolved (e.g., two-dimensional) information about mixing, temperature, or combustion radical concentration (e.g., OH, HCHO). However, imaging the time history using laser-based techniques is difficult because of limitations of lasers and/or intensified cameras and most systems resort to a single image acquisition during the event thereby providing little information about the time sequence leading up to the particular image. In addition, quantitative concentration information by laser-based techniques remains difficult because of the harsh engine environment.

Several innovative laser-based techniques have recently been developed to overcome the single-image-per-cycle limitation. Smith and Sick used [13] a high-repetition rate laser coupled to a high-speed intensified camera to provide continuous mixing information in direct-injection spark-ignited engine at a rate of 12 kHz. With this technique, hundreds of successive mixing images are acquired. Alternatively, researchers from Lund University [14,15] have assembled an array of lasers and cameras to operate in a "burst" mode, acquiring as many as eight successive laser-induced fluorescence images over a prescribed period. These techniques add information about the temporal development of mixing and combustion, at the expense of more sophisticated instrumentation.

On the other hand, high-speed schlieren visualization is possible using simple, continuous light sources (e.g., lamps). Although schlieren is a line-of-sight diagnostic, very fast acquisition speeds are possible over time periods resolving the entire cycle or injection and

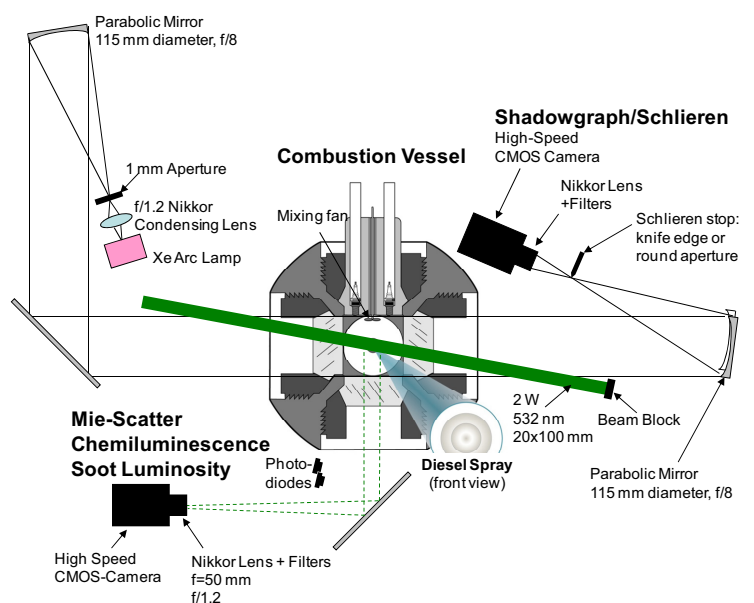


Figure 1. Combustion vessel and high-speed imaging setup. Mirror spacing and angle not to scale.

combustion event. Hundreds of images can be stored to document the event.

Figure 1 shows the lighting and imaging arrangement utilized to perform shadowgraph and schlieren imaging. Also shown is the Mie-scatter laser and imaging setup described in the next section. The setup is essentially the Z-type schlieren setup described in [8]. A 150 W (electrical power) mercury-xenon arc lamp with a small (1.5 mm) arc distance system was used as a continuous white light source. A white light source is convenient, and in fact, preferred in schlieren imaging over a laser because it avoids diffraction (or speckle) effects that occur with coherent light sources [8]. Light from the arc was collected with an 50-mm focal length f/1.2 Nikkor camera lens, offering superior broad wavelength performance compared to a simple achromatic condensing lens. The light was passed through a 1-mm aperture to form a high-quality point source that was collimated by an 115-mm diameter f/8 mirror, offset by a minimal, 5°-angle from the light source. After passing through the combustion vessel, the collimated beam was re-focused using a second f/8 mirror (positioned 760 mm from the combustion vessel center) and a series of flat folding mirrors (not shown in Fig. 1). The converging light reached a focal point approximately 100 mm before entering a high-speed CMOS camera (Phantom v7.1) equipped with several different Nikkor lenses and filters.

For this study, several different schlieren stops were used at the collection focal point as shown in Fig. 1. A knife edge is the classic schlieren stop. The degree of knife-edge cutoff affects the system sensitivity to refractive index gradients. The distance from the test section to the image plane also affects sensitivity. With 0% cutoff (no knife edge), the sensitivity is weakened and the system is technically no longer a schlieren setup, but rather a “focused shadowgraph” [8]. With high cutoff, the sensitivity to refractive index gradients increases. A round aperture can be used as a schlieren stop to remove some of the directional sensitivity to refractive index gradients. Settles [8] refers to an aperture schlieren stop as a “bright field” method, since it tends to leave the background bright, and darken regions where there is a schlieren effect. Alternatively, a full cutoff of the focal spot yields a “dark field” and the schlieren object appears bright above a dark background. These different methods may be useful, for example, in terms of image processing to detect the boundary of a jet. We will discuss the application of these different schlieren stops throughout the paper and in the Appendix.

Several different camera filters, Nikkor lenses, image exposure times, and framing rates were used for schlieren collection, depending upon the particular experimental conditions. Table 2 lists several of the possibilities, along with the image resolution in pixels (camera pixel size is 22x22 μm). In all imaging setups, the field of view was approximately 100-mm, to match the dimension of the combustion vessel. By adjusting

the exposure duration, the background light collection was typically adjusted to fall in the middle of the full camera range (12 bit, 4096 counts) to maximize the dynamic range of the image acquisition. Filter arrangement **A** was used for speed and minimum exposure duration. Filter **B**, a zero-incidence 532-nm mirror, was needed to block laser scatter from spray droplets, if the laser shown in Fig. 1 was turned on. Filter **B** effectively acted as notch filter near 532 nm, while still transmitting a high percentage of the white light source. Consequently, a short exposure duration (5 μs) was used even though the image size was increased compared to **A**. Filter **C** was used under reacting conditions to block intense soot luminosity if it occurred during combustion. The short-wave-pass filter rejected much of the soot luminosity, but also much of the broadband arc lamp, necessitating a longer exposure duration and slower framing rate.

Table 2. Shadowgraph/schlieren system filters and camera settings. The framing period is the inverse of the images-per-time framing rate. Lens focal length (f).

Filter	Lens f [mm]	Framing Period [μs]	Exp. dur. [μs]	Pixels
A) none	50	13.25	2.0	64x256
B) 532-nm 0° mirror	105	34.25	5.0	128x512
C) 450-nm SPF	105	50.0	42	128x512

MIE-SCATTER IMAGING- Scattered light from diesel spray droplets was imaged simultaneously with the shadowgraph system using a second high-speed CMOS camera and continuous-wave laser as shown in Fig. 1. As discussed in Ref. [9], shadowgraph/schlieren techniques alone cannot resolve the liquid-phase of the evaporating spray. The liquid spray may have strong extinction where there is a region of droplets, which appears dark in the shadowgraph image, but strong gradients in refractive index caused by the cool, low-density fuel vapor can also cause dark regions. Another technique must therefore be used to detect the liquid-phase apart from the vapor phase. The time-resolved pair of shadowgraph and Mie-scatter images identifies the instantaneous position of both the vapor and liquid phases of the fuel spray. This information is critical to understand the diesel spray evolution.

The continuous-wave laser source for the Mie-scatter imaging was a frequency-doubled Nd:YAG laser (532 nm) operating with 2 W power. Instead of a laser sheet, the laser beam was formed into a 100-mm wide by 20-mm thick “volume” to illuminate only the liquid-phase region of the spray and also to avoid interference with the shadowgraph setup (Fig. 1). The volume illumination method was utilized to ensure that all droplets spreading from the nozzle were illuminated to identify the maximum axial and radial distances of any liquid-phase fuel [16]. A volume illumination method is also expected to be the most useful for comparison with the shadowgraph technique, as shadowgraphy is also a volume detection technique along a line of sight.

A high-speed CMOS camera fitted with a 532-nm bandpass filter (10 nm FWHM) and a 50-mm focal length f/1.2 lens was used to image Mie-scattered light at a near-right angle to the laser source. The bandpass filter was used to reject background soot and thermal radiation from heated vessel walls. The camera was operated at reduced resolution 48 x 512 to allow fast framing periods (~20 μ s) needed to capture dynamics of very fast diesel sprays. The lens was set to the maximum aperture (f/1.2) and the camera at maximum exposure duration (17 μ s) to intentionally saturate the camera in the dense region of the spray while leaving sufficient dynamic range to identify regions of the spray where liquid completely evaporates. However, changes in laser power or exposure duration did not significantly affect the measurable liquid penetration, similar to [16].

CHEMILUMINESCENCE IMAGING- Broadband chemiluminescence imaging was also performed using the same high-speed CMOS camera and lens as the Mie-scatter imaging, but with no filtering. Visible-transmission camera sensors and lenses may be used for chemiluminescence imaging in reacting fuel jets because of chemiluminescence emission from CH* and other radicals in the visible spectrum and past research has shown that high-quantum-efficiency CMOS cameras are capable of detecting high-temperature chemiluminescence with short exposure durations [17]. In addition, if the Mie-scatter laser is powered, both high-temperature chemiluminescence and liquid-phase regions may be identified. The high-speed chemiluminescence imaging works best for fuel jets that are non-sooting or lightly-sooting because the intense soot luminosity will quickly dominate over the much weaker chemiluminescence. Short-wavelength bandpass filters were not used to reduce soot luminosity because the loss in transmission made the chemiluminescence no longer detectable to the non-intensified CMOS camera.

In addition to the high-speed imaging, single-frame chemiluminescence imaging of specific radicals was also collected during injection. For example, first-stage, cool flame chemiluminescence (such as HCHO*, HCO*) [17] and high-temperature chemiluminescence (OH*) [19] were imaged at a specific time during the high-speed shadowgraph visualization. The imaging arrangement is the same as that shown in Fig. 1, except short-gate intensified cameras, UV lenses and filters were utilized. The specific setup will be discussed as needed below.

PRESSURE, CHEMILUMINESCENCE, AND SOOT LUMINOSITY SENSING- Throughout the image acquisition, other high-speed data was acquired to better understand the imaging results. Pressure measurements were obtained using a piezoelectric pressure transducer located in a lower corner of the vessel, opposite to the injector. The pressure measurements can be used as an indicator of ignition and heat release. In addition, a pair of photodiodes was used to detect the rise in

chemiluminescence at ignition, as well as the rise in soot luminosity after ignition. The photodiodes were positioned to view the entire 108 mm area of the combustion chamber, as shown in Fig. 1. One photodiode was operated with high gain to provide sensitivity to chemiluminescence emission occurring during and after ignition. At this gain setting, this photodiode would saturate when soot forms and there is more intense soot luminosity (incandescence). Accordingly, a second photodiode operating with low gain was also used to detect the level of soot emission without saturation. The spectral sensitivity of both photodiodes is in the range from 300 to 1100 nm.

RESULTS AND DISCUSSION

This section is divided into seven different sub-sections. The first section addresses the need to account for variation in refractive index gradients created by convective boundary layers on the outside of the vessel. The next section continues this discussion and demonstrates how simultaneous Mie-scatter and shadowgraph images are processed to track the liquid and vapor phases of the spray independently. We then show how differences between non-vaporizing, non-reacting, and reacting sprays are used to better understand reaction progress. The next section discusses implications for cool-flame imaging and unburned hydrocarbon detection. In the next two sections, we show simultaneous shadowgraph, chemiluminescence and soot luminosity imaging. Finally, we show how these diagnostics and insights can be applied to understand a multiple injection event.

BACKGROUND VARIATION OF REFRACTIVE INDEX- High sensitivity to refractive index gradients is desired, if one wishes to measure the very outer boundary of a vaporizing fuel spray. However, natural density gradients exist within, and surrounding, the heated combustion vessel and these will create a schlieren effect as well. These variations in background density gradients must be accounted for in order to ensure that schlieren effects caused by the spray are measured, rather than other artifacts.

The background gradients in refractive index (essentially density gradients caused by non-uniform temperature) change significantly as conditions are varied within the vessel. Typically the walls of the combustion vessel are pre-heated to a temperature of 455 K. For experiments with sprays that have minimal vaporization, pressurized gases are fed into the vessel passing through the body of the heated vessel. The temperature of the gases quickly reaches the wall temperature of 455 K and there are minimal non-uniformities of refractive index within the chamber.

For vaporizing and reacting spray experiments, the vessel is filled with a combustible mixture and then spark-ignited to create a high-temperature, high-pressure environment within the chamber. The gases

cool over time by heat transfer to the walls to reach the target pressure and temperature of interest, at which time the diesel spray is injected. Obviously, the temperature cannot be uniform within the chamber because the wall temperature is lower than the gas temperature and strong density gradients are created, particularly near the boundary layer along the wall. A mixing fan, shown in Fig. 1, can be used to prevent strong temperature stratification due to buoyancy effects. Indeed, measurements of the gas temperature within the vessel show that the average core temperature varies by only 1% along the axis of the injector [1]. However, instantaneous fluctuations in temperature do exist, causing variation in refractive index. The gradients in refractive index also become more severe as the ambient density increases.

For experiments where the gases within the vessel are the same as the wall temperature (455 K), there are also density gradients caused by free convection with room air (300 K) outside of the vessel. Therefore, background variations in refractive index are a reality for all experiments with a heated vessel.

To explain our methods of correction for these background variations, we first show an experiment where the vessel wall and internal gases are uniform at 455 K. Figure 2 shows selected images from an original schlieren image sequence on the left, and after background correction, on the right. The schlieren stop was a knife edge, with approximately 80% cutoff, for high-sensitivity to refractive index gradients [8]. Camera setup **A** was used to maximize image acquisition speed,

achieving approximately 75,000 frames per second (fps).

The original schlieren image shows non-uniformities in intensity even prior to fuel injection. These non-uniformities are mainly caused by the free-convection heat transfer on the outside of the window, as discussed above. The vessel is slightly pressurized, to 3.4 bar, but this has no effect on the schlieren non-uniformities because the temperature within the vessel is uniform. The free convection is easily visualized by image sequences of several seconds in length; large-scale structures move slowly upwards in the field of view. During injection, the spray appears dark because of extinction and scattering by liquid droplets, in addition to any schlieren effects. Liquid droplets are present because the 455-K temperature is too low to vaporize significant diesel fuel [3], which Table 1 shows has a boiling point temperature of approximately 600 K. Although the spray penetrates across the chamber, the background features remain essentially constant during injection. We can use this fact to correct the images for background variation.

The right images show the result after background correction, where the image intensity before injection (I_0) has been subtracted from the image intensity at any time during injection (I). An offset is also added so that the images have the same grayscale level in the ambient as before, and the images are shown with more contrast to highlight features of the spray. This is why the spray appears darker, for example. The background correction appears to work well as the ambient now appears flat. The correction scheme capitalizes on one of the advantages of high-speed imaging in that the background immediately before injection is recorded. Background images acquired at a different time, or time-averaged, would not work.

With the background correction, more interesting characteristics of the spray penetration are now visible. A shock wave is generated as the spray penetrates for a time at supersonic velocities [20]. The spray eventually decelerates as it mixes with the ambient and a detached, bow shock wave is formed. The shock wave reaches the back wall of the vessel and is reflected back towards the incoming spray, as indicated on the figure. Note that shock waves are not formed at all diesel injection conditions, because the ambient gas temperature and density are usually higher than those shown here [20]. Recall that the gas temperature is only 455 K, producing slower sonic speeds than that of the gases at top-dead-center (TDC) in an engine (e.g., approximately 900 K).

The need to account for background variations in the shadowgraph/schlieren images is demonstrated, in principle, in this section but the problem of background variations is much more severe at high-temperature, high-pressure conditions. We will continue to address

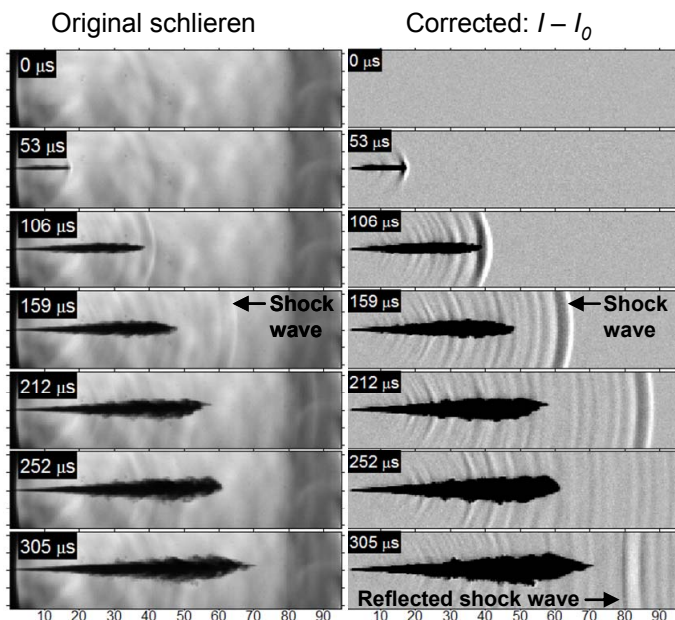


Figure 2. Schlieren imaging of a penetrating fuel spray with the vessel and gases at 455 K. (Left) Original schlieren image. (Right) After background correction using the image intensity before injection I_0 . Schlieren setup **A**. Ambient conditions: nitrogen, 455 K, 2.55 kg/m³, 0.34 MPa. Injector conditions: #2 diesel, 373 K, 150 MPa, 0.094-mm nozzle. Image scale in mm from the injector.

the factors that affect background variation, and methods for correction in the following sections.

SIMULTANEOUS LIQUID AND VAPOR IMAGING- A demonstration of simultaneous liquid and vapor high-speed imaging is shown in Fig. 3. The figure shows Mie-scatter imaging of liquid droplets at the left, original shadowgraph images in the middle, and background corrected shadowgraph images at the right. For this particular experimental condition, the temperature and pressure are fairly low as may be expected for an early-injection timing well before TDC in an engine [7]. However, the temperature is still higher than the vessel wall temperature, which will create density gradients within the vessel.

The Mie-scatter images show an intense liquid core region that saturates the camera during the time of injection. The time after the start of injection (ASI) is given at the image top-left. The injection event is brief, lasting only approximately 200 μs (0.7 mg fuel). After the end of injection (AEI), the spray detaches from the nozzle and continues to penetrate across the chamber. Liquid at the center of the spray is eventually evaporated. Blue lines are shown on the figure at liquid regions with a grayscale threshold of 3% of full scale to indicate the liquid-phase boundary of the spray.

The shadowgraph images in the middle, overlaid with this same liquid boundary in blue, show that liquid remains at the leading edge of the spray well after the

end of injection. In addition, the liquid region appears quite dark in the shadowgraph image, probably due to extinction and significant refractive-index-gradient steering of the shadowgraph beam. Although the shadowgraph and Mie-scatter imaging is performed at right angles to each other, there also appears to be fair coincidence between “dark” shadowgraph regions and the liquid boundary region. Subtle differences between the computed liquid and vapor boundaries are also believed to be caused by differences in exposure duration (5 μs for shadowgraph and 17 μs for Mie-scatter), particularly at early penetration times when the spray velocity is high.

Although the liquid eventually evaporates, the shadowgraph image shows that fuel vapor remains in the region extending back to the nozzle and in the head region of the jet. The location of these fuel vapor regions is, of course, important to the final combustion of the fuel. For this condition, we have purposefully suppressed combustion by injecting into an inert (0% O_2) environment.

The remaining vapor regions are somewhat difficult to visualize in the original shadowgraph images because of the “background” refractive index gradients that exist in the original ambient gases prior to injection. As already discussed, these features are caused by temperature gradients found in the ambient gases and in boundary layers at windows of the vessel. Although specific features in the background do not appear to change

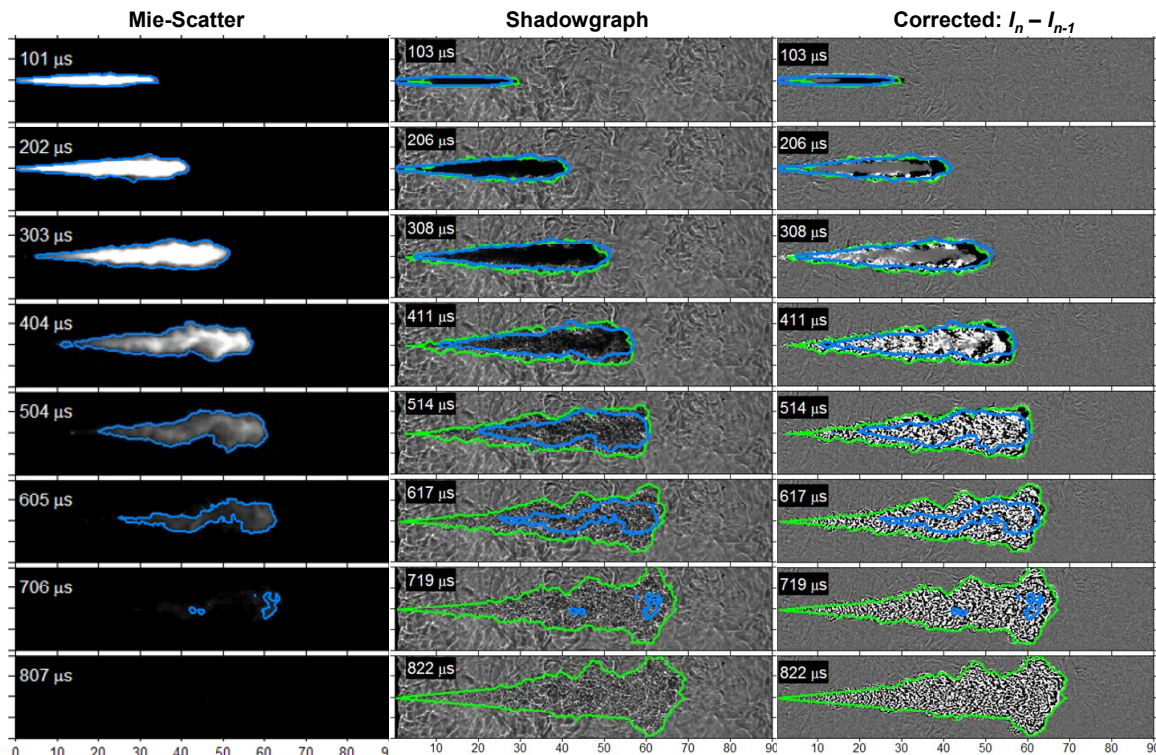


Figure 3. Simultaneous (left) Mie-scatter and (middle) shadowgraph imaging time sequence. A corrected shadowgraph image is also shown at the right. The low-level boundary (8 cts) of the liquid phase is shown in blue in all images. A boundary for the vapor phase is given in green for the shadowgraph images. Shadowgraph collection using setup **B**. Ambient conditions: 600 K, 5.22 kg/m³, and 0% O_2 . Injector conditions: 0.108 mm orifice, 110 MPa pressure, diesel fuel at 373 K, 200 μs injection duration. Scale is distance in mm from the injector.

significantly during injection, a simple correction using the intensity of the background prior to injection does not work effectively, as it did for Fig. 2. The reason is that the finer structure in the background of the shadowgraph in Fig. 3 actually does change slightly during the course of injection. A potential solution to this problem is to use the background from a preceding image for the correction. The right of Fig. 3 shows this result, which is literally the intensity of the current image (I_n) minus the intensity of the previously acquired image (I_{n-1}) plus a grayscale offset. For the camera settings used for Fig. 3, there is only 34 μs between acquired images and there is little change in the background during such a short time.

The corrected shadowgraph images at the right now show that the vapor region of the jet is unambiguous. The correction method makes any part of the image that does not change from frame to frame indistinct, appearing as solid gray regions. Some regions of the jet, like the dense core of the spray, therefore appear rather gray. However, the motion of the jet tends to cause changes in most of the regions of the jet between successive frames. The head of the penetrating jet generally appears dark, and drift in small-scale structures behind the jet, make the edges of the jet recognizable. These variations allowed development of software to detect the edge of the vapor region, as shown by the green border line in Fig. 3. The details of this software will not be explained here, but they can be summarized as an edge-detection that is in agreement with obvious boundaries shown by eye. This vapor boundary detection method is used for results presented here and in other papers [7]. Once again, the success in eliminating background effects is enabled by high-speed, successive imaging, where previous frames can be used to account for background variation.

We will demonstrate the success of these background correction techniques in higher ambient-temperature, ambient-density environments in following sections. These corrections have been applied with success in ambient densities as high as 30 kg/m^3 , but a high camera framing rate is required to reject variation in the ambient gases and accept variation in the moving spray. It is also helpful to examine both the original shadowgraph and corrected shadowgraph to view the dense spray region, or any other region of the spray that may not change between successive frames.

The variation in the background ambient can be decreased by decreasing the refractive index sensitivity of the system through adjustment of the position of optical components (see [8]). However, these adjustments also decrease the sensitivity of the system to detect the vapor boundary of the spray. Alternatively, the addition of schlieren stops increases the sensitivity of the system to refractive index gradients, which isn't necessarily desired since it makes the background more non-uniform. In fact, the "focused shadowgraph" method used in Fig. 3 appears to have the necessary sensitivity

to detect the vapor boundary without any schlieren stops, most likely because the higher ambient density naturally creates strong gradients. For this reason, we have primarily used the shadowgraph system for high-temperature, high-pressure experiments. The advantages of shadowgraph over various schlieren stops in this environment are discussed in more detail in the Appendix.

This section shows that high-speed shadowgraph imaging, combined with high-speed Mie scatter imaging, can provide simultaneous liquid and vapor boundaries for a developing diesel spray. This information is valuable for understanding many of the processes of diesel combustion. We will continue to apply these joint high-speed diagnostics in subsequent sections.

COMPARISON OF NON-VAPORIZING, NON-REACTING, AND REACTING SPRAYS- The effects of combustion on a diesel spray may be assessed by comparison of a reacting spray to a non-vaporizing (and non-reacting) spray at low ambient temperature (455 K) and also by comparison to a vaporizing but non-reacting spray at high temperature (900 K). Shadowgraph images are shown in Fig. 4 for identical injector and ambient density conditions. The ambient density is more than four times higher than that of Fig. 3, and is more typical for conditions near TDC in an engine. The temperature was varied from 455 K to 900 K to show the effect of temperature on spray vaporization and the oxygen concentration was changed from 0% to 12% to show the effect of reaction. The liquid boundary, obtained by simultaneous Mie-scatter imaging, is shown on the two vaporizing spray shadowgraph images, but not on the non-vaporizing spray as it is all liquid.

To further assess the effect of background variation of refractive index gradients, we show the original shadowgraph image at the left, and after background correction, at the right. The non-vaporizing spray shows no significant background variation with the less-sensitive shadowgraph setup, in comparison to sensitive schlieren setup shown in Fig. 2. A background correction using the intensity before injection is therefore sufficient. However, the background variation in the high-temperature, high-density ambient (the reacting and non-reacting sprays) has a much smaller scale and higher contrast than the low-temperature, low-density conditions shown in Fig. 3. Nevertheless, the fuel spray remains detectable above the background.

At the first time ASI shown (514 μs), the liquid and vapor phases of the spray have already separated in the vaporizing sprays (non-reacting and reacting). Liquid penetrates to about 20 mm, but no further. This is in contrast to the non-vaporizing spray, where the liquid droplets cause light extinction throughout the entire spray, appearing as dark regions in the shadowgraph images. Although not as dark, the vapor head of the non-reacting and reacting jets is clearly visible and has about the same appearance in the original and corrected