

Comparison of Near-Field Structure and Growth of a Diesel Spray Using Light-Based Optical Microscopy and X-Ray Radiography

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ABSTRACT

A full understanding and characterization of the near-field of diesel sprays is daunting because the dense spray region inhibits most diagnostics. While x-ray diagnostics permit quantification of fuel mass along a line of sight, most laboratories necessarily use simple lighting to characterize the spray spreading angle, using it as an input for CFD modeling, for example. Questions arise as to what is meant by the "boundary" of the spray since liquid fuel concentration is not easily quantified in optical imaging. In this study we seek to establish a relationship between spray boundary obtained via optical diffused backlighting and the fuel concentration derived from tomographic reconstruction of x-ray radiography. Measurements are repeated in different facilities at the same specified operating conditions on the "Spray A" fuel injector of the Engine Combustion Network, which has a nozzle diameter of 90 μm . Long-distance microscopy at >100 kHz speeds is used to characterize the opening, steady, and closing phases of injection. X-ray radiography (5 μm beam width) is applied from multiple positions and projection angles. Tomographic reconstruction for the ensemble-average fuel mass distribution (or liquid volume fraction) shows that the near-field mixing layers and growth are related to the nozzle exit geometry, with an intact liquid core moving downstream to approximately 2.5 mm. Optical microscopy at various thresholds identifies boundaries of the spray which correspond to low mixture fraction near the detectable limit of the corresponding x-ray measurement. Defining the spray edge as that with an optical thickness of approximately one, the corresponding projected fuel mass from the x-ray measurement is on the order of only 1 $\mu\text{g}/\text{mm}^2$. Radiography-reconstructed planes at the spray center show local LVF of approximately 1% at the same spray width/edge. We recommend that these values be used as a quantitative projected mass or LVF for the spray "edge" derived from optical backlit microscopy.

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INTRODUCTION

Engine combustion simulation and optimization relies upon the accuracy of fuel spray mixing prediction. However, experience shows that existing spray models lack true predictive capability in practice, leading the design engineer to iterate with spray model constants and boundary conditions. Reviews of overall CFD engine simulation capability even call spray modeling *the* major uncertainty [1,2]. Sources for these uncertainties lie in the complexity of the high-pressure liquid flow passing through intricate injector and nozzle geometries and the two-phase mixing with the charge gas outside of the nozzle. Even subtle changes in injector hardware can create variances in basic spray parameters such as penetration rate and spreading angle.

Developing an understanding of the downstream spray breakup or dispersion leads one back to the nozzle exit itself, or even within the nozzle. This dense spray region is difficult to probe using optical diagnostics, but it is possible to track the outer boundary and extent of the spray, including its instantaneous structure. With typical injector hole diameters of only 0.1-0.2 mm, optical measurements require long-distance microscopy to visualize the near-field development within the first few millimeters of the hole [3,4,5,6,7,8,9,10,11,12,13,14]. Likewise, ballistic imaging [15-16] and x-ray phase-contrast imaging [17-18] are applied to assess the structure of mixing layers at the edge of the spray in the near field. Typical quantities returned in these studies include spray width and spreading angle. More detailed experimentation and analysis at the spray periphery reveals instability length scales and droplet size. The growth rate of the spray has been shown to

depend upon nozzle shape [3,4,11], upstream cavitation [11], needle valve position [9], and distance from the nozzle [14], among other parameters.

Theoretically, a measured spray width and spreading angle could be used to guide understanding and spray model boundary conditions. However, further consideration reveals that there is no quantitative fuel concentration or liquid volume fraction (LVF) to associate with the measured spreading angle when using the optical techniques listed above. The specification of spreading angle itself is incomplete without this information, and consequently, there is no direct way to guide model inputs or compare to model outputs with surety.

Quantitative measurement of fuel concentration in the dense region of the spray has been pursued using x-ray radiography [e.g. 21,22]. Monochromatic x-rays originating from a synchrotron source are passed through the spray to measure the total fuel mass along a line of sight. Recent developments to decrease the x-ray probe size from approximately $15 \times 100 \mu\text{m}$ [21] to just $5 \times 6 \mu\text{m}$ [22] and to increase the power of the x-ray beam have enabled a new quantitative analysis for fuel density in the near field of the spray with improved spatial resolution. Using ensemble-average fuel mass projection data from four different viewpoints to assess asymmetry in the spray, the local fuel concentration (or LVF by use of the liquid density) has been computed along the radial direction at axial distances greater than 3 mm [21]. As quantitative, spatially resolved LVF information is generated, this type of data can potentially be used to evaluate model predictions of the near-field spray more critically. However, the uniqueness of a monochromatic synchrotron source means that the x-ray diagnostic cannot be widely applied to study sprays at commercial or research laboratories throughout the world.

The major objective of this paper is to compare the spray dispersion and spreading angle using backlit optical microscopy to the quantitative LVF derived using x-ray radiography. By performing measurements on the same injector at similar operating conditions, our goal is to provide a relationship between x-ray and optical measurements in sprays, thereby providing understanding and interpretation for the more common optical measurements applied in the engine development process. A second major objective is to revisit the radiography data obtained in Ref. [21] to extract the local LVF very near the injector, in critical regions beginning immediately at the nozzle exit and moving downstream. By so doing, we will characterize the initial mixing layer and intact liquid core of the spray.

The idea to combine diagnostics obtained in different facilities at the same operating conditions comes from the Engine Combustion Network (ECN) working group on spray combustion [23]. Researchers from around the world have applied diagnostics at tightly controlled boundary conditions to develop highly leveraged datasets appropriate to engines, with contributions from many voluntary participants. Because the dataset is extensive, it is a logical focal point for CFD

development and calibration. For this study, we use the "Spray A" operating conditions of the ECN at low-temperature ambient conditions where the fuel vaporization is minimal. At high-temperature ambient conditions (900 K, 60 bar) and at the same ambient density, there are extensive data sets detailing the liquid and vapor penetration, velocity, vapor mixture fraction, ignition timing and location, soot concentration, and so forth [23].

EXPERIMENTAL

The experimental section first describes the x-ray radiography [21] and optical long-distance microscopy [13] setups. Both of these experimental setups have been described elsewhere and so only a brief explanation is provided. Next, the operating conditions in each setup are given.

Fuel Mass X-Ray Radiography

The x-ray radiography experiments in this work were performed at the 7BM beamline of the Advanced Photon Source (APS) at Argonne National Laboratory [20]. A monochromatic beam of x-rays at 8 keV photon energy was focused to a $5 \times 6 \mu\text{m}$ FWHM focus size to probe the spray with high spatial resolution as shown in Fig. 1. The radiography measurements represent a pathlength-integrated measure of the fuel mass along one beam path through the spray. To measure the spatial distribution of the fuel, a two-dimensional raster-scan approach is used, with each point measured from a different set of 256 spray events/injections. Though the data are ensemble-averaged, they are time-resolved, with a temporal resolution of $3.68 \mu\text{s}$. The resulting data provide the line-of-sight integral of fuel mass projected onto a 2D plane.

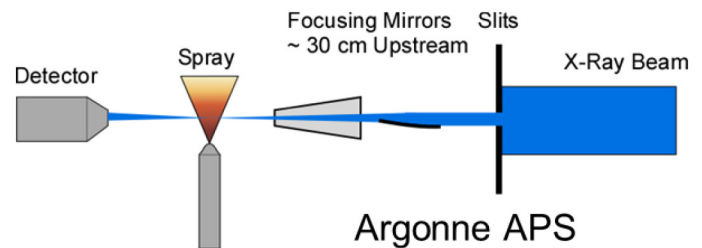


Figure 1. Line-of-sight fuel mass measurement.

Optical Long-Distance Microscopy

Figure 2 shows the high-pressure, high-temperature vessel at Sandia National Laboratories equipped with a diffused backlit optical microscopy system. Sandia's vessel is cubical-shaped with 108 mm on each side and fitted with sapphire windows for line-of-sight access.

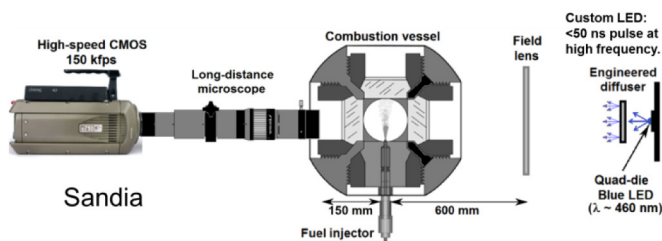


Figure 2. Schematic of the combustion vessel with long-distance microscopy imaging.

Diffused back-illumination with short (50 ns) light-bursts generated by a custom LED is used to “freeze” the motion of the spray [13]. A high-speed camera equipped with a long-distance microscope is used to image the development and structure of the spray at rates exceeding 100 kHz. The lens is configured for a magnification slightly over 4× for a resolution of 4.7 $\mu\text{m}/\text{pixel}$ to image a field of view of about 1.4 mm in a 320×96 pixel region of interest. At this resolution, the image acquisition speed was 156,000 frames per second (fps). Although the camera exposure time was set to 2 μs , the illumination system pulse duration (50 ns) determines the exposure timescale.

The numerical aperture of the system for the main configuration was 0.16 (corresponding to a collection angle of about 320 mrad). Both the resolving power and the diffraction limit are below 2 μm or less than half a pixel, and thus are not limitations in the current imaging system. The actual spatial resolution was assessed in Ref. [13] in terms of contrast quality and a circle of confusion, showing resolution that corresponds to a 13 μm circle of confusion at the conditions of the current study. Note that blurred spray-ambient interfaces will affect quantification of light extinction as will be discussed later.

Operating Conditions

The target condition in either facility for this study is the ECN Spray A condition, with the exception that the ambient density is matched at cooler, non-vaporizing conditions. The nominal specifications for this condition are given in Table 1 (see [23] for more detail), along with the specific operating conditions for the setups at Argonne and Sandia. The argument for a constant ambient density between low and high ambient temperature conditions is supported by research that shows penetration and mixing are determined mainly by ambient density [26], particularly with small nozzle diameter and higher ambient density. Indeed, the ECN database shows that the penetration rate at 440 K is essentially the same as that at 900 K for these conditions [23].

Table 1. Spray A operating conditions.

Injector conditions			
Type	Bosch common-rail #210675		
Nozzle	Single-hole KS1.5/0.86		
Nozzle	0.090 mm, hydroground		
Rail Pressure	150 MPa		
Fuel	n-dodecane		
Inj. Duration	1.5 ms		
Operating cond.:	Spray A	Argonne	Sandia
Nozzle T. [K]	363	333	343
Gas	0 % O ₂	Nitrogen	Nitrogen
Gas T. [K]	900	303	440
Pressure [bar]	60	20	30
Density kg/m ³	22.8	22.8	22.8

Injection into a low-temperature environment is necessary at Argonne in order to prevent damage to x-ray transparent polymer windows. A slightly elevated ambient temperature (440 K) at Sandia is required because of seal design for the high-temperature chamber. The ambient temperature in either facility is lower than the boiling point temperature for n-dodecane (489 K at 1 bar) such that minimal vaporization occurs. However, some vaporization is expected wherever there is low fuel mixture fraction because of the partial pressure of the fuel or increased temperature as the spray decelerates. Note that the measured nozzle tip temperature was also slightly lower than the Spray A specification, but was within 10 K at each institution.

As detailed in Ref. [22], the axial-hole injector was rotated to four different positions for x-ray radiography experiments: -30° , 0° , $+60^\circ$, and $+90^\circ$, with the convention for the orientation of the injector depicted in Fig. 3. The ECN convention is that the fuel tube is vertical at the 0° orientation as shown at the left. The $+90^\circ$ position is when the fuel tube is rotated to the right (facing the injector), as shown at the right of the figure. In this orientation, the projection plane for the radiography data is the x-z plane as the z-axis at $+90^\circ$ is in the vertical direction and the x-rays travel horizontally parallel to the fuel tube.

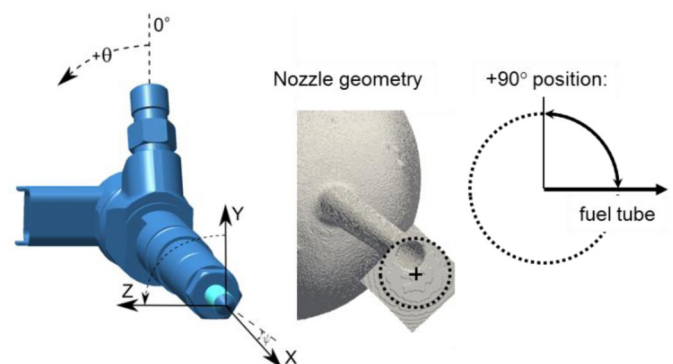


Figure 3. Injector orientation convention and actual nozzle geometry.