

Quantification of Shot-to-Shot Variation in Single Hole Diesel Injectors

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ABSTRACT

Recent advancements in x-ray radiography diagnostics for direct injection sprays at Argonne's Advanced Photon Source have allowed absorption measurements of individual spray events, in addition to ensemble-averaged measurements. These measurements offer insight into the shot-to-shot variation of these sprays in the near-nozzle, spray formation region. Three single hole diesel injectors are studied across various injection and ambient pressures, spanning 14 different conditions.

We calculated two dimensional maps of the standard deviation in line of sight mass distribution between individual spray events. These illuminated the spatial and temporal extent of variability between spray events. Regions of large fluctuations were observed to move downstream during the initial spray period and reached a steady state location after this initial transient. This steady state location was observed to have strong dependencies on rail pressure and ambient pressure, and a weaker dependency on nozzle hole diameter. Regions of elevated shot-to-shot variation in mass may indicate regions of initial instability, spray formation, and mixing.

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INTRODUCTION

The importance of the fuel injection dynamics on performance, efficiency, and emissions has been well established [1]. As manufacturers increase injection pressure, decrease hole size and implement novel injection strategies, an understanding of true operating envelopes becomes critical. Moreover, stringent emissions requirements necessitate a deeper understanding of the role the injection process plays in the in-cylinder combustion.

Capturing both mean and fluctuating behavior is important when validating models against data; however, comparisons of simulations and x-ray data have historically focused on mean flow results. Simulations which take a Reynolds-averaged approach are not representative of an individual event. Large Eddy Simulations (LES) are able to capture the instantaneous events of these spray events and exhibit better agreement with individual event auto-ignition and flame lift-off experiments [2]. Understanding shot-to-shot variation is critical in the understanding of spray dynamics, and comparing the high fidelity LES results with experiments.

Through the last decade, a suite of x-ray diagnostics has been developed at Argonne National Laboratory [3] to examine the structure and quantitative fuel distribution from single- and multi-hole diesel and gasoline sprays. These include phase contrast imaging for internal flow/valve motion and external spray visualization, x-ray radiography measurements for detailed time-resolved quantitative

measurements of the fuel distribution, and ultra-small angle x-ray scattering measurements for droplet sizing. The current work is concerned with the x-ray radiography technique.

X-ray radiography has become a well-established diagnostic for quantitatively measuring the mass of fuel in the near-nozzle spray formation region. These measurements have been applied to both diesel and gasoline sprays [4], as well as gas injection [5]. Additional features which can be extracted include: penetration speed [6], cone angle, spray density [7], liquid axial velocity, [8], entrainment wave behavior [9], and end-of-injection fuel dribble behavior [10]. These measurements are mass-based, and have proven particularly useful for examining the internal structure of the spray and validating computational spray models.

Nearly all of these works have presented ensemble averaged mass measurements, which do not provide any information on shot-to-shot variation. A previous work by Kastengren *et al.* [11] was the first to use x-ray radiography to investigate single shot behavior in an axial single-hole nozzle. A 208 μm nozzle was studied at rail pressures of 500 and 1000 bar, an ambient pressure of 5 bar (N_2 at 25 $^\circ\text{C}$), and a time resolution of 1.84 μs . They presented several ensemble averaged traces at two spatial locations and overlaid a typical single shot trace. The study observed several features including: variability in the leading edge and trailing edge of the spray as a function of rail pressure, noise in the single shot measurements, and an autocorrelation analysis, which exhibited no dominant time scales above 2 μs .

Another set of single shot studies was performed with a tabletop flash x-ray source developed at the Université d'Orléans [12]. The source, capable of delivering nano to microsecond pulses at 5-200 keV (50 Hz rep rate), was used in an investigation of an argon gas jet [13]. The authors were able to obtain single-shot x-ray radiography images of the jet and produce contour curves of the grey levels. While data was qualitative and had a low signal-to-noise, it served to demonstrate the technique's viability to single-shot thermofluid measurements.

The current work spans a parametric space covering 3 nozzle hole diameters, 3 injection pressures, and 3 ambient pressures. The experimental setup and methodology behind the calculations will be discussed. Individual traces will be presented for select condition along with ensemble averages, and ensemble standard deviations. Finally, two-dimensional ensemble average and ensemble standard deviation plots will be presented to visualize the spatial and temporal extent of shot-to-shot variation.

EXPERIMENTAL METHOD

Experiments were performed at the 7-BM beamline at Argonne National Laboratory's Advanced Photon Source [14]. A focused, monochromatic, x-ray beam with a photon energy of 8 keV was passed through a pressurized chamber which houses the injector nozzle. Polyimide windows were used to hold the gas pressure and allow transmission of the x-ray beam. A 75 mm path length of compressed gas existed between the windows. The x-ray beam then passed to a PIN diode, whose signal was recorded by an oscilloscope, then saved to a PC. The PIN diode is a 10×10 mm, Hamamatsu diode, and was assembled by an in-house detector group. A schematic of the setup is shown in Figure 1.

These high-quality, single-shot measurements were a result of recent upgrades to the beamline including: a set of Kirkpatrick-Baez focusing mirrors, the PIN diode detector, and a Yokogawa DLM2054 oscilloscope. The K-B mirrors allowed the focusing of a larger solid angle of x-rays to a smaller spot size (5×6 μm, previously 36×100 μm). This increased both spatial resolution and flux, thus increasing the signal to noise ratio for individual traces. The PIN diode has a wider dynamic range and lower noise than the previously used avalanche photodiode. Improvements to data collection and storage permitted faster acquisition of data, making the collection of large numbers of single-shot events feasible.

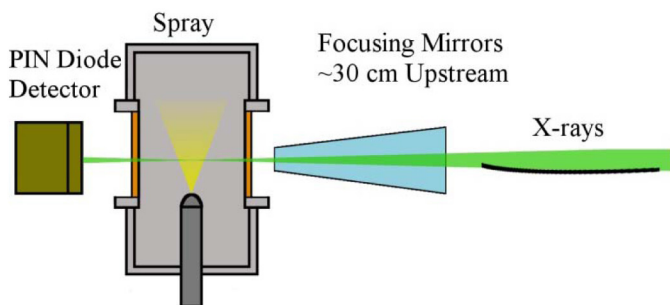


Figure 1. A schematic of the x-ray radiography setup. X-rays travel from right to left.

An automotive common rail diesel fuel system was used in conjunction with a stand-alone injector driver hardware and software package to drive the injector. A series of three nozzles were used in the current work with diameters $D = 110 \mu\text{m}$, $130 \mu\text{m}$, and $180 \mu\text{m}$. All nozzles were mounted on solenoid-actuated injectors, with a nominal geometry of $K_s=1.5$, and were hydro-ground. Gas was continuously purged through the pressure vessel at 4 L/min. The fuel used was a commercial diesel calibration fluid (Viscor 1487), doped with a cerium contrast agent (Rhodia DPX9 at 0.2% Ce of the mixture by mass) to increase the absorption of x-rays.

Three rail pressures ($P_{\text{rail}} = 500, 1000, 1500 \text{ bar}$) were used in conjunction with three ambient pressures ($P_{\text{amb}} = 1, 10, 20 \text{ bar}$) across the three nozzles. A commanded injection time of 1.0 ms was used. These conditions were based on typical values of diesel engine operating conditions. Select combinations of these conditions were performed due to the time intensive nature of the data collection.

A total time of 5ms of data was recorded for each spray event with a resolution of 20 ns. Data was integrated over each x-ray pulse from the 24 electron bunches in the orbit, resulting in a final time resolution of 153 ns. At each location, 32 spray events were individually recorded. The flow field was raster-scanned up to 9mm downstream of the nozzle exit. At each downstream location (X), between 40 and 60 data points were collected in the transverse (Y) direction, for a total of approximately 750 total coordinates. A typical raster scan measurement grid is shown in Figure 2.

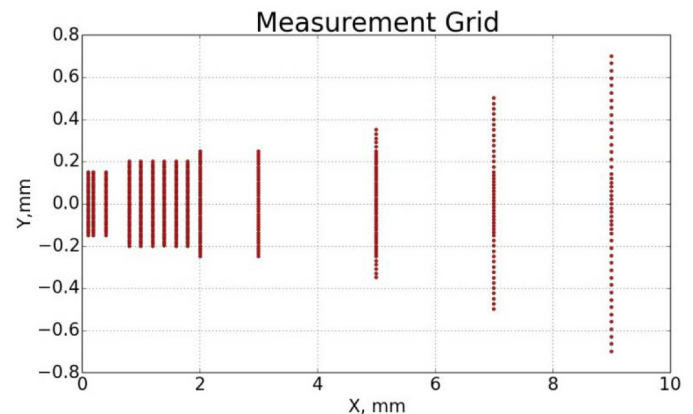


Figure 2. A typical raster scan measurement grid for the current experiments. The nozzle exit centerline is at $X=0$, $Y=0$ and flow moves from left to right.

X-RAY RADIOGRAPHY RESULTS

Methodology

Intensity data are collected by the PIN diode both before ($I_0(x,y)$) and during the spray ($I(x,y,t)$). Through the use of the Lambert-Beer law (Equation 1), the projected mass $M(x,y,t)$ ($\mu\text{g}/\text{mm}^2$) can be calculated. It is a function of both spatial coordinates, x and y , and time, t .

$$\frac{I(x,y,t)}{I_0(x,y)} = e^{-\mu M(x,y,t)}$$

The mass absorption coefficient μ ($\text{mm}^2/\mu\text{g}$) is determined from calibration of the fuel's absorption in a cuvette of known size, and is compared against a liquid with a known absorption coefficient (distilled water).

The ensemble average of the individual traces is calculated via Equation 2, and the unbiased ensemble standard deviation is calculated via Equation 3.

$$\overline{M(x, y, t)} = \frac{\sum_{i=0}^N M_i(x, y, t)}{N} \quad (2)$$

$$M'(x, y, t) = \sqrt{\frac{\sum_{i=0}^N [M_i(x, y, t) - \overline{M(x, y, t)}]^2}{N-1}} \quad (3)$$

Through the use of Equation 3, the spatial extent and temporal dependence of the shot-to-shot fluctuations can be visualized. In the current work, $N=32$ throughout the entire flow field. To calculate $M'(x, y, t)$, the ensemble average, $\overline{M(x, y, t)}$, for each spatial location must be calculated from the 32 events. This yields a single time trace at each spatial location. At each point in time (and at a given spatial location) the standard deviation is calculated from the 32 events and thus the transient standard deviation can be constructed. An example of the results of these calculations is shown in Figure 3.

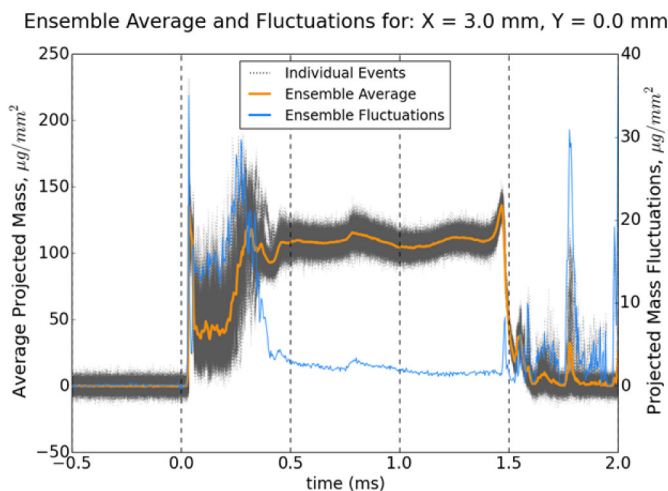


Figure 3. The results of the ensemble average and standard deviation calculations are shown. The data is presented for the 110 μm nozzle, $P_{\text{rail}} = 500$ bar, $P_{\text{amb}} = 1$ bar ambient pressure. Data are taken at $X = 3.0$ mm and $Y = 0.0$ mm (centerline of the spray).

In Figure 3, 32 individual spray events are shown with grey dashed lines, overlaid on each other. The start of injection (SOI) is defined when fuel is first observed exiting the nozzle at the nearest X location to the nozzle exit. This is set to $t=0$ ms. A level of baseline fluctuations is seen before the start-of-injection, which is a result of both experimental noise, and droplets suspended in the chamber from previous spray events. The ensemble average is shown with the orange line. The ensemble average faithfully represents the mean behavior of the individual events over time, but fails to capture the areas of large fluctuations. Lastly, the ensemble standard deviation is

shown in blue. This highlights several regions of interest. These include: “before injection” (BI, $t < 0$ ms), the “start of injection” (SOI, $t = 0$ ms), a region of elevated fluctuations during the spray’s “transition to steady-state” (TTSS, $t = 0$ to 0.3 ms), a drastic reduction in fluctuations during the “steady-state” (SS, $t = 0.3$ to 1.5 ms) period of injection, and lastly, various peaks after “end of injection” (EOI) at approximately $t=1.5$ ms. A spike in the fluctuations is apparent slightly after $t=0$ ms when the fuel first crosses this X location. This spike is due to slight variations in the true start of injection, due to the injection system timing jitter and injector (as measurements are triggered from the commanded start of injection). The timing variations from event to event range from 6-10 μs for all conditions in this work at the nozzle exit. The EOI fluctuations may indicate the presence of fuel dribble from the injector [15,16].

Single Point, Near Nozzle-Exit Standard Deviation Data

A series of single location ensemble standard deviation traces are examined in this section to investigate the effects of rail pressure, ambient pressure and nozzle size. These are taken very near to the nozzle exit. All data have had the mean level of fluctuation prior to injection subtracted, to make comparisons of fluctuation levels above the measurement noise floor. Figure 4 illustrates three traces spanning the different nozzle hole sizes in this study. Data are taken at a rail pressure of 500 bar and an ambient pressure of 1 bar. After the initial SOI spike, each profile exhibits a startup transient. This occurs within the first 0.5 ms for all hole sizes; for $t > 0.5$ ms, the traces approach a steady value before EOI. The steady portion of the profile, seen between 0.5 and 1.4 ms, slightly increases in magnitude with increasing hole size. This increase may be due to the increased fluid volume along the line of sight with increasing nozzle size. Additional fluctuations may occur because of this additional volume. Lastly, at EOI there is a large increase in the fluctuations as the nozzle ejects fuel dribble.

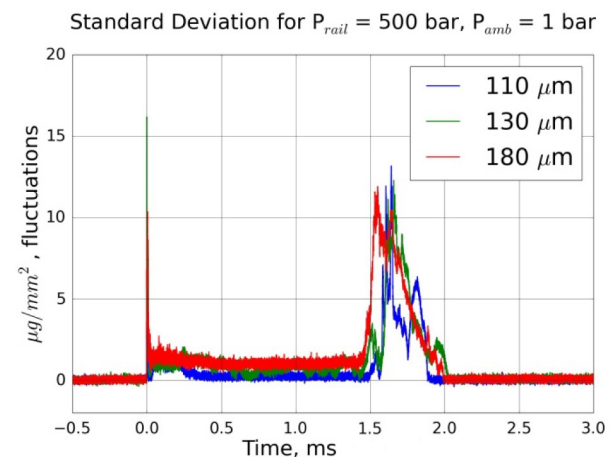


Figure 4. The results of the ensemble standard deviation calculations are shown for three nozzle hole sizes. Data are taken at $X = 0.2$ mm and $Y = 0.0$ mm (centerline of the spray).

The next figure (Fig. 5) presents data spanning two ambient pressures, seen in Figure 5. Data are presented for the 110 μm nozzle at 1500 bar rail pressure. After the SOI spike, there is almost no delay