

Time-resolved X-ray Tomography of Gasoline Direct Injection Sprays

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ABSTRACT

Quantitative measurements of direct injection fuel spray density and mixing are difficult to achieve using optical diagnostics, due to the substantial scattering of light and high optical density of the droplet field. For multi-hole sprays, the problem is even more challenging, as it is difficult to isolate a single spray plume along a single line of sight. Time resolved x-ray radiography diagnostics developed at Argonne's Advanced Photon Source have been used for some time to study diesel fuel sprays, as x-rays have high penetrating power in sprays and scatter only weakly. Traditionally, radiography measurements have been conducted along any single line of sight, and have been applied to single-hole and group-hole nozzles with few plumes. In this new work, we extend the technique to multi-hole gasoline direct injection sprays. By taking time-resolved measurements over a raster-scan pattern from multiple lines of sight, we are able to tomographically reconstruct the time-resolved ensemble mean density field in a plane intersecting the spray. Traditional Fourier back-projection methods are not well-suited for this experiment, so a model-based iterative reconstruction algorithm has been employed in this particular application. Three gasoline direct injection sprays with various 6-hole patterns were studied at injection pressures of 100 to 175 bar and atmospheric back pressure, at selected axial positions several mm downstream of the nozzle. These measurements reveal that the sprays are quite unsteady and interact with each other strongly during the early phase of injection. The spray plume cross-sections are very non-uniform, exhibiting small rich regions on the outer sides of the plumes surrounded by much leaner regions on the inner sides. We propose that this may be due to spray-spray interaction, interaction with the nozzle hole counter-bore, and inhomogeneities in the sprays due to the hole geometry and needle lift.

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INTRODUCTION

The structure of direct injection multi-hole sprays in close proximity to the nozzle play an important role in the pre-ignition mixing process. Investigation of the near-field spray structure is necessary in order to understand the relationship between the nozzle geometry, the initial conditions (ie. injection pressure, ambient conditions) and the resulting mixture preparation.

Direct injection sprays are typically investigated using visible-light diagnostic techniques [1, 2, 3, 4]. If the droplet field is dilute enough, laser-based diagnostics may be employed [5, 6]. However, conventional imaging techniques are not particularly well-suited to the near-field region of the spray, due to the large amount of multiple scattering and high optical density of the droplet field [7].

Multi-hole gasoline direct injection (GDI) sprays are particularly difficult to study using conventional techniques. In addition to the problem of multiple scattering, the close proximity of the spray plumes relative to their skew angles and diameters causes them to substantially overlap. This leads to an increased likelihood of spray-spray interaction and makes the identification of individual plumes challenging [8, 9, 10].

In the last decade, x-ray diagnostics have seen increasing use in the study of near-field spray dynamics. X-rays scatter only weakly from gas-liquid interfaces and have high penetrating power [11]. The high flux available at synchrotron sources permits sufficiently high spatial and temporal resolution such that the transient dynamics of fuel sprays can be studied using a variety of complementary techniques [12].

Time-resolved x-ray radiography techniques provide quantitative line of sight measurements of fluid density [13]. From a single line of sight, the spray can be raster-scanned through a focused x-ray beam to provide a planar distribution of projected mass [12]. When considering only a single spray plume, a three-dimensional representation of the density distribution may be estimated by solving an analytical function for the mean density using projection data from a small number of viewing angles [14, 15, 16]. If the density field is axisymmetric, an Abel inversion may be used to estimate the density distribution, as is done for the case of cavitation in a nominally axisymmetric nozzle [17, 18]. In the case of multi-hole GDI sprays, the close overlapping of the plumes makes reconstruction from a few limited views difficult. The sprays are in such close proximity that spray-spray interactions cannot be neglected and analytic models are unsuitable.

To understand the three-dimensional structure of multi-hole sprays, computed tomography (CT) can be used to obtain planar density distributions [19]. X-ray CT has been used to study fluid flows for some time [20] and has been applied to a range of problems such as flow in porous media [21] and pipe cavitation [22]. In previous applications to large-scale flows, medical or bench-top x-ray CT sources have been used [23, 24]. Recently, Allocca, Marchitto et al. have demonstrated x-ray CT of transient fuel sprays using a benchtop source [25,26]. They used polycapillary optics to collimate the beam, improving the spatial resolution. However, the low flux of benchtop sources is still a limiting factor. The limited low spatial and temporal resolution makes analysis of small transient features challenging. As an alternative, well-collimated monochromatic x-rays from a high-flux synchrotron source are ideal for this application.

Synchrotron light has previously been applied to tomography of multi-hole fuel sprays by Liu et al [27, 28, 29]. In their experiments, an area detector recorded x-ray radiographs from multiple view angles. The pixel pitch of the area detector limited the spatial resolution to approximately $150\mu\text{m}$. By comparison, the time-resolved x-ray radiography measurements presented here use a focused x-ray beam. The increased flux enables time-resolved measurements, and the focused beam improves the spatial resolution by a factor of thirty ($5\mu\text{m}$). Due to these improvements, the spatial resolution and signal to noise ratio are sufficient to permit time-resolved realization of individual injection events, and ensemble statistics (shot to shot variations in density) can be investigated.

In this paper, we present time-resolved tomographic x-ray radiography measurements of three GDI sprays under atmospheric ambient conditions. Density fields are reconstructed at several slices downstream of the nozzle using a specialized emission tomography algorithm [30]. This allows us to identify the individual plumes of the spray, where this is not possible from a single line of sight projection. The data reveal inhomogeneities within individual spray plumes, and unsteady spray-spray interactions.

EXPERIMENTAL METHOD

The x-ray measurements were conducted at the 7-BM beamline of the Advanced Photon Source (APS) at Argonne National Laboratory. The facility is specifically designed to make time-resolved measurements of multiphase flows, and is described in detail by Kastengren et al [31]. A simplified schematic of the setup is shown in Fig. 1.

Each of the three fuel injectors studied were supplied with gasoline-type calibration fluid at constant pressure using a piston-accumulator pressurized by regulated inert gas. Each injector was placed in a rotating tomography chamber with thin Kapton windows to permit transmission of the x-ray beam. The chamber was pressurized to approximately 1.2 bar abs at room temperature. A continuous purge flow of nitrogen gas was used to clear droplets from the field of view between each spray event and provide uniform initial conditions.

The x-ray source was a monochromatic beam with mean energy of 8 keV, a bandpass of 1.4% full width at half-maximum (FWHM) and a flux of approximately 2.5×10^{11} ph/s/mm². The beam was focused to a spot size of $5 \times 6 \mu\text{m}$ FWHM with a pair of 300 mm, Rhcoated Kirkpatrick-Baez mirrors. The focused beam acts as a microprobe, allowing a small area to be probed along a line of sight. The experiment was traversed through the fixed beam.

Before the beam interacted with the experiment, it passed through an intensity monitor $I_0(x, y, \theta, t)$ correcting for fluctuations in the incoming beam. The experiment was placed 36.5m downstream from the source; the detector was approximately 10cm downstream of the experiment. The beam passed through the Kapton windows and spray chamber, and was collected by a $300 \mu\text{m}$ thick PIN diode, providing a measurement of transmitted intensity $I(x, y, \theta, t)$. The amplified transmission signal was sampled at 20 MHz. The signal was integrated over each synchrotron orbit period, giving a temporal resolution of $3.68 \mu\text{s}$. The signal to noise ratio of individual injection events was sufficient to allow multiple injections to be individually recorded at each sample point for post-hoc statistical analysis.

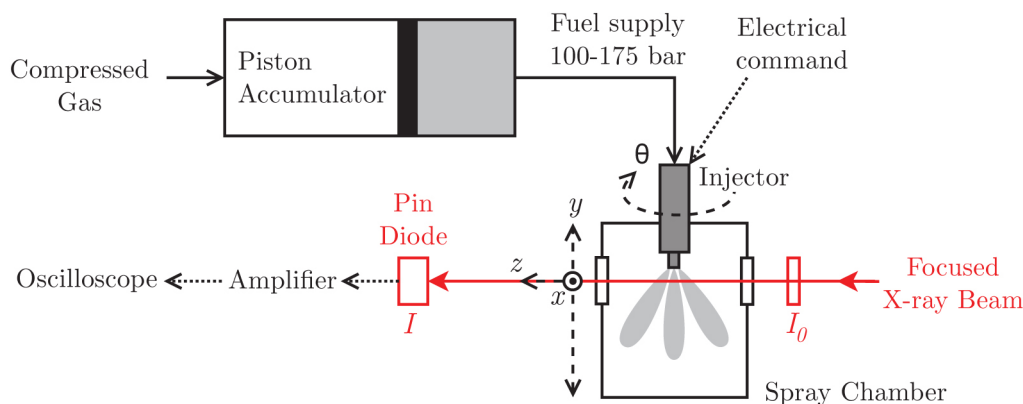


Figure 1. Schematic of x-ray radiography setup for GDI tomography experiments. Note the co-ordinate system (x, y, z) where x is pointing out of the page, y is along the injector body axis, and z is parallel to the x-ray beam. The rotation angle θ is defined with respect to the injector body axis.

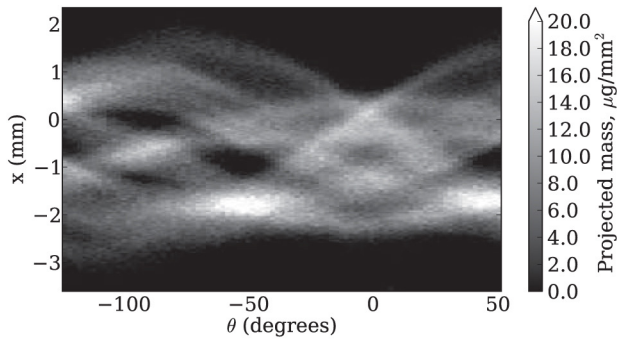


Figure 2. Sinogram of ensemble average projected density for Injector A at $y = 2\text{mm}$ from the nozzle, at a single point in the time series.

The transmission signal was normalized by the intensity prior to the arrival of the spray, thus cancelling out the absorption in the ambient chamber gas, windows, and air gap. Using the Lambert-Beer law, the projected mass in the line of sight of the beam due to the spray (M , $\mu\text{g}/\text{mm}^2$) is given as

$$M(x, y, \theta, t) = -\frac{1}{\mu} \log \left[\frac{I(x, y, \theta, t)}{I_0(x, y, \theta, t)} \right] \quad (1)$$

where μ is the attenuation coefficient of the fuel, which is determined by calibration in a cuvette. Since the x-rays are monochromatic, the absorption of x-rays provides a direct quantitative measure of the projected mass of liquid in the path of the beam. The projections $M(x, y, \theta, t)$ are equivalent to the line of sight integral of the density field ρ , $\mu\text{g}/\text{mm}^3$ averaged at each point over the beam spot size A ;

$$M(x, y, \theta, t) = \frac{1}{A} \iint \rho(x, y, z, \theta, t) dz dA. \quad (2)$$

As per Fig. 1, the translation axis x is orthogonal to the injector body axis and y is along the injector body axis. The line of sight of the x-ray beam is in the z axis, and the nozzle rotation θ is aligned with the geometric center of the nozzle holes, which is not always coincident with the injector body axis. The system (x, y, z) is fixed with respect to the x-ray beam. We also define a co-ordinate system (x', y, z') fixed to the injector, such that z is parallel to the electrical connector on the injector body. A set of raster-scan measurements with a sample resolution of $35\text{--}75\text{ }\mu\text{m}$ was collected for each θ and the injector was rotated, producing a time-resolved projected density sinogram in a single y -plane, as shown in Fig. 2. These sinograms were reconstructed to retrieve the time-resolved planar density field $\rho(x', z', t)$.

Repeating the measurements N times per sample point gives a time-resolved ensemble-mean projected density field $\bar{M}(x, y, \theta, t)$, which is reconstructed to provide the time-resolved ensemble-average density field $\bar{\rho}(x', z', t)$. Similarly, the ensemble standard deviation $\sigma_M(x, y, \theta, t)$ is reconstructed to provide $\sigma_\rho(x', z', t)$, which gives a time-resolved measure of the spatial distribution of shot-to-shot variation over a set of injection events. Since both $\sigma_\rho \geq 0$ and $\bar{\rho} \geq 0$ at all points in the (x', z') plane, the same reconstruction method can be applied to both σ_M and $\bar{M}$; σ_ρ represents the planar distribution of standard deviation that best explains the projected values σ_M . Since there is a possibility of a non-normal distribution in σ_M , σ_ρ may contain some systematic error, and cannot be assumed to represent a precise quantitative local standard deviation. However, σ_ρ does provide a relative indication of the areas in the spray that are most likely to be variable and best explain the shot-to-shot variations in the projections.

Table 1. Injector geometries and operating conditions for the three cases considered in this study.

	Injector A	Injector B	Injector C
Make/Model	Bosch HDEV 5 GDI	Bosch HDEV 5 GDI	Bosch HDEV 5 GDI
No. holes	6	6	6
Hole geometry	stepped counterbore	stepped counterbore	stepped counterbore
Skew angle (center of hole pattern)	22°	22°	0°
Injection pressure	100 bar abs	175 bar abs	100 bar abs
Ambient pressure	1.2 bar abs	1.2 bar abs	1.2 bar abs
Commanded injection	1 ms	1 ms	5 ms
Fuel	Gasoline-type calibration fluid	Gasoline-type calibration fluid	Gasoline-type calibration fluid w/400ppm Br additive
Hole pattern			

Since the reconstruction is comprised of a large number of injection events, discussion of the spatial and temporal unsteadiness of the flow is taken in a statistical context. Analysis of the time-resolved ensemble mean field reveals spatial and temporal fluctuations which represent repeatable unsteady events which deviate from steady-state spray behavior. Analysis of the time-resolved ensemble standard deviation field reveals shot-to-shot variations and the degree to which individual injection events deviate from the ensemble mean.

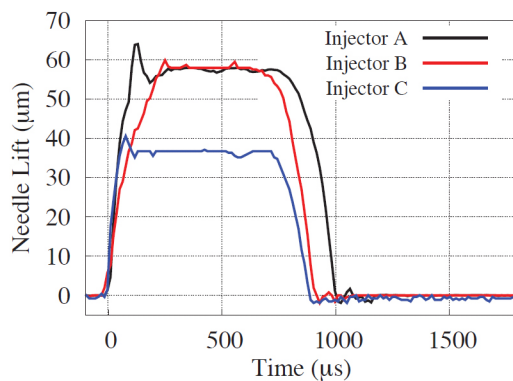


Figure 3. Needle lift profiles for all three injectors in the study, for a 1ms commanded injection duration.

TOMOGRAPHIC RECONSTRUCTION

We used a penalized-maximum likelihood (PML) approach to reconstruct internal distribution of densities from time-resolved tomographic datasets. The PML algorithm outperforms conventional filtered back-projection algorithms, and is particularly well suited for this application because of its ability to deal with experimental noise and outliers. With the PML approach, rather than maximizing the data-likelihood alone, an additional penalty term is used to enforce desired (e.g. smoothness, sharpness) and/or certain (e.g. non-negativity) properties of the solution [32]. This approach leads to objective functions that combine data misfit and penalty terms, which can be optimized using various iterative and global search methods. This provides a higher-quality reconstruction, particularly for spatio-temporal datasets where the spatial and temporal density gradients are physically bounded. For these data, we performed 40 PML iterations with the smoothness/sharpness parameters $\delta = 1$, $\beta = 10$ –25 for the mean, and $\beta = 25$ –60 for the standard deviation.

The reconstructions presented here are performed using the open-source software *TomoPy* [30]. Data storage was managed using the *Data Exchange HDF5* schema [33]. The reconstructions were performed on Mira, a 10-petaflops IBM Blue Gene/Q system at Argonne National Laboratory. We used up to 512 nodes where each node consists of 16 physical cores (8192 cores in total) and 16 GiB memory.

RESULTS

Specifications for the three injectors considered in this study are shown in Table 1. All injectors were operated at non-evaporating conditions; 1.2 bar absolute pressure at 25°C, with a proprietary low-volatility gasoline surrogate. For Injector C, 400ppm of

tetrabromomethane was blended in the fuel as a contrast agent; this did not notably affect the viscosity or density of the fuel. Injection pressures varied from 100 to 175 bar abs.

The internal geometries and needle lift profiles of the three injectors listed in Table 1 were examined using x-ray phase contrast imaging [18]. Static phase contrast images such as those shown in Figure 4 were used to measure the hole and counterbore diameters, the size of the mini-sac, and the inclination angles of each of the holes. The results are given in Table 2.

The tolerances indicate the degree of variability from hole to hole. High-speed images were used to make measurements of needle lift for a 1 ms commanded injection. Mean lift profiles are shown in Figure 3. We note that injector C has a much lower needle lift than A or B, and has a higher L/D ratio for the hole. We also note that injector C has the smallest variation in hole inclination angle (13°), whilst Injectors B (22°) and A (40°) have progressively more variation.

Time-resolved measurements of projected spray density were first taken over a single plane for each injector, over a large field of view. Ensemble-average measurements of $N = 32$ injection events were obtained. The time averaged projected mass during the steady phase of injection is shown in Fig. 5 for all three injectors. Regardless of the projection angle, it is not possible to view any of the spray plumes without overlap.

In the time-resolved data, weak fluctuations in the spray plumes are observed, particularly during the first few hundred milliseconds of the injection event. The nature of these fluctuations cannot easily be determined from a projected view (*see supplementary movies - <http://goo.gl/MrBdih>*). For injector C, Fig. 5c suggests that the lower pair of plumes which are less obscured may be bifurcating, but since they are superimposed, this cannot be directly determined.

Tomographic reconstructions at $y = 2\text{mm}$ from the nozzle for injector A are shown in Fig. 6. In all the reconstructions, the (x', z') plane is oriented so that the spray is coming out of the page, and the units of density are expressed as a fraction of the fuel density at standard conditions, $\rho_f = 0.7734\text{ g/cm}^3$. Since the spray is unsteady during the first 200 μs (20%) of the injection event, the reconstructions have been temporally averaged over several time ranges. Figures 6a, 6b, 6c show the progression of injector A's mass distribution during the first 10%, second 10% and final 80% of the injection event. It should be noted that since these are the ensemble average of $N = 16$ injection events per sample point, the distributions here represent the mean spray behaviour over several hundred thousand individual injections.

The first point of note in Fig. 6 is the shape of the spray plumes. Rather than being axisymmetric jets, the sprays are typically crescent shaped or highly skewed, with their center of mass typically near the edge of the plume rather than the geometric center. The plume denoted (i) in figs. 6a, 6b, 6c is a good example of a crescent-shaped spray. Most of the spray's mass is located in the upper part of the crescent, and the geometric center is deficient in density.