

High-Resolution X-Ray and Neutron Computed Tomography of an Engine Combustion Network Spray G Gasoline Injector

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ABSTRACT

Given the importance of the fuel-injection process on the combustion and emissions performance of gasoline direct injected engines, there has been significant recent interest in understanding the fluid dynamics within the injector, particularly around the needle and through the nozzles. The pressure losses and transients that occur in the flow passages above the needle are also of interest. Simulations of these injectors typically use the nominal design geometry, which does not always match the production geometry. Computed tomography (CT) using x-ray and neutron sources can be used to obtain the real geometry from production injectors, but there are trade-offs in using these techniques. X-ray CT provides high resolution, but cannot penetrate through the thicker parts of the injector. Neutron CT has excellent penetrating power but lower resolution. We present results from a joint effort to characterize a gasoline direct injector representative of the Spray G injector as defined by the Engine Combustion Network. High-resolution (1.2 to 3 μm) x-ray CT measurements from the Advanced Photon Source at Argonne National Laboratory were combined with moderate-resolution (40 μm) neutron CT measurements from the High Flux Isotope Reactor at Oak Ridge National Laboratory to generate a complete internal geometry for the injector. This effort combined the strengths of both facilities' capabilities, with extremely fine spatially resolved features in the nozzles and injector tips and fine resolution of internal features of the needle along the length of injector. Analysis of the resulting surface model of the internal fluid flow volumes of the injector reveals how the internal cross-sectional area and nozzle hole geometry differs slightly from the design dimensions. A simplified numerical simulation of the internal flow shows how deviations from the design geometry can alter the flow inside the sac and holes. The results of this study will provide computational modelers with very accurate solid and surface models for use in computational fluid dynamics studies and experimentalists with increased insight into the operating characteristics of their injectors.

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INTRODUCTION

The design of gasoline direct injection (GDI) systems plays a central role in determining the efficiency of modern spark ignited (SI) engines. The timing, targeting and mixture fraction of GDI sprays have a significant impact on combustion and emissions [1,2,3].

The internal geometry of the injector plays a significant role in determining the properties of the fuel spray, as it determines the fluid mechanical parameters of the internal nozzle flow [4,5]. This in turn determines bulk parameters such as penetration, cone angle, rate of injection, rate of momentum and discharge coefficient [6,7,8]. Variations in these measurements are often correlated with gross geometric parameters such as hole diameter, length, and hole radius of curvature through numerical simulations [9]. One of the present challenges in predicting these parameters from numerical simulations is that the gross geometry of the injector (such as the cross-sectional area of the upstream flow passages and nozzle holes) can vary substantially between the nominal engineering dimensions and the as-manufactured dimensions [10].

Variations in key geometric parameters such as nozzle diameter are not the only factor that makes it difficult to predict the gross properties of GDI sprays. The details of the internal geometry can also have an effect on transient phenomena such as turbulence and cavitation. Factors such as wall roughness and microscopic manufacturing defects can change the vorticity and turbulence intensity of the flow and induce cavitation around the nozzle hole and needle seat [11]. However, these small-scale details are often not included in the wall geometry of numerical models, since the features are often assumed to be smaller than the mesh resolution. Although the wall boundary layer is often modeled at sub-grid scale, the wall geometry is not. Recent work [12] has shown that asymmetries in the hole diameters due to manufacturing limitations can lead to asymmetric flow both inside and outside the injector. These asymmetries appear to remain in the entrainment field long after the end of injection as the sprays interact [13]. In light of these observations, it is necessary to consider how the small-scale geometric deviations of a real fuel injector will affect the predictive capabilities of three-dimensional spray simulations.

In order to better understand the fluid mechanics and combustion behavior of GDI sprays, the Engine Combustion Network (ECN) has specified the "Spray G" standard as a common platform for researchers to perform measurements under standardized conditions [14]. A matched set of eight-hole valve covered orifice type GDIs have been made available to experimentalists internationally. The Spray G standardized operating conditions are then used as a basis for computational fluid dynamics (CFD) simulations of the sprays [15,16]. This allows modelers to take advantage of both the wellcharacterized boundary conditions and the large amount of experimental data available for validation, with the goal of improving the predictive capability of spray simulations and better understanding the underlying physics.

As a part of the ECN Spray G effort, x-ray computed tomography has been used to provide realistic measurements of critical geometric parameters to aid modelers in capturing the effects of the nozzle

geometry on the sprays [10]. However, the simulated geometries are still simplified with respect to the true geometry [12]. The next step in improving the realism of the simulated geometry is to move from a nominal geometry that has been rescaled to match the hole diameters and lengths of the CT data to a full isosurface of an as-manufactured injector, which includes three-dimensional details where the injector geometry deviates from the design dimensions.

The prevalent method of characterizing injector geometry is x-ray computed tomography (CT) [17]. This is typically done using a commercial CT machine with a tube source [18]. However, commercial CT is typically limited in terms of effective spatial resolution. Although state-of-the-art CT machines have detectors with nominal micron resolution, there is a trade-off between penetrating power and resolution due to the divergent nature of the x-ray source and the energy of the x-rays. The resolution of the resulting isosurface is lower than the resolution of the detector and depends on the local signal-to-noise ratio.

An alternative means of performing x-ray CT is to use a synchrotron x-ray source [19]. A synchrotron has a highly collimated and coherent beam whose energy spectrum can be controlled. These facilities have orders of magnitude more flux than a tube-source CT and as such can complete a CT measurement in a fraction of the time with very high signal-to-noise ratio. Typically, synchrotron CT beamlines are used to perform high-resolution measurements on small, weakly absorbing samples. The quality of the x-ray source allows researchers to take advantage of both phase contrast (refraction) and absorption contrast methods. These facilities are not typically optimized for large (millimeter size) and dense (metallic) samples such as fuel injectors. In the last year, the 7-BM beamline of the Advanced Photon Source (APS) at Argonne National Laboratory has developed a specialized capacity to perform CT measurements on fuel injectors [10]. The beamline has been designed to maximize spatial resolution and dynamic range through dense metallic samples with an effective spatial resolution of approximately 1.5 μm .

The dynamic range and x-ray energies used in x-ray CT limit these facilities in terms of the maximum path length of metal through which a CT measurement can be performed. Furthermore, there is a trade-off between field of view and resolution that prohibits imaging the entire injector. The body of a GDI (above the needle seat) is typically too large to image using x-ray CT. Neutron CT is well suited to this problem [20]. Neutrons generally interact with matter less strongly than x-ray photons, and can therefore penetrate much thicker materials. Neutron interaction varies on the material - generally, most metals interact weakly, and hydrogenous materials interact strongly [20]. In this study, the CG-1D beamline at the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory was used for neutron imaging [21]. There are several trade-offs in using a neutron source. The resolution of the detector is lower (in this paper, 40 μm , as compared to less than 2 μm for the x-ray CT). This makes it difficult to perform metrology on the needle seat and holes of the injector. The flux is also lower, requiring longer scanning times. Finally, the neutron beam can activate the sample, prohibiting its use for an extended period after the measurement.

Despite these limitations, neutron CT can measure regions of the injector that are too large for x-ray CT. The combination of neutron and x-ray CT measurements provides a viable method of mapping the entire internal geometry of the injector, with high resolution at the nozzle tip where it is required, and reduced resolution in the upstream flow passages where the geometry is much larger. In this paper, we present a combined effort to use both neutron and synchrotron x-ray CT to generate the first complete model of an as-manufactured Spray G injector. The geometry is characterized and used to generate a computational fluid dynamics (CFD) mesh. A simplified Reynolds-averaged Navier-Stokes (RANS) simulation is then used to demonstrate how these data can be used to aid modeling efforts for GDIs.

METHODS AND MATERIALS

The Spray G Injector

The ECN Spray G injector is an eight-hole valve covered orifice type GDI. The injector is nominally symmetric. A set of 12 nominally identical injectors were characterized by mechanical patterning. The 6 best-matched injectors from this set were selected and circulated between participating institutions. A matched engine control unit (ECU) was provided with each injector. In this study, our measurements focus specifically on injector AV67-028.

The ECN Spray G standard specifies a 680 μ s injection duration at 200 bar with iso-octane at 90 °C into 300 °C air at approximately 6 bar ambient pressure [14]. These pressures and temperatures will be matched in the simulations shown later. The CT measurements were performed on an empty, static injector with the needle closed, at room temperature.

X-Ray CT Facilities at Argonne

The x-ray CT component of the work was conducted at the 2-BM and 7-BM beamlines of the APS at Argonne National Laboratory. The 2-BM beamline is a general-purpose high-resolution CT facility [22]; it was used to obtain wide-field images of the needle seat region of the injector. In addition to being able to make time-resolved measurements of fuel sprays [23], the 7-BM facility has been specially designed for high resolution measurements of fuel injector nozzles [24]. It was used to image the nozzle holes and tip [10]. A simplified schematic of both facilities is shown in Figure 1.

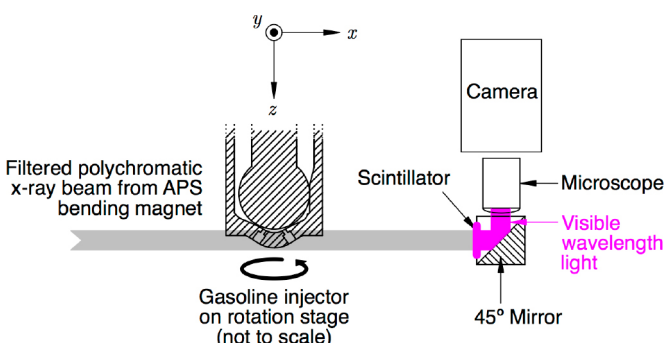


Figure 1. Simplified schematic of the x-ray computed tomography facilities at the 2-BM and 7-BM beamlines of the APS. The beam enters from the left.

The raw polychromatic x-ray beam from the synchrotron bending magnet was passed through a set of slits to define the beam profile, and a set of filters to remove low-energy components from the beam which do not contribute to the image and would otherwise be absorbed by the nozzle. At the 2-BM facility, a 1 mm carbon filter and 15 mm silicon filter were used. An additional 50 mm glass filter was placed upstream of the nozzle. At the 7-BM facility, a 25 μ m molybdenum filter and a 250 μ m copper filter were used, and a rotating chopper was used to limit the duty cycle of the beam exposure on the nozzle to 10%. Bronze shielding was used to protect the camera and objective. In both facilities, the filtered beam was passed through the nozzle and onto a 100 μ m thick LuAG scintillator, which converted the x-rays into a visible-light image. The emission of visible light from the scintillators was bounced off a 45-degree mirror and recorded by a conventional digital camera (Point Grey GS3) using a microscope objective and extension tube.

The wide-field images taken at the 2-BM facility used a 2 $\times$ objective lens, which provided an effective pixel resolution of 2.95 μ m per pixel and a field of view of 10 $\times$ 4.7 mm. A CCD sensor (Sony ICX814) was used. At the 7-BM facility, a 5 $\times$ objective was used to obtain a spatial resolution of 1.17 μ m per pixel and a field of view of 2.25 $\times$ 1.4 mm. A CMOS sensor (Sony IMX174) was used. Further details are listed in Table 1.

It is important to note that the effective spatial resolution of the CT reconstruction (i.e. the smallest possible feature than can be captured) is larger than the quoted pixel resolution or voxel size. The transfer functions between the beam, object and imaging system result in a loss of spatial resolution, due to the nature of the interaction between the beam and the sample. The slight divergence of the beam and phase contrast due to the weak refraction of the x-rays at the edges of the injector cause a slight loss in spatial resolution that the reconstruction algorithm cannot fully compensate for [25]. The polychromatic nature of the x-ray beam also causes some variation in the depth in the scintillator at which the beam is absorbed and visible light is emitted. Since the depth of field of the microscope is small, the diffraction limit of the imaging system further reduces the resolution.

In Table 1, we list the estimated effective spatial resolution of each of the imaging techniques used. These values were calculated and verified by several means. For the 7-BM x-ray CT, a gold calibration pattern with linearly decreasing fringe spacing was imaged to determine the smallest resolvable feature. Secondly, the width of the point-spread function (PSF) at the metal-air interface was measured at several hundred locations throughout the images by fitting Gaussian error functions. The width parameter in the fit provided a quantitative measurement of the sharpness of the interface for the sample under study, allowing for local variations in signal-to-noise ratio. Thirdly, precision pin gauges with known diameters were imaged and their diameters measured, to confirm that there was no systematic error in the imaging system. The ratio of the width of the PSF to the diffraction limit was used as a scaling factor to determine the uncertainty in the neutron CT data and the 2-BM x-ray data. This scaling factor accounts for the error in the Otsu isosurfacing algorithm, which was assumed to have an uncertainty (in pixels) proportional to the PSF width. The PSF is

all image sets were measured in the same manner, and the uncertainties were scaled according to the pixel size and PSF width. Further details are outside the scope of this paper and will be covered in more detail in future work.

The complete workflow for isosurfacing the injector is described in Figure 3. Several pre-processing steps were applied in order to prepare the x-ray CT images for tomographic reconstruction. At both facilities, bright-field images (taken without the injector in the beam) were used to normalize out spatial variations in the image intensity due to the properties of the beam and the scintillators, and dark-field images (taken with the x-ray shutter closed) were subtracted to remove sensor noise. At 7-BM, two additional steps were performed in order to maximize the effective spatial resolution. These include:

1. Median-averaging of multiple exposures at each projection angle to increase dynamic range and remove high-energy photons ("zingers", see [17]) which occasionally saturate pixels as they pass through the sensor.
2. Beam-hardening correction. The polychromatic x-ray source results in preferential absorption of lower x-ray energies, resulting in a nonlinear relationship between material thickness and attenuation at the scintillator [17]. Beam hardening introduces artificial density gradients into the CT reconstruction which make iso-surfacing the material difficult. A model of the known spectrum of the incident x-rays was used to generate a one-to-one lookup table which modeled the intensity deposited on the scintillator as a function of material thickness in terms of an equivalent path length of iron. Inverting the lookup table allows the recorded intensity to be converted to a material path length.

Neutron CT Facility at Oak Ridge

The neutron CT component of the work was conducted at the CG-1D beamline of the HFIR at Oak Ridge National Laboratory [26]. The High Flux Isotope Reactor is the highest-flux neutron source in the U.S. used for open scientific research, and it supports 12 instrument beamlines. The CG-1D beamline is one of three instrument stations on the Cold Guide 1 neutron beam, and it provides a range of imaging capabilities using several sensor configurations [26]. A simplified schematic is shown in Figure 2.

Neutrons from the HFIR reactor core travel through guide passages via the cold source. At the guide exit is a motorized aperture and diffuser system. The aperture has cadmium/boron nitride components, and the aperture diameter D may be adjusted between 3.3 and 16 mm. As the distance L from the aperture to the sensor plane is fixed at 6.59 m, pinhole geometries L/D of 400 to 2000 are achievable. For the work described here, the aperture was 11 mm, for $L/D = 600$. The diffuser spatially homogenizes the beam and is composed of a 2 mm thick Al_2O_3 nanoparticle matrix, with a beam transmission of approximately 90%. Beam divergence has been measured at 2.7° . Between the aperture and the detector plane is a He-filled flight tube with silicon windows and motored boron-nitride exit slits. At the detector, typical neutron flux is approximately 10^7 n/cm²/s.

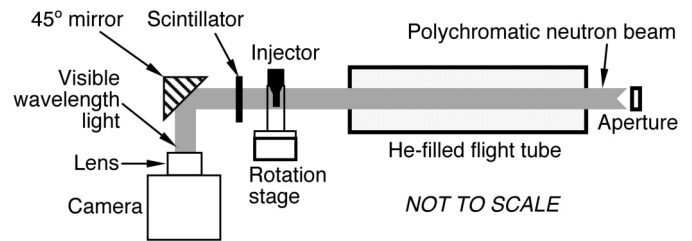


Figure 2. Neutron CT facility at ORNL. The beam enters from the right.

Table 1. Statistical comparison between x-ray and neutron datasets, and final CT geometry.

	ORNL Neutron	ANL X-ray (2-BM)	ANL X-ray (7-BM)	Merged isosurface
Field of view / size of domain	79 × 79 mm	10 × 4.7 mm	2.25 × 1.4 mm	11.1 × 11.1 × 44.25 mm
Pixel Resolution	40 μm/pixel	2.95 μm/pixel	1.17 μm/pixel	-
Effective spatial resolution (smallest feature)	80 μm	4 μm	1.5 μm	-
Exposure time	37 s × 1 frame/angle	50 ms × 1 frame/angle	6 ms × 20 frames/angle	-
Data collection time	22.2 hours	1 hour	2.5 hours	-
Size of raw dataset	14 GB (16-bit)	15 GB (16-bit)	193 GB (16-bit)	-
Size of reconstruction dataset	2.3 GB (16-bit)	19 GB (32-bit)	16.5 GB (32-bit)	-
Angular resolution	0.1° (1831 views)	0.12° (1500 views)	0.1° (1800 views)	-
Size of volume (voxels)	874 × 874 × 1637	3376 × 3376 × 1600	1920 × 1920 × 1200	-
Size of volume (physical)	34.96 × 34.96 × 65.48 mm ³	9.959 × 9.959 × 4.720 mm ³	2.246 × 2.246 × 1.404 mm ³	-
Size of isosurface	9M Triangles / 442 MB	15M triangles / 732 MB	27M triangles / 1.3 GB	14M triangles / 703 MB

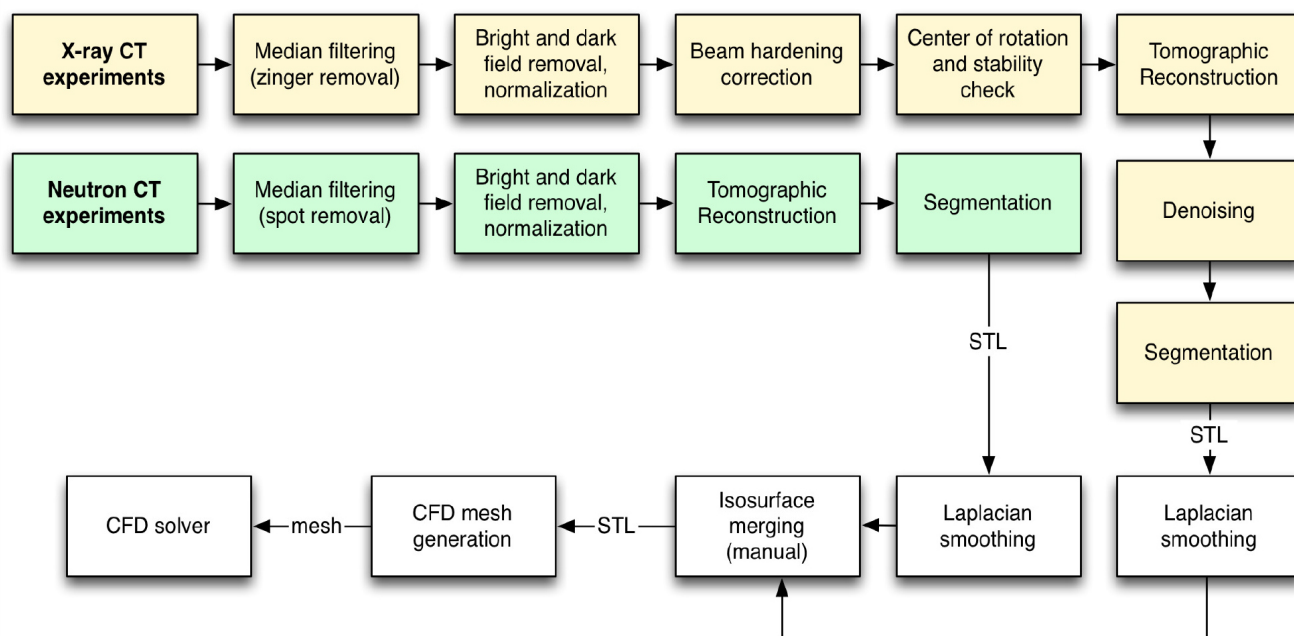
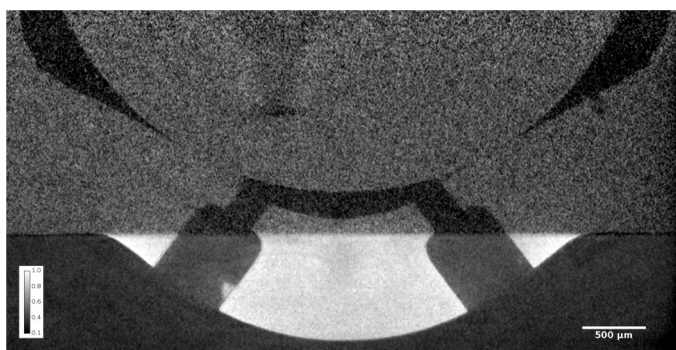
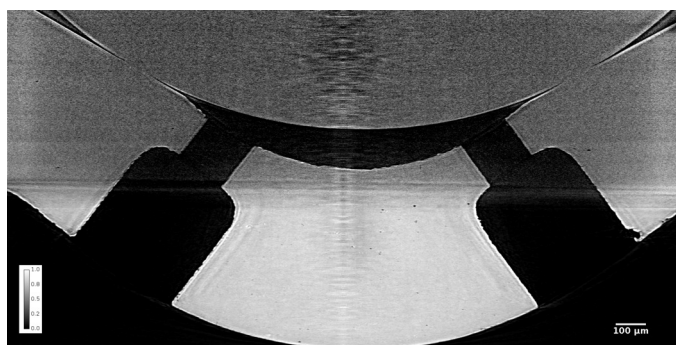


Figure 3. Workflow for final isosurface and CFD mesh generation.



a. Sagittal view of needle seat region from 2-BM facility.



b. Sagittal view of nozzle tip from 7-BM facility.

Figure 4.

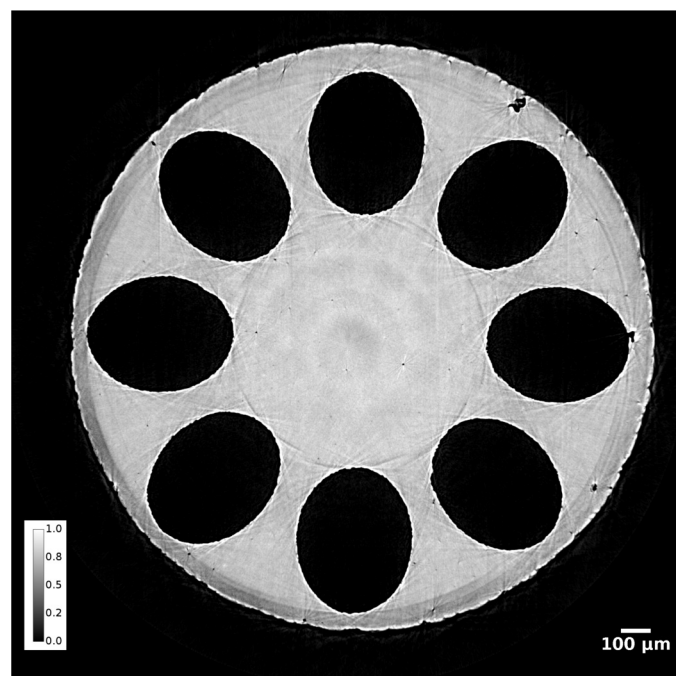
c. Transverse cut plane of injector tip from 7-BM facility, $z = 0.39$ mm from the nozzle tip. The holes are round, but appear elliptical because they are intersected at an angle.

Figure 4. (cont.) Sample reconstruction planes from ANL x-ray CT, showing the sac, holes, and seat region.