

Recent Developments in X-ray Diagnostics for Cavitation

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ABSTRACT

Cavitation plays an important role in fuel injection systems. It alters the nozzle's internal flow structure and discharge coefficient, and also contributes to injector wear. Quantitatively measuring and mapping the cavitation vapor distribution in a fuel injector is difficult, as cavitation occurs on very short time and length scales. Optical measurements of transparent model nozzles can indicate the morphology of large-scale cavitation, but are generally limited by the substantial amount of scattering that occurs between vapor and liquid phases. These limitations can be overcome with x-ray diagnostics, as x-rays refract, scatter and absorb much more weakly from phase interfaces. Here, we present an overview of some recent developments in quantitative x-ray diagnostics for cavitating flows. Measurements were conducted at the Advanced Photon Source at Argonne National Laboratory, using a submerged plastic test nozzle. X-ray radiography provides quantitative line-of-sight density measurements of cavitation void fraction by measuring relative changes in absorption, with a relatively constant uncertainty of 2% of a typical peak value. Single point measurements are built up into a vapor fraction distribution by raster-scanning the nozzle through the fixed beam. X-ray fluorescence, a novel alternative diagnostic, can provide a similar quantitative point measurement, but measures the emission of fluorescent x-rays from an excited tracer in the fuel rather than the directly transmitted beam. An uncertainty of 1.1% of the projected void fraction is achieved, giving a more precise measurement near the nozzle wall. X-ray phase contrast imaging provides a temporally and spatially resolved view of the flow due to absorption and diffraction, revealing small-scale dynamic behaviors that are difficult to observe in point-based measurements.

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INTRODUCTION

Cavitation is an issue of growing importance in direct injection internal combustion, as injection pressures continue to increase and hole sizes and injection durations decrease. The acceleration of the fuel as it travels from the sac through the restricting orifice of the nozzle hole can cause rapid decreases in static pressure, leading to local cavitation in the entrance of the nozzle hole [1]. The formation and collapse of cavitation bubbles can lead to nozzle wall damage and component wear. Furthermore, the coalescence of cavitation bubbles into large pockets or films of vapor can reduce the effective area of the nozzle hole, altering the spray structure [2, 3]. Changes in spray behavior ultimately affect combustion efficiency and pollutant formation [4, 5].

Under some conditions, cavitation can be suppressed by tapering of the nozzle hole, which shifts the location of minimum static pressure to the nozzle exit, rather than the inlet [6]. However, as nozzle holes become smaller and pressures increase, the limits of manufacturing tolerances and increasing injection pressures make it more difficult to eliminate cavitation completely. Altering the nozzle hole geometry may also cause undesirable changes in discharge coefficient and spray breakup. In the case of multi-hole nozzles, the turning of the flow into the hole can cause asymmetric wall-bound cavitation and freestream cavitation which cannot be completely suppressed [6, 7]. Under some conditions, cavitation may even be beneficial to spray breakup.

Nozzle cavitation has been extensively investigated using optical diagnostic techniques in transparent models [8, 9, 10]. The effects of geometric variations have also been investigated in large-scale model injectors [11]. Real-size injectors have also been successfully modified for optical access, to allow flow visualization of cavitation at typical engine-relevant injection pressures [12, 13, 14]. However, such techniques are limited by several factors. The multiple scattering of visible light makes it difficult to probe regions with many phase interfaces, such as dense clouds of small bubbles. Refraction around larger vapor-liquid interface regions also introduces beam steering problems which make line of sight extinction measurements difficult.

In addition to macroscale studies of nozzle cavitation focused specifically on fuel injection, the study of bubble nucleation and collapse at smaller scales has been an active area of research for many decades [15]. The behavior of individual cavitation bubbles is reasonably well understood [16], but the connection between the nanoscale physics and macro-scale properties of cavitating nozzle flows is not yet fully understood. In strongly cavitating cases, large void regions occur where cavitation bubbles interact and merge, and non-equilibrium thermodynamics become important [17]. Realistic wall geometries, surface roughness and the effects of dissolved gases complicate the problem further. Improved experimental diagnostics for cavitation may benefit our understanding of how the micro to macroscale properties of cavitation are connected to the nanoscale physics. A major complication for experiments, however, is the fact

that nucleation does not scale with other hydro-dynamic properties; this changes the cavitation behavior of scaled-up models. In order to make measurements at the scale of production injector nozzles, spatial resolution below the diffraction limit of visible light is desirable.

Aside from experimental diagnostics, numerical models are commonly used to simulate cavitating nozzle flow [7, 10, 18]. The wide variety of numerical models presently in use employ a range of different submodels to account for phase change and multi-phase thermodynamics [19, 20]. Different models give different results under otherwise identical conditions, and often show inconsistency with experiments. Quantitative experimental validation under well-defined canonical test conditions is critical to their further development [21, 22].

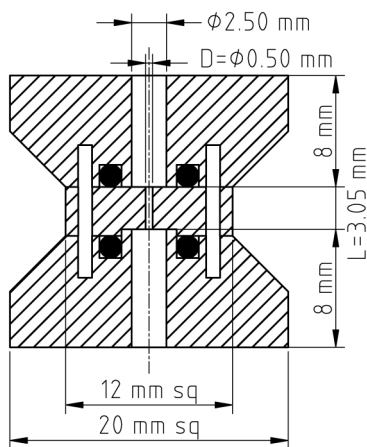


Figure 1. Cross-section of nozzle geometry, showing throat diameter D and nozzle length L .

X-ray diagnostics have been used for some time to study dense multi-phase flows, as they are not encumbered by the same limitations as visible-light measurements [23]. X-rays scatter from phase boundaries far more weakly than visible light. CT scanning techniques have been used to make measurements of nozzle geometry and dynamics [24, 25, 26]. However, they do not have sufficiently high spatial resolution and flux to measure density variations on the micron length scales and microsecond time scales of fuel injector flow. X-rays from synchrotron sources are ideally suited to such problems, as they have high flux within a narrow energy bandwidth, are well-collimated, and may be focused to a micron-size probe region, providing sufficiently high spatial and temporal resolution to make measurements in nozzles approaching the scale of fuel injectors.

Over recent years, several synchrotron x-ray diagnostics for fuel injection and sprays have been developed at the Advanced Photon Source (APS) at Argonne National Laboratory [27]. Many of these techniques may be effectively applied to studying cavitation as well as sprays. X-ray radiography provides an accurate, quantitative line of sight measurement of the density of a sample at very high spatial and temporal resolution through the measurement of the attenuation of monochromatic x-rays. Radiography has been used for some time to study fuel sprays [28, 29], and has also been demonstrated to be a

useful tool for measuring projected fluid density in a cavitating nozzle [30]. The quantitative nature of the measurement makes it ideally suited for the validation of numerical simulations [22, 31].

One of the primary limitations of x-ray radiography is the inability to distinguish species in a multi-component flow. Recently, new x-ray fluorescence based diagnostics have been developed at APS to address such problems in multi-component and reacting flows [32]. By tagging a gas or liquid flow with a tracer species that undergoes x-ray fluorescence, it is possible to measure the concentration of the tagged flow in the beam path. For the purpose of measuring cavitation bubbles in a fluid, fluorescence has the advantage that the liquid density measurement is made against a very low background level, as opposed to the radiography measurement where the fractional change in the transmitted x-ray beam can be very small, leading to high noise sensitivity. Using a sensitive photon-counting detector, fluorescence measurements may be less noisy and more accurate than radiography for this particular application.

Finally, x-ray phase contrast imaging (PCI) relies on spatially propagated interference between weakly refracted and undisturbed x-rays. Phase contrast techniques are sensitive to density gradients but insensitive to absolute density, and can reveal intricate structural detail of dense objects in a time-resolved planar projected field of view [33]. Recently, we have demonstrated how x-ray phase contrast imaging may be used to detect the presence of cavitation inside unmodified steel injectors by doping the fuel with an x-ray absorbing additive [6]. Although it is very difficult to obtain quantitative measurements of fluid density, phase contrast imaging reveals spatial and structural details that correspond to density variations that are too weak to be observed by radiography or fluorescence.

In this paper, we review the application of the three aforementioned diagnostics to the problem of internal nozzle cavitation. A simplified, canonical submerged test nozzle is used. We demonstrate the effectiveness of x-ray radiography and fluorescence in providing accurate time-average line of sight projections of the vapor fraction in a degassed cavitating nozzle, and how these results can be compared to numerical simulations. Furthermore, we investigate temporal dynamics and the effects of dissolved gases using x-ray phase contrast imaging.

METHOD

A cross-section diagram of the nozzle used in these experiments is shown in Fig. 1. For the purposes of x-ray radiography and fluorescence, the sample nozzle must be transparent to x-rays (8-15 keV energy) of a wavelength which will absorb well in fuel [31] or will excite appropriate fluorescence transitions. The nozzle is nominally axisymmetric, and has a diameter of $D = 0.5\text{mm}$ and a length of $L = 3.05\text{mm}$ at a tolerance of 0.5%, giving $L/D = 6.1$. The contraction/expansion area ratio is 25, and the nozzle has a discharge coefficient of approximately 0.7 (determined by the flow rates and pressures measured during the experiment).

Selection of material for the nozzle samples must satisfy several criteria. In addition to having a sufficiently high modulus so as to not deform under rapid changes in internal pressure, the material must be transparent to x-rays in the appropriate energy range, must not degrade rapidly when exposed to high levels of x-ray radiation, must be chemically compatible with the fuel, and must be able to be machined with a suitably smooth and uniform surface finish, since cavitation nucleation is highly sensitive to the local wall roughness and geometry.

The x-ray energy range of the radiography and fluorescence measurements (8-15 keV) limit the material choice to plastics. Several plastics were tested for this study, including standard and gamma-stabilized polycarbonates, and PEEK (polyetheretherketone). PEEK was selected for the experiment, since it is most resistant to radiation damage. All plastics suffer from a degree of micro-scale surface defects (burring, chipping and scratching) when using traditional machining processes. Several abrasive surface treatments were tested, and it was found that untreated PEEK gave the sharpest and most uniform inlet geometry. The PEEK samples still have many micron- sized scratches which can act as nucleation sites. The final nozzle hole diameter and eccentricity tolerance is approximately 0.5% of the nominal diameter.

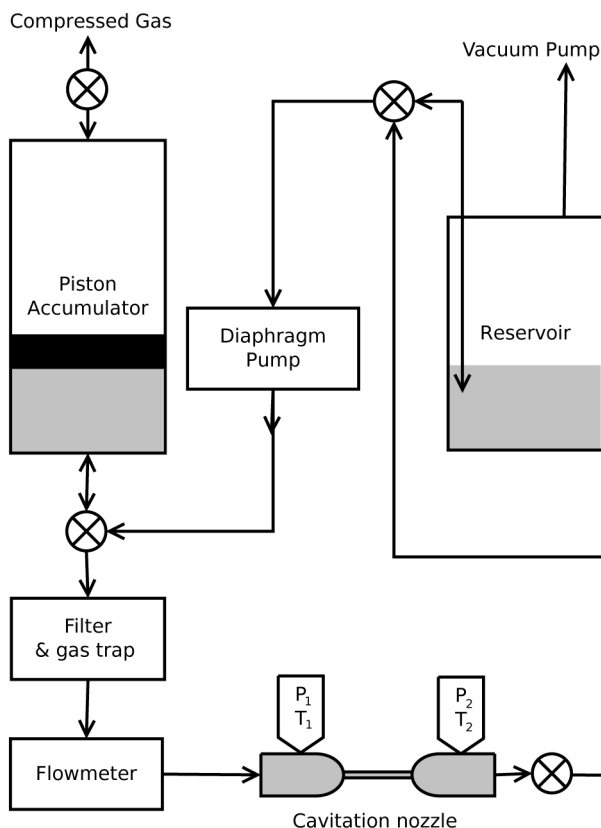


Figure 2. Schematic of fuel delivery system.

The working fluid is a gasoline surrogate with a density of $\rho_1 = 778 \text{ kg/m}^3$, a viscosity of $\nu = 1.5 \text{ cSt}$ and a vapor pressure of $P_v = 4.6 \text{ torr}$ at 25°C (measured to NIST standards by isoteniscope test). A schematic

of the fuel delivery system is shown in Fig. 2. In order to remove dissolved gases, the fuel is stored in an evacuated tank, and pumped at low pressure using a diaphragm pump into a piston accumulator. The accumulator is charged with compressed gas, and the fuel flows through the nozzle back into the evacuated tank. The accumulator piston o-rings maintain a seal between the gas and liquid sides, keeping them isolated. A $10 \mu\text{m}$ filter and gas trap on the upstream end ensure that no debris or gas bubbles are present in the test section.

The accumulator gas pressure determines the upstream liquid pressure P_1 , and a needle valve on the downstream side of the flow circuit determines the back pressure P_2 . The pressures are monitored by transducers connected to static taps in the plenum spaces immediately upstream and downstream of the nozzle. The inlet and outlet plenum temperatures are monitored, and the mass flow rate of fluid is measured using a magnetic turbine flowmeter. The key operating parameters are the Reynolds Number, and Cavitation Number;

$$\text{Re} = \frac{D\bar{U}}{\nu} = \frac{4\dot{V}}{\pi\nu D}, \quad (1)$$

$$\sigma = \frac{P_1 - P_2}{P_2 - P_v}. \quad (2)$$

The bulk velocity inside the nozzle is inferred from the measured volumetric flow rate $\dot{V}$; from this quantity the nozzle discharge coefficient can also be measured. The nozzle is held in a compression fixture which is placed in the path of the x-ray beam. The compression fixture has an integral mesh screen and slowly tapering straight section which conditions the flow to be fully developed as it enters the nozzle.

In the experiments presented here, $P_1 = 10 \text{ bar abs}$, $P_2 = 1 \text{ bar abs}$, and $\dot{V} \approx 18 \text{ L/hr}$, at a temperature of 25°C . For $D = 0.5 \text{ mm}$ and the fluid properties specified above, $\text{Re} = 1.1 \times 10^4$ and $\sigma = 9.06$.

X-RAY RADIOGRAPHY

X-ray radiography measurements are performed at the 7-BM beamline of the APS [34]. In this experiment, we use a monochromatic x-ray beam of mean photon energy 8 keV , 1.4% full width at half maximum energy bandpass, with a flux of approximately $2.5 \times 10^{11} \text{ ph/s/mm}^2$. The beam is focused to a spot approximately $5 \times 6 \mu\text{m}$ in size using a pair of Rhcoated Kirkpatrick-Baez mirrors. The beam focus is aligned with the center of the nozzle; the divergence of the beam is small compared to the diameter, such that the beam area remains relatively constant across the nozzle diameter. The beam intensity is monitored upstream of the experiment (I_0), and the transmitted beam (I_1) is measured with a PIN diode. The nozzle compression assembly is traversed through the fixed x-ray beam in order to build up a raster-scan pattern of measurements.

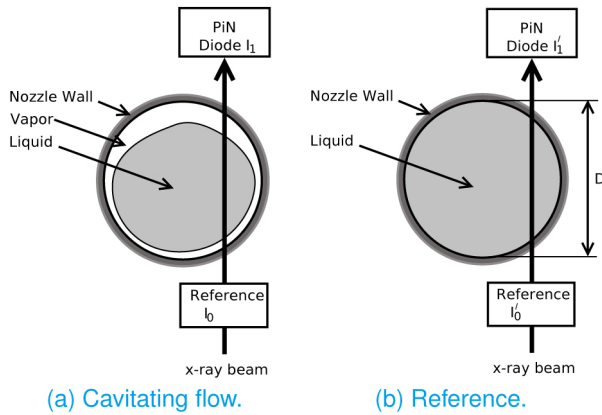


Figure 3. Cross-section diagram of cavitation nozzle, demonstrating an x-ray radiography measurement (a) compared to a reference case (b).

The radiography measurement is depicted in the schematic given in Fig. 3. Data are collected along a line of sight δz at a particular point of interest through the nozzle, as per Fig. 3a. The experiment is repeated at a non-cavitating condition where the nozzle is filled with liquid at the same inlet pressure, but over a small pressure gradient (typ. 0.1 bar) where there is no cavitation (denoted I'), as per Fig. 3b. The presence of void regions in the nozzle results in an increase in the transmitted beam intensity due to a reduction in the absorbing mass in the beam path. As a result, the projected density of fluid in the beam path is defined by the Lambert-Beer law;

$$\frac{I_1/I_0}{I'_1/I'_0} = e^{-\mu_l(M_l - M'_l)} \quad (3)$$

The mass of displaced liquid per unit beam area ($M_l - M'_l$) between the experiment I_1/I_0 and the reference case I'_1/I'_0 is positive in the presence of cavitation vapor. The attenuation coefficient of the working fluid (μ_l , units m^2/kg) is obtained via calibration of the working fluid against a known absorbing medium in a cuvette. For the fluid used in these experiments, $\mu_{l,pl} \approx 0.3124 \text{ mm}^{-1}$. M is normalized by the known density of the liquid phase to convert mass per unit area to a path length δz_v , which represents the projected volume fraction of vapor α in the path of the beam;

$$\delta z_v = \frac{-1}{\mu_l \rho_l} \log_e \left(\frac{I_1/I_0}{I'_1/I'_0} \right) \equiv \int_{\delta A} \int_{\delta z} \alpha dA dz \quad (4)$$

The uncertainty in the measured radiography signal due to photon shot noise and signal processing noise is small, since the flux is large. The uncertainty in δz_v is amplified mainly due to the relatively weak contrast between the cavitating and reference signal levels. The contrast in the intensity (I/I') varies from 1 to 1.06 in the present experiment, giving an uncertainty in the time-average projected void fraction of $\pm 3.5 \mu\text{m}$, which is 0.7% of the nozzle diameter or 2% of a typical peak value of δz_v . The uncertainty in the projected void fraction depends mainly on the intensity contrast, and under these conditions it remains relatively constant. The noise floor imposed by the uncertainty limits the ability to measure particularly small

quantities of vapor, and small fluctuations in vapor. This is particularly important near the nozzle wall, where the projected geometric path length δz is quite small. Further details may be found in previous work [22, 31].

Results are shown in Figs 4a and 4b for de-gassed gasoline-type calibration fluid under cavitating conditions with $P_1 = 10 \text{ bar}$, $P_2 = 1 \text{ bar}$, $\text{Re} = 1.1 \times 10^4$, $\sigma = 9.06$. The time-average projected void fractions at two orthogonal views correspond to an approximately axisymmetric vapor distribution with nearly pure vapor in an attached bubble near the inlet wall, and no cavitation along the nozzle centerline. The results compare favorably to compressible high-resolution large eddy simulations of the same flow, computed using a homogeneous relaxation model (HRMFOam) using OpenFOAM [20, 35]. The void fraction quantitatively agrees to within 15%. In these simulations, fluid properties are obtained via look-up table [36], and the simulation is three-dimensional with a minimum cell size of $3.125 \mu\text{m}$ across the nozzle throat, at which point the solution approaches grid-independence ($\delta/D \approx 160$). A projection of vapor fraction matching the quantity measured by radiography has been performed by volume-integrating the simulation domain onto a plane. Further details may be found in Duke et al. [22]

X-RAY FLUORESCENCE

X-ray fluorescence is an alternative diagnostic which can overcome some of the limitations of radiography. As in optical fluorescence, the number of detected fluorescence photons can be directly correlated to the number density of a particular tracer species in the path of the beam, once the appropriate corrections are made [32]. In the case of x-ray fluorescence, the high photon energies eject core-shell electrons rather than the valence electrons, so the energy of the fluorescence photons which are emitted as the K-shell hole is filled depend only on atomic number, rather than molecular structure.

For the purposes of these experiments, the flow is doped with 400 ppm concentration of tetrabromomethane (CBr_4), which dissolves readily in hydrocarbon fuels. Bromine is an ideal tracer species, since it has a high fluorescence yield and high K-shell fluorescence energies (11.88 - 11.92 keV). This high energy allows approximately 50% of the fluorescence photons to survive to the detector without reabsorption through the nozzle wall material and air [37].

X-ray fluorescence measurements are performed at the 7-BM beamline of the APS, with the same focusing mirror arrangement as for the radiography experiments described above. In order to overcome the K-shell electron binding energy of bromine, the mean energy of the monochromatic x-ray beam is increased to 14.7 keV, 1.0% full width at half maximum bandpass energy.

The experiment setup is shown in Fig. 5. The focused beam is passed through the cavitating flow, the same as for the radiography measurement (Fig. 3a). A photon-counting silicon drift detector is placed at approximately a right angle to the incident beam. Since the density of the liquid fuel is many orders of magnitude larger than the cavitation void regions and the concentration of Br in the liquid fuel is homogeneous, the fluorescent emission I_{Br} above the background level $I_s(E)$ within the expected energy range E_{Br} is proportional