X-ray Diagnostics for Cavitating Nozzle Flow

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Abstract. Cavitation plays a critical role in the internal flow of nozzles such as those used in direct fuel injection systems. However, quantifying the vapor fraction in the nozzle is difficult. The gas-liquid interfaces refract and multiply scatter visible light, making quantitative extinction measurements difficult. X-rays offer a solution to this problem, as they refract and scatter only weakly. In this paper, we report on current progress in the development of several x-ray diagnostics for cavitating nozzle flows. X-ray radiography experiments undertaken at the Advanced Photon Source at Argonne National Laboratory have provided measurements of total projected void fraction in a 500 µm submerged nozzle, which have been directly compared with numerical simulations. From this work, it has been shown that dissolved gases in the liquid also result in the formation of vapor regions, and it is difficult to separate these multiple phenomena. To address this problem, the liquid was doped with an x-ray fluorescent bromine tracer, and the dissolved air substituted with krypton. The fluorescent emission of Br and Kr at x-ray wavelengths provide a novel measurement of both the total void fraction and the dissolved gas component, allowing both cavitation and dissolved gas contributions to be measured independently. [199/200 words]

1. Introduction
Cavitation is known to play an important role in high-pressure direct fuel injection systems [1]. Although the fundamental physics of cavitation nucleation is reasonably well-understood [2], the combination of cavitation and turbulent fluid flow in a fuel injector nozzle can lead to complex multi-phase flow structures which are not fully understood and remain an area of active research. It has been established that cavitation inside the nozzle can affect atomization and combustion, and that cavitation leads to erosion and emissions control issues [3].

Visualization experiments have revealed a great deal about the morphology of nozzle cavitation [4]. However, it is difficult to obtain quantitative vapor fraction measurements from these experiments. Visible light refracts strongly at both the nozzle walls and larger gas-liquid interfaces, and will also be multiply scattered by clouds of small bubbles, making measurements of the void fraction difficult.

In recent years, x-ray radiography has been demonstrated as a useful diagnostic for studying dense fuel sprays [5], since x-rays refract and scatter only very weakly [6]. With an appropriate choice of wavelength, x-ray absorption can be easily related to the projected density of the flow field [7]. These techniques are equally applicable to cavitating nozzle flows. Void fraction measurements in a cavitating pipe have previously been demonstrated using x-ray CT scanning [8]. However, x-ray tube sources are limited in spatial and temporal resolution. Focused, monochromatic synchrotron x-rays provide orders of magnitude more flux, and can probe flow at scales relevant to fuel injection, with a spatial resolution on the order of 5 microns [9]. X-ray radiography can be directly compared to numerical simulations, since a line-of-sight projection of the void fraction can be easily computed from a 3D model.

Recent work has shown that non-condensable gas can also play an important role in determining the vapor distribution in a cavitating nozzle [10]. Since x-ray radiography cannot distinguish between vapor due to gas bubbles and vapor due to cavitation, we have developed an x-ray fluorescence experiment which uses separate tracers in the fuel and gaseous phases to separate these effects [11]. Unlike visible light, x-rays are sufficiently energetic to interact with core shell electrons, such that elemental species can be tracked without regard for the valence state. The fluorescence photons are themselves x-rays [12];
they also interact weakly with the sample. We report on progress in the development of x-ray radiography and fluorescence techniques for the study of cavitation in a submerged model nozzle.

2. Methods

The test geometry was a submerged plastic nozzle 500 µm in diameter and 3.05 mm in length \((L/D = 6.1)\), with an expansion/contraction diameter ratio of 5. The working fluid was a commercial gasoline surrogate (Viscor 16br) at 25\(^\circ\)C with a vapor pressure of 3 torr and a density of 0.773 g/cc. A piston accumulator (Fig. 1) was used to supply a continuous flow of fuel to the nozzle, with a static inlet pressure of \(P_1 = 10\) bar abs. A needle valve downstream of the experiment was used to regulate the back pressure on the nozzle to \(P_2 = 1.0\) bar abs, with the fuel returned to a storage tank held under partial vacuum [9]. In this nozzle, \(Re_D = 1.5 \times 10^4\) and cavitation number \(\sigma = 0.11\).

The experiments were performed at the 7-BM beamline of the Advanced Photon Source at Argonne National Laboratory [13]. A monochromatic x-ray beam was focused to a spot of \(5 \times 6\) µm cross-section, and the nozzle was traversed through the fixed beam to build up a two-dimensional raster map of measurements. Fig. 2 shows the setup with a cross-section through the nozzle throat. For radiography, the beam energy was set at 8 keV (3.0% full width at half-maximum bandpass), and was passed through a reference intensity monitor \((I_0)\) and collected by a PiN diode \((I_1)\). The absorption of x-rays in the liquid is related to the projected void fraction \(\alpha\) by the Beer-Lambert Law;

\[
\int \alpha \, dz = -\frac{1}{\mu_l \rho_l} \ln \left( \frac{I_1}{I_0} \frac{I_0'}{I_1'} \right),
\]

where \(I_1'/I_0'\) is a reference measurement with the nozzle full of liquid and no vapor, \(\rho_l\) is the liquid density and \(\mu_l\) is the attenuation coefficient for the liquid fuel, which is calibrated against a known standard [9].

For the fluorescence experiments, the same setup was used, but an energy-resolving silicon drift diode was placed at a 100-degree angle to the incident beam, capturing the fluorescent emission where the beam interacts with the flow. The liquid was doped with tetrabromomethane, which dissolves well in hydrocarbons. Dissolved air in the fuel was substituted with krypton, which has similar solubility to nitrogen at standard conditions, despite its higher density [14]. The beam energy was increased to 14.7 keV (1.0% FWHM bandpass), and the Br and Kr K\(_\alpha\) emission lines were used to track the elemental concentrations.

The projected fluid density is determined from the integrated count rate of Br K\(_\alpha\) emission \(I_k = I_{Br}\);

\[
\int \rho_k \, dz = \frac{c_k f_s(x, y)}{I_0 f_a(x, y, I_1/I_0)} \frac{t_{live}}{\Delta t} I_k,
\]

where \(c_k\) is a constant scaling coefficient which depends on the detector solid angle, fluorescence yield and species concentration, \(f_a\) is a correction function for the absorption of the beam in the sample, and \(t_{live}/\Delta t\) is the fraction of time that the detector is active. The sample time per point was \(\Delta t = 5\) s. \(f_s\) is a signal trapping function which corrects for the increasing absorption of photons in the fluid and nozzle.

Figure 1: Fuel delivery system.

Figure 2: Schematic of x-ray experiment setup, showing a cut-plane of the nozzle.
Projected void fraction at 0 degrees.

Projected void fraction at 90 degrees.

Projected void fraction from LES.

Figure 3: Projected total void fraction $\int \alpha \, dz$ with degassed fuel at $P_1 = 10$ bar, $P_2 = 1$ bar from (a,b) two orthogonal views using x-ray radiography and (c) large eddy simulation. Flow is left to right.

wall as the distance between the beam and detector increases. It was iteratively solved by updating the estimates of the fluid density distribution in a plane, applying an Abel inversion, and computing the absorption toward the detector [11]. The path length of non-condensable gas is similarly solved using Eqn. 2 with $I_k = I_{Kr}$. Given the known path length through the nozzle $\delta z$, the fluid density, and the partial density of the gas, it is possible to solve for the total projected vapor $\int \alpha \, dz = \delta z - \int \rho_{Br} \, dz/\rho_{l}$ and the non-condensable gases $\int \alpha_{g} \, dz = \int \rho_{Kr} \, dz/\rho_{v}$. When $\int \alpha \, dz > \int \alpha_{g} \, dz$, we assume that the additional vapor is due to cavitation: $\int \alpha_{v} \, dz = \int \alpha \, dz - \int \alpha_{g} \, dz$.

3. Results and Discussion

In the first set of experiments, we removed all dissolved air from the fuel and made a time-averaged radiography measurement of the total projected vapor fraction from two orthogonal views. Figs. 3(a-b) show that most of the vapor is attached to the nozzle wall and persists until about one nozzle diameter from the exit. The results compare favorably with three-dimensional large eddy simulations of the flow (Fig. 3c), which were performed using a homogeneous relaxation cavitation sub-model [15, 16].

During the experiments, we found that the introduction of dissolved air caused a large decrease in the fluid density [9]. Simulations suggested that this was due to gas in the fuel coming out of solution due to the sudden pressure drop at the nozzle inlet [10]. To investigate further, we turned to the x-ray fluorescence diagnostic. Kr was substituted for air at standard conditions, giving a mass ratio of $0.039 \times 10^{-4}$. The results are shown in Fig. 4. The total projected vapor and gas from Br fluorescence is markedly increased (Fig. 4a) compared to the degassed case (Fig. 3a). The projected volume fraction of Kr (Fig. 4b) shows a large amount of gas throughout the nozzle. An increase in the centerline Kr concentration with $x$ indicates addition gas coming out of solution. With a bulk velocity $U \approx 58$ m/s, we note that the nozzle transit time is 53 $\mu$s. This process occurs orders of magnitude slower than cavitation inception, but its time scales are still relevant for diesel injection.

The difference between the Br and Kr measurements (Fig. 4c) reveals that the only region of true cavitation is an annular bubble which is asymmetric and disappears by $x/D = 4$. The asymmetry may be partially due to machining defects in the nozzle which differ between the two experiments. However, the reduction in true cavitation relative to the completely degassed case suggests that nucleating gas bubbles (which have orders of magnitude higher density and pressure than the cavitation vapor) are displacing the cavitation zones which would otherwise occur.
Projected total vapor from bromine fluorescence.

Projected non-condensable gas distribution from krypton fluorescence.

Projected cavitation distribution.

Figure 4: X-ray fluorescence measurements of fuel with dissolved krypton gas at $P_1 = 10$ bar, $P_2 = 1$ bar. Fluorescence of (a) the liquid phase gives the total void fraction, from which (b) the non-condensable gas contribution can be removed to compute (c) the contribution due to cavitation. Flow is left to right.

4. Conclusions

These early results suggest that simulations of cavitation in fuel injection systems need to take into account the dynamics of dissolved gases in order to yield accurate predictions. Furthermore, when the fluid contains non-condensible gas, experimental studies must account for the fact that many of the observed voids may not be true cavitation, particularly in the scaled-up case where the transit time through the nozzle can be longer, allowing more opportunity for phase change.

X-ray radiography and fluorescence measurements permit useful quantitative analysis of cavitating flows, which in future work may be readily extended to spraying nozzles and transparent injectors.

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