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X-Ray diagnostics of Cavitation, Gas Injection, and Shot-to-Shot Variation

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Abstract
X-ray diagnostics have the potential to make quantitative measurements in environments where optical diagnostics are difficult, particularly inside opaque materials and in highly scattering multiphase flows. The high brightness and increasing availability of synchrotron x-ray sources has made these diagnostics feasible, and enabled their application to a range of challenges for fuel injection. This presentation will describe the measurements which are possible using synchrotron x-ray sources and their application to cavitation, gas injection, and quantitative measurements of shot-to-shot variation.

X-ray radiography has been applied to a gas jet from a natural gas injector in order to build a time-resolved, quantitative map of the average fuel distribution. X-ray absorption by natural gas is particularly weak because of its low density and low atomic number; argon gas was substituted in order to increase absorption and thus signal-to-noise ratio. In Figure 1, the average fuel distribution from an outward opening plug injector is shown at about 1 ms after the start of injection. The red colors indicate the regions of highest argon density. These data are being used to validate computational simulations of natural gas injection, and to improve the predictive capabilities of full-engine simulations.

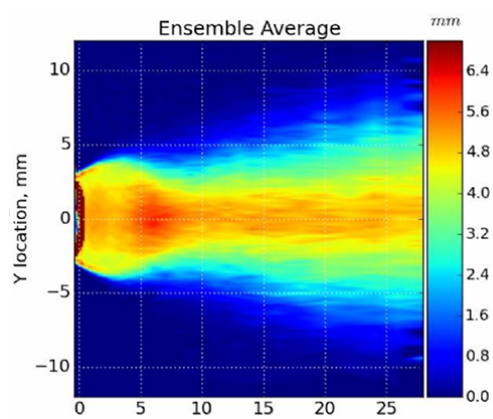

Figure 1. Line of sight projection of argon gas emitted from an outward opening natural gas injector. The injection pressure was 10 bar Ar, injected into an ambient of 1 bar N_2. These data were collected at approximately 1 ms after the start of injection. The color units are in mm of argon gas at room temperature and pressure.

In Figure 2, the use of radiography to quantify shot-to-shot variation is shown. On the left is a measurement of the ensemble-averaged projected density of a spray from a single-hole diesel injector. At right, the ensemble standard deviation is shown. The ensemble average shows regions of high fuel concentration, while the ensemble average shows regions of high variability in this quantity from one event

to the next. The ensemble standard deviation is thus a useful metric to quantify, in units of mass/area, where and when the spray shows variability. In addition, we believe it is an indicator of strong mixing between the fuel and the ambient, as the observed regions of variability correspond to the regions where mixing is expected to be strong[1].

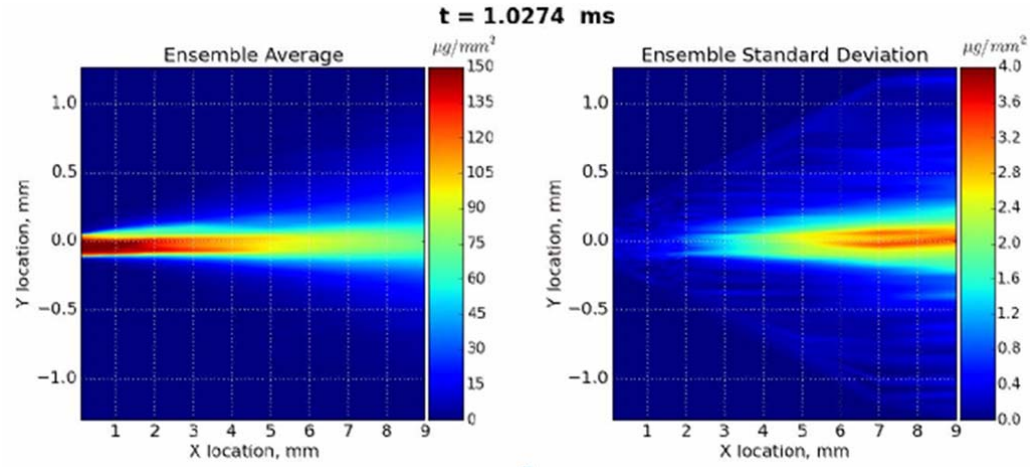

Figure 2. Line of sight projections of the ensemble average (left) and the ensemble standard deviation (right) of a spray from a single-hole diesel injector. The injection pressure was 500 bar, injected into an ambient of 20 bar N_2. These data were collected at approximately 1 ms after the start of injection.

X-ray fluorescence has been used to map the density distribution of the fluid inside a plastic nozzle[2]. Because fluorescence is sensitive to the identity of atomic elements, it allows mixing between different fluids to be tracked quantitatively. Here, bromine acts as a tracer for the liquid fuel, while krypton gas is dissolved in the fuel to indicate regions where dissolved gas comes out of solution. In Figure 3, the regions where the dissolved gas (krypton) comes out of solution have been subtracted from the total gases, leaving the signal that results from cavitation. This allows the interplay between cavitation and dissolved gas to be studied quantitatively for the first time.

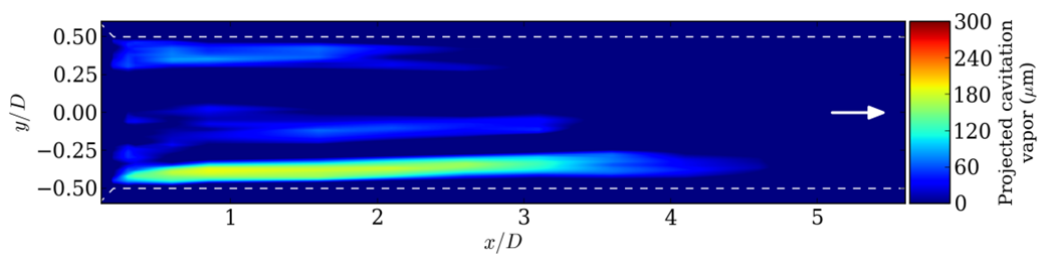

Figure 3. Line-of-sight density projection of cavitation inside an x-ray transparent nozzle. In this Figure, the fluorescence signal from the krypton (dissolved gas) has been subtracted from the total gas measured using the bromine fluorescence. The color units are microns of vapor in the line of sight.

1. Swantek *et al*, SAE International Journal of Fuels and Lubricants, 8(1) pp. 160-166, April 2015.
2. Duke *et al*, SAE International Journal of Fuels and Lubricants, 8(1) pp. 135-146, April 2015.