X-Ray Diagnostics for Fuel Injection and Sprays

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Thanks to the Organizing Committee
“Still, let’s do an x-ray just to be sure.”
Sprays are Critical for Efficient Engines

- Fuel and air mixing must be carefully controlled
- Fuel sprays have been an area of active research for 30+ years.
  - Measurements rely primarily on visible light
  - Imaging, scattering, fluorescence, spectroscopy
- These techniques have limited ability to quantify the fuel density
  - Large number of droplets leads to multiple scattering
  - Limits penetration of visible light
  - Obscures fuel distribution
  - Limits the data available for engine design, computer simulations
X-Ray Diagnostics Reveal the Fuel Distribution

Mie Scattering Image Locomotive Injector

Image courtesy of Essam El-Hannouny, Argonne

Diesel Spray X-Ray Radiography

Fuel Injector

Visible Light

Scattering

Absorption

X-Rays

Axial Position (mm)

Mass/Area (µg/mm²)
The Idea to Use X-Rays for Sprays Was *Not* Invented at Argonne

G. Zimmerman & V. Aust, Fraunhofer EMI, 1997

K. Kuo, K. C. Hsieh, and J. M. Char
Penn State, 1990
The Advanced Photon Source at Argonne National Laboratory

- Spray studies require fast time resolution, high spatial resolution – FLUX!
- $10^6$ times more x-rays than a benchtop source.
- Similar sources worldwide
- Laboratory dedicated to spray research
**X-Ray Radiography**

\[ \frac{I}{I_0} = \exp\left(-\mu_M M\right) \]

- **Weak signal, maximum absorption \( \sim 2\% \)**
- For best S/N, need to concentrate flux in small area
- Must raster scan to build 2D information

\( I_0 \)  Incident x-ray flux
\( I \)  Transmitted x-ray flux
\( \mu_M \)  Fuel absorption constant
\( M \)  Integrated Mass/Area
Radiography Gives Quantitative Measurement of the Fuel

- Ability to penetrate optically dense sprays
- Line-of-sight, ensemble-averaged, time-dependent fuel distribution
- 5 \( \mu m \) spatial resolution, 1 \( \mu s \) time resolution
- High pressure, but room temperature
- Quantitative data for development and validation of spray models
Spray Tomography

90 Lines of Sight allow density (kg/m$^3$) to be determined precisely
3D Reconstruction of Gasoline Sprays

- Many lines of sight, mathematical reconstruction
- Shows average, time-resolved density at several “slices” through the spray
- Fine space, time, density resolution (25 μm, 5 μs, 15%)
- Provides very stringent test of models

2 mm 5 mm 10 mm
Radiography Quantifies Shot-to-Shot Variability

- Can quantify variability in fuel distribution in units of mass
  - *Spray variability may contribute to combustion variability*

- LES Spray models predict shot-to-shot variation
  - These data can be used to validate those predictions

\[ P_{\text{inj}} = 500 \text{ bar} \]
\[ P_{\text{amb}} = 20 \text{ bar} \]
\[ \phi = 180 \mu \text{m} \]
Principle of X-Ray Phase-Contrast Imaging

- Diffraction at density gradients enhances the contrast in an image
- High speed visualization
- Resolution $\sim 1 \, \mu m$, 10 ps
- Image brightness is no longer directly related to density of sample

Diffraction at density gradients enhances the contrast in an image. High speed visualization. Resolution $\sim 1 \, \mu m$, 10 ps. Image brightness is no longer directly related to density of sample.
High Speed X-Ray Imaging of Needle Valve Motion

- Off-axis motion is undesirable
- Affects flow inside, outside the injector
- Useful for defining time-resolved simulation geometry
Needle Eccentricity Affects Nozzle Flow

- Simulations using measured, eccentric needle motion
- In 3 hole nozzle, vortex flow develops in sac near SOI and EOI
- This decreases fuel flow to one of the holes.

Battistoni & Som, SAE Congress 2014
• Cavitation in the nozzle during the flow
• Bubbles pulled into the sac after injection
Cavitation is an Important Problem in Injectors

- Cavitation: fuel can vaporize in low pressure regions of the flow
  - Causes nozzle erosion
  - Increases with injection pressure
- Not well understood
- Difficult to measure
  - Multiple scattering
  - Optically opaque

Giannadakis et al.
Radiography Measures Density of Cavitating Flows

- No interference from multiple scattering
- Allows for more stringent validation of flow simulations
- Radiography cannot distinguish between cavitation and dissolved gas emerging from solution
  - Requires working with degassed fuels
  - Not a good model for real fuel systems
X-Ray Fluorescence Can Track Chemical Elements

- Visible light fluorescence excites vibrational states in molecules
- X-ray fluorescence excites inner core electronic states
- Not affected by bonding, T, visible light emission, soot, phase, etc
- Characteristic wavelength (energy) for each element
Studies of Jet Mixing Using X-Ray Fluorescence

- Two impinging liquid jets
- One jet doped with copper, other with zinc
- Probe the flow with x-ray beam
- Track the concentrations of these elements as the jets mix
Studies of Jet Mixing Using X-Ray Fluorescence

- Elemental tracers track the impinging jets
- Jets collide, partially mix
- Streams cross, stay on opposite side of merged jet
- Powerful tool to understand mixing processes
First Measurements of Cavitation and Dissolved Gas

- X-ray fluorescence
  - Bromine tracer dissolved in the fuel
  - Saturate fuel with krypton gas
  - Br and Kr emit x-rays of different wavelengths

- Under non-cavitating conditions
  - Uniform distributions of Br and Kr

- Under cavitating conditions
  - Regions of low bromine concentration indicate gas and/or vapor
  - If these regions contain krypton, it indicates dissolved gas coming out of solution
  - First measurement that can resolve dissolved gas and cavitation

Duke et al, SAE 2015-01-0198
Near-Nozzle Droplet Sizing is Difficult with Visible Light

- Droplet sizing is critical for understanding spray breakup
- Little is known in the near-nozzle region
- Optical droplet sizing breaks down because of multiple scattering
- X-rays can penetrate this region of the jet, multiple scattering is negligible

Labs and Parker
*Atomization and Sprays*
v. 16, 2006
Small-Angle X-Ray Scattering Measures Surface Area of a Sample

- Measure number of x-rays scattered as a function of angle
- Absolute magnitude of the scattering depends on the *surface area* of the scatterers
- We measure *density* using radiography
- Can determine Sauter Mean Diameter (diameter of a sphere with the same volume/surface area ratio)

Calculated SAXS signal of different size droplets at fixed density

\[
\frac{d\Sigma}{d\Omega}, \text{Å}^{-1} \text{str}^{-1}
\]

- 2 μm Diameter
- 20 μm Diameter
Small Angle X-ray Scattering

- Measurement: count the number of scattered x-rays as a function of angle
- Result: very small SMD, even very near the nozzle
- Size dramatically decreases within the first few mm of the nozzle
- Measurements provide another constraint on spray simulations: Quantitative measurements of near-nozzle spray breakup
Summary

- **Radiography** enables measurements of mass, even in multiphase flows
  - Sprays, cavitating flows
  - Can’t resolve species, currently limited to room temperature

- **Phase Contrast Imaging** allows very high speed imaging, even through steel
  - Image internal components, sprays
  - Can’t quantify the brightness in the images

- **X-Ray Fluorescence** can track atomic species, even in harsh environments
  - Mixing, cavitation, evaporating sprays, combustion, sooting flames
  - Complicated corrections required to analyze the data

- **X-Ray Small Angle Scattering** can measure particle size, without interference from multiple scattering
  - Near-nozzle SMD, soot sizing
  - Not yet validated against other techniques