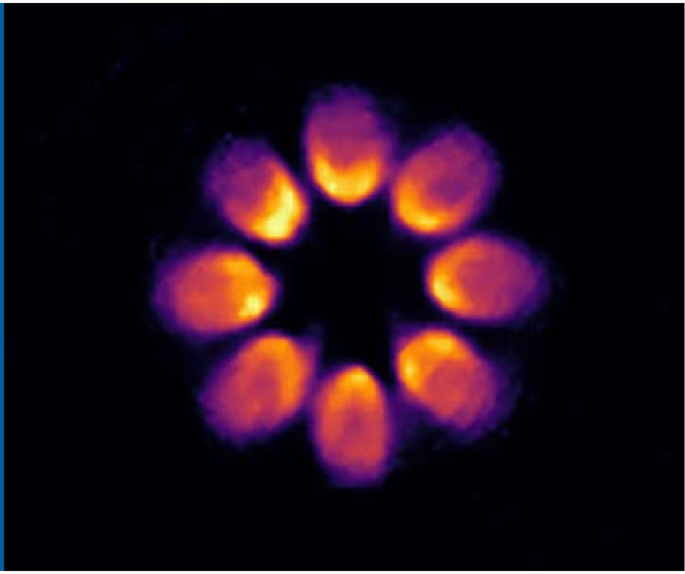
PROJECT ID ACE010

FUEL INJECTION AND SPRAY RESEARCH USING X-RAY DIAGNOSTICS



CHRISTOPHER POWELL, BRANDON SFORZO, ANIKET TEKAWADE

Argonne National Laboratory

11 June 2019

TEAM LEADERS:
Gurpreet Singh
Michael Weismiller

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OVERVIEW

Timeline

- Project began under FY2019 DOE Lab Call
- Project ends in FY2021

Budget

- FY2018: $485K
- FY2019: $600K

Partners

- Engine Combustion Network, UMass-Amherst, Argonne, Sandia, Oak Ridge
- Aramco, Georgia Tech, Co-Optima, Spray Combustion Consortium

Barriers

- “Inadequate understanding of the fundamentals of fuel injection”
- “Inadequate capability to simulate this process”
- “The capability to accurately model and simulate the complex fuel and air flows”

RELEVANCE AND OBJECTIVES OF THIS RESEARCH

- Understanding of fuel injection is a significant barrier to improving efficiency and emissions
- Argonne's world-class x-ray source and facilities enable unique measurements of fuel injection

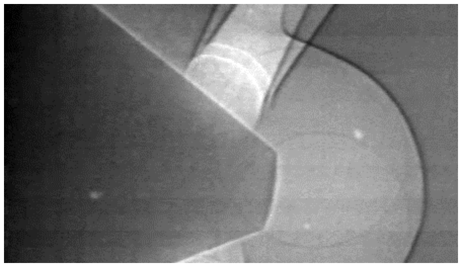
- **Use our unique ability to measure near the nozzle to improve the fundamental understanding of fuel injection and sprays**
- **Assist in development of improved spray models using quantitative spray diagnostics**
- **Make these measurements accessible to our industrial partners and the wider community**

OBJECTIVES AND MILESTONES

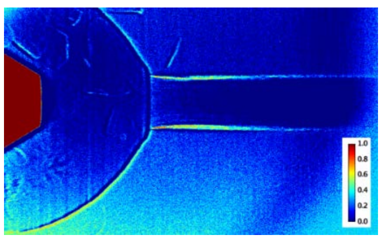
Date	Objective	Technique	Status
March 2019	Complete measurements of ECN Spray G under flash-boiling conditions	Fuel Density	Complete
March 2019	Complete measurements examining nozzle geometry effects on mixture formation in HD injectors. Measurements will focus on the effect that cavitation has on the fuel distribution and the near-nozzle breakup.	Nozzle Geometry, Cavitation Tomography, Fuel Density	Complete

TECHNICAL APPROACH: X-RAY DIAGNOSTICS

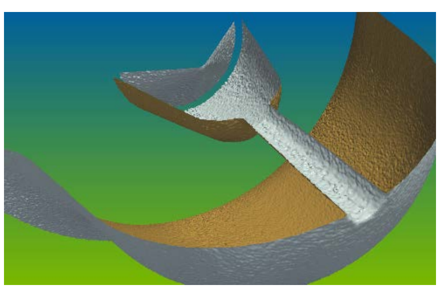
Needle Motion

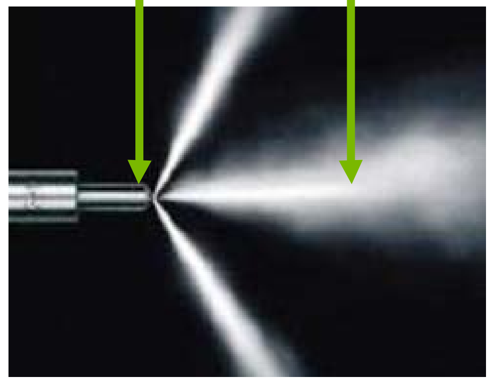


Nozzle Cavitation



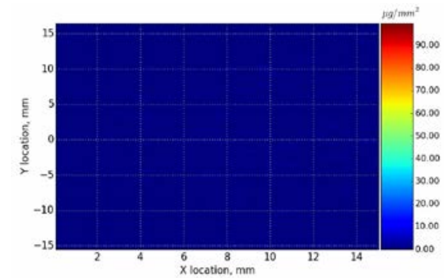
High Precision Nozzle Geometry



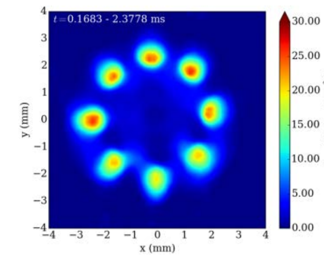


X-rays enable unique capabilities, both *inside* and *outside* the nozzle

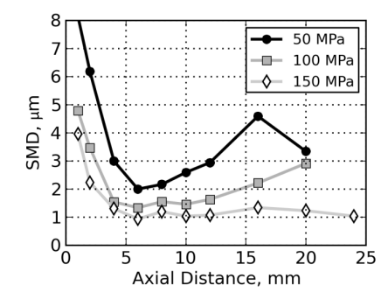
Near-Nozzle Fuel Density



Spray Tomography



Near-Nozzle Drop Sizing



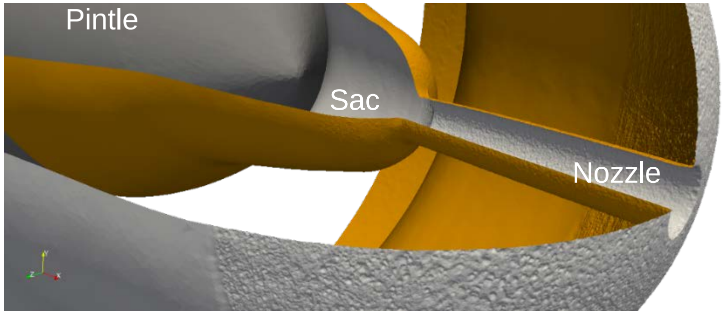
TECHNICAL APPROACH FOR 2019

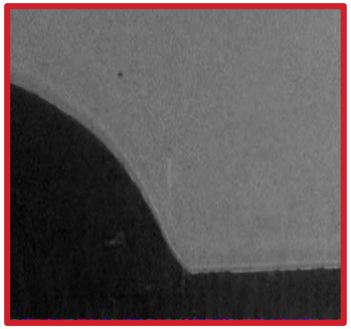
- Heavy Duty Work
  - The link between nozzle geometry and fuel distribution is not well understood
  - Simulations combining internal nozzle flow with spray formation are now becoming possible
  - **Use our unique in-nozzle and near-nozzle diagnostics to generate a rich data set on diesel injection**
  - **Partner with simulation groups to incorporate our results into advanced models**

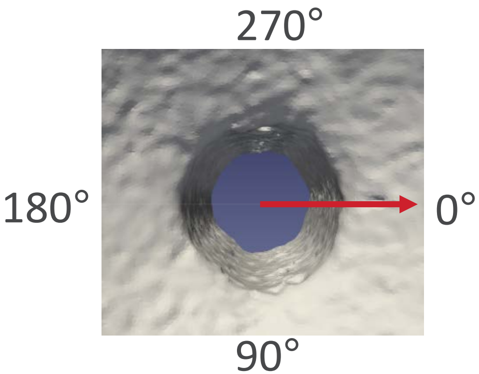
- Light Duty Work
  - Flash boiling is a challenge for low-load conditions
  - There is little experimental data available
  - **Measure the near-nozzle fuel distribution and surface area in flash-boiling GDI sprays**
  - **Partner with simulation groups to incorporate our results into advanced models**

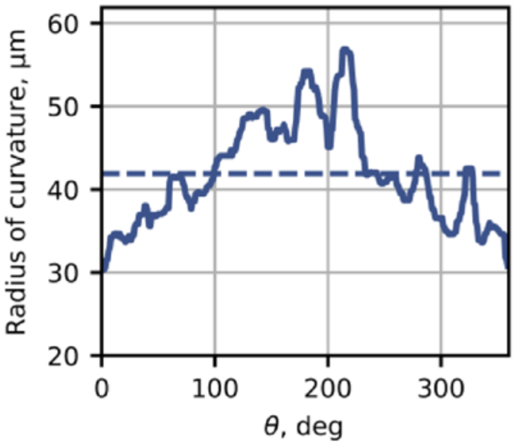
FY2018 ACCOMPLISHMENT: LINKING CAVITATION WITH INJECTOR GEOMETRY

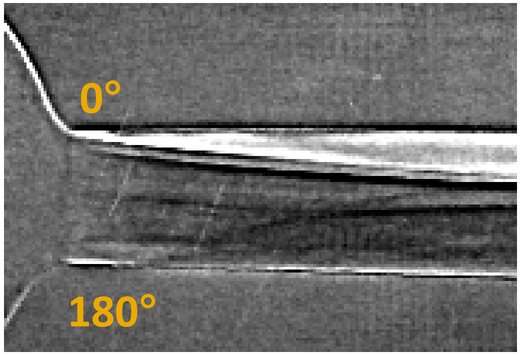
- ECN Spray C: Minimal hydrogrinding, sharp inlet corner
- Last year:
  - High resolution geometry measurements
  - X-ray imaging of cavitation
  - Link between inlet corner radius and cavitation
  - 2018 USCAR Annual Highlight

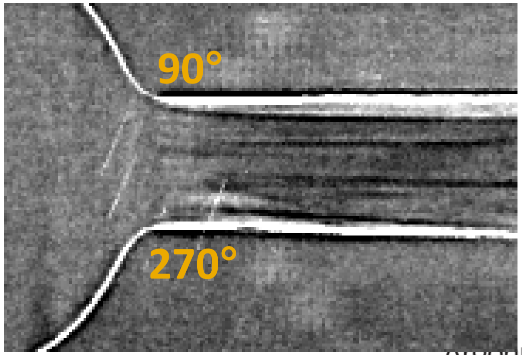








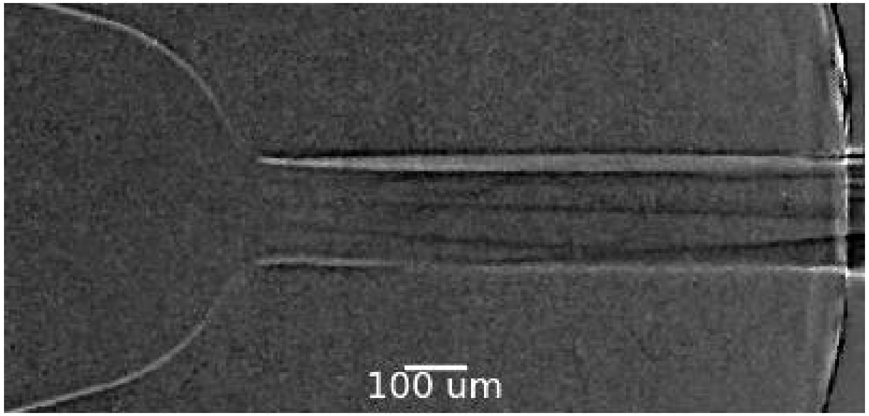


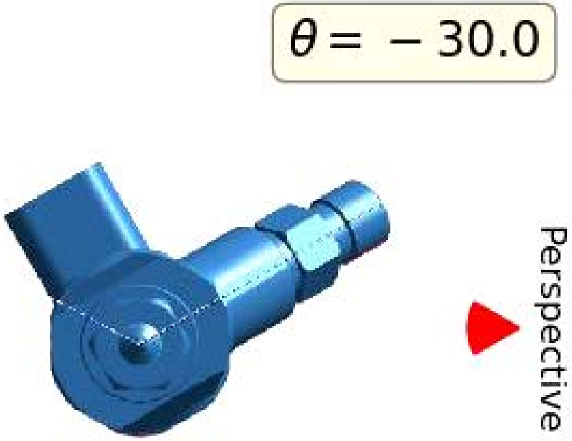


ACCOMPLISHMENT: 3D IMAGING OF CAVITATION IN ECN SPRAY C

X-ray tomography applied to imaging of nozzle flow

- Images of cavitation inside the steel injector were acquired from 360 viewing angles
- Distinct and asymmetric flow separation layer (cavitation) extends to the nozzle exit
- These projections form a dataset for computed tomography





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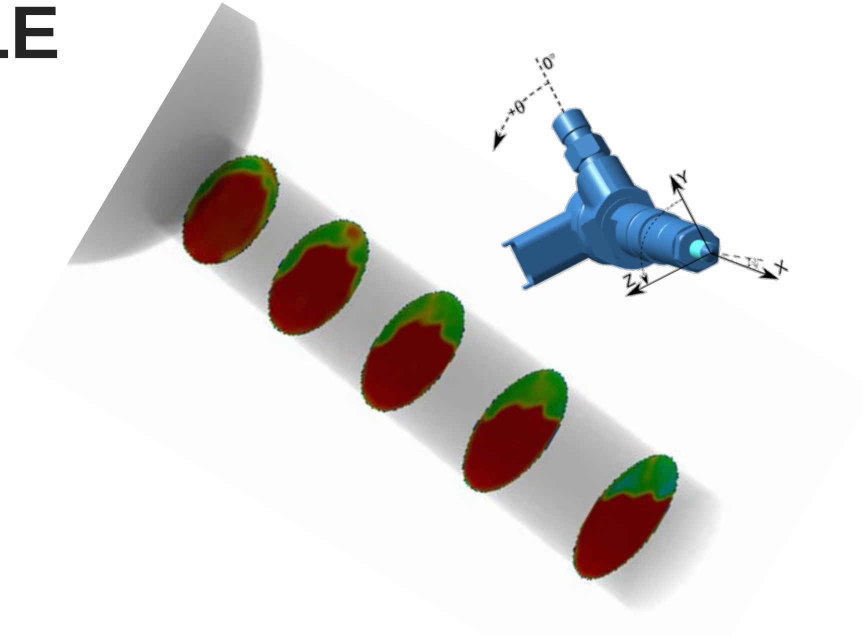
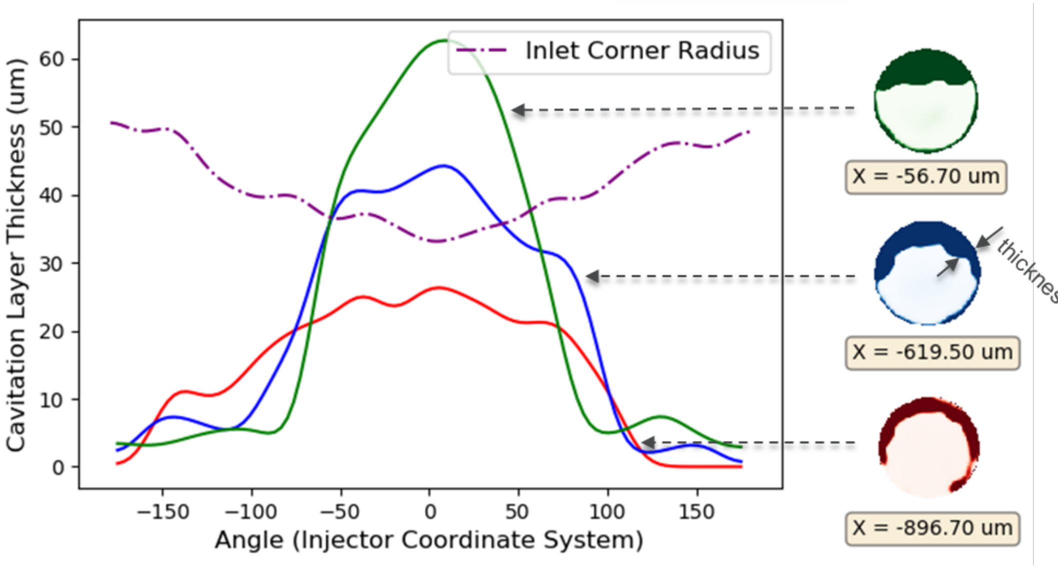
ACCOMPLISHMENT: 3D MEASUREMENT OF FLOW IN A STEEL NOZZLE

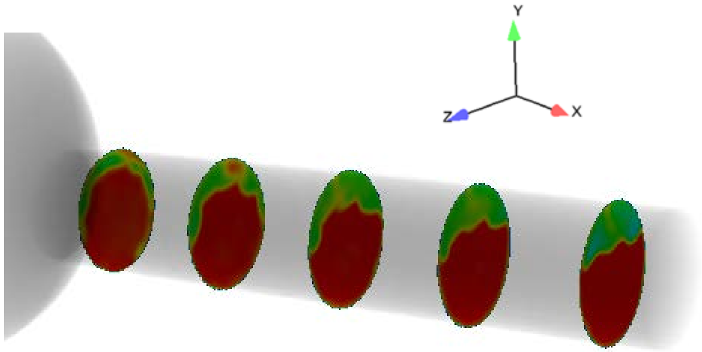


- Computed tomography reveals 3D shape of gas/liquid boundary inside the nozzle
- Six slices shown, 250 slices were measured
- Qualitative, shows only the time-averaged boundary between gas and liquid, not density
- This dataset is unique
  - Round, steel nozzle
  - Real size, pressures, surface finish
  - Most measurements of cavitation use plastic nozzles, large size, 2D slot geometry
- Thickness of gas layer corresponds with inlet corner radius

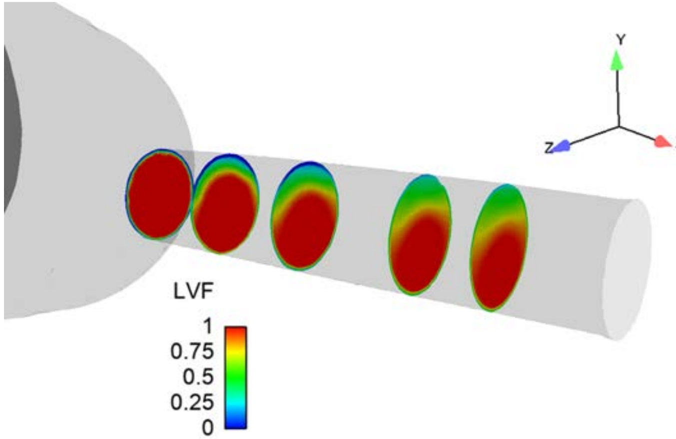


ACCOMPLISHMENT: MEASUREMENTS USED FOR CFD VALIDATION

3D Measurements used to Validate CFD Predictions

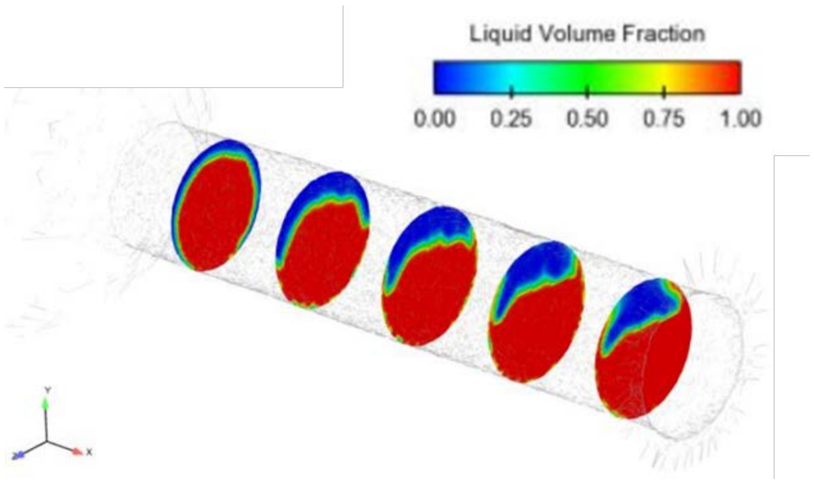


X-ray Measurements, Argonne



Mitra and Schmidt, UMass Amherst

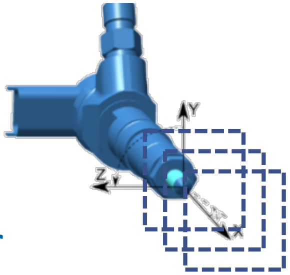
- CFD simulations of internal flow
  - Nominal geometry
  - Argonne-measured geometry
- The overall agreement in the flow morphology is good.
- Experiments show a thin separation layer extending the full circumference of the nozzle
- Experiments capture a "wrinkled" liquid-gas interface likely caused by micron-scale irregularities at inlet corner.



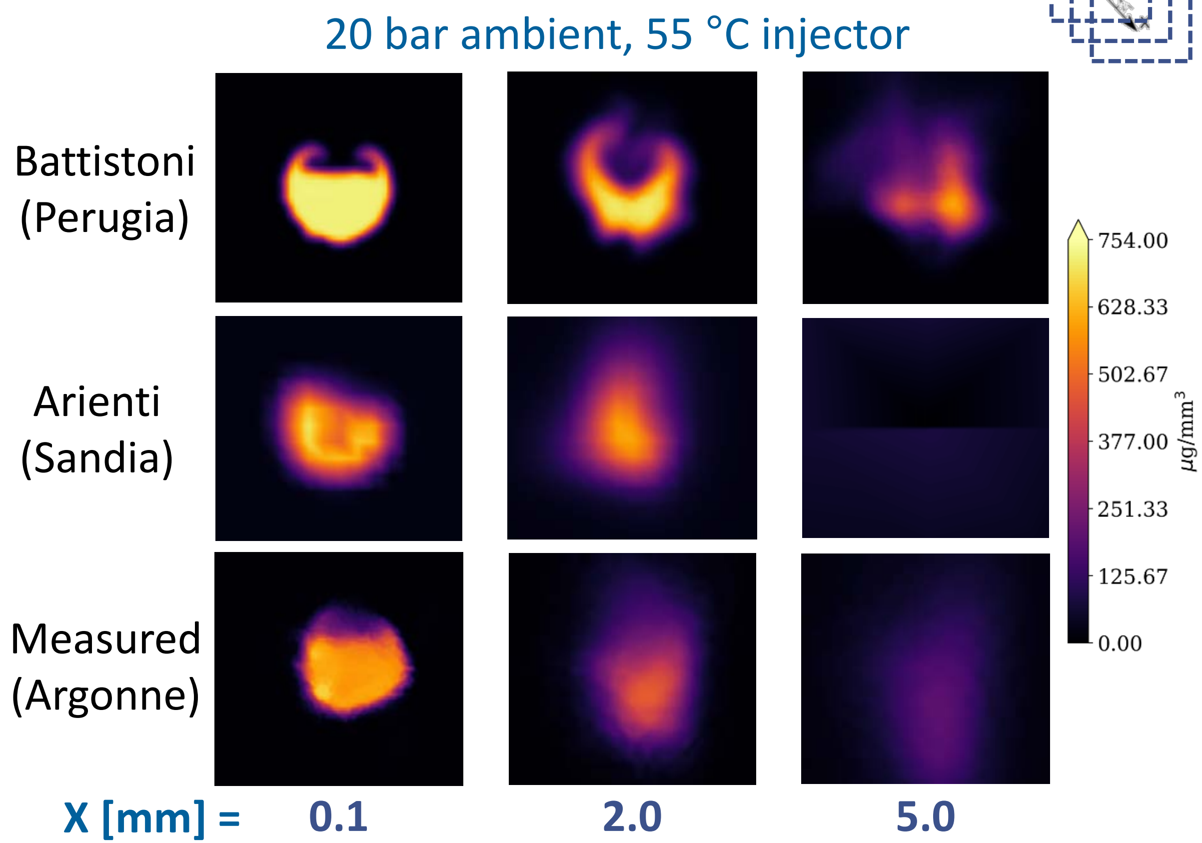
Battistoni, Univ. of Perugia

ACCOMPLISHMENT: DENSITY MEASUREMENTS SHOW IMPACT OF NOZZLE FLOW AND CFD COMPARISON

Spray Measurements and Simulations from 6th Workshop of ECN



- Spray tomography reveals fuel distribution
- Asymmetric flow inside the nozzle causes void, non-uniformity
- Simulations of nozzle flow and near-nozzle spray used Argonne's measured geometry
- Good prediction of void and near-nozzle fuel distribution
- Discrepancies in symmetry and density



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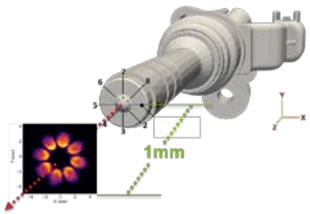
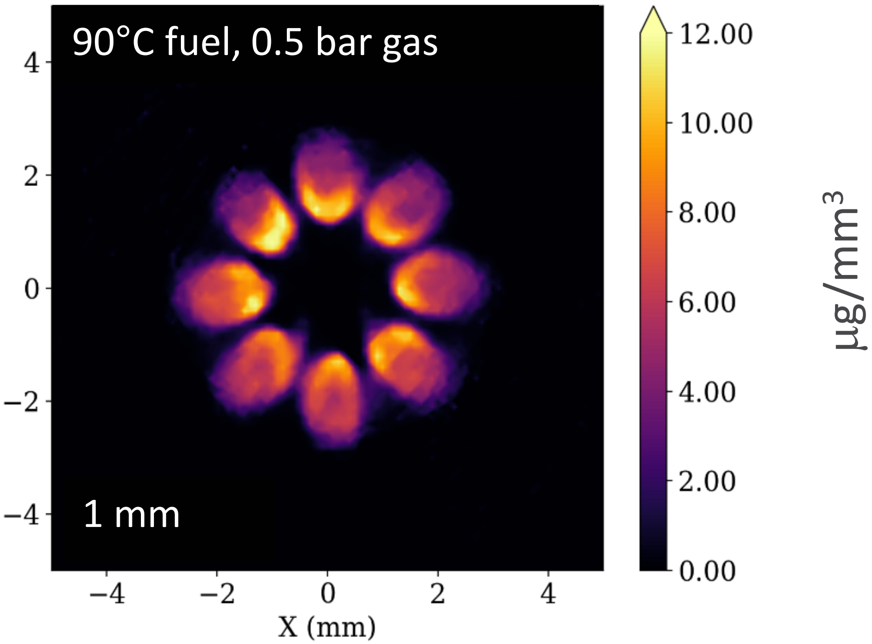
FY2018 ACCOMPLISHMENT: NEAR-NOZZLE DENSITY MEASUREMENTS IN FLASH-BOILING SPRAYS

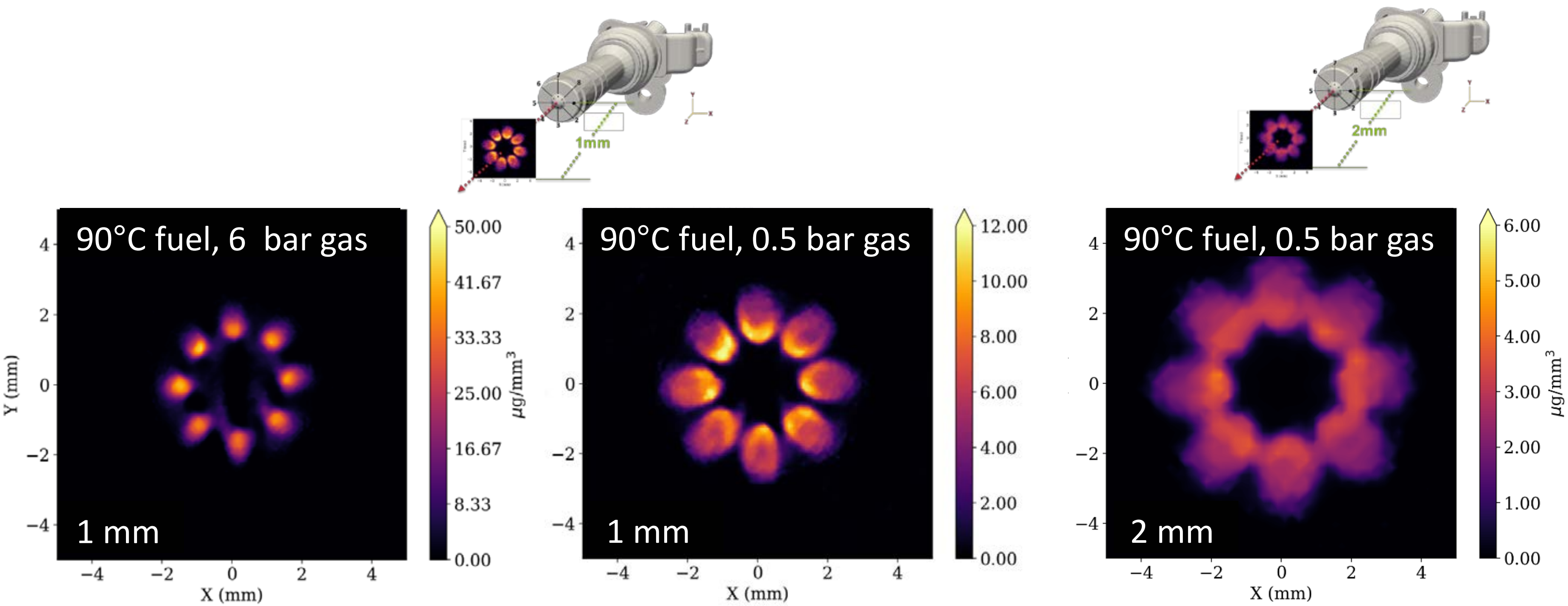


- Flash-boiling is a challenging condition for GDI at low-load
- Low cylinder pressure and high fuel temperature leads to rapid fuel boiling, and a drastic change in the fuel distribution
- The phenomenon is not well-understood, little experimental data exists, and it is difficult to simulate



Iso-octane @ 90°C, 200 bar, 0.5 bar ambient @ 55°C

MEASUREMENTS OF THE NEAR-NOZZLE FUEL DISTRIBUTION IN FLASH-BOILING GDI SPRAYS



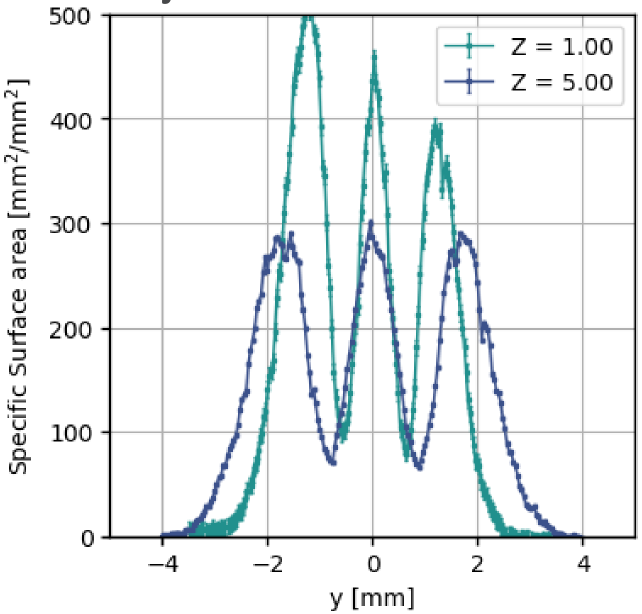
- X-ray tomography has been used to quantify the liquid fuel density in several slices downstream of the injector (uncertainty of ~0.4 μg/mm3)
- As expected, spray plumes are more diffuse under flash-boiling conditions
- Significant spray-spray interactions at 2 mm
- Measurements with other fuels presented as part of Co-Optima

2D slices obtained using x-ray tomography show the iso-octane density under non-vaporizing and flash-boiling conditions

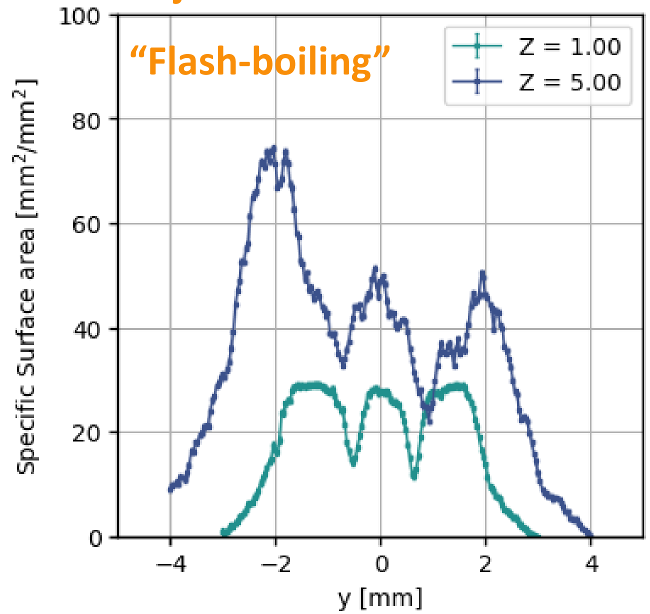
SPRAY / DROPLET SURFACE AREA

X-ray scattering proportional to spray surface area

Ambient P: 6.0 bar
Injector T: 90°C



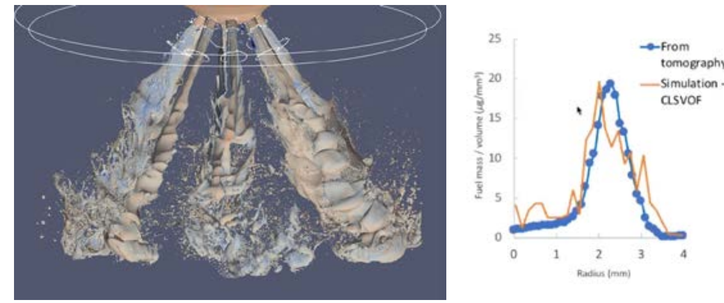
Ambient P: 0.5 bar
Injector T: 90°C



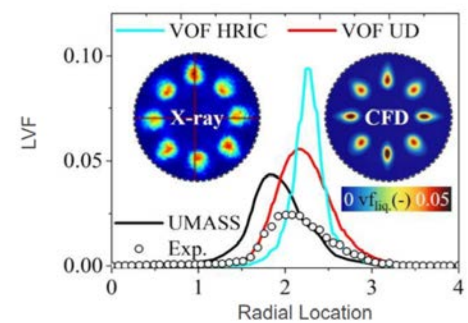
- X-ray scattering intensity is proportional to the surface area in the X-ray path
- Spray surface area was measured for many projections through Spray G
- Surface area is less at flash-boiling condition, plumes are more diffuse
- When combined with density measurements, we can determine SMD

COLLABORATIONS IN 2018-2019

- **Sandia National Labs**
  - Coordination of Experimental Targets with Pickett, Skeen, Arienti
  - Data sharing and analysis
- **Engine Combustion Network**
  - Measurements of nozzle geometry, needle lift, near-nozzle fuel distribution, droplet size
  - Both GDI and diesel
  - Close collaboration with simulation groups to interpret measurement results
- **Simulations Team at Argonne**
  - Joint development of experimental and modeling targets
  - Close collaboration to interpret measurement and simulation results
  - **2018 USCAR highlight** for LD measurement and simulation
- **Simulations at UMass-Amherst**
  - Joint development of experimental and modeling targets
  - Close collaboration to interpret measurement and simulation results

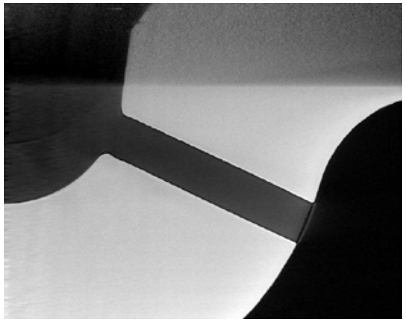


CLSVOF simulations of Spray G at Sandia used geometry and density measurements
Arienti *et al.*, 2019

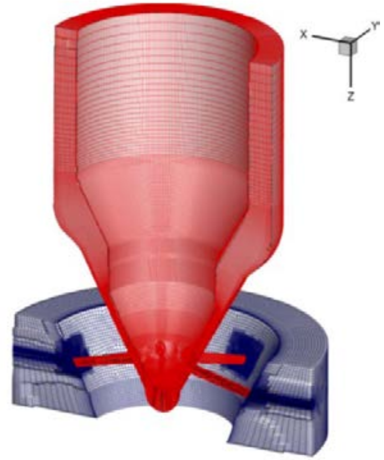


VOF Simulations of Spray G at UMass used geometry and density measurements
Schmidt *et al*, 2018

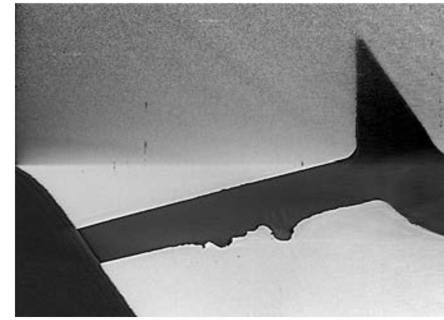
ARGONNE'S MEASUREMENTS ARE ACTIVELY USED TO SUPPORT RESEARCH EFFORTS WORLDWIDE



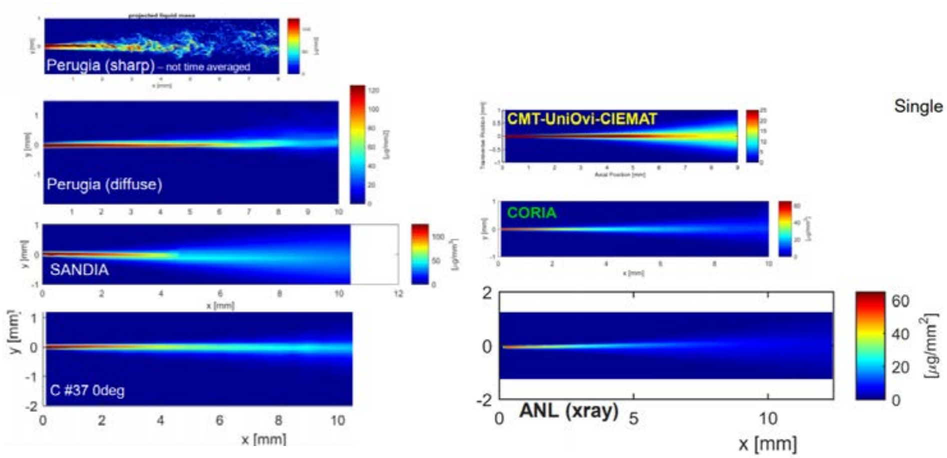
Long-term tracking of injector erosion at **Argonne** using geometry measurements
Kolodziej, 2019



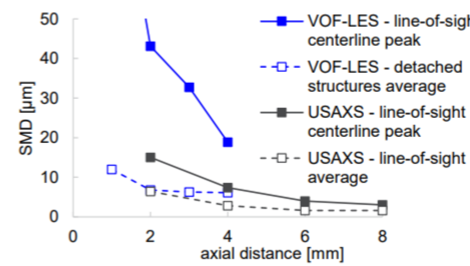
Transient diesel simulations at **BP** utilized needle motion
Gold *et al.*, 2018



Studies of Erosion in Diesel Injectors at **Aramco** used geometry measurements
Tzanetakis *et al.*, 2019



Simulations of ECN Spray A, C, D at **Aachen, CMT, CORIA, Perugia, Sandia, UMass** used nozzle geometry and density measurements
ECN6 Workshop, 2018



Diesel simulations at **Perugia, Argonne** used measurements of near-nozzle SMD
ECN6 Workshop, 2018

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RESPONSES TO FY2018 REVIEWERS' COMMENTS

"continue looking for fundamental questions to answer, not just providing geometries and data for simulation"

- We agree, and we pursue these ideas whenever we can
- Future LD work will explore measurements of wall impingement

"include wider variations of injection pressure and nozzle design, and explore multiple-hole nozzles for spray to spray effects"

- We plan to pursue more work on multi-hole nozzles in our HD work, measurements of cavitation will be especially interesting.
- For LD, we plan to continue our focus on flashing sprays and incorporate more work on spray-spray interactions, spray collapse

"collaboration with ANL's work on modeling injector degradation through cavitation (Som's work) should be strengthened"

- Experiments in FY2020 will use our unique capability to contribute to studies of this type

REMAINING CHALLENGES AND BARRIERS

- Cavitation in multi-hole nozzles is significantly more complicated than in single-hole
  - Fuel “turns a corner”
  - Needle motion can generate complicated flows in sac
  - String cavitation can reach from hole-to-hole
  - Need measurements in multi-hole nozzles
- The link between cavitation and nozzle erosion is not well-understood
  - Need reliable predictions of cavitation, AND models of erosion
  - Models are being developed, but fundamental data is lacking.
- Flash-boiling and spray collapse can cause sudden, extreme changes in the fuel/air mixture
  - This cannot be reliably predicted, need systematic measurements
- Sprays impinging on walls can cause emissions challenges
  - Current wall-wetting models rely on 20-year-old measurements of simplified systems, can’t accurately predict splashing, evaporation, spreading

PROPOSED FUTURE WORK IN FY2019 AND FY2020

- Heavy Duty Injection
  - 3D Measurements of cavitation in multi-hole injector
  - Non-destructive x-ray measurements of geometry will be used to track nozzle erosion over time
    - Collaboration with Kolodziej, Caterpillar
    - Collaboration with Som, Magnotti
    - Searching for collaboration with industry partner
    - Data will be used to support development of erosion models
- Light Duty Injection
  - Will transition to the Light Duty Combustion Consortium
  - Flash boiling sprays – explore parametric variations
  - Measurements of spray collapse
  - Sprays impinging on surfaces
    - X-rays can quantify the density distribution, surface area, SMD
    - Before and after spray impact
    - Effect of wall temperature (cold start), roughness

Any proposed future work is subject to change based on funding levels

SUMMARY

- Improve the understanding of fuel injection and sprays by measuring fundamental spray phenomena
  - Measurements of internal injector geometry and flow
  - Measurements of near-nozzle breakup
  - These are unique capabilities of x-ray diagnostics
- Assist in development of improved spray models
  - Partnerships on nozzle and spray modeling with UMass Amherst, CMT, Georgia Tech, Perugia, Som, Sandia
  - Data contributed to ECN is assisting model development at IFP, CMT, CORIA, Sandia, Argonne, UMass, GM, Convergent Science, others.
  - SPPs with Spray Combustion Consortium, CMT, CRADA with Aramco, FOA with Georgia Tech
- Share the results
  - Nozzle geometry, needle motion, near-nozzle spray density, near-nozzle surface area
  - ECN Spray A, B, C, D, G
  - Openly available at https://anl.box.com/v/XRaySpray

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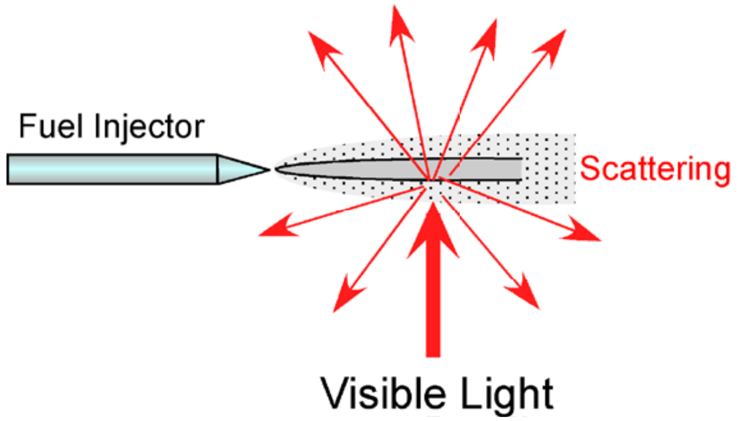
Technical Back-Up Slides

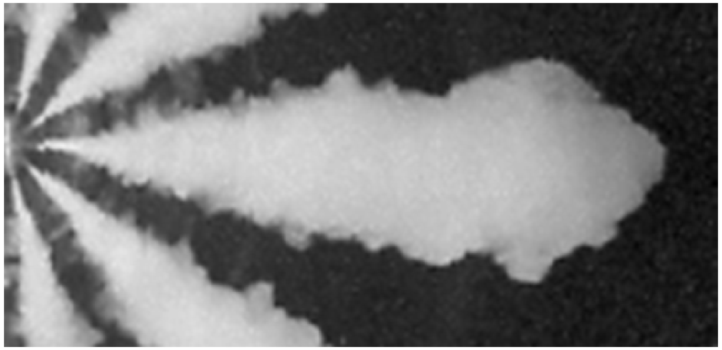
(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

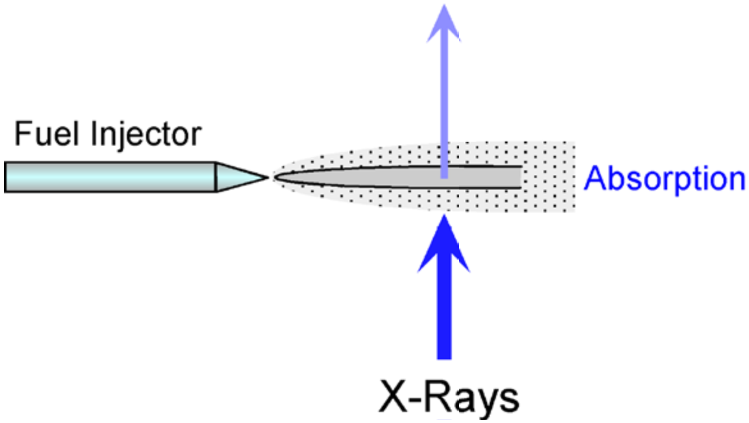
TECHNICAL APPROACH – X-RAY DIAGNOSTICS

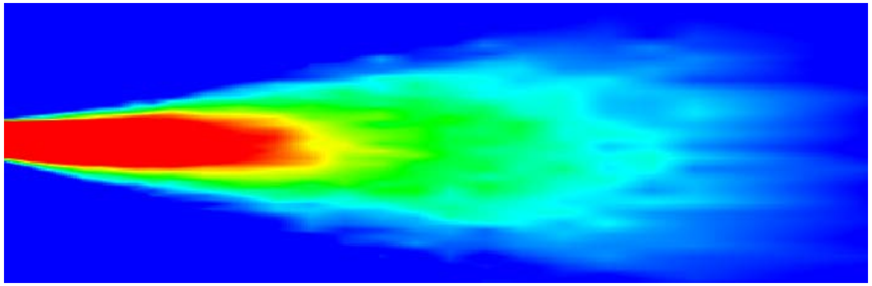
- **X-rays enable unique diagnostics**
  - Near-nozzle measurements of fuel injection
  - Mass-based measurements of the fuel distribution
  - Penetrate through steel to measure geometry, flow, motion
  - Fast time resolution (<5 ms)
  - Fine spatial resolution (< 5 μm)
- **Limitations**
  - Can't penetrate more than ~10 mm of steel (or glass, sapphire)
  - Room temperature ambient (plastic windows)
  - Techniques developed require a synchrotron x-ray source
- **Strategy**
  1. Measurements of relevant injectors and conditions
  2. Partnerships with model developers to utilize these measurements

TECHNICAL APPROACH – X-RAYS REVEAL FUNDAMENTAL SPRAY STRUCTURE





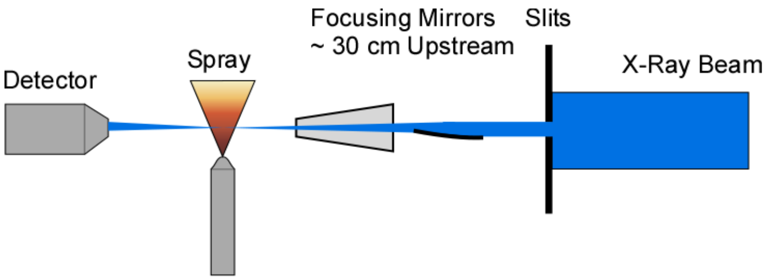


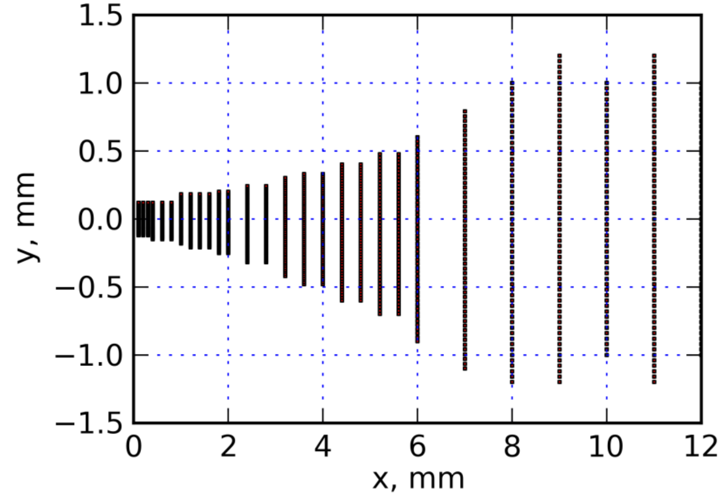


- Room temperature
- Ensemble averaged
- Pressure up to 30 bar

EXPERIMENTAL METHOD

- Focused beam in raster-scan mode
- Beam size 5 x 6 µm FWHM
  - Divergence 3 mrad H x 2 mrad V
  - Beam size constant across spray
- Time resolution: 3.68 µs
- Each point an average of 32-256 injection events
- Beer's law to convert x-ray transmission to mass/area in beam
- Fuel absorption coefficient: 3.7×10^{-4} mm^2/µg
  - Accounts for displacement of chamber gas by liquid
  - Maximum absorption in dodecane ~2%

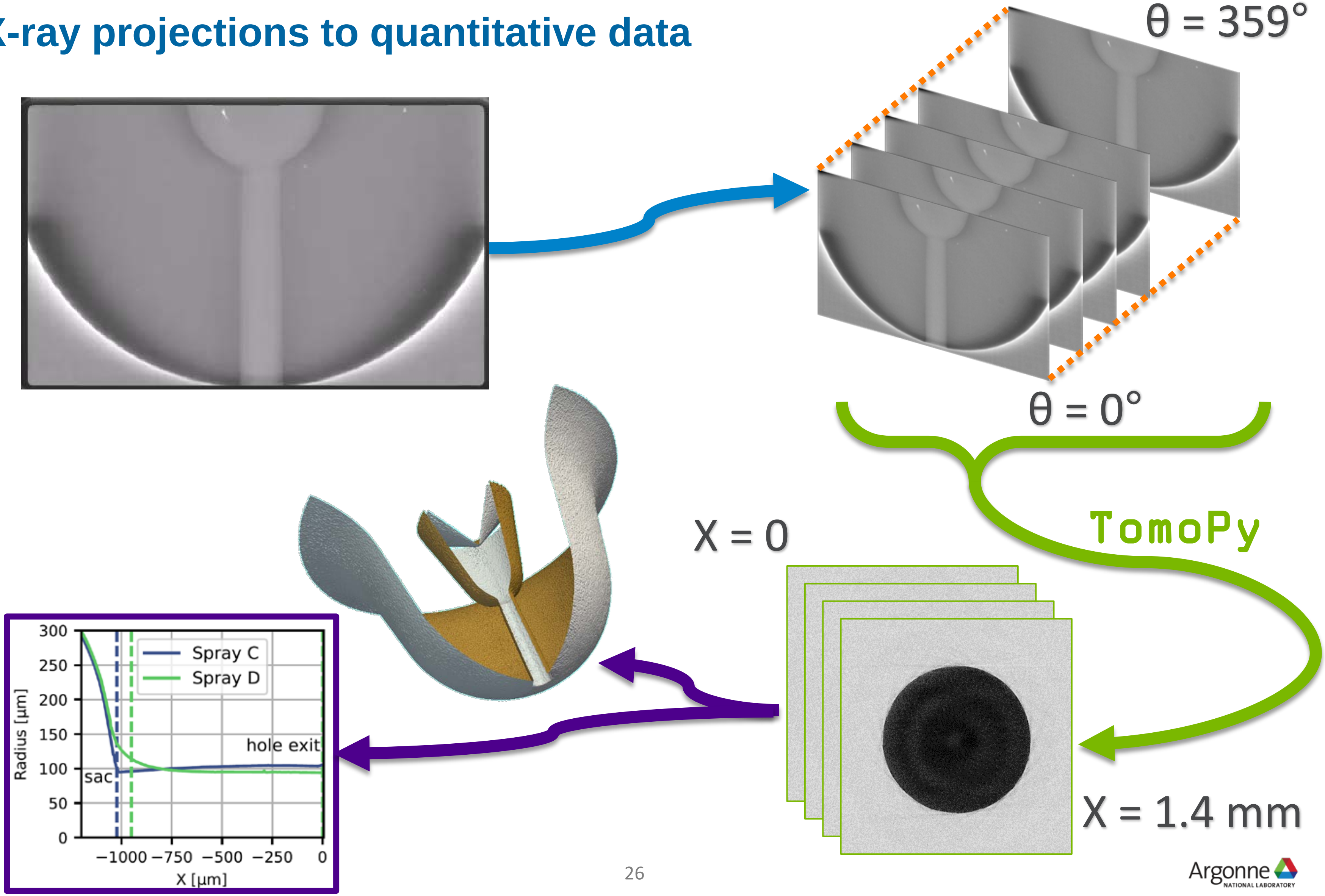




Example Measurement Grid

NOZZLE TOMOGRAPHY PROCESSING

X-ray projections to quantitative data



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THE PATHWAY TO STUDIES OF HIGH TEMPERATURE SPRAYS

Barriers:

1. X-ray windows
2. Low fuel density
3. How to generate the temperature?

X-Ray Windows

1. X-ray transparent
2. High T, P

- Diamond has been demonstrated
- Need vendor that can certify P,T rating

Low Fuel Density

1. Absorption not sensitive enough
2. Need high x-ray flux

- New capability for broadband x-rays last year, 5x increase
- 5x increase in flux with APS upgrade

Temperature

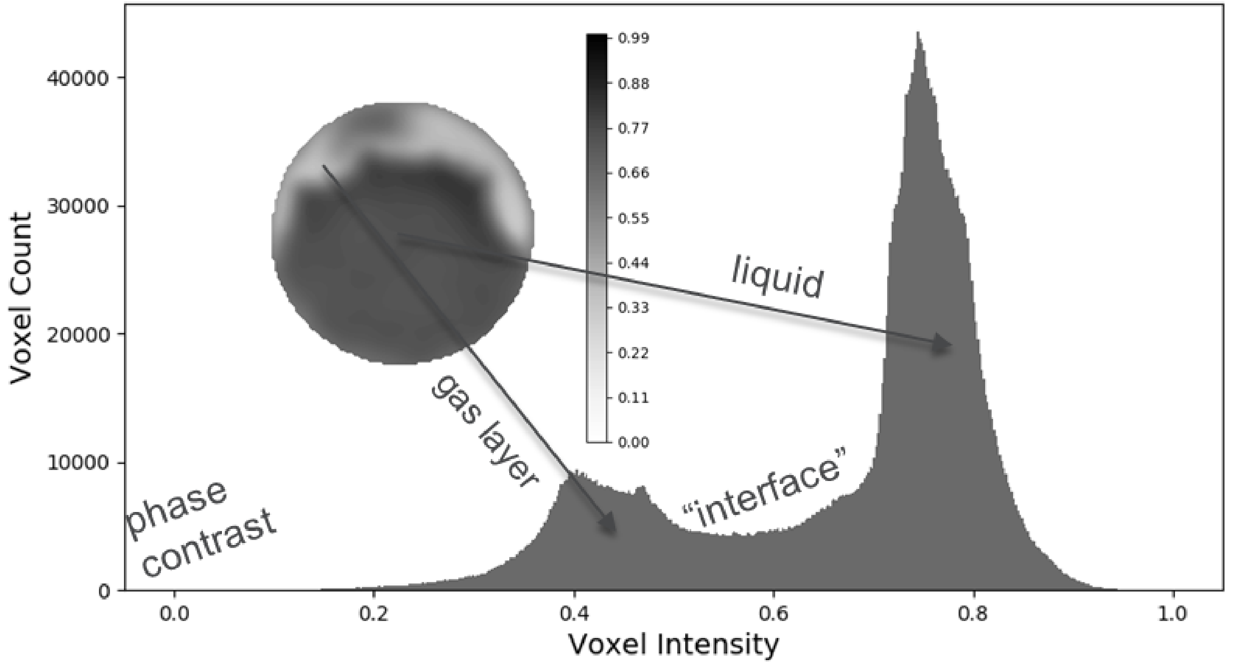
1. Electric? Pre-burn? Shock Tube? RCM? Engine?

- Start by heating fuel to explore flash-boiling gasoline: Completed February 2018
- Seeking funding to fabricate facility for high temperature sprays, combustion

INTERPRETATION OF LIQUID & GAS PHASE

Histogram of intensities reveals “two-phase” nature of flow

- Two characteristic Gaussians: gas & liquid phase.
- “liquid phase” may contain dissolved gas and “gas phase” may contain liquid parcels.
- Extreme values are voxels with phase contrast not completely recovered from filter – decreases resolution of liquid-gas interface



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