COMBUSTION RESEARCH FACILITY

Spray Combustion Cross-Cut Engine Research

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Sandia National Laboratories

FY 2015 DOE Vehicle Technologies Program Annual Merit Review
Project ACE005, 1:45 – 2:15 PM, Tuesday, 9 June 2015

Sponsor: **DOE Vehicle Technologies Program**
Program Managers: **Gurpreet Singh and Leo Breton**

Overview

Timeline

- Project provides fundamental research that supports DOE/ industry advanced engine development projects.
- Project directions and continuation are evaluated annually.

Budget

- Project funded by DOE/VT:
  FY14 - $800K
  FY15 - $900K

Barriers

- Engine efficiency and emissions
- Understanding direct-injection sprays
- CFD model improvement for engine design/optimization

Partners

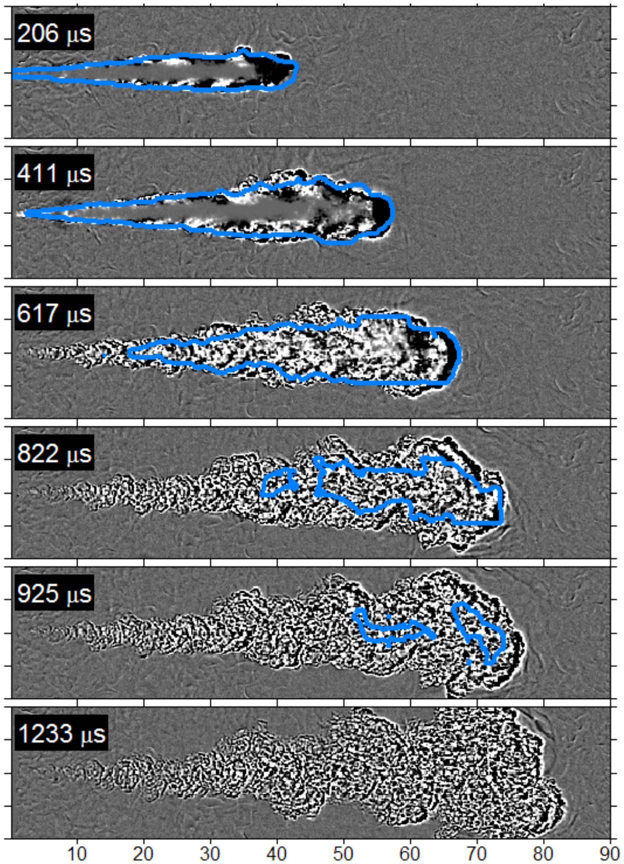
- 15 Industry partners in MOU: Advanced Engine Combustion
- Engine Combustion Network
  - >20 experimental + >20 modeling
  - >120 participants attend ECN3
- Project lead: Sandia
  - Lyle Pickett (PI)

Spray combustion research is relevant for high-efficiency engines

- Future high-efficiency engines use direct injection
  - Diesel, gasoline direct injection, partially-premixed compression ignition
- Complex interactions between sprays, mixing, and chemistry
  - Two-phase system, including multiple injections
  - Spray-induced mixture preparation
  - Complicated internal flows within injectors
- Optimum engine designs discovered only when spray modeling becomes predictive
  - Predictive modeling shortens development time and lowers development cost
  - Makes efficient engines more affordable
- Relevant to EERE Advanced Combustion Engine research and development goals

Schlieren: vapor boundary

BLUE: liquid boundary

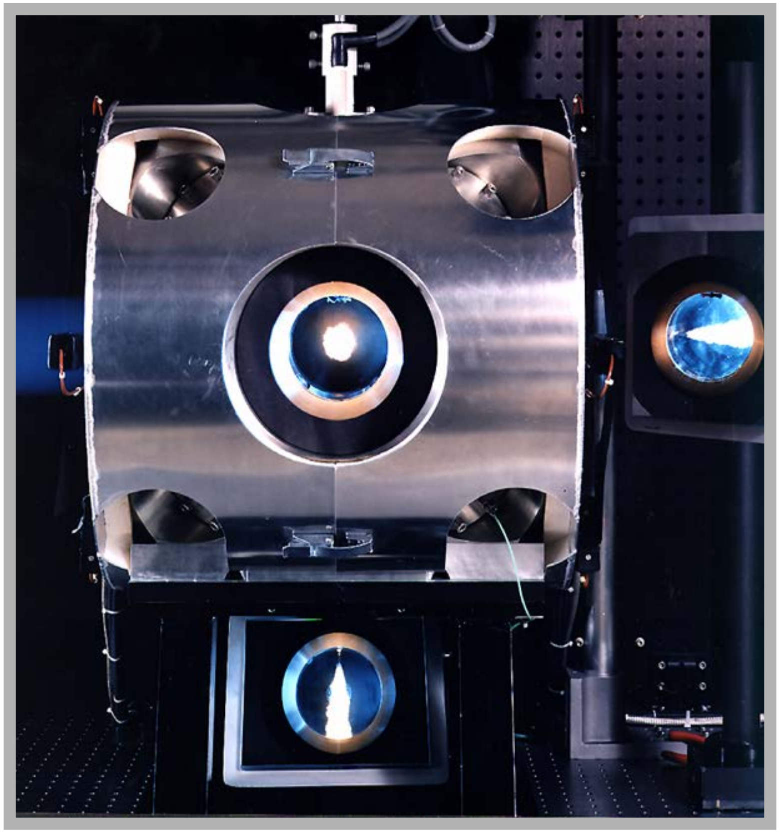


Project Objectives – Relevance

Major objective: experimentation at engine-relevant spray conditions, allowing development of predictive computational tools used by industry

- Lead an experimental and modeling collaboration through the Engine Combustion Network with >100 participants (http://www.sandia.gov/ECN)
  - Use target conditions specific to low-temperature diesel and DI gasoline.
    - Development of quantitative datasets that provide a pathway from experimental results to more predictive CFD modeling in codes used by industry
    - Research spans from inside the injector all of the way to combustion
- Provide fundamental understanding to make transient diesel and gasoline spray mixing predictive
  - Predictive combustion must be preceded by predictive mixing—still a weak link
  - Fundamentals of mixing cool liquid fuel with gases at high P and T
  - Investigation of multi-hole diesel dynamics compared to single-hole injector
  - Multi-hole gasoline injectors with plume-plume interactions
- Quantification of combustion indicators (ignition delay, ignition site, combustion recession after the end of injection)
  - Models are deficient in these areas with serious consequences on emissions and efficiency
  - Focus on multiple injections and products/radicals present after first injection

Experimental approach utilizes well-controlled conditions in constant-volume chamber



- Well-defined ambient conditions:
  - 300 to 1300 K
  - up to 350 bar
  - 0-21% O_2 (EGR)
- Injector
  - single- or multi-hole injectors
  - diesel or gasoline (cross-cut)
- Full optical access
  - 100 mm on a side
- Boundary condition control needed for CFD model development and validation
  - Better control than an engine
  - Easier to grid

How does this experimental data impact computational tools used by industry?

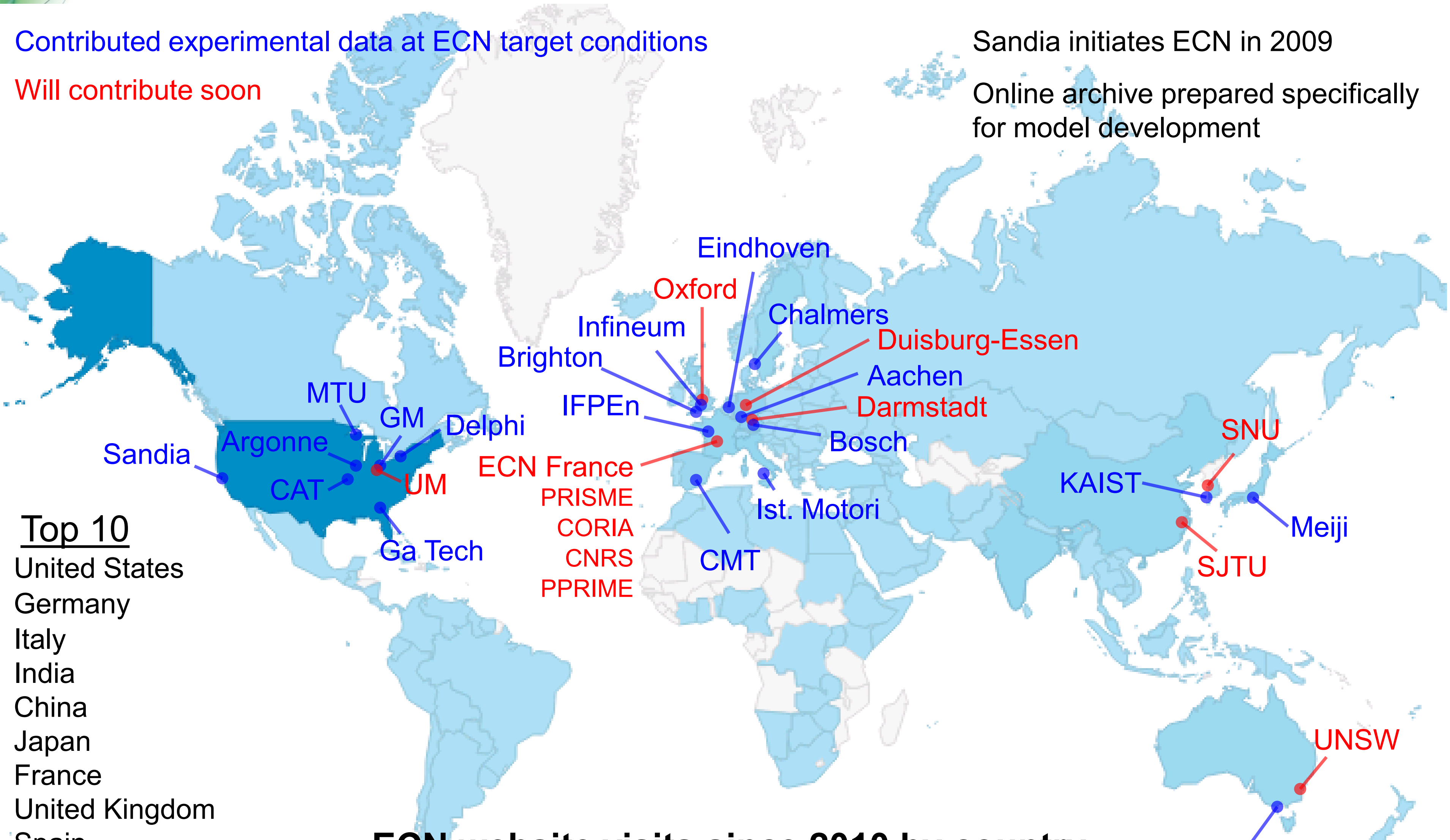
Results are disseminated, and combined from multiple institutions, using the Engine Combustion Network

Contributed experimental data at ECN target conditions

Will contribute soon

Sandia initiates ECN in 2009

Online archive prepared specifically for model development



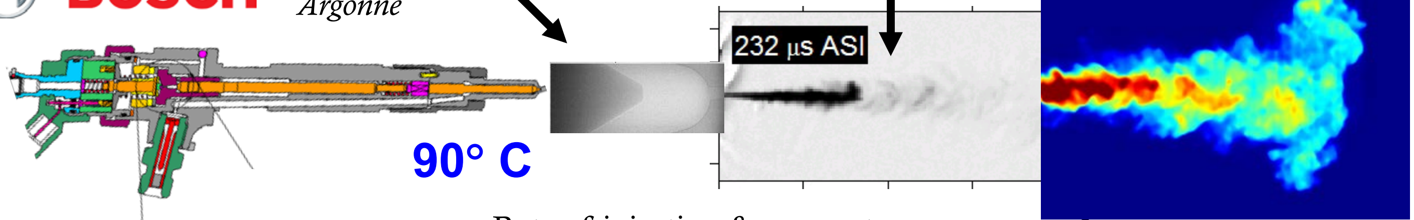
__Top 10__

United States
Germany
Italy
India
China
Japan
France
United Kingdom
Spain
Australia

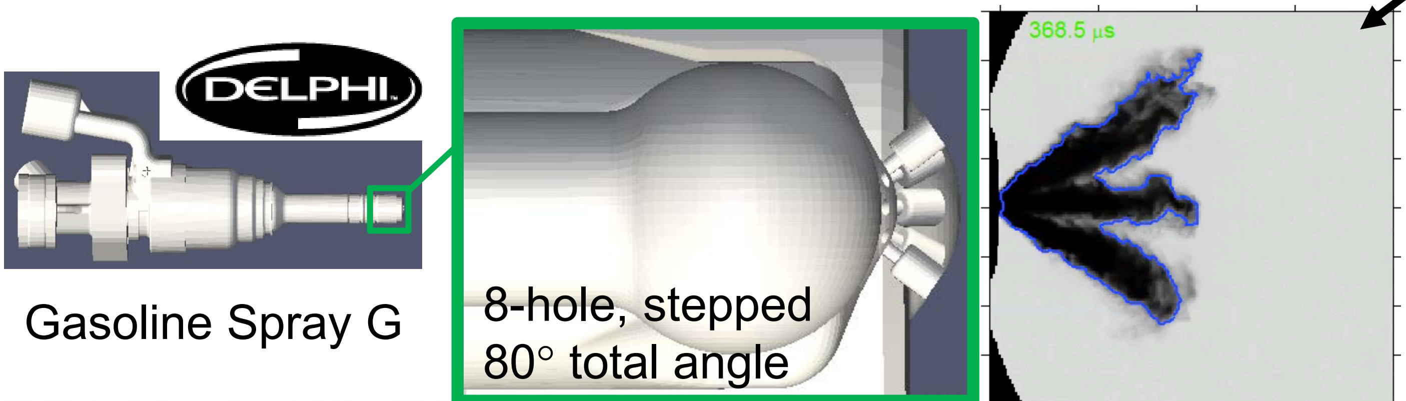
ECN website visits since 2010 by country
(www.sandia.gov/ECN)

Leveraging target conditions greatly accelerates research

- Diesel and gasoline research at target conditions with many modeling and experimental contributions



Diesel Spray A



Gasoline Spray G

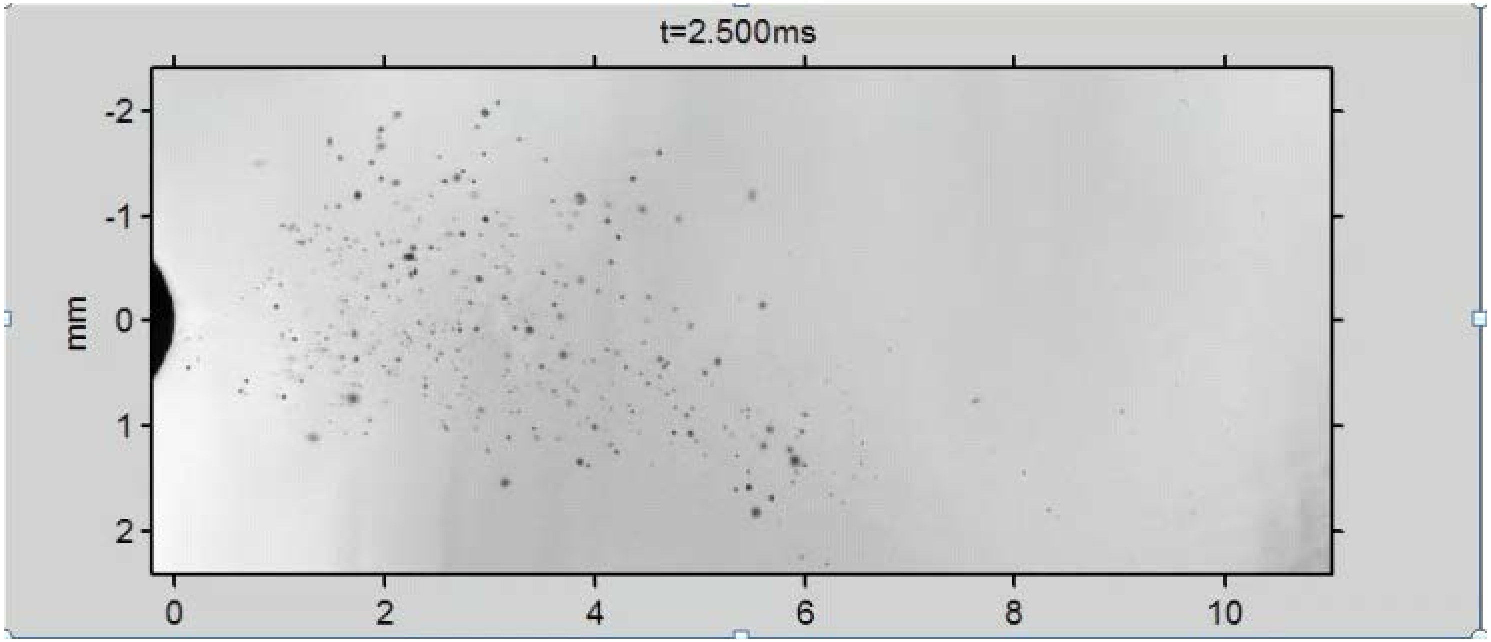
Approach - Milestones

- ✓ **June 2014**
  Compare spray and combustion behavior of Spray B (multi-hole) to Spray A
- ✓ **Aug 2014**
  Investigate the structure of fuel sprays at possible “supercritical” conditions
- ✓ **October 2014**
  Characterize the plume-plume interaction of gasoline Spray G at various operating conditions, in light of internal geometry measurements
- ✓ **December 2014**
  Characterize multiple-injection ignition processes at Spray A conditions
- ✓ **March 2015**
  Develop rig for internal nozzle flow characterization
- **May 2015**
  Compare spray and combustion behavior of diesel Spray C (cavitation) and Spray D
- **July 2015**
  High-speed velocity measurements of Spray G and Spray A
- **September 2015**
  Date of ECN4, the fourth workshop of the Engine Combustion Network, with topics organized to promote experimental and modeling advancement in gasoline and diesel

Spray liquid structure visualized at high T & P by improvements to high-speed microscopy

- At lower T & P: droplets visible in mixing layer and at the end of injection
  - Atomization and vaporization processes observed for many droplets
  - Surface tension: Droplets deform/oscillate, ligaments converge into spheres
  - Clear interface: Droplets have high contrast and they refract light
  - Classical evaporation: Droplet size reduces, leaves vapor trail

363 K n-hexadecane - **900 K**, 60 bar (22.8 kg/m^3) ambient

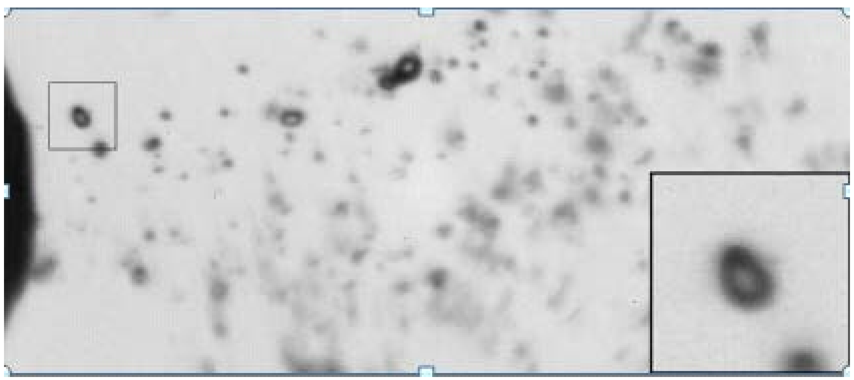


A transition to "miscible mixing" occurs at high temperature and pressure

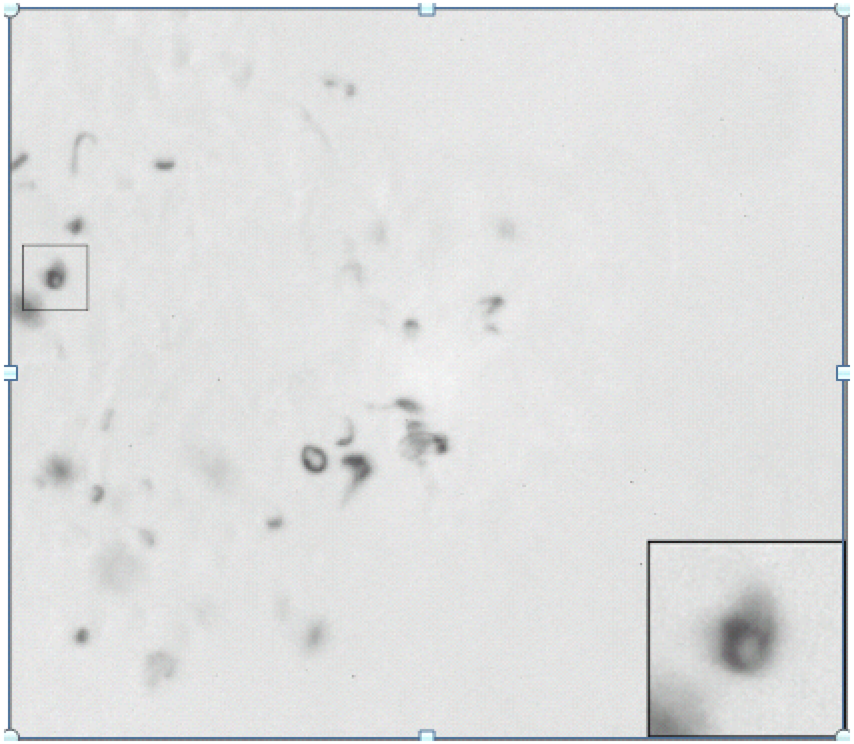
- Droplets and ligaments visible at the end of injection, but a transition to a different type of mixing occurs
  - Droplets transition to miscible fluid blobs:
  - Surface tension: Droplets deform/oscillate, ligaments converge into spheres
  - Miscible mixing: Liquid deforms with slight velocity, becomes non-spherical, does not exhibit surface tension.

2.5 mm to 5.0 mm

Nozzle to 2.5mm



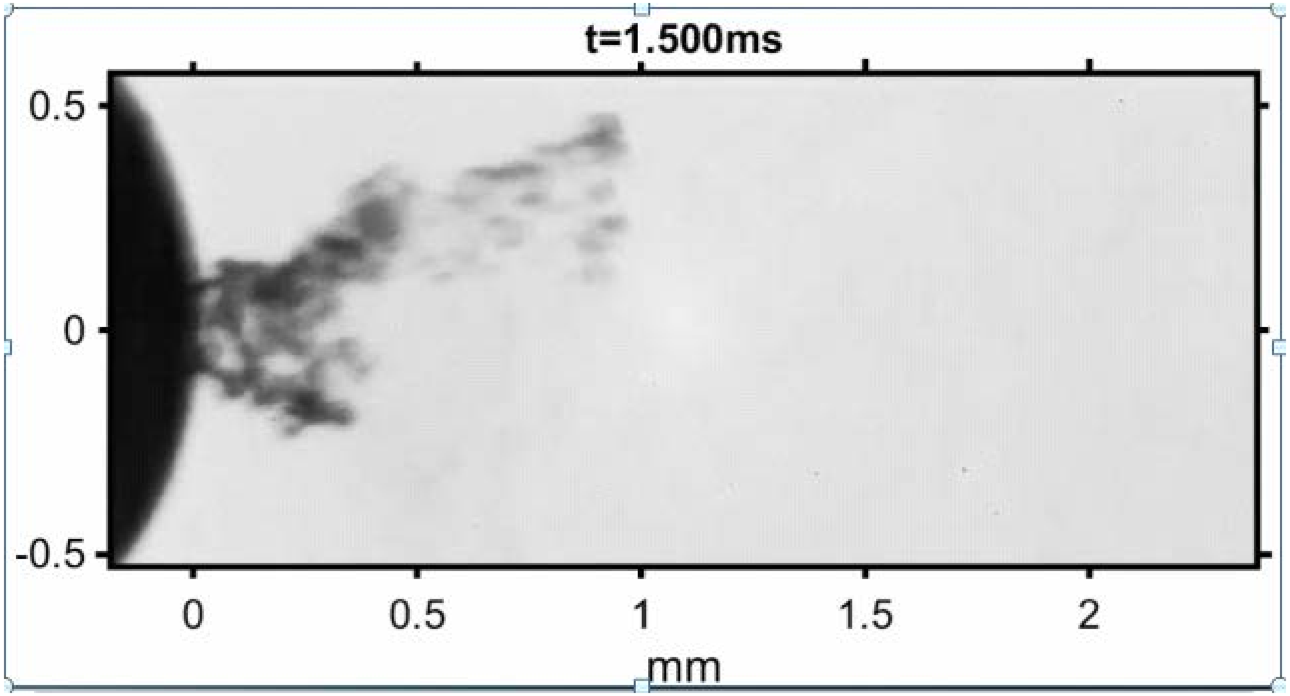
363 K n-hexadecane - **1200 K**, 104 bar (30.4 kg/m^3) ambient



Exploring different fuel properties shows a very quick transition with no evidence of surface tension

- Liquid structures at the end of injection mix/disappear quickly without evidence of surface tension
  - No surface tension: Fluid blobs stretch, but no elastic behavior is observed
  - Miscible mixing: Fluid spreads and rapidly becomes optically thin (disappears)

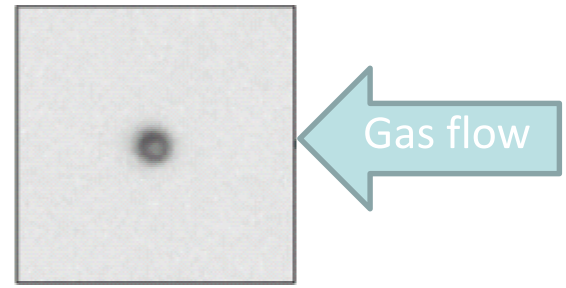
363 K n-heptane - **1200 K**, 104 bar (30.4 kg/m^3) ambient



Atomization and miscible mixing

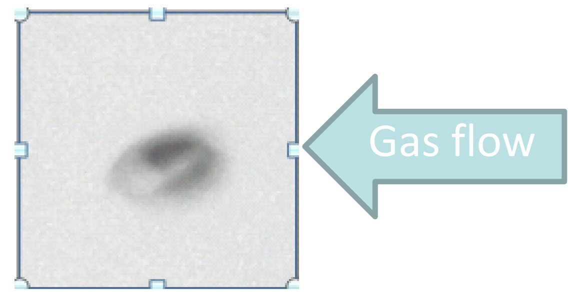
- Classical evaporation:
  - Vaporization happens on the surrounding of the droplet
  - Progressive mass transfer from liquid to gas
- Evaporation and miscible mixing
  - Rapid transition from spherical fluid spheroid into stretched fluid
  - Deforms easily and quickly disappears
- Miscible mixing
  - Fluid stretches without a clear elastic behavior (lacks surface tension)
  - Fluids with different densities mix together
  - Mixing happens quickly

n-dodecane 62 bar, 707 K (30.4 kg/m^3)



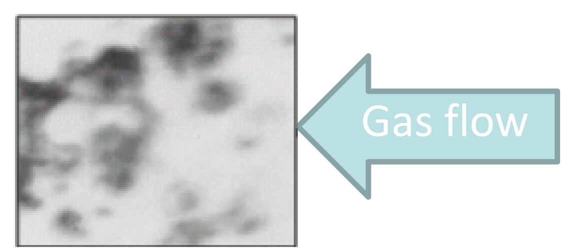
35 μm droplet

n-dodecane 88 bar, 1000 K (30.4 kg/m^3)



50 μm droplet

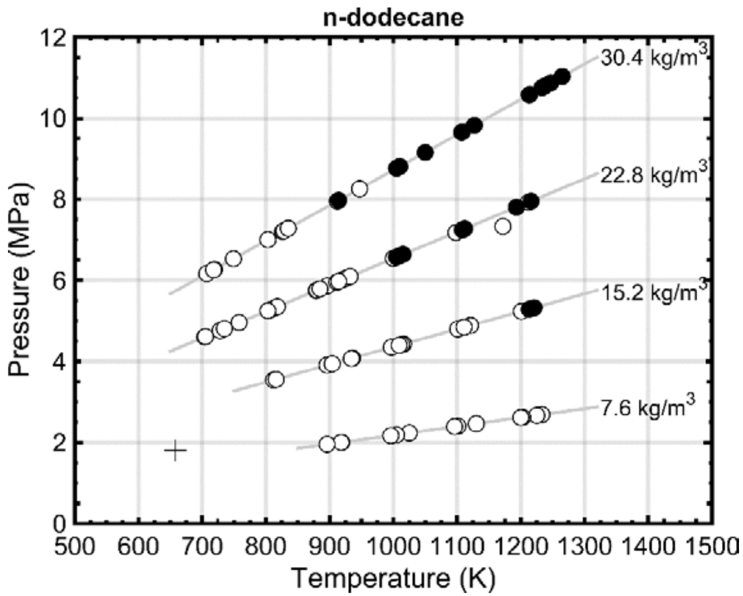
n-heptane 104 bar, 1200 K (30.4 kg/m^3)

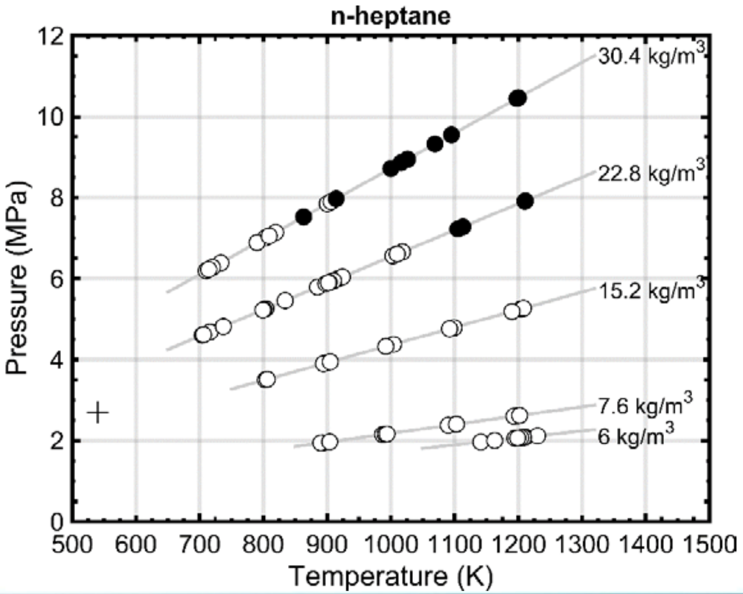


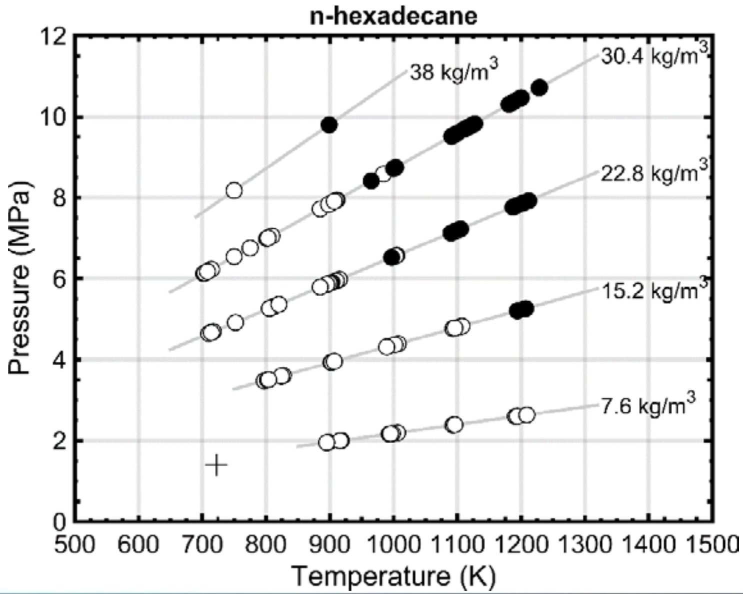
No droplet(s)

Conditions where a transition to miscible mixing is evident are well above the critical P and T

- Dark symbols are when miscible mixing behaviour was observed, but droplets and surface tension may also be present for a limited time
- Difficult to classify dense region of spray during injection—need to track individual structures
- Prefer not to use the term “supercritical” as liquid fuel into air is a two-component system
- Understanding interfacial mixing is the key

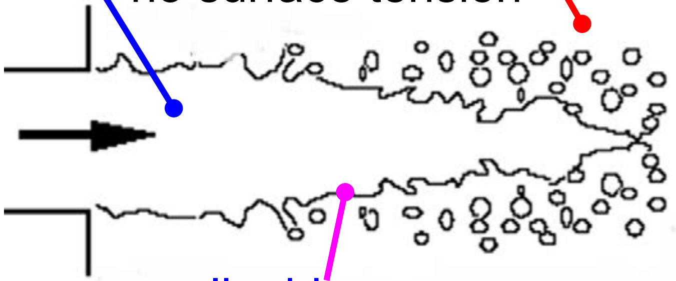






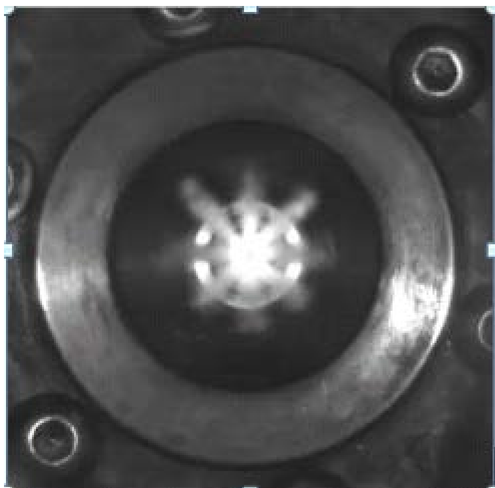
How our high-speed microscopy results could affect engine spray modeling:

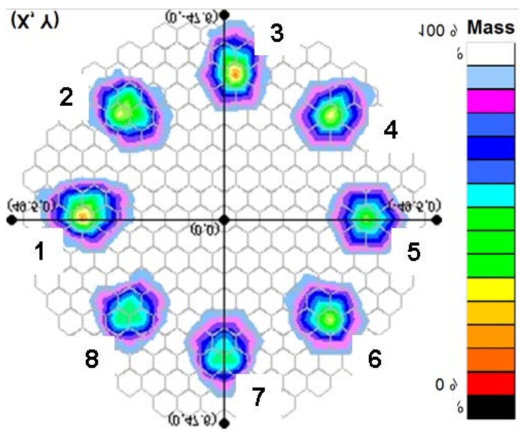
- Classic spray modeling assumes liquid breakup with surface tension forces and vaporization rates based on droplet-gas dynamics
- Dense fluid modeling assumes no effects of surface tension—Navier/Stokes equations apply throughout
- Our results show that a transition to miscible mixing is not sudden
  - Surface tension effects and "miscible mixing" zones exist *in the same spray* at a given ambient gas pressure and temperature
    - Fluid near the nozzle exhibits surface tension while downstream liquid does not
    - Suggests a finite timescale for transition
  - Transition with increasing P and T is also not immediate
    - Solely miscible-mixing occurs only at highest P and T (with n-heptane)
  - A "continuum" towards miscible mixing suggests that even droplet-dominant regimes may experience effects (faster evaporation) that depart from classic low-P theories
- Experimental results are consistent with the modeling work of Dahms and Oefelein
    - Dahms & Oefelein, Phys. Fluids 25, 2013 (Liquid-gas interface broadens at high T and P)
    - Dahms & Oefelein, Proc. Combust. Inst. 35, 2015 (Surface tension vanishes after finite time)



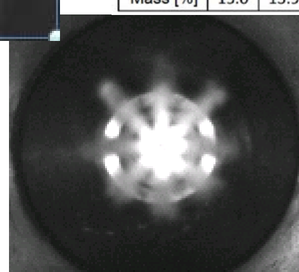
Understanding sources of plume-to-plume dispersion and plume-to-plume interaction (Spray G)

- Top plumes appear to penetrate more quickly, at least initially
- In agreement with atmospheric patternation and imaging performed at Delphi for the same injector (#28)



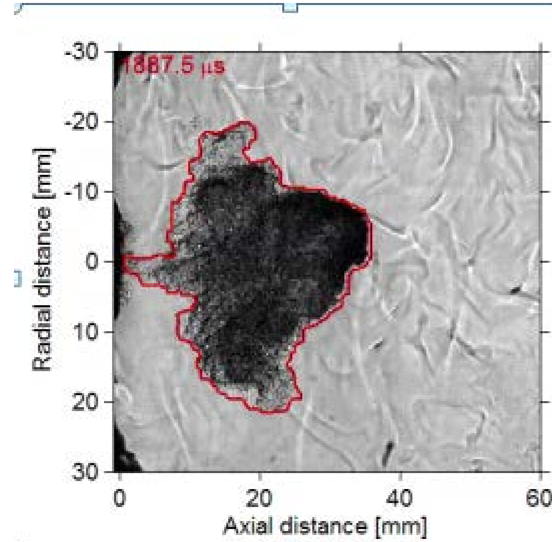


Hole #	1	2	3	4	5	6	7	8
Mass [%]	15.0	13.9	13.3	11.9	11.6	11.9	11.2	11.2

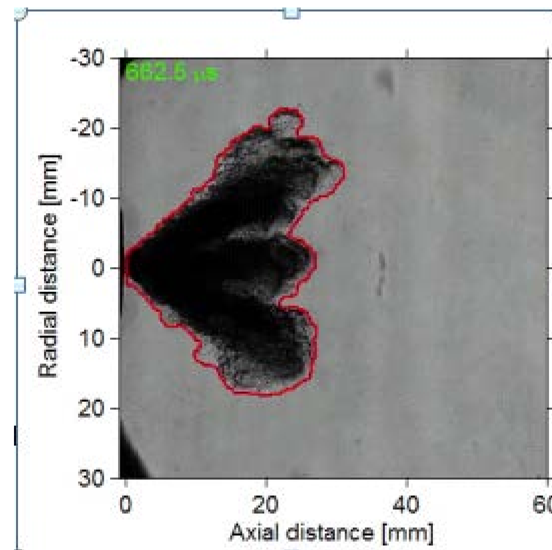


Front-View
Mie-scatter
Spray G

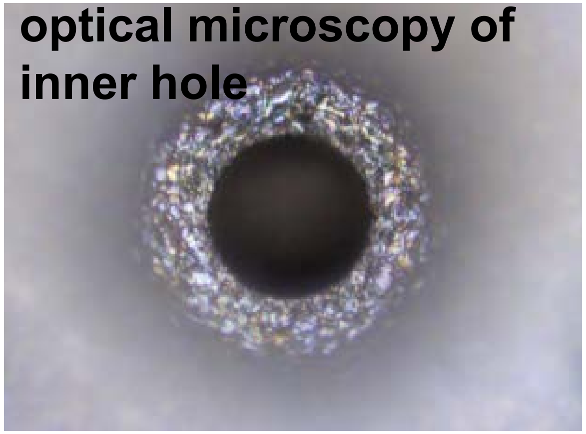
Ambient
15 bar
9 kg/m^3

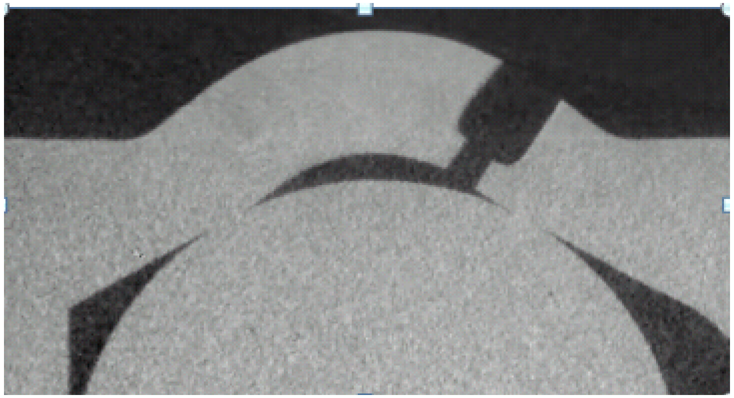


5.8 bar
3.5 kg/m^3

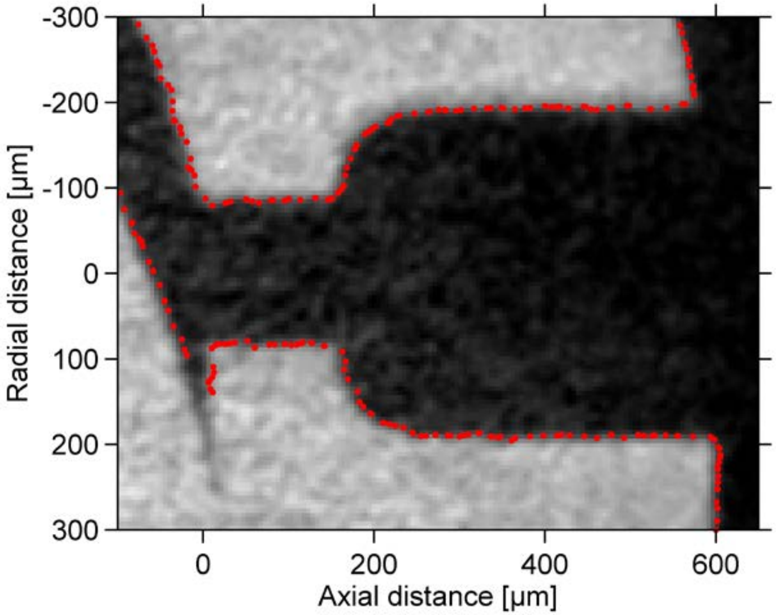


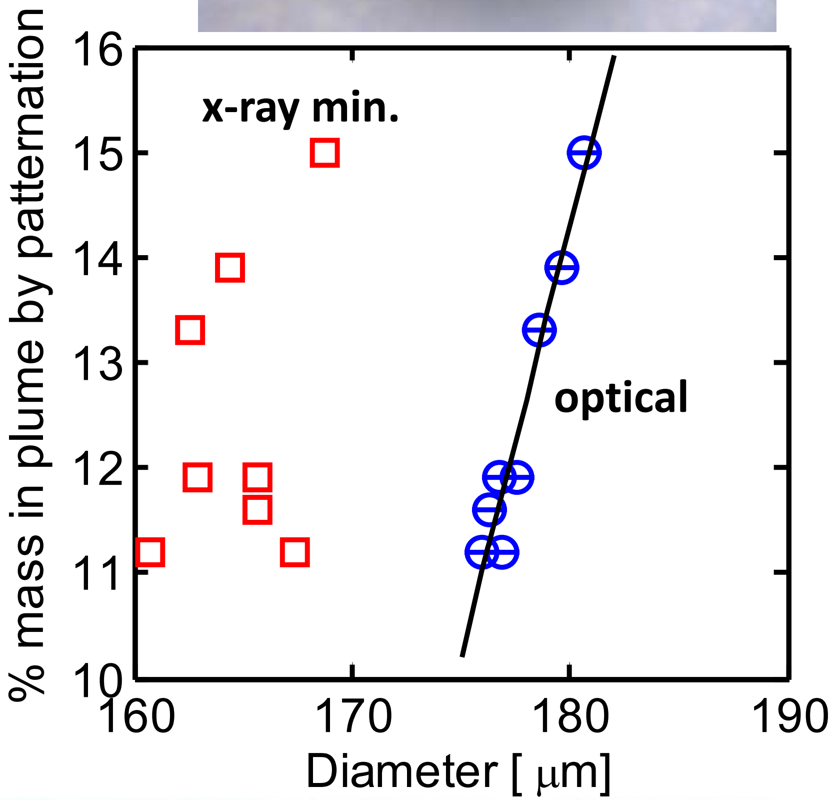
Hole size accounts for some variance between plumes





commercial x-ray tomography

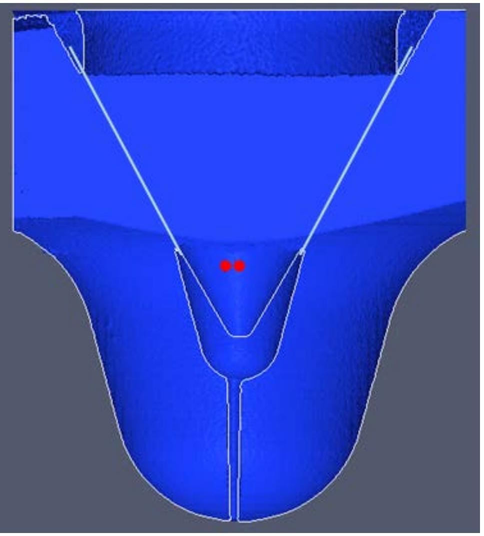




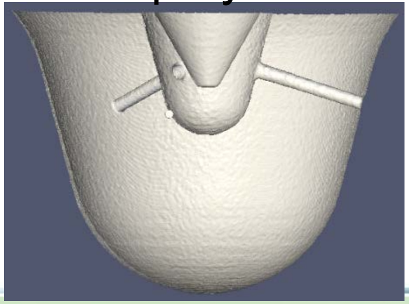
multi-hole Spray B penetration is unsteady, unlike single-hole Spray A

- Spray B liquid penetration responds to transient spreading angle

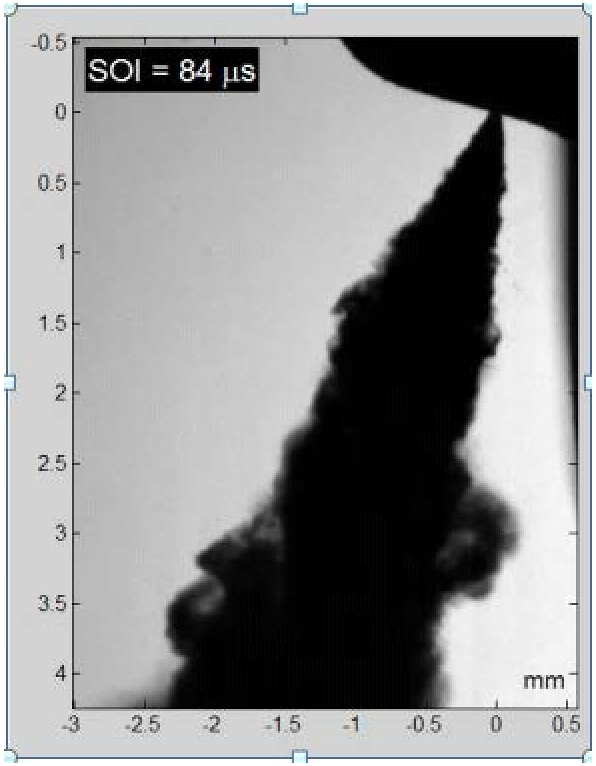
Spray A

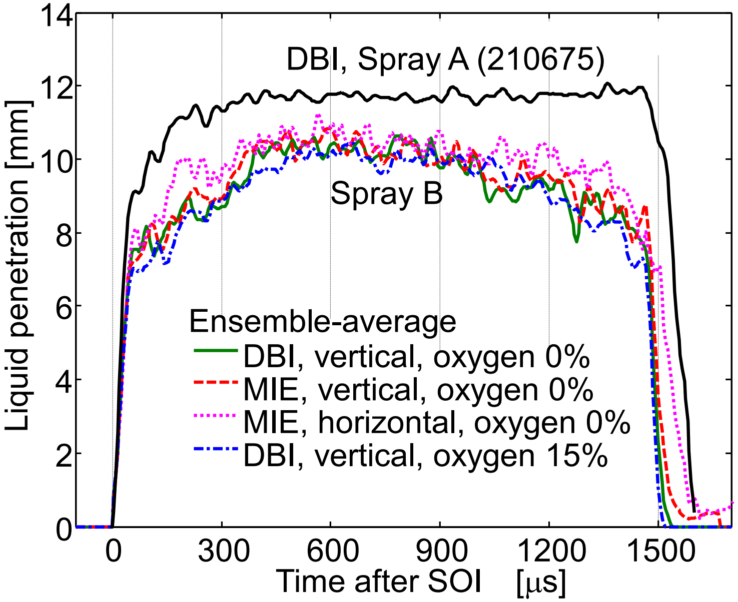


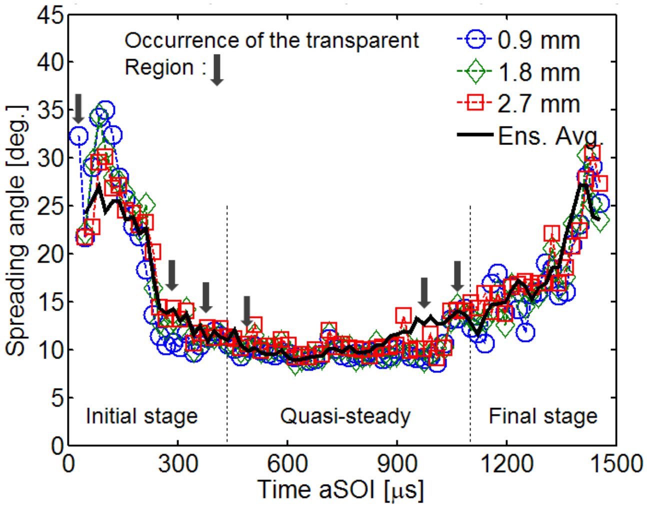
Spray B



Spray B near field







Close collaboration and pathway to better CFD tools

Experiment

Sandia	Mich. Tech.
Argonne	Meiji
IFPEN	Infineum
CMT	Chalmers
CAT	KAIST
GM	Aachen
Delphi	Melbourne
Bosch	Brighton
TU/e	
Ist. Motori	

CFD codes used

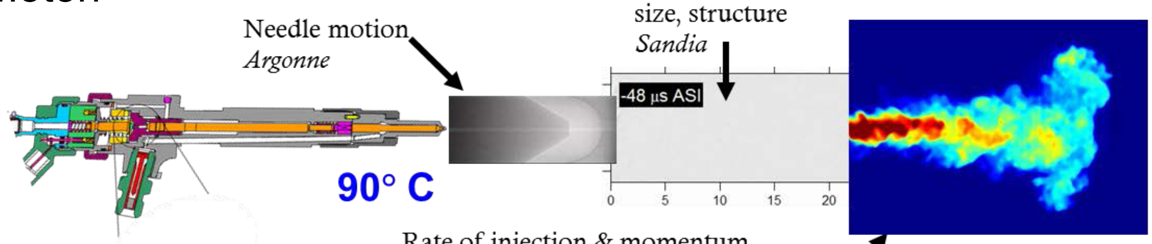
CONVERGE™
Star CD®
Open FOAM®
KIVA
ANSYS Fluent & CFX
FORTE
RAPTOR
other research codes…

CFD approaches

RANS
LES
High-fidelity LES
Eulerian-Eulerian
Eulerian-Lagrangian
Dense fluid
many spray and combustion variants…

Modeling submissions

Sandia
Argonne
IFPEN
CMT
PoliMi
UMass
UNSW
Penn St.
TU/e
UW-Madison
Purdue
ETH-Zurich
Aalto
Aachen
DTU
Cambridge
Georgia Tech
Chalmers
GM…



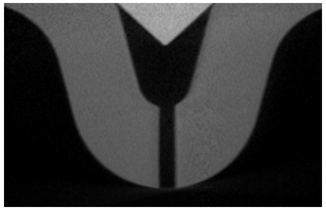
ECN organization

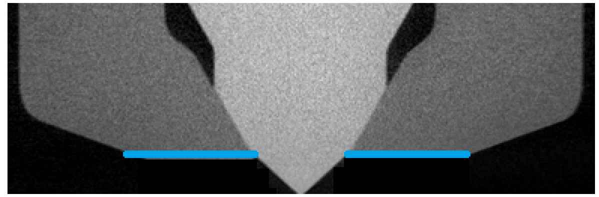
- Monthly web meetings
- Workshop organizers gather experimental and modeling data, perform analysis, understand differences, provide expert review
- Very tight coordination because of target conditions

Most industry use ECN data to test their CFD practices

Transparent nozzle assembly development

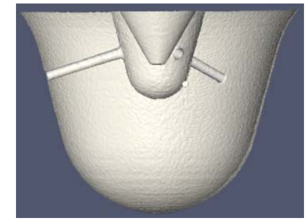
Single-hole

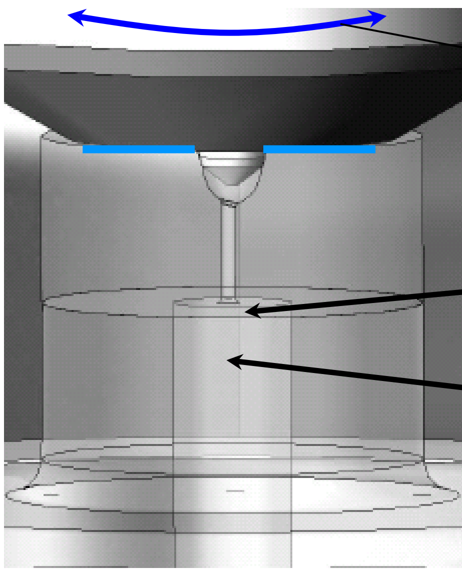




Diesel nozzle ground flat at sealing area

Multi-hole



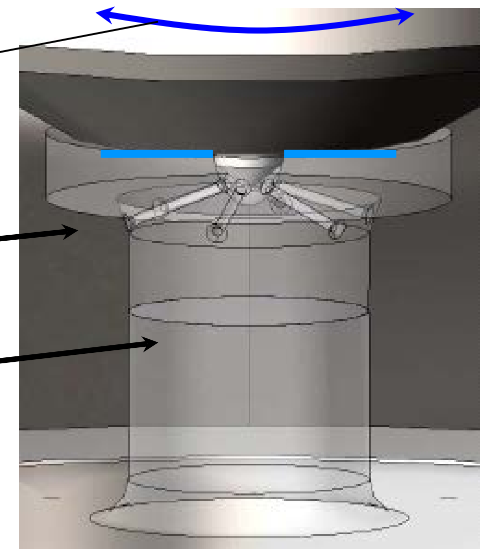


Rotation of assembly for full 3D access with optical or x-ray

Measurement of spray near-field spreading angle

Cylinder with pressurized N2

Transparent base for visualization from below



- Capability for single- or multi-hole nozzles with full 3D access
- Nozzles made to the precise shape of the measured metal nozzle target
- Visualization within the sac, nozzle hole, and exiting spray

Future work

- Expand Spray G gasoline dataset (FY15-FY16)
  - Conditions that span from flash boiling to late injection
  - Quantitative mixture fraction and velocity for model validation datasets
  - Fuel effects (ethanol)
- Diesel research activities (FY16)
  - Investigate the (miscible) structure of fuel sprays with fuel blends and at other conditions
  - How does the variable spreading angle of Spray B affect ignition/combustion/soot?
  - Investigate large-nozzle injectors (0.2 mm diameter) to intentionally create interaction between liquid regions and combustion regions of the spray
  - Compare cavitating and non-cavitating nozzles

Responses to previous year reviewer comments

- How injector details affect spray mixing:
  - "identify the sensitive factors influencing spray characteristics such as spreading angle and liquid core height, which could then aid CFD model development to reduce dependence on arbitrary tuning parameters"
  - "explore parameters for various high-pressure nozzles", "diesel and gasoline"
  - "consider looking at internal injection flow coupling with downstream sprays"
  - Response: Our ECN work and collaborators now use 5 different injectors, including multi-hole diesel and gasoline. We have initiated a transparent nozzle activity.
- How charge gas details affect spray mixing:
  - "Future work should consider addressing in more detail how applicable constant volume experimental results were to real engine conditions"
  - "modelers are moving towards exercising Eulerian spray approaches that transition to Lagrangian droplets. Are unique experiments available to help with the transition criteria?"
  - Response: Our chamber-characterized Spray B (diesel) and Spray G (gasoline) injectors are currently in use in engines, and their cross comparison is one of the topic areas for upcoming ECN workshops. Structure can be addressed using high-speed microscopy experiments. With a "breakthrough" in imaging quality under harsh conditions, we have demonstrated that even the assumption of droplets with surface tension needs to addressed in future modeling efforts.

Presentation Summary

- Project is relevant to the development of high-efficiency, low-emission engines, which all use direct-injection sprays
  - Observations of combustion in controlled environment lead to improved understanding/models for engine development
  - Sprays of interest will also be characterized in engines
- FY15 approach addresses deficiencies in spray combustion modeling
  - Experiments confirm that miscible mixing with liquid spray is a reality over a range of engine-relevant conditions—new modeling approaches are needed
  - Plume-to-plume interactions cause collapse of gasoline direct-injection sprays at certain conditions. Hole size variation explains part of plume-to-plume variation.
  - Dynamics of multiple injections characterized, showing a critical sensitivity to the state of ignition in the first injection
  - Multi-hole injectors exhibit transient spray structure different than single-hole nozzles. Spray liquid penetration is unsteady.
- Collaboration through the ECN expanded to accelerate research and provide a pathway for improved CFD tools used by industry
- Future plans will continue ECN-type research in diesel and gasoline

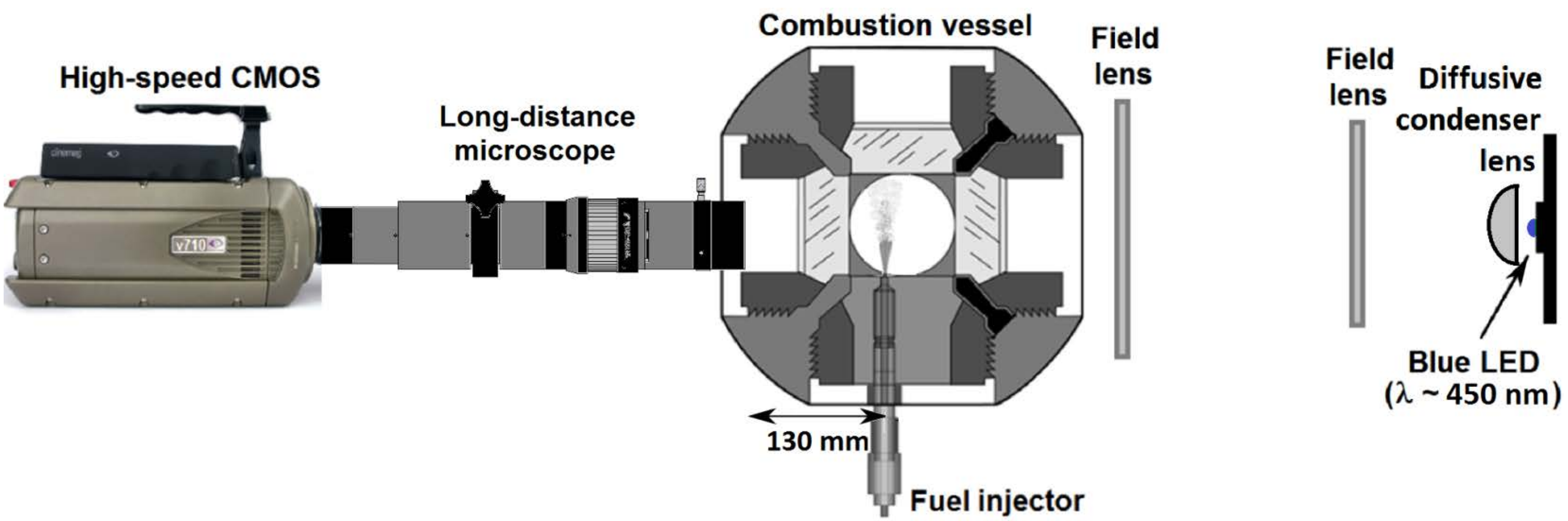
Acknowledging FY15 staff and visitors performing spray combustion research at Sandia

- Scott Skeen, Sandia National Laboratories
- Julien Manin, Sandia National Laboratories
- Cyril Crua, University of Brighton
- Yongjin Jung, Korean Adv. Inst. of Science and Technology (KAIST)
- Fredrik Westlye, Technical Univ. of Denmark

Technical Backup Slides

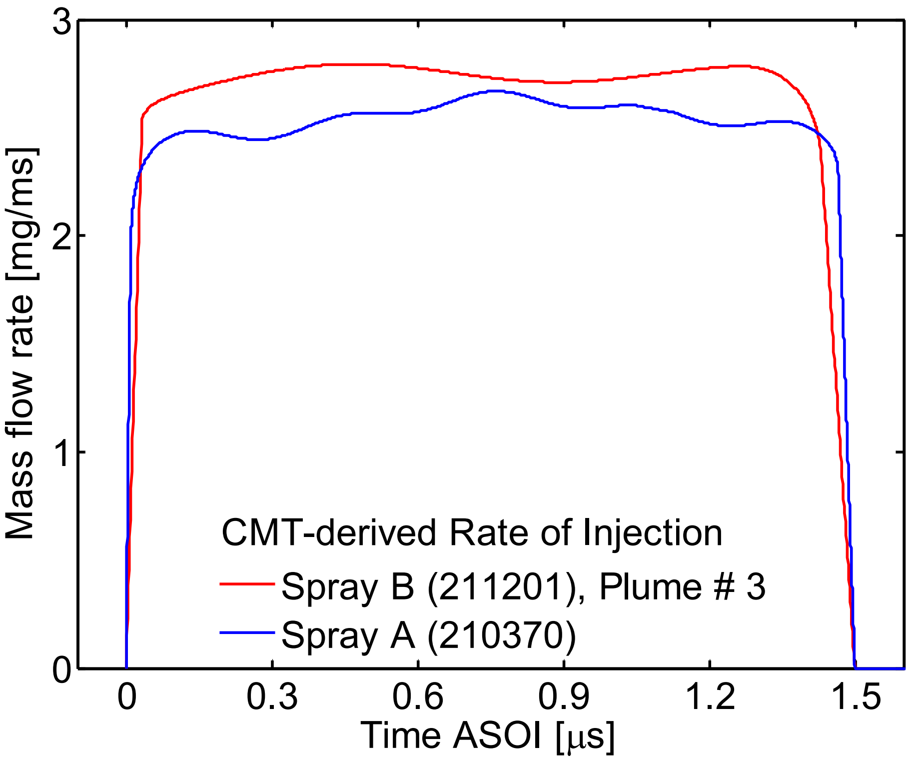
Improved optical arrangement

- New optics have been designed and assembled to offer improved optical magnification, light collection and image clarity
  - Infinity K2/DistaMax lens with purposely made magnifiers for a final digital resolution below 2 µm/pixel
  - Shortened effective working distance by designing an offset window, bringing the injector closer to the imaging system
  - Optimized lighting to offer diffuse yet efficient illumination to fill the numerical aperture of the system



Flow comparison of Spray B to Spray A

	Spray B (211201)	Spray A (210370)	Spray A (210675)
Nominal nozzle outlet diameter [μm]	90.0	←	←
Actual nozzle outlet diameter [μm]	91.0 (hole 1) 92.2 (hole 2) 95.8 (hole 3)	90.8	89.4
Nozzle k-factor	1.5	←	←
Sac volume [mm^3]	0.2	←	←
Discharge coefficient**	0.84 (hole 1), 0.88 (hole 2), 0.84 (hole 3)	0.89	0.90
Area contraction coefficient	0.98	0.98	0.98

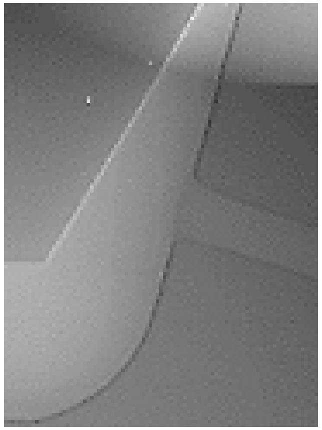


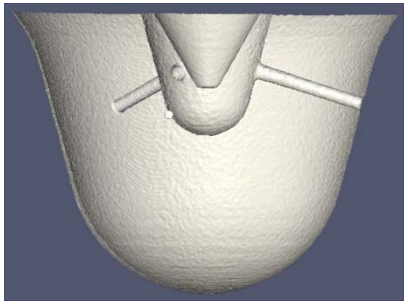
Rate of injection measurements performed by CMT Motores Termicos

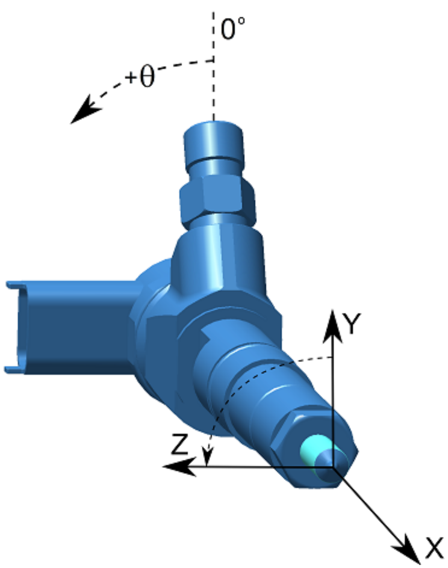
ECN Spray B nozzle

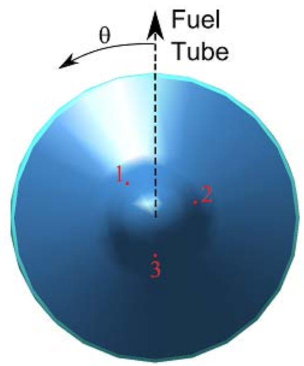
- Has the same size and KS specification as Spray A, but with a shorter length
- Side hole with ψ = 72.5° (145° full included angle)
- Plume 3, opposite the fuel tube, is the plume of interest

Spray B

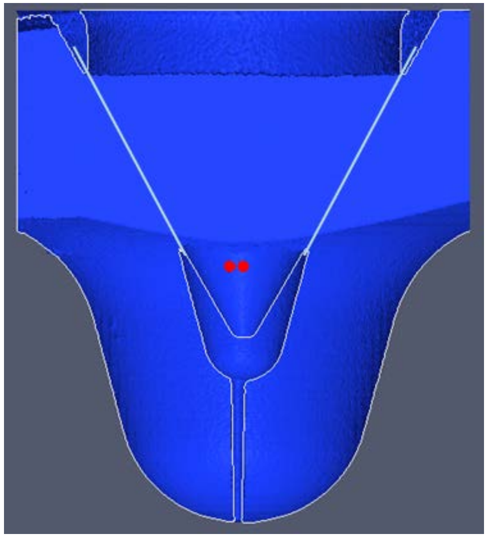






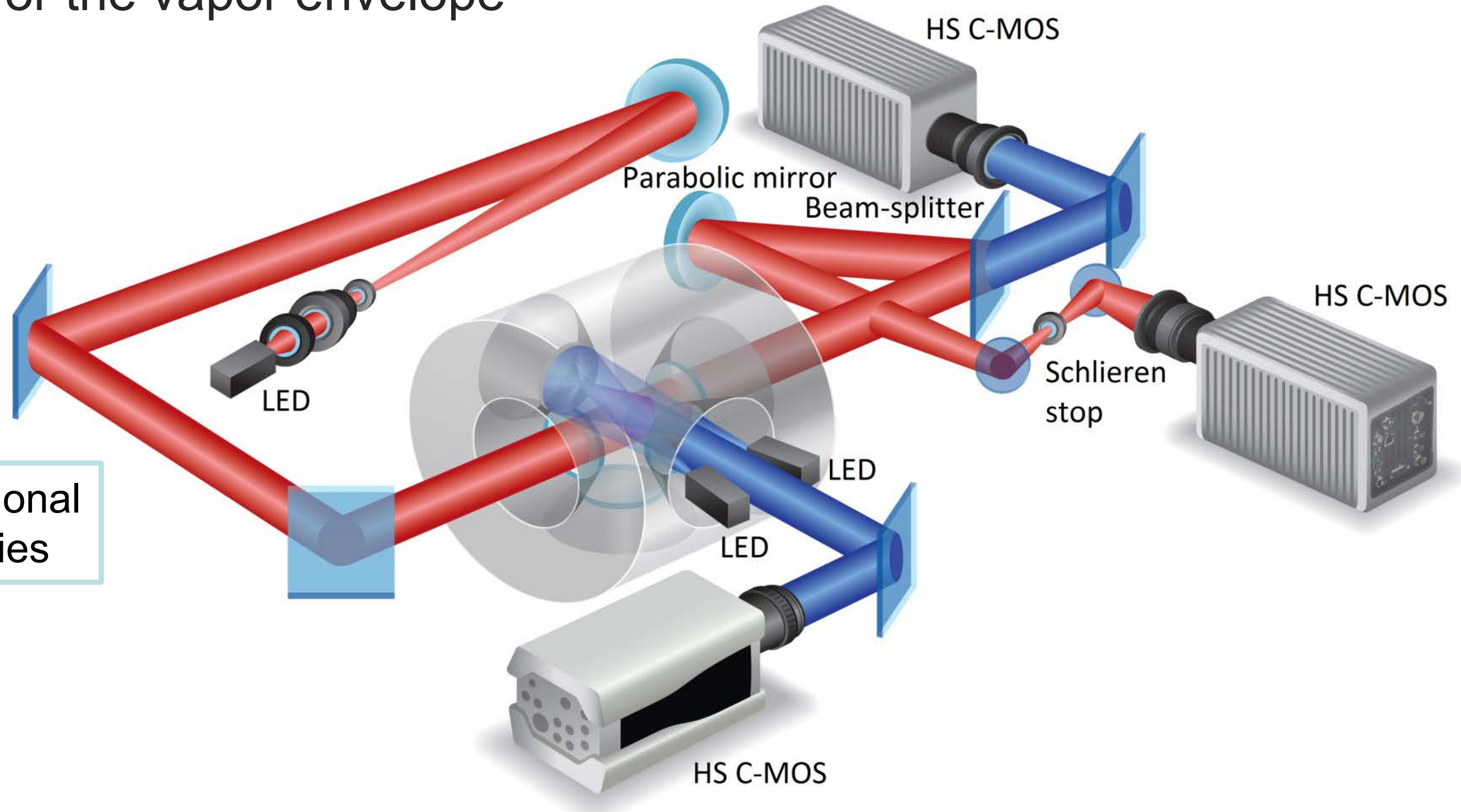


Spray A



Optical setup for gasoline direct-injection visualization

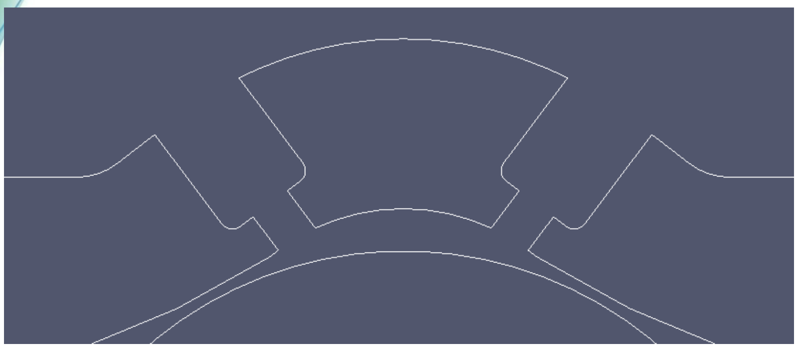
- Mie scatter as a measure of liquid penetration
- Schlieren for the vapor envelope



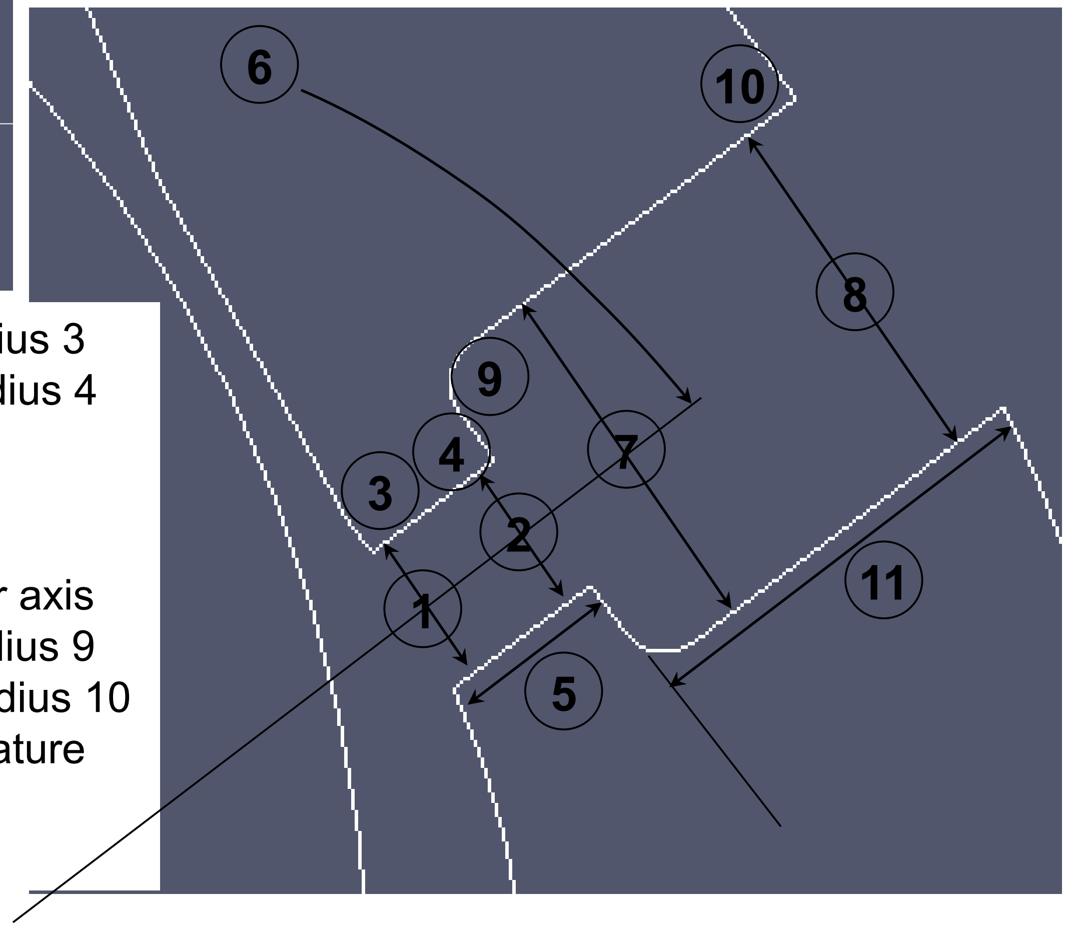
Sandia National Laboratories

- Sandia also performed front-view Mie scatter visualization of the sprays

Geometry measurements guide refinement of nominal features for internal nozzle flow simulations



“Specified” geometry with “open” pintle/ball



1. Inner hole inlet diameter after inlet radius 3
2. Inner hole exit diameter before exit radius 4
3. Inner hole inlet radius of curvature
4. Inner hole exit radius of curvature
5. Inner hole length
6. Inner hole drill angle relative to injector axis
7. Outer hole inlet diameter after inlet radius 9
8. Outer hole exit diameter before exit radius 10
9. Outer hole inlet reverse radius of curvature
10. Outer hole exit radius of curvature
11. Outer hole length