Sandia National Laboratories

ENGINE COMBUSTION NETWORK

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CAVITATION SOURCES FOR SPRAY D

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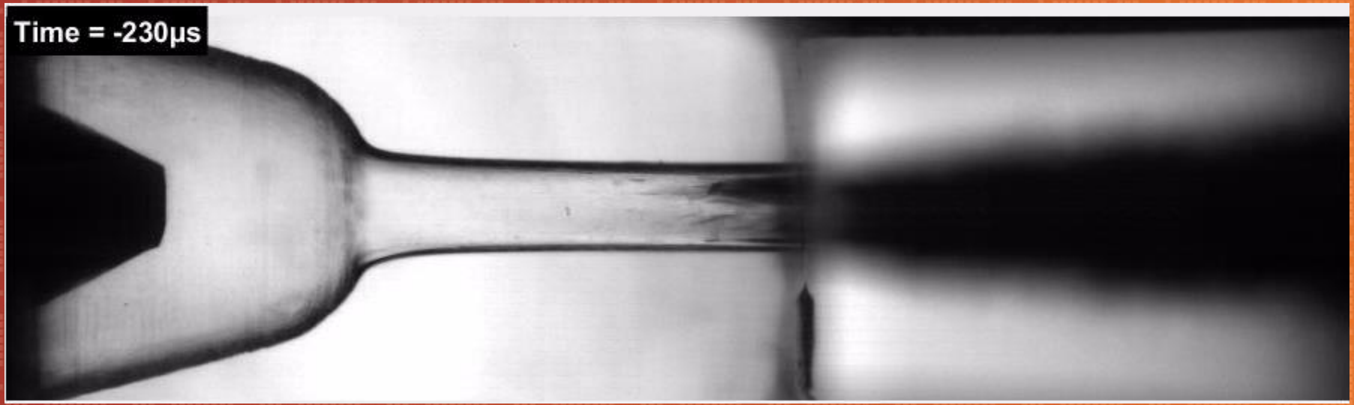
- Spray Combustion Consortium of automotive industry sponsors
- U.S. DOE Office of Vehicle Technologies

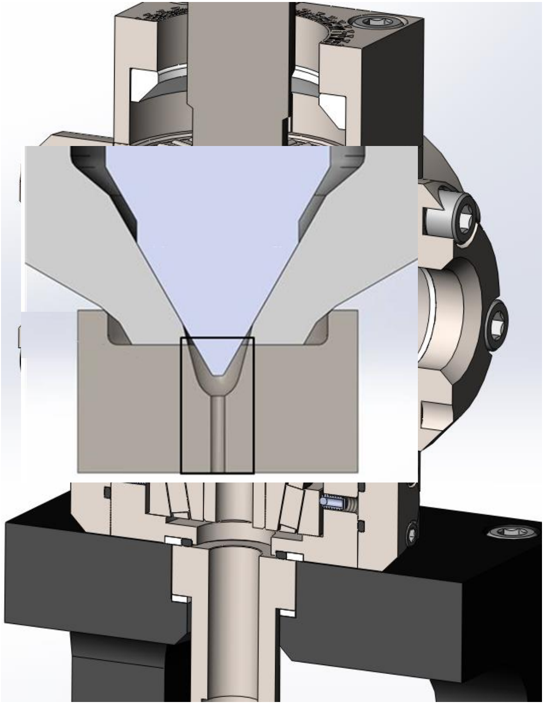
This study was performed at the Combustion Research Facility, Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SPRAY COMBUSTION CONSORTIUM

High-speed visualization through shaped diesel injector. Nozzle matches ECN Spray D



INTERNAL NOZZLE FLOW INSTALLATION



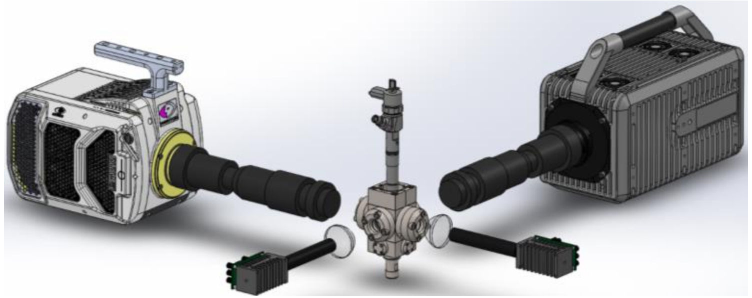
- Custom-designed chamber for optical flow characterization in transparent nozzles
  - Continuous flow
  - Vacuum and high-pressure (6-MPa) capabilities
- Real-size transparent nozzles made of cast acrylic
  - Refractive index close to fuel (n-dodecane)
  - Geometrical match for ECN Spray D (190 μm)
    - Nozzle support allows spray visualization and "realistic" air entrainment
    - High-precision syringe pump for fuel system
      - 150+ MPa capabilities (+/- 0.01 MPa)

J.Manin et al., Transient cavitation in transparent diesel injectors, ICLASS 2018

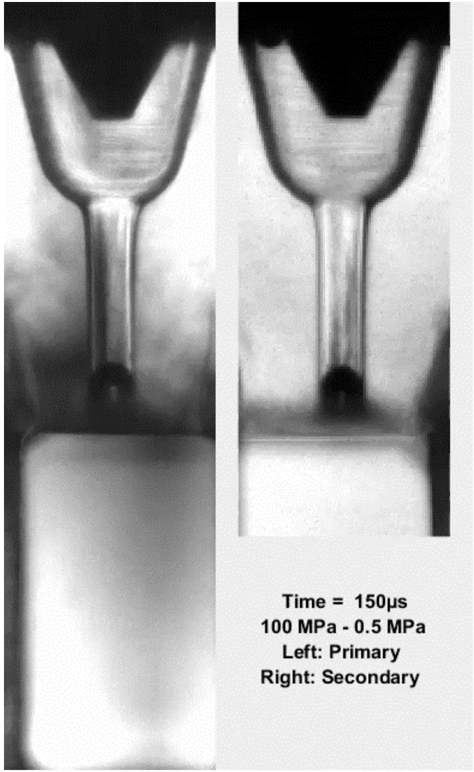
SPRAY COMBUSTION CONSORTIUM

STEREO HIGH-SPEED MICROSCOPY

- Synchronized and spectrally-separated stereo-microscopy setup
  – Allows stereo/3-D visualization of needle motion and flow processes



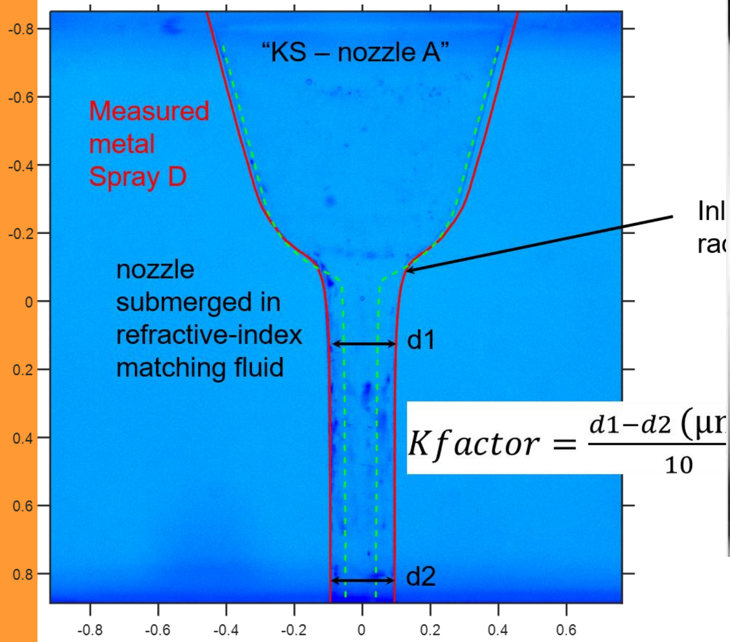
- Primary system (Phantom):
  – 8X magnification (3.5 μm/pix)
  – 120 – 380kHz acquisition rates
- Secondary system (Photron):
  – 3X magnification (7 μm/pix)
  – 270kHz acquisition rate
- Illumination via Sandia ultrafast high-power LED pulsers
  – Custom single and multi-die LED emitters
  – 30 ns pulse duration to freeze flow motions



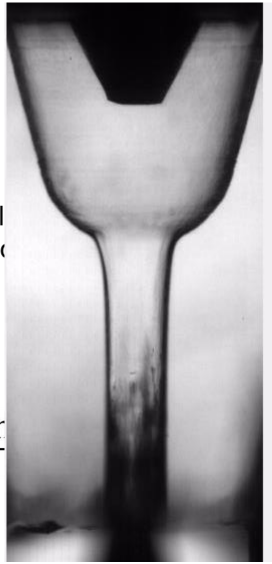
SPRAY COMBUSTION CONSORTIUM

J.Manin et al., Transient cavitation in transparent diesel injectors, ICLASS 2018

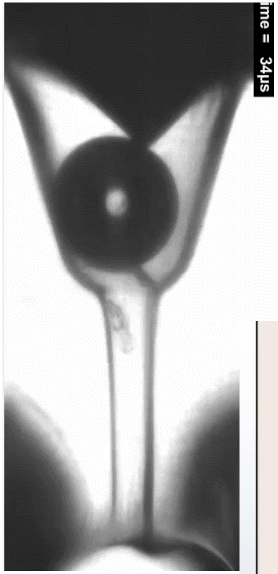
TARGET NOZZLE GEOMETRY

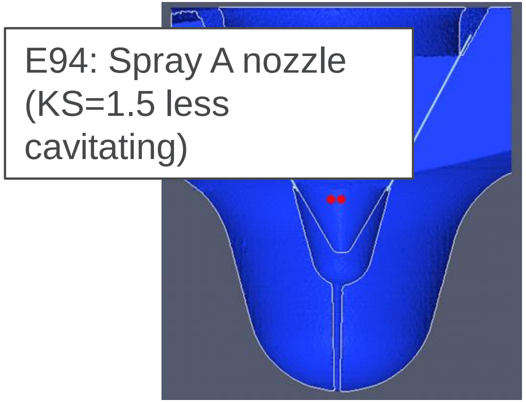


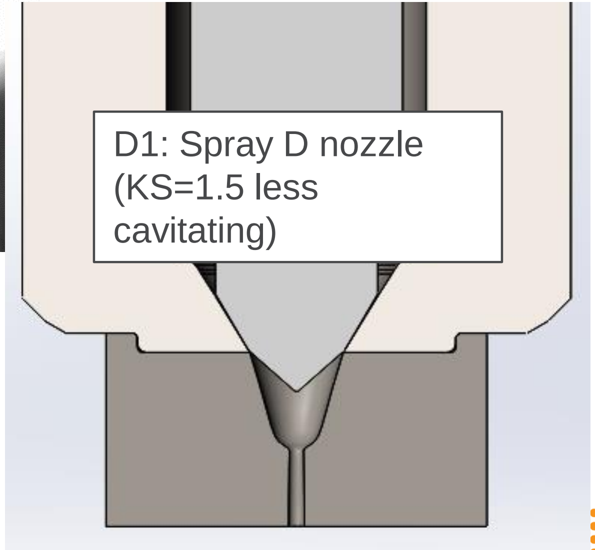
Spray A (E94)
100 MPa – 5 bar



Spray D (D1)
100 MPa – 5 bar







- Nozzle constructed to match Spray D shape using mechanical drilling and hydroerosion
- Mounted to either Spray A or Spray D injector/needle/sac ground flat—successfully operate to 100 MPa pressure
- Actual shape of hole (convergence) is important

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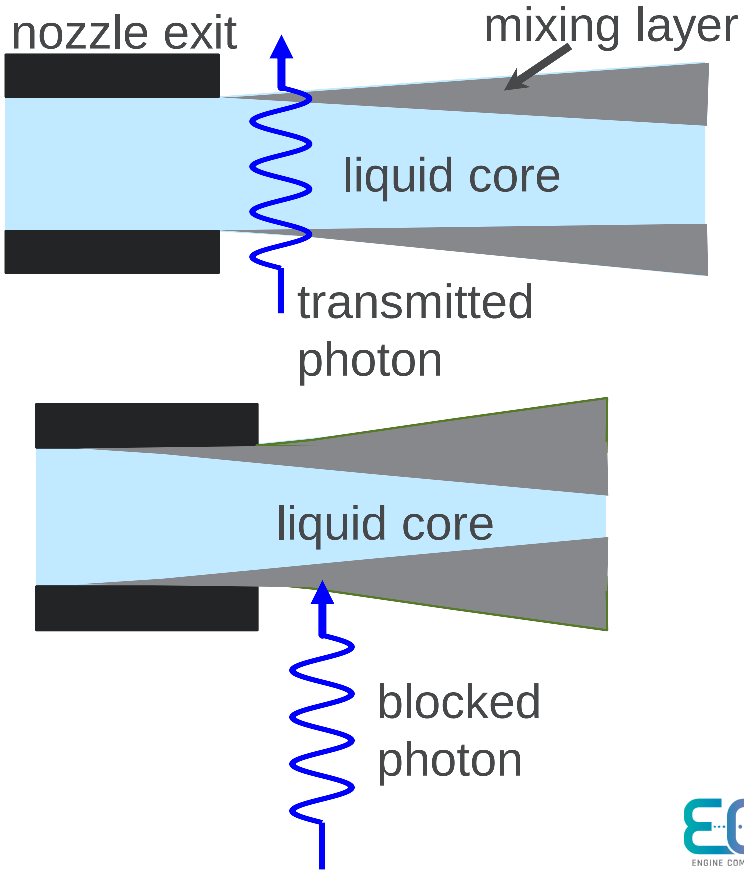
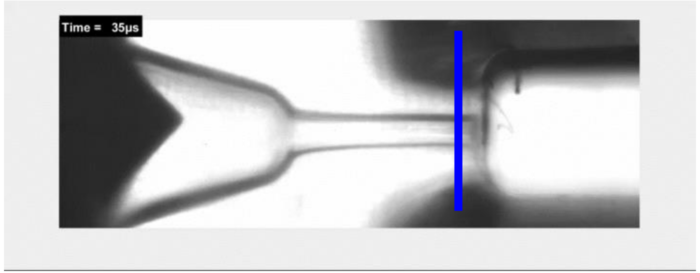
SCHEMATIC OF MIXING LAYER INSIDE OR OUTSIDE OF NOZZLE SHOWS HOW LIGHT IS BLOCKED OR TRANSMITTED

- If mixing layer is thin, or optically thin, and present on both sides, a “transmitting liquid core” should be shown
- If the mixing layer blocks light, through cavitation or rapid breakup, a transparent liquid core will not be visible

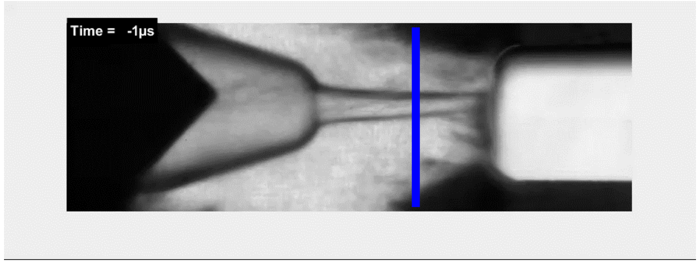


VISUALIZATION OF DIFFERENT NOZZLES (100MPA-2MPA)

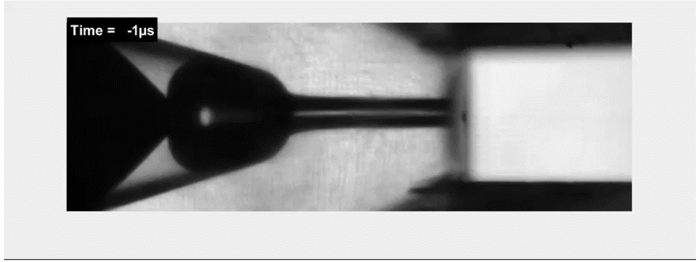
D1-15



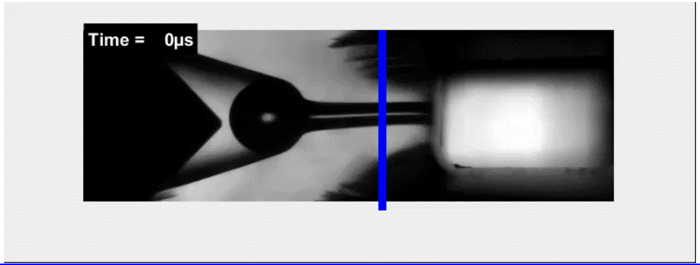
D1-16



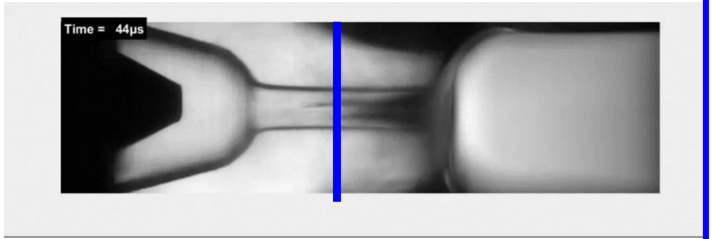
D1-18(50MPa-2MPa)



D1-19

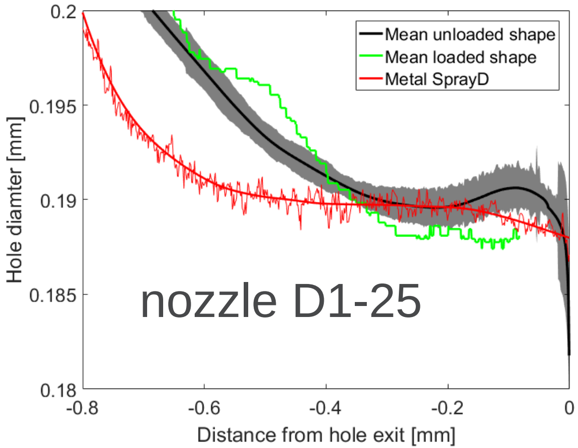


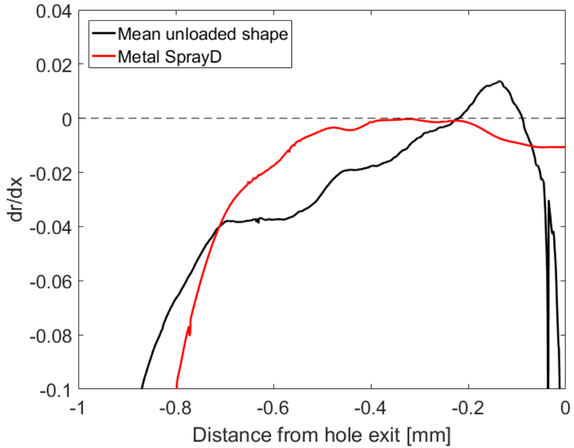
Spray A (E94-003)

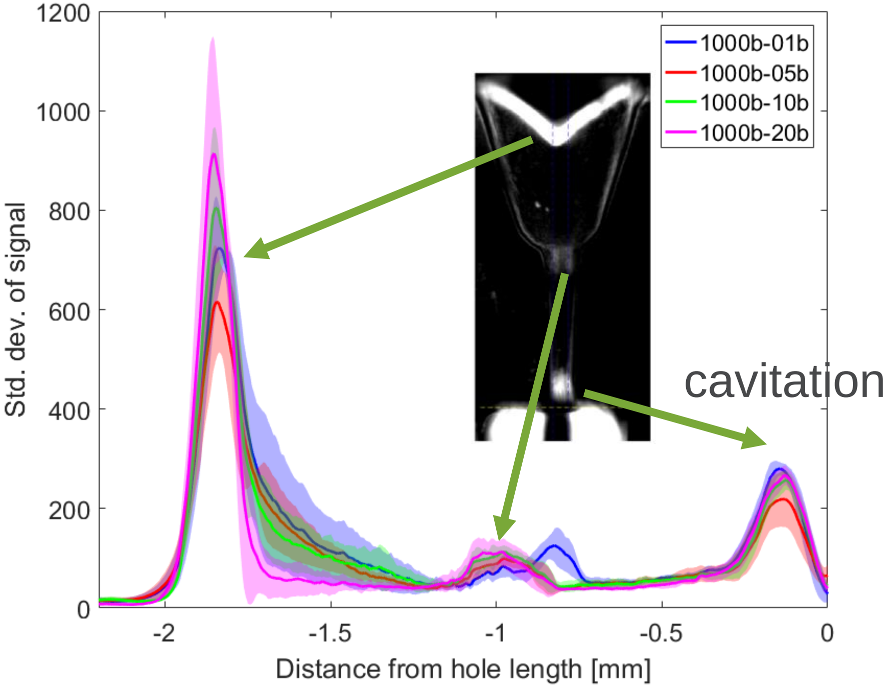


15 Cavitation close to exit
16 Cavitation farther upstream
18 Intact liquid core, almost no cavitation
19 Cavitation close to exit
E94-003 Strong cavitation farther upstream

HOLE GEOMETRY EFFECT ON CAVITATION

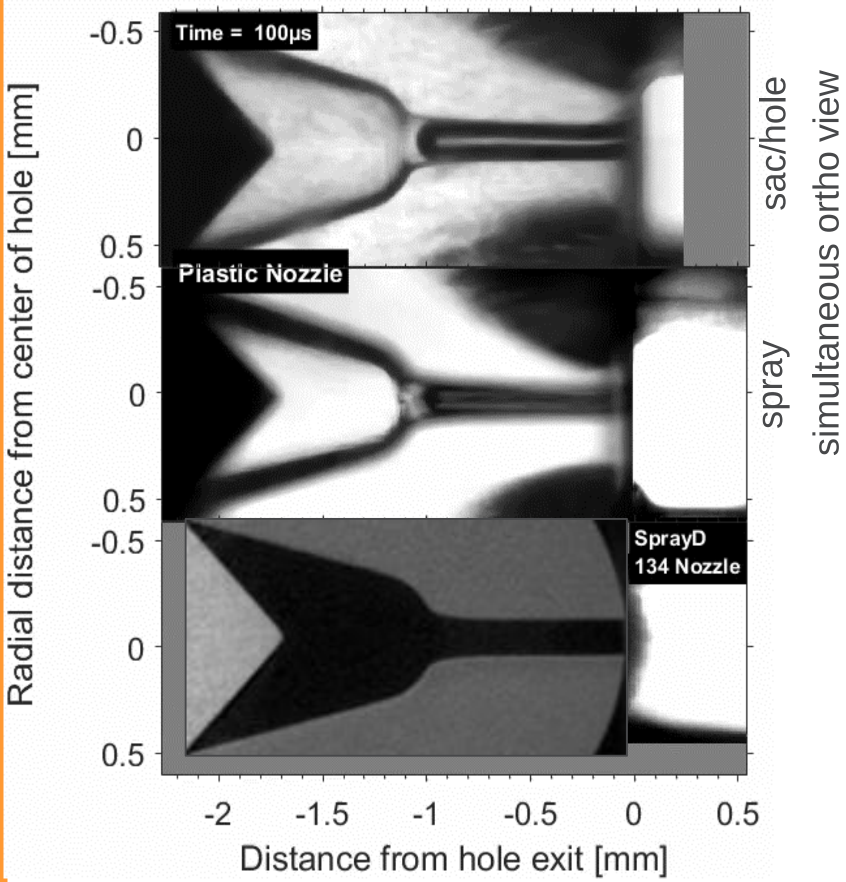






- Slope relaxes near exit of nozzle, for both optical nozzle AND Spray D!

ASSESSMENT OF “TRANSPARENT LIQUID CORE” FOR SPRAY D AT 100 MPA



- Initial transparent liquid core is similar for both acrylic and metal
- At steady conditions: acrylic nozzle show shows transparency liquid core at nozzle exit, but ALSO internal cavitation!
- Metal nozzle (Spray D 134) also shows transparent liquid after adjusting image contrast (I/I_0 = 0-25% for both spray images), but transparent core is even less visible than with cavitating acrylic nozzle.

- Strongly suggests that some internal cavitation is also occurring for metal Spray D, particular at 150 MPa inj. pressure

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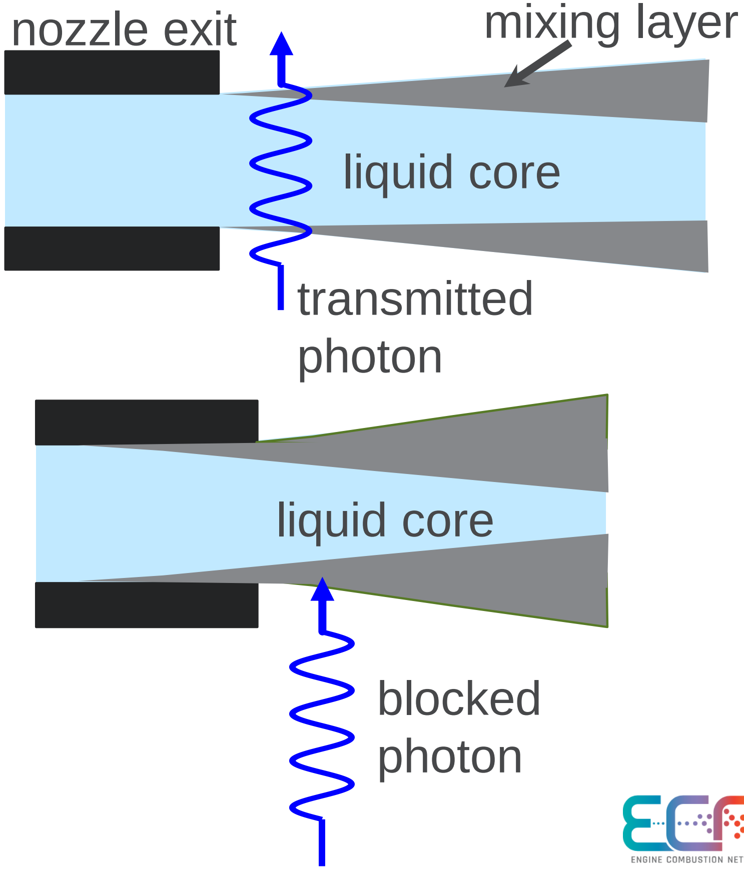
ANALYSIS OF MANY OPTICAL NOZZLES AND OPERATING CONDITIONS

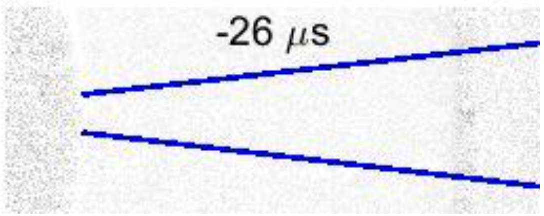
- There are a number of example where cavitation layers are present, and we do see occasional transmitting liquid core
  - Cavitation usually somewhat close to the nozzle exit
- If cavitation occupies a significant fraction (1/3 or more) of nozzle exit, it is rare to see transmitting liquid core
- What about othe ECN injectors?



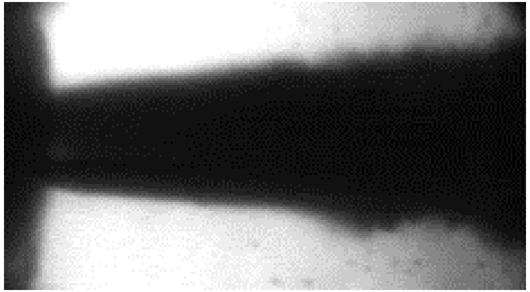
SPRAY A (NOZZLE 370) MORE CONVERGING THAN SPRAY D (D134)-- BOTH PRODUCE TRANSMITTING LIQUID CORE

n-dodecane at 300-310 K

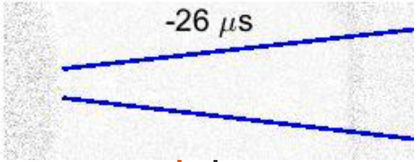
Spray A nozzle 370
100 MPa – 20 bar

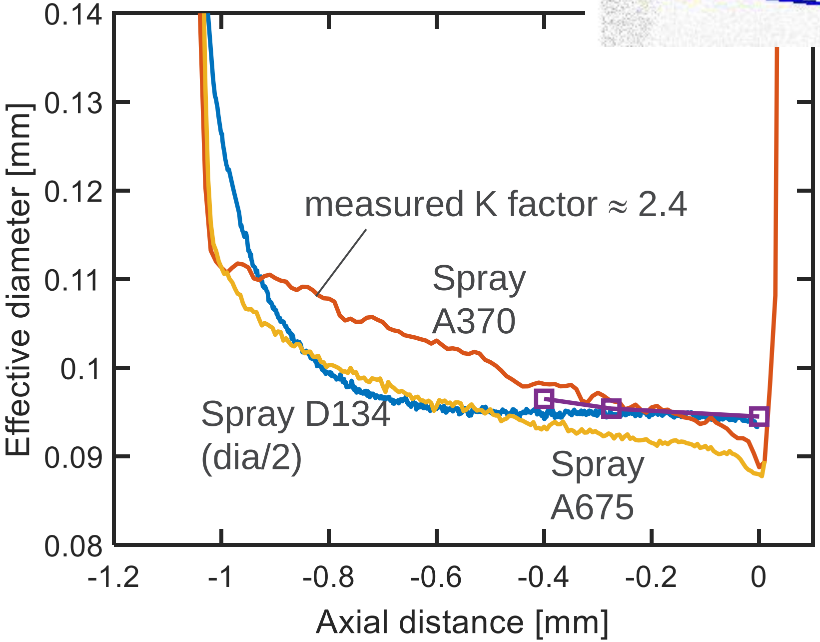


Spray D
100 MPa – 20 bar



Spray A nozzle 370
500 bar – 20 bar





COLLABORATIVE RESEARCH THROUGH THE ENGINE COMBUSTION NETWORK ACCELERATES CFD MODEL DEVELOPMENT

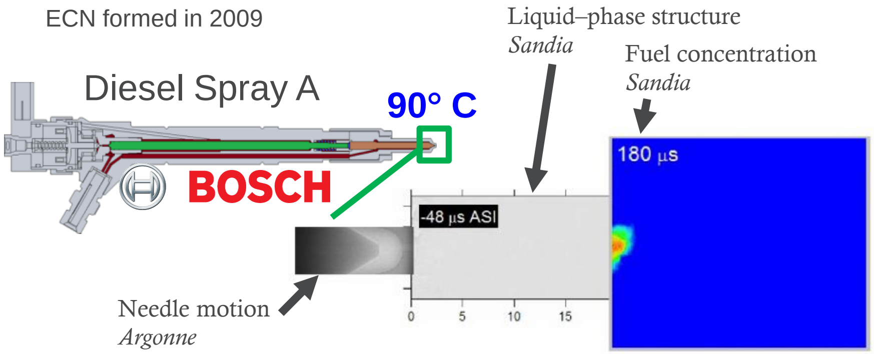
Approach

- Develop diesel and gasoline target conditions with emphasis on CFD modeling shortcomings
- Comprehensive experimental and modeling contributions
- Diesel Spray A, B, C, D
- Gasoline Spray G
- Results submitted to online archive (ecn.sandia.gov) with fields (like geometry and uncertainty) specifically tailored for CFD simulations

Impact

- Established in 2009, there are already 1400 citations of the ECN data archive
- Most automotive industry (light- and heavy-duty) use ECN archive to test their own CFD methods

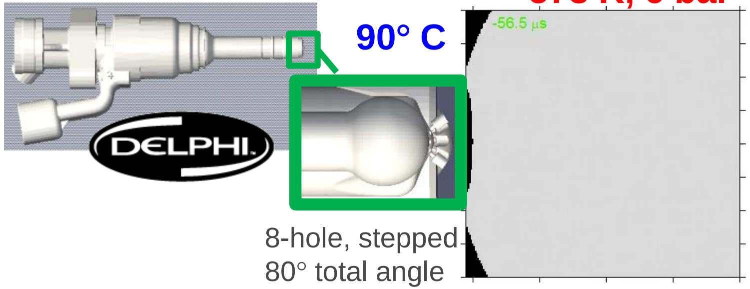
ECN formed in 2009



>70 measurements/diagnostics contributed from >15 institutions

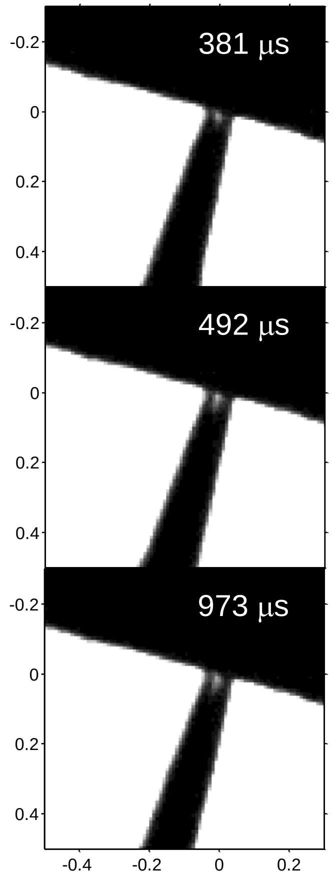
900 K
60 bar

Gasoline Spray G

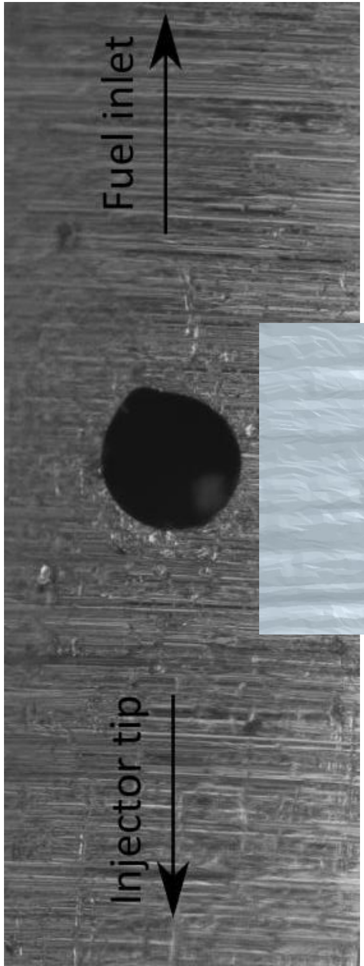


8-hole, stepped
80° total angle

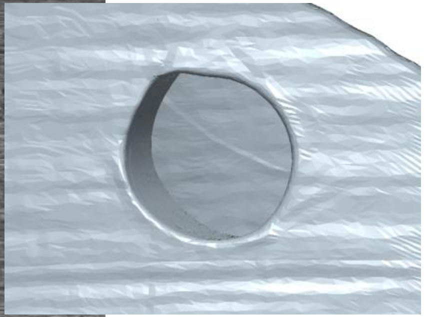
MICROSCOPY IMAGING SHOWS INTACT LIQUID CORE FOR SPRAY B



Jung et al. 2015

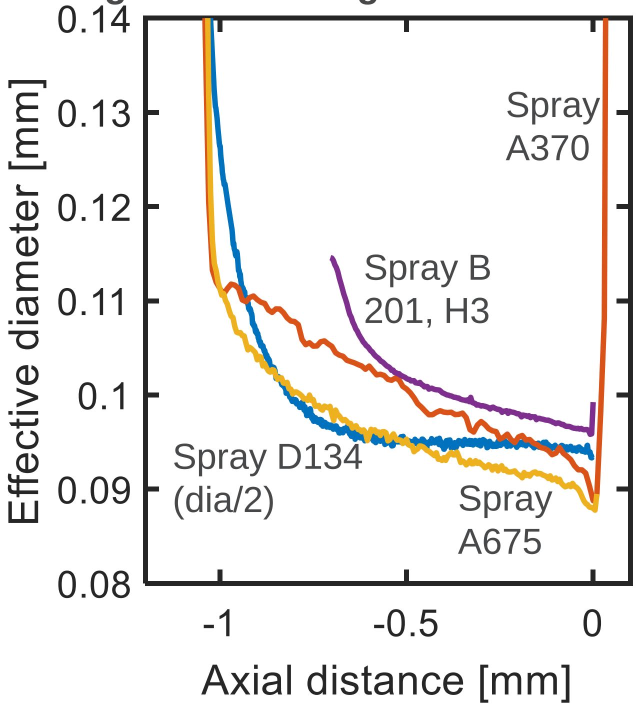


Hole asymmetry persists inside the nozzle



Surface from high-fidelity x-ray tomography at ESRF (Peter Hutchins)

Spray B Inj 201 hole #3: Irregular shape, but hole length is short and convergence is strong



SUMMARY

- A transparent replica of ECN Spray D has been fabricated with close similarity in geometry, and operated up to 100 MPa injection pressure.
- Actual nozzle shape, including local slope changes, is critical to the flow.
- Internal cavitation AND a transparent liquid core at the nozzle exit is possible.
- Metal nozzle (Spray D 134) transitions to a nearly cylindrical shape toward the hole exit.
- Spray D 134 shows an occasional transparent liquid core, but with less transparency than some nozzles where there is known internal cavitation.
- Strongly suggests that some internal cavitation is also occurring for metal Spray D, and possibly other ECN metal injectors (with positive K specification)

MEASURING DEFORMATION UNDER LOAD

- Small rig made to load nozzle with the same injector and support contact points
- Rig is submerged in the refractive-index matching fluid inside cuvette, allowing short-working-distance, high-resolution microscopy for size characterization.
- Evaluates load deformation/elasticity
  - Not injection pressure effects