AEC001: Heavy-Duty Low-Temperature and Diesel Combustion & Heavy-Duty Combustion Modeling

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FY 2010 DOE Vehicle Technologies Program Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
8:30 – 9:00 AM, Tuesday, June 8, 2010

Sponsor: **U.S. Dept. of Energy, Office of Vehicle Technologies**

Program Manager: **Gurpreet Singh**

Heavy-Duty Combustion Project Overview

Timeline

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

Barriers

- Inadequate understanding of fundamental in-cylinder Low-Temperature Combustion (LTC) processes
- HC and CO emissions
- Limited understanding of multiple-injection processes

Budget

- Project funded by DOE/VT:
  FY09-SNL/UW: $580/115K
  FY10-SNL/UW: $660/115K

Partners

- University of Wisconsin
- 15 industry partners in the AEC MOU
- Project lead: Sandia (Musculus)

Heavy-Duty In-Cylinder Combustion Objectives

Long-Term Objective

Develop improved understanding of in-cylinder LTC spray, combustion, and pollutant-formation processes required by industry to build cleaner, more efficient, heavy-duty engines

Current Specific Objectives:

① SNL - Understand the spatial and temporal evolution of soot formation in low-temperature diesel combustion

② SNL - Identify the in-cylinder post-injection processes that oxidize squish-volume soot from the main injection

③ UW+SNL - Improve modeling of both flame propagation and distributed autoignition in LTC diesel engines

④ (SNL/2011 - Quantify the potential for post-injections to reduced unburned hydrocarbon emissions)

Heavy-Duty In-Cylinder Combustion Milestones

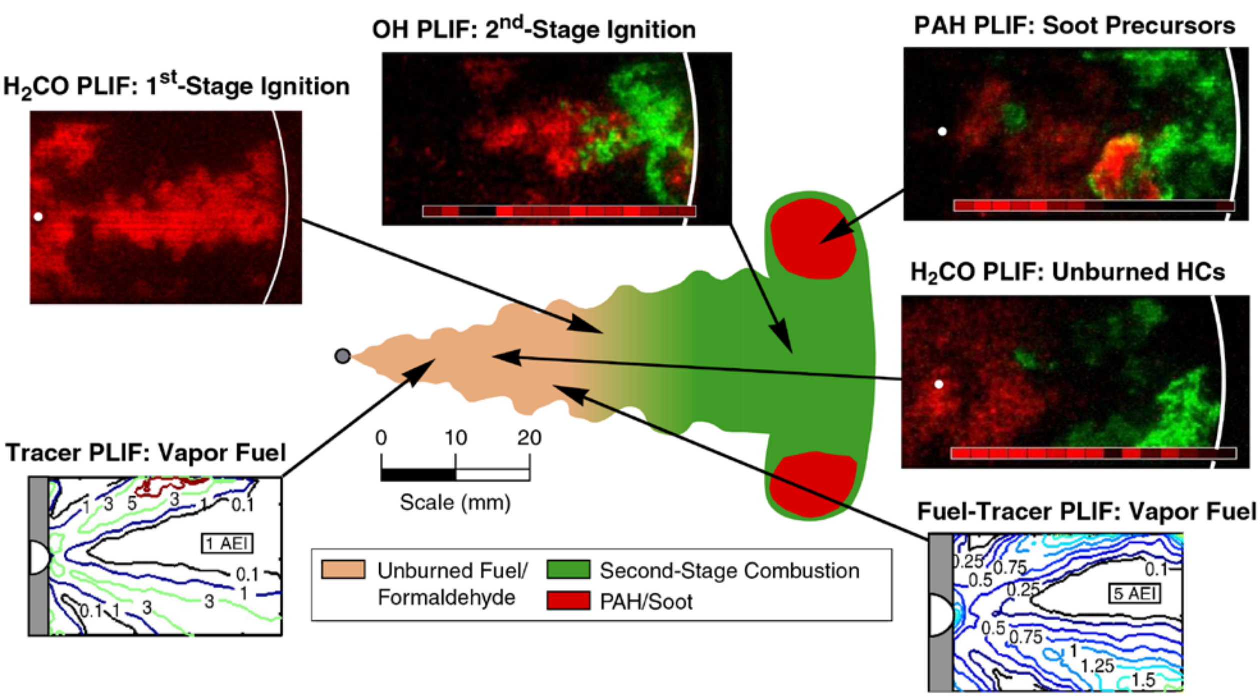
① (Dec. 2009 - SNL) Compare spectral and spatial distribution of soot and its precursors with 532 and 1064 nm laser excitation.

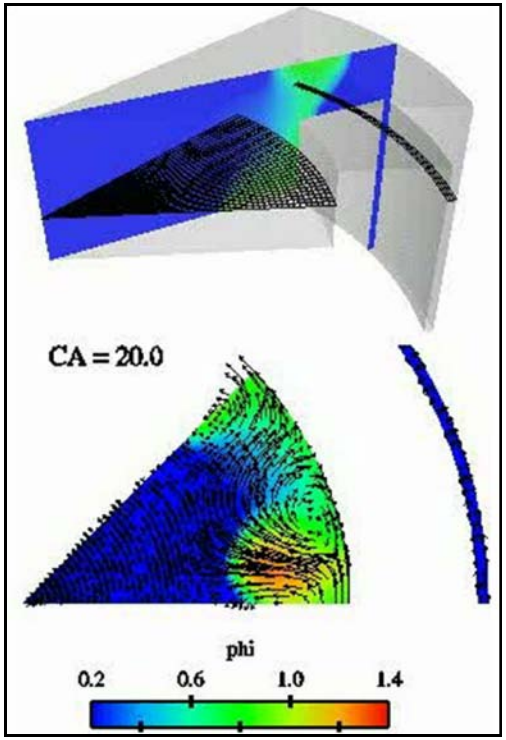
② (June 2010 - SNL) Describe the in-cylinder mechanisms by which post-injections oxidize soot in the squish volume.

③ (Sept. 2010 UW+SNL) Demonstrate dual-fuel system in SNL heavy-duty optical engine

Approach: Optical Imaging and CFD Modeling of In-Cylinder Chemical and Physical Processes

- Combine planar laser-imaging diagnostics in an optical heavy-duty engine with multi-dimensional computer modeling (KIVA) to understand LTC combustion
- Transfer fundamental understanding to industry through working group meetings, individual correspondence, and publications





Collaborations

- All work has been conducted under the Advanced Engine Combustion Working Group in cooperation with industrial partners
  - Cummins, Caterpillar, DDC, Mack Trucks, John Deere, GE, International, Ford, GM, Daimler-Chrysler, ExxonMobil, ConocoPhillips, Shell, Chevron, BP, SNL, LANL, LLNL, ANL, ORNL, U. Wisconsin
- New research findings are presented at biannual meetings
- Tasks and work priorities are established in close cooperation with industrial partners
  - Both general directions and specific issues (e.g., UHC for LTC, soot in higher load conditions)
- Industrial partners provide equipment and support for laboratory activities

Accomplishments (11 slides)

- Accomplishments for each of the four current specific objectives below are described in the following eleven slides

Current Specific Objectives:

① **(SNL) Understand the spatial and temporal evolution of soot formation in low-temperature diesel combustion**

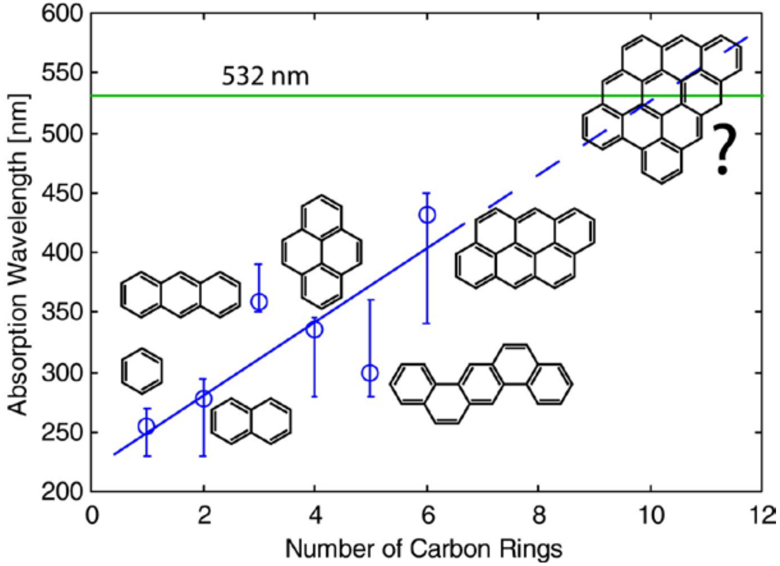
② **(SNL) Identify the in-cylinder post-injection processes that oxidize squish-volume soot from the main injection**

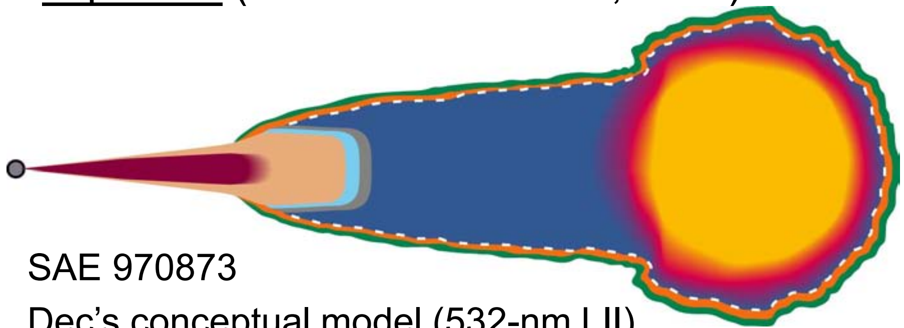
③ **(UW+SNL) Improve modeling of both flame propagation and distributed autoignition in LTC diesel engines**

④ **(SNL/2011) Quantify the potential for post-injections to reduce unburned hydrocarbon emissions**

① Recent diagnostic developments provide new tools for studying in-cylinder LTC soot

- LTC particulate matter (PM) can be different than conventional PM
  - size, density, and chemical composition - esp. PAH (SAE 2007-01-1945, CMT)
- In-cylinder soot may be visualized by laser-induced incandescence (LII)
  - Typically, laser excitation at 532 nm (green) has been used for LII





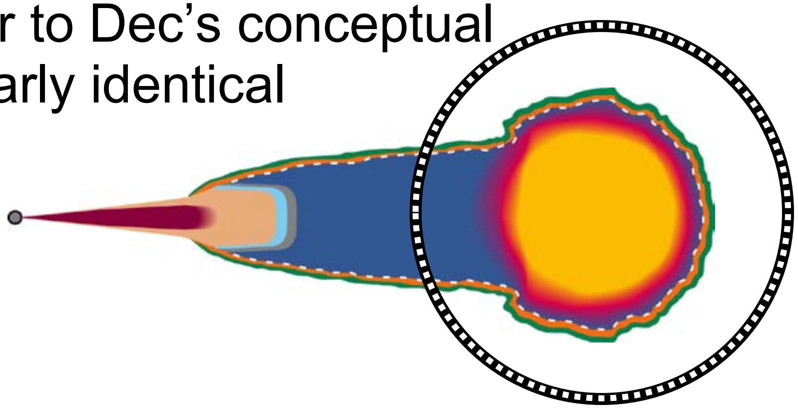
SAE 970873
Dec's conceptual model (532-nm LII)

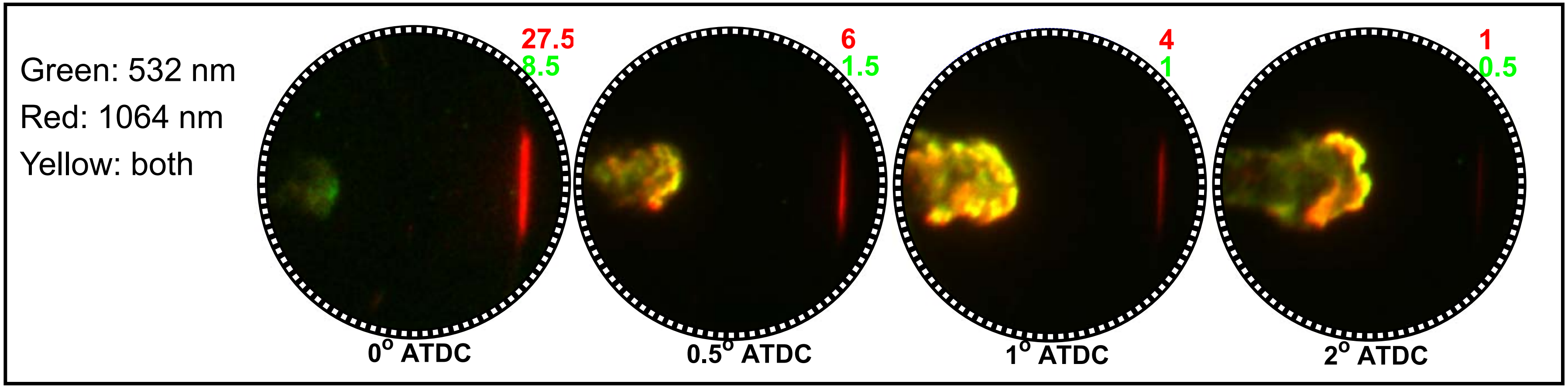
- Recent flame data indicate 532-nm LII signals may include large PAH and other fluorescence
  - Absorption wavelength increases with number of PAH rings
- With laser excitation at 1064 nm (IR), fluorescence interference is insignificant

What can we learn about in-cylinder soot and PAH formation by using simultaneous 532 nm and 1064 nm excitation?

① Conventional diesel: 532 and 1064-nm LII are virtually identical - rapid soot formation (hot)

- For conventional diesel conditions similar to Dec's conceptual model, 532 and 1064-nm soot LII are nearly identical
  - At premixed burn, weak 532-nm signal (green) appears at jet head
  - Very quickly (0.5 CAD), 1064-nm LII (red) appears: signals are nearly identical



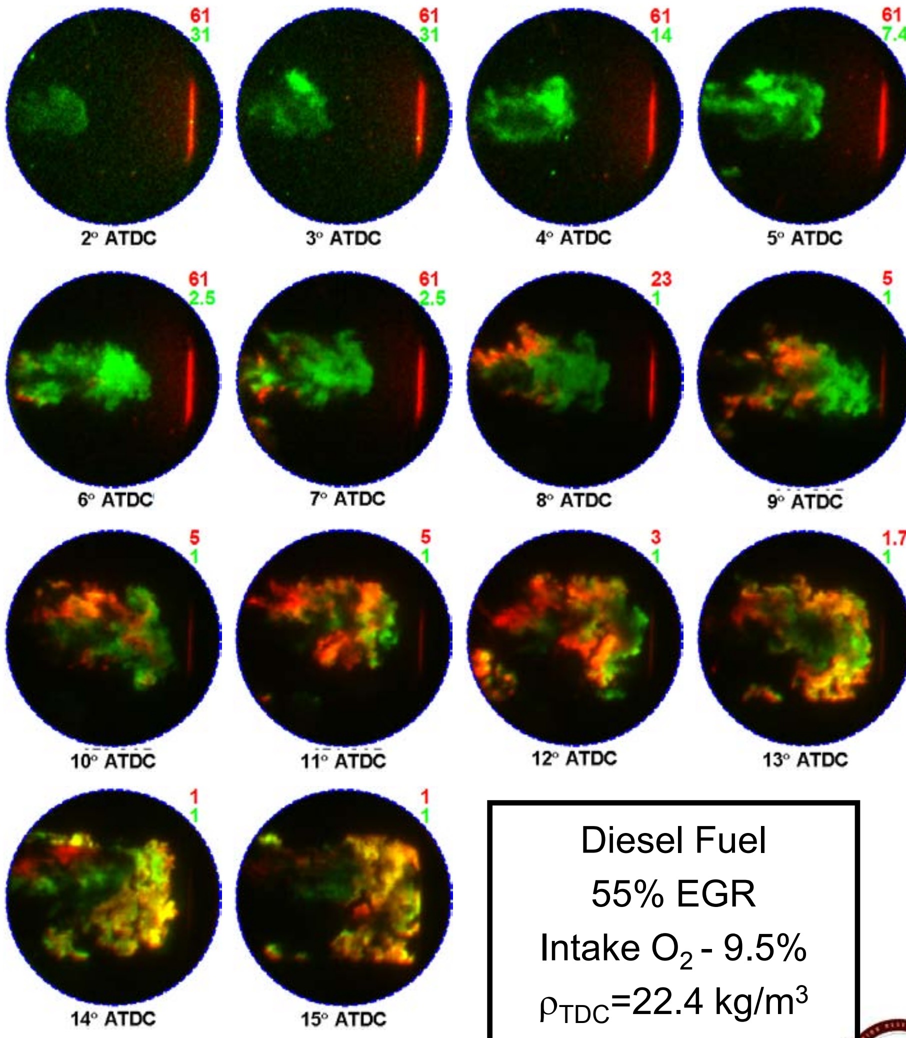


Conventional diesel soot formation is rapid, consistent with Dec's conceptual model (no EGR, high temp. combustion)

① LTC diesel: 532 signals precede 1064-nm LII by several CAD - slow soot formation (cooler)

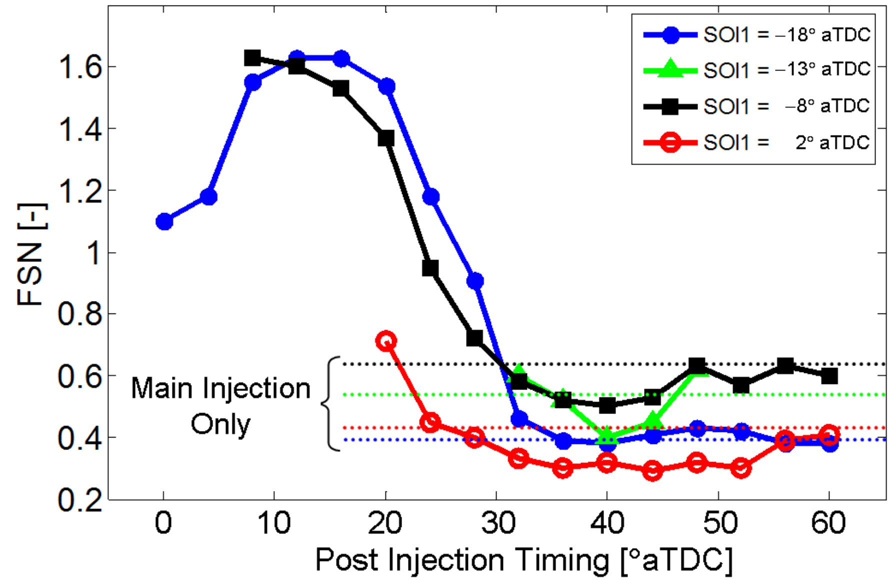
- For high-EGR (55%) LTC diesel, 532 & 1064-nm signals are markedly different
  - At premixed burn, 532-nm signal (green) appears at jet head
  - 532-nm signal grows for 4-5 CAD without any 1064-nm LII (red)
  - 1064-nm LII (soot, red) appears upstream, 532-nm downstream
  - 1064-nm LII (soot) propagates for 7-8 CAD to fill downstream jet

LTC (high EGR) soot formation is slower, with extended synthesis of (probable) large PAH that appear in exhaust PM



② Some uncertainty remains for in-cylinder soot reduction mechanisms of post-injections

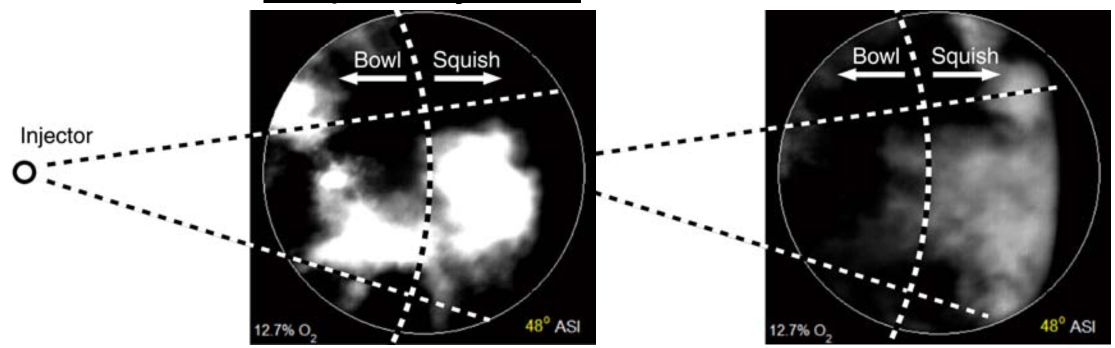
- Last year: Late post-injections reduce exhaust soot most efficiently for later main injections
- 2-color technique: In-cylinder soot in squish region is reduced, but some uncertainties:
  - 2-color soot temperature bias (is cold soot “invisible”?)
  - Is soot oxidation enhanced or is soot formation reduced?



This year: Add laser diagnostics to reduce temperature uncertainty and explore oxidation mechanisms

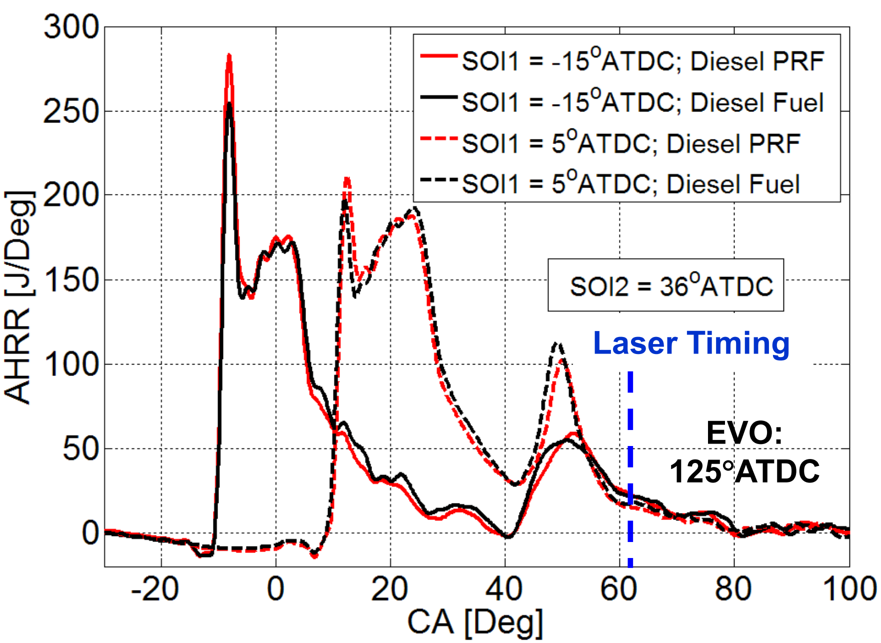
No post-injection

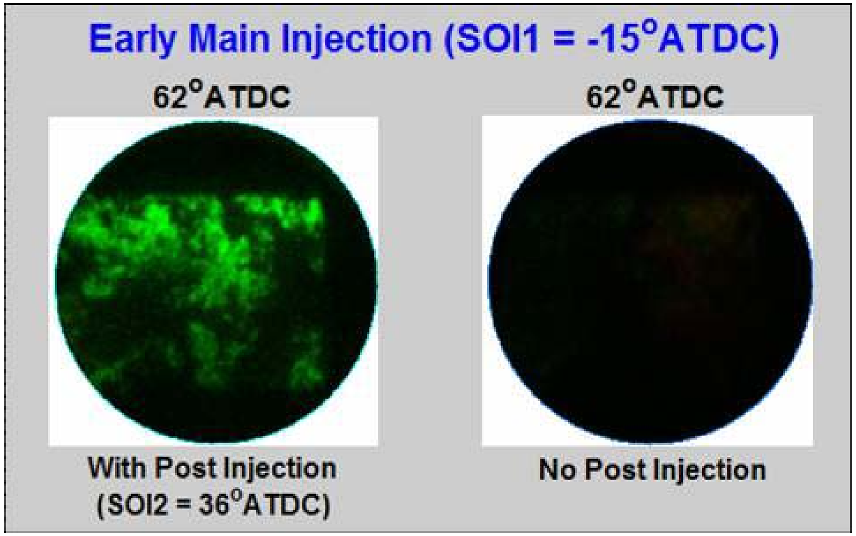
With post-injection

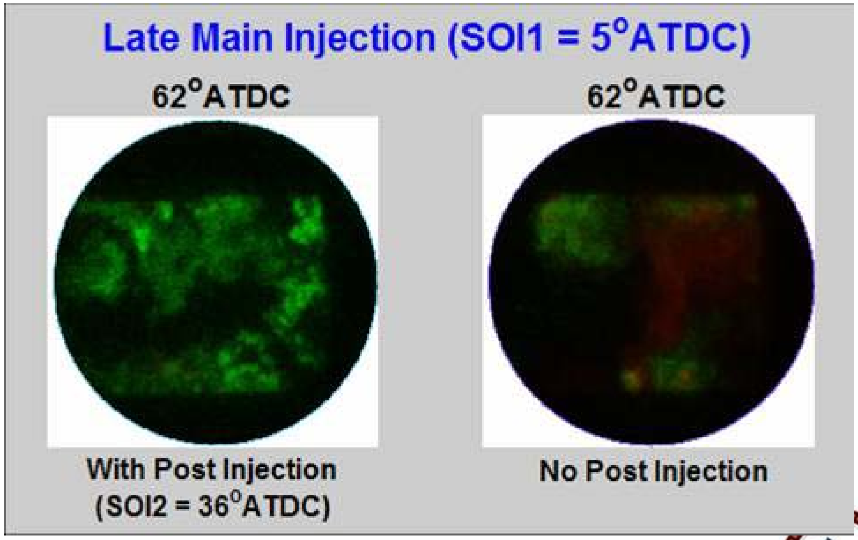


② Late main injection has accessible squish-soot for post-injection interaction (spray targeting)

- Early main injection: no soot (LII, red) in squish region (spray targeting)
  - Post inj. increases OH (green), but no soot to oxidize
- Late main inj.: more squish soot (red)
  - Post inj. increases OH (green) and decreases soot (red).





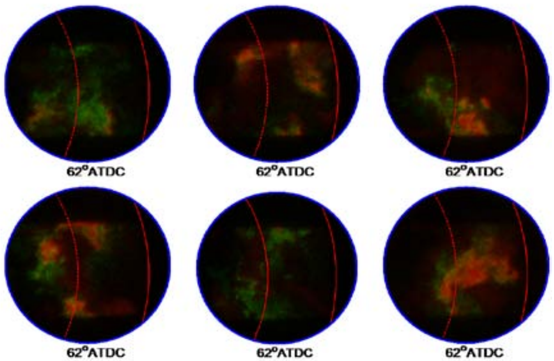


② Post injection generates late-cycle OH in squish region to oxidize soot

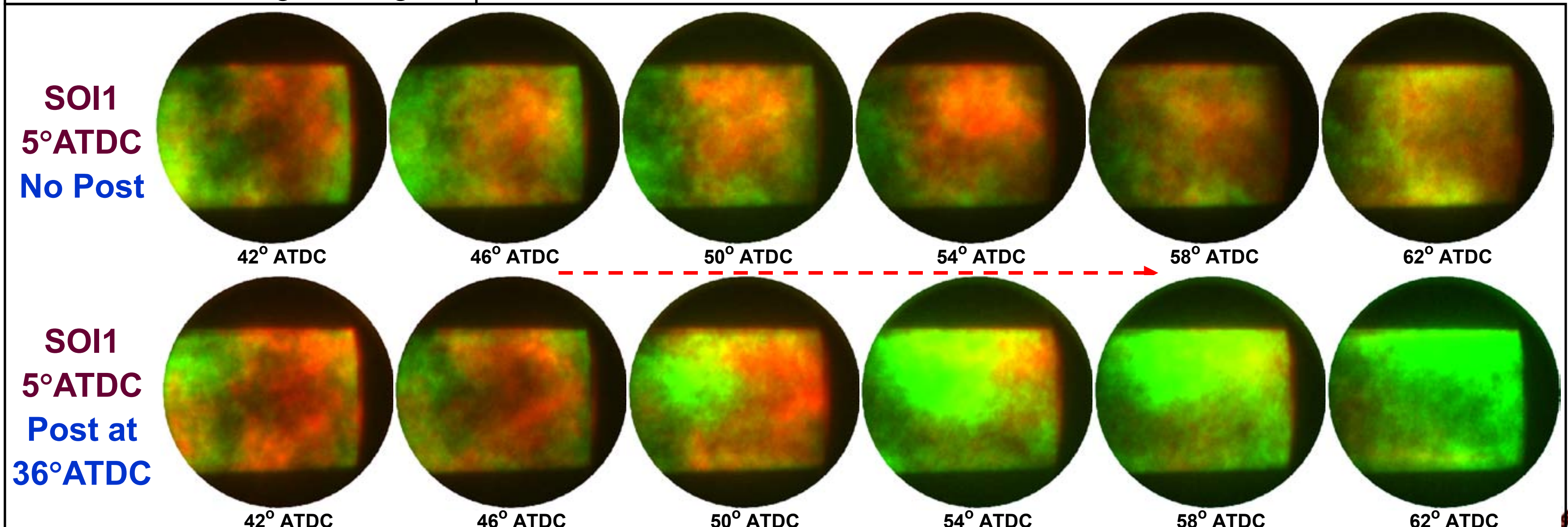
- Trends are not obvious in single-shot images (soot and OH distributions are stochastic)
- Ensemble-averaging reveals general behavior
- Without post injection, soot (red) generally persists late in cycle while OH (green) generally decreases
- With post injection, oxidizing OH increases markedly, while squish-soot decreases (most likely oxidation)

Single-shot images

SOI1 = 2°ATDC, No post-injection

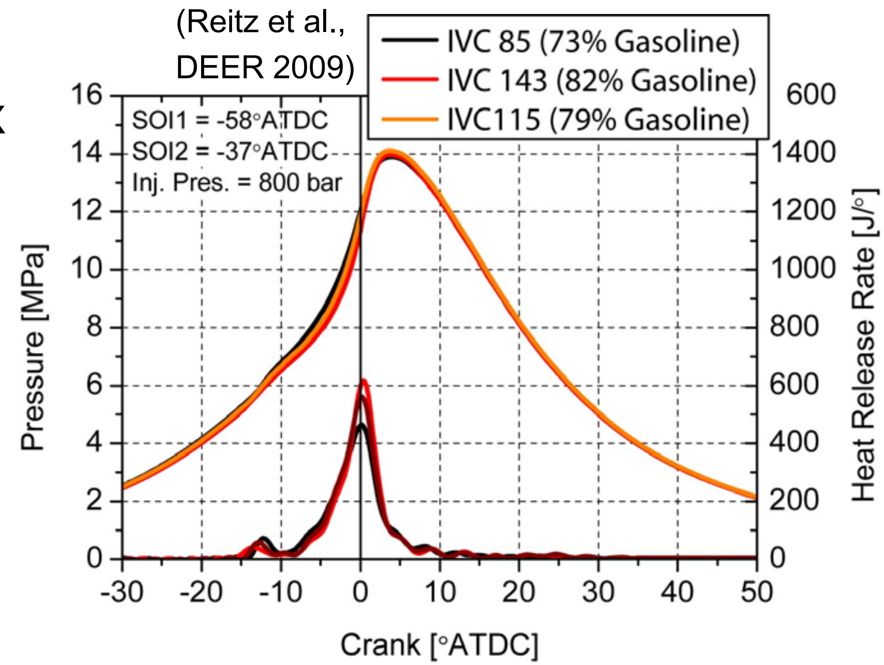


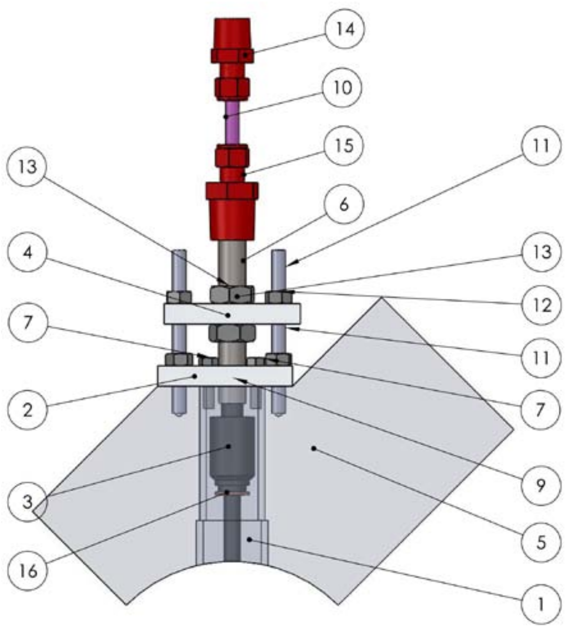
Ensemble-averaged images



③ Developing new GDI system to expand capabilities to dual fuels, premixed charge

- U. Wisc. (Reitz et al.) has shown mid-load η_{th}> 50% at 2010 PM/NOx in-cyl. with dual-fuel gasoline/diesel
- Presents both a modeling challenge and a diagnostic opportunity
  - Both distributed autoignition and flame propagation are possible.

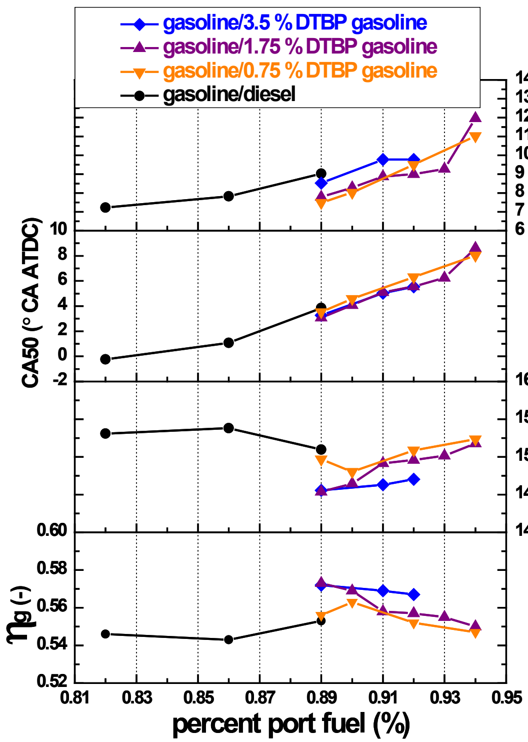


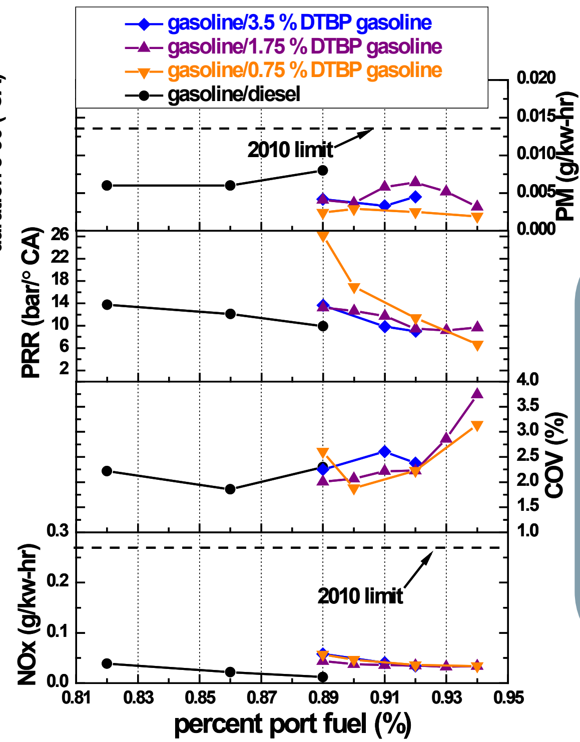


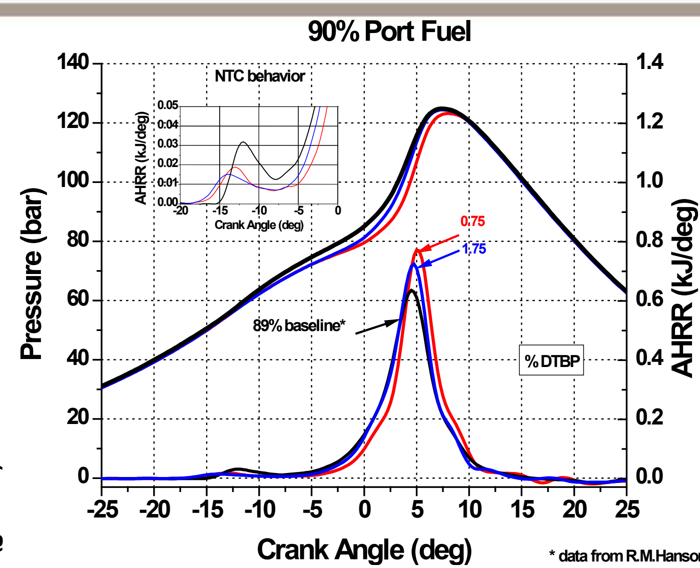
- Design of side-injector in optical engine for gasoline fuels completed, fabrication underway
- UW modeling student (Sage Kokjohn) to visit Sandia 6-9 months in FY2010/11
  - Optical diagnostic study of flame propagation / autoignition to improve model fidelity

③ Various dual-fuel/injection combinations give controllable high efficiency with low emissions

- Fuel/injection opportunities other than port/DI gasoline and DI diesel also exist
- Port-injection gasoline with GDI of gasoline+DTBP cetane improver has similar efficiency & emissions



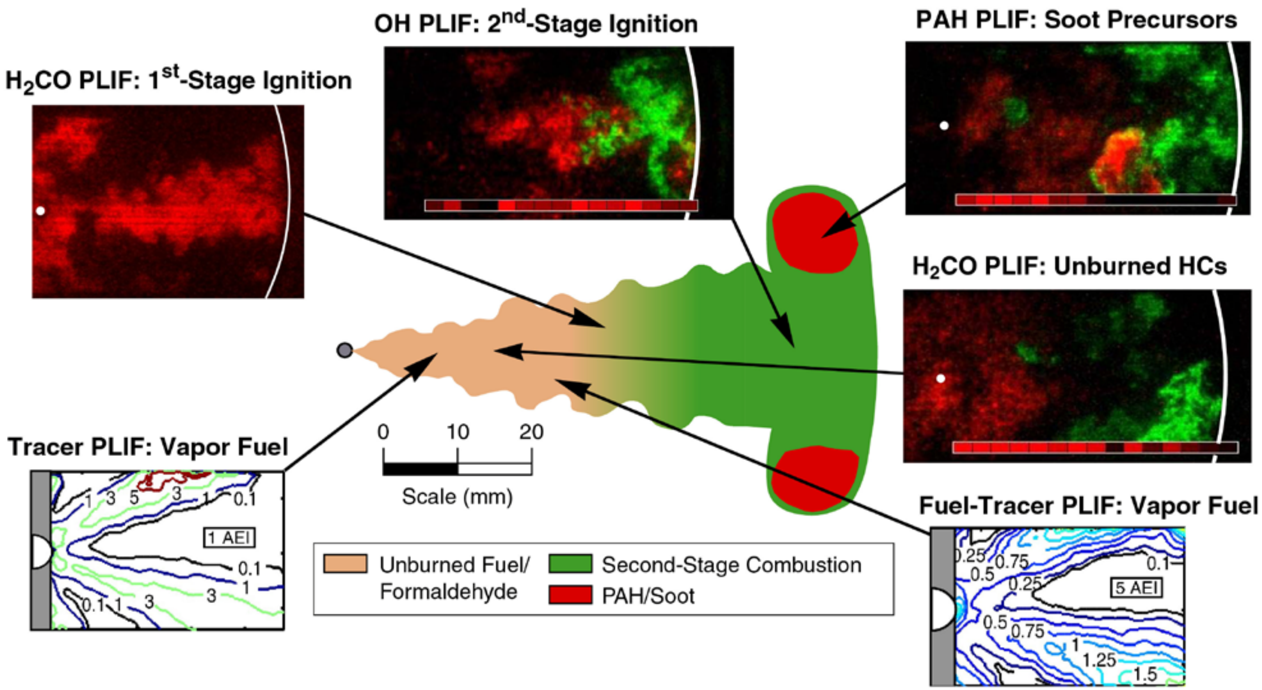




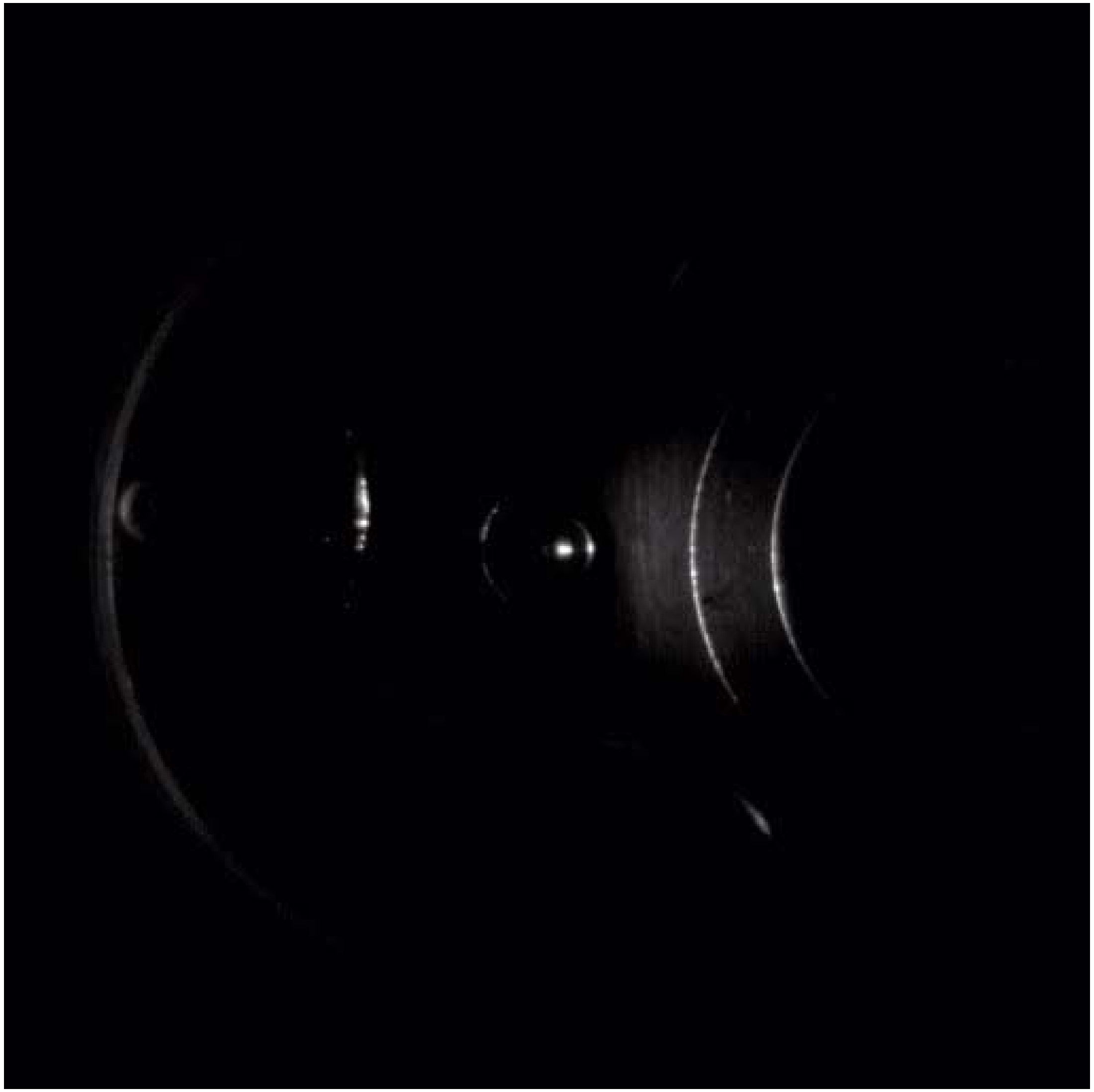
Practical dual-fuel experiments at UW provide database for design of optical engine diagnostic experiments to improve models

④ Can post-injections help to oxidize UHC in over-lean near-injector regions?

- Previous Years: Increased mixing after the end of injection can create over-lean mixtures near the injector that do not achieve complete combustion and lead to UHC emissions
  - Is it possible to oxidize UCH with post-injection?
- Student (Chartier) visit from Lund Univ. = opportunity to jump ahead to 2011 task and study post-injection effects on UHC
- (Still time for narrow-angle post-injection effects on bowl-soot in 2010)



④ Single-injection LTC condition: no combustion luminosity in center of chamber (UHCs)



Movie: Liquid Fuel + Combustion Luminosity

Single Injection
3 bar IMEP
Fuel: CN 42.5 Diesel PRF (nC_{16} + iso-C_{16})
SOI: -5 ATDC
Intake O_2: 12.7%

- Previous laser diag. of similar condition show late-cycle UHC in center of chamber
  - No combustion luminosity in center of chamber

④ Single-injection LTC condition: no combustion luminosity in center of chamber (UHCs)

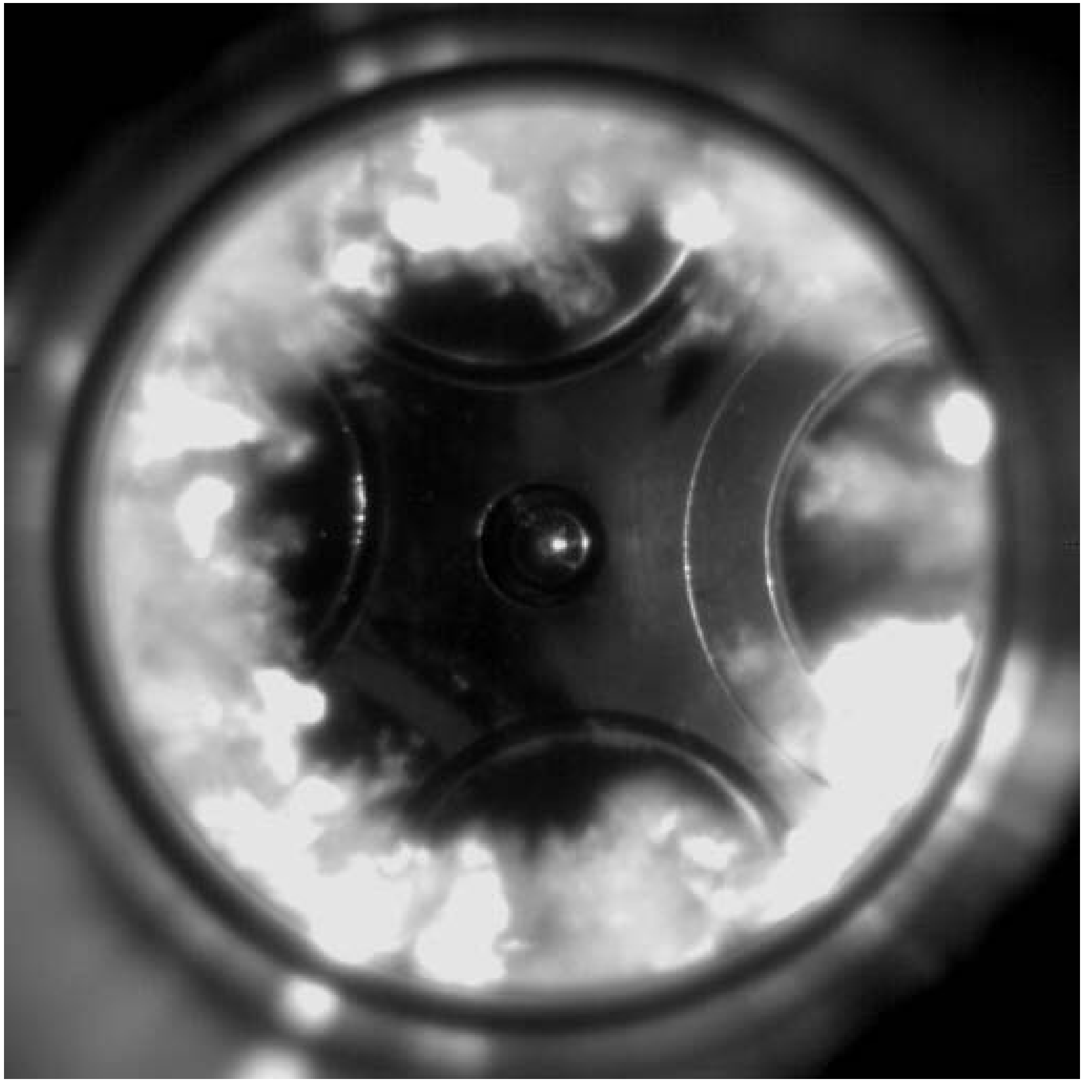


Image: 10ATDC
Combustion Luminosity

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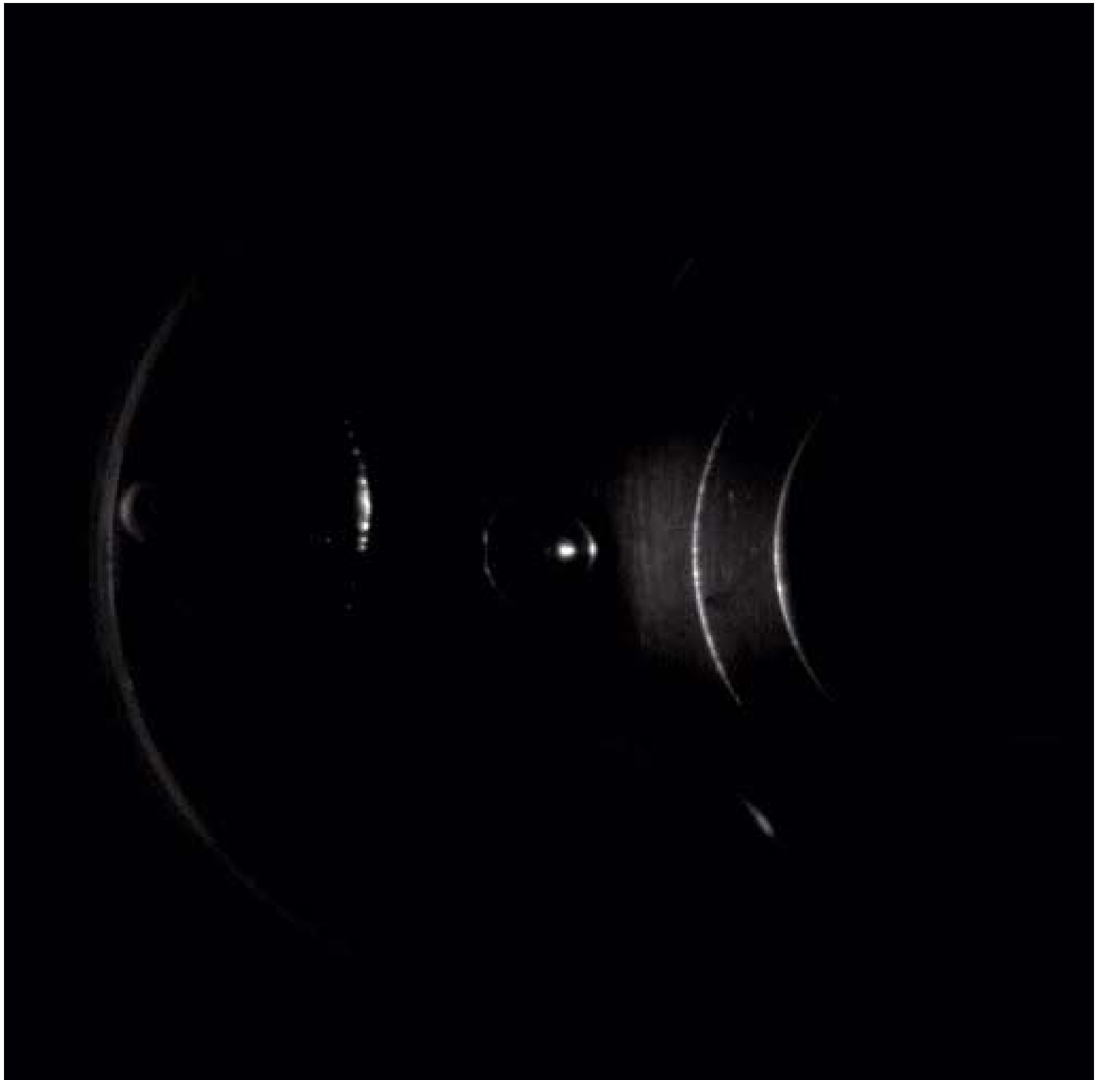
④ Post-injection LTC condition: combustion luminosity appears in center of chamber



Movie: Liquid Fuel + Combustion Luminosity

Single+Post Injection

SOI: -5, +3 ATDC

3 bar IMEP (same as single)

Fuel: CN 42.5 Diesel PRF (nC_{16} + iso-C_{16})

Intake O_2: 12.7%

- At same load, tiny post-injection decreases exhaust UHC by 15-25%
  - Strong combustion luminosity near center of chamber
  - UHC oxidation?

④ Post-injection LTC condition: combustion luminosity appears in center of chamber

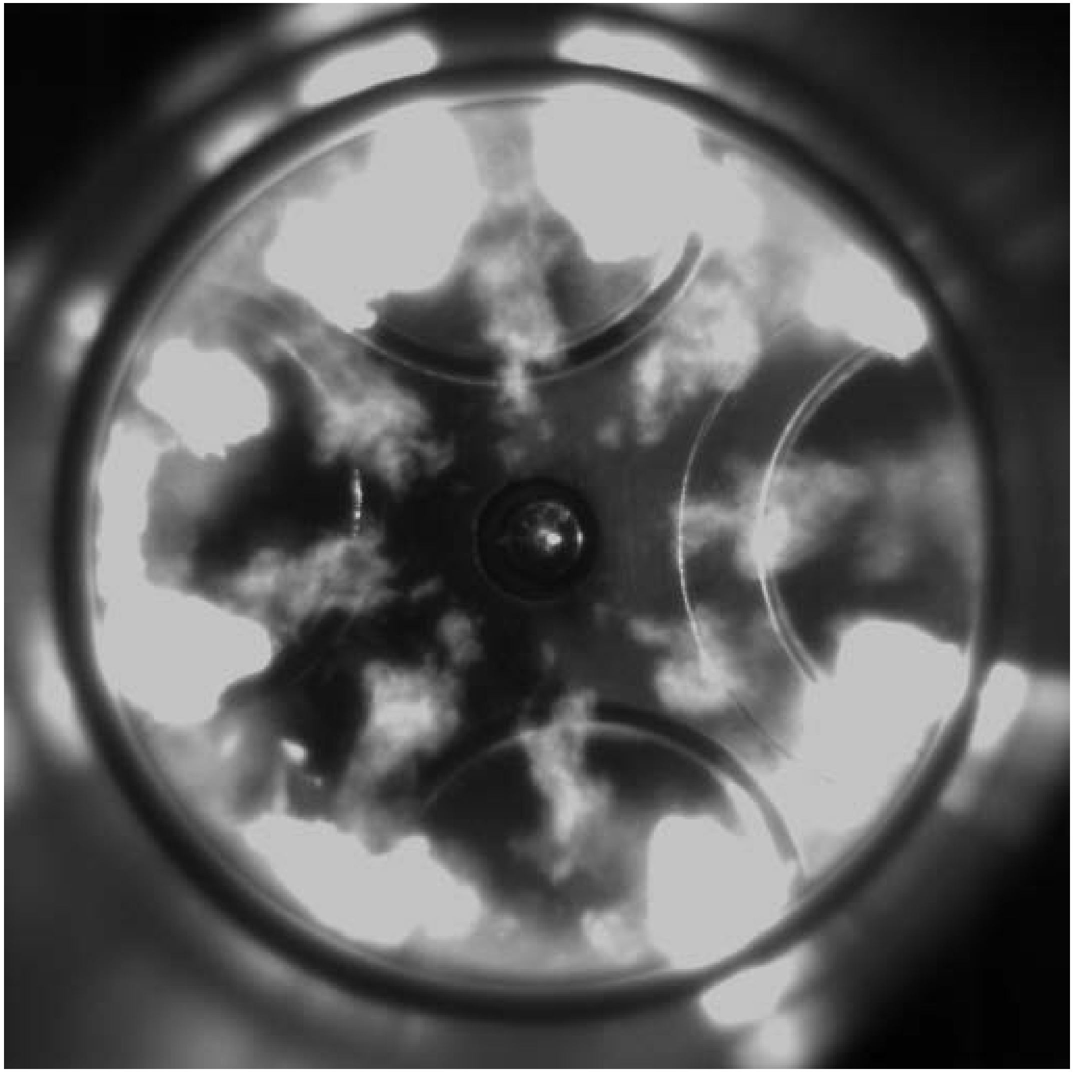


Image: 10ATDC
Combustion Luminosity

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  - Strong combustion luminosity near center of chamber
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Future Plans: Post injections, LTC soot studies, and experiments+modeling of dual fuels

- Explore UHC reduction by post-injections in greater depth
  - Quantify UHC improvements across parameter space to identify critical requirements for operating condition and post injection
  - Use laser diagnostics (fuel-tracer, formaldehyde, and OH PLIF) to understand UHC oxidation mechanisms of post-injections
- Build understanding of in-cylinder LTC soot and PAH
  - Use multiple laser wavelengths and high-temporal-resolution imaging/spectroscopy to track PAH growth and conversion to soot
- Probe in-cylinder mixing and combustion processes and improve modeling for high-efficiency dual-fuel operation
  - Use laser/optical diagnostics to discern flame propagation from distributed autoignition and define conditions that govern transitions from one combustion regime to the other
  - Incorporate insight and validation data from optical experiments to improve model fidelity

Heavy-Duty Combustion and Modeling Summary

Recent research efforts provide improved understanding of in-cylinder LTC spray, combustion, and pollutant-formation processes required by industry to build cleaner, more efficient, heavy-duty engines

1. (SNL) LTC conditions have a distinct period of large PAH formation with much slower soot formation
2. (SNL) Late post-injections can generate OH to oxidize main-injection soot, but spray targeting is important
3. (SNL+UW) Optical engine hardware mods. for dual-fueling underway, student experiment/modeling visit to follow
4. (UW+SNL) Building on previous work, post-injections can help to oxidize UHC from over-lean near-injector regions