ACE001: Heavy-Duty Low-Temperature and Diesel Combustion & Heavy-Duty Combustion Modeling

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FY 2015 DOE Vehicle Technologies Program Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
11:00 – 11:30 AM, Tuesday, June 9, 2015

Sponsor:	**U.S. Dept. of Energy, Office of Vehicle Technologies**
Program Manager:	**Leo Breton, Gurpreet Singh**

ACE001

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Overview: Heavy-duty combustion project

Timeline

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

Barriers

From DOE VTP Multi-Year Program Plan 2011–2015:

•2.3.A: Lack of fundamental knowledge of advanced engine combustion regimes

•2.3.B: Lack of cost-effective emission control

•2.3.C: Lack of modeling capability for combustion and emission control

Budget

- Project funded by DOE/VTP:
  FY14-SNL/UW: $710k/115k
  FY15-SNL/UW: $735k/99k

Partners

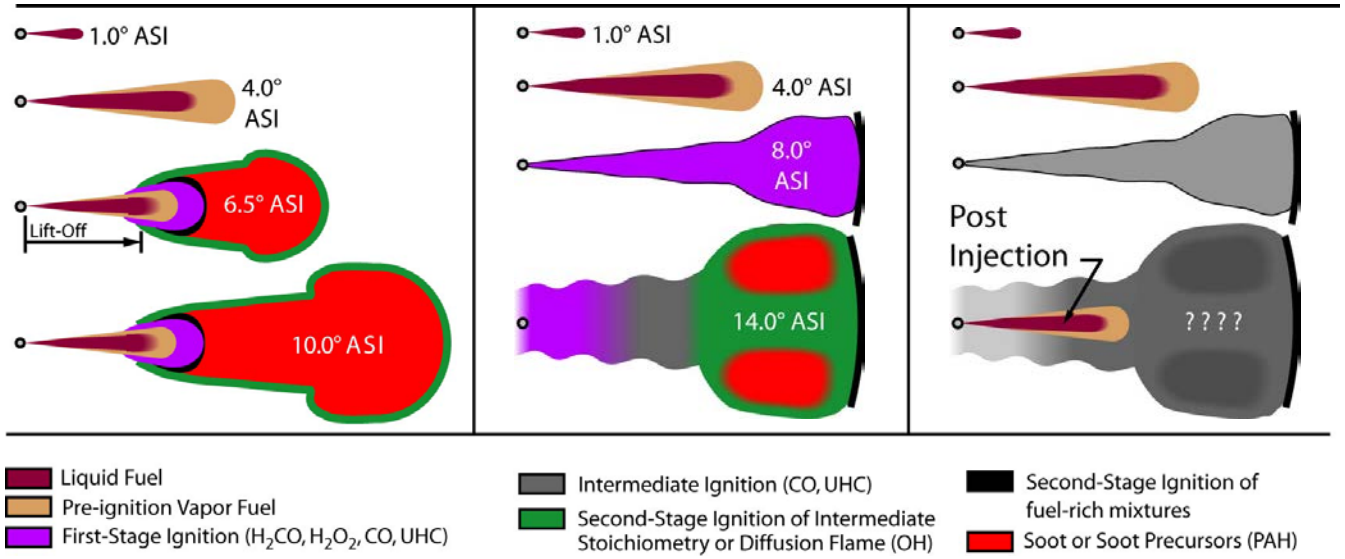
- University of Wisconsin, Delphi, Cummins, Convergent Science
- 15 industry partners in the AEC MOU
- Project lead: Sandia (Musculus)

Relevance/Objectives: HD In-Cylinder Combustion

Long-Term Objective

Develop the science base of in-cylinder spray, combustion, and pollutant-formation processes for both conventional diesel and LTC that industry needs to design and build cleaner, more efficient engines

1997: **Conventional Diesel** (Single Injection) | 2012: **LTC Diesel** (Single Injection) | 2013+: **Multiple Injection** (Conventional & LTC)



Milestones/Objectives: H-D In-Cylinder Combustion

Long-Term Objective

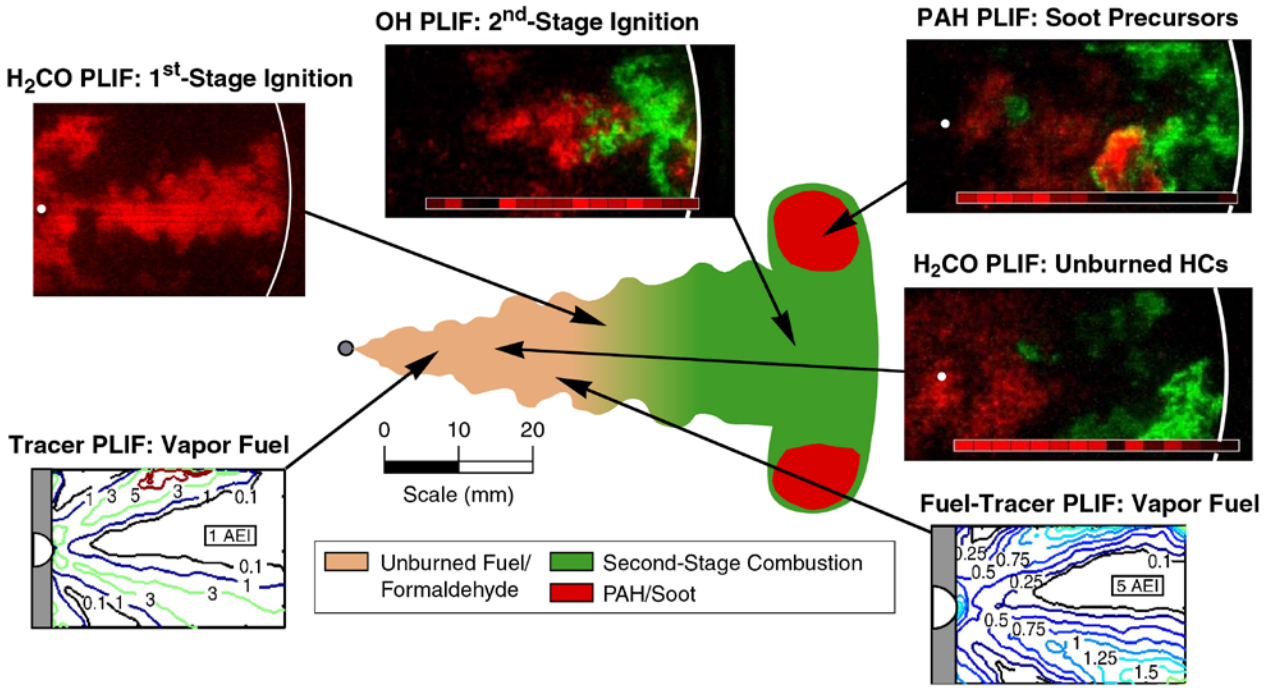
Develop the science base of in-cylinder spray, combustion, and pollutant-formation processes for both conventional diesel and LTC that industry needs to design and build cleaner, more efficient engines

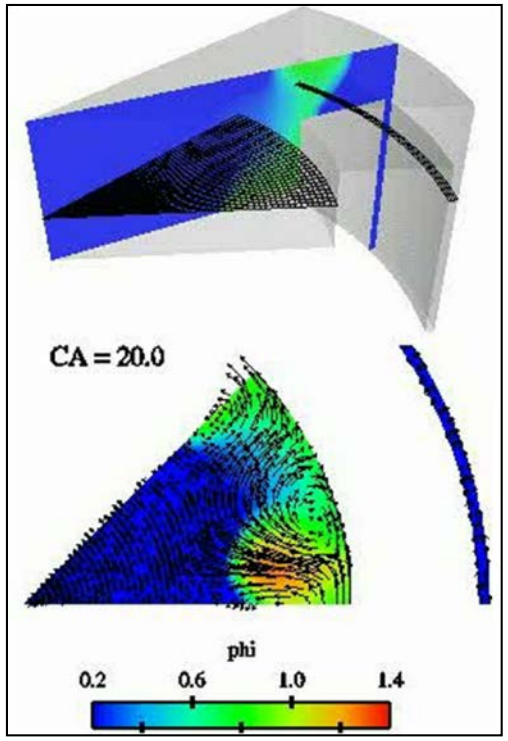
Current Milestones/Objectives:

1. SNL – Reveal fluid-mechanical processes of injection rate-shaping to control mixing
2. SNL – Provide Spray B in-cylinder engine data for ECN
3. SNL – Develop/demonstrate in-cylinder surface heat transfer diagnostic capability
4. SNL – Improve computer-model simulation/analysis tools to complement experimental measurements

Approach/Strategy: Optical imaging and CFD modeling of in-cylinder chemical/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., LTC soot precursor modeling with Cummins/Convergent Science/UW)
- Industrial/University partnerships support laboratory activities
  - FY2015: Delphi, Cummins – continued injector support
  - FY2015: Wayne State University – IR diagnostic development

Technical Accomplishments & Progress (15 slides)

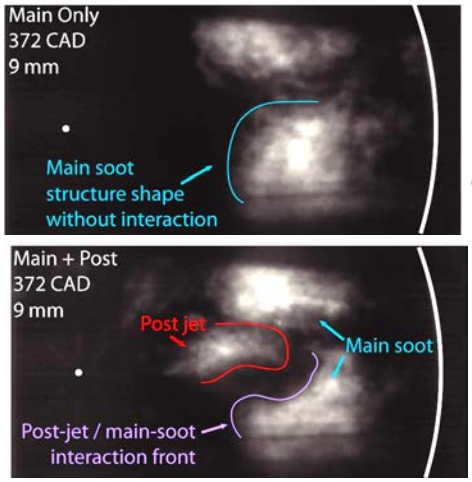
- Accomplishments for each of the four current milestones / objectives below are described in the following fifteen (15) slides

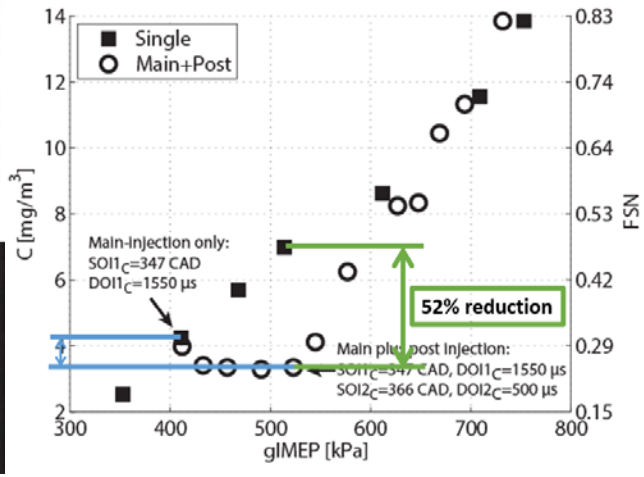
Current Milestones/Objectives:

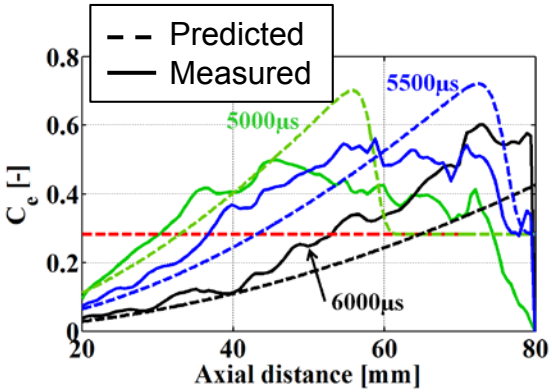
1. **SNL – Reveal fluid-mechanical processes of injection rate-shaping to control mixing**
2. **SNL – Provide Spray B in-cylinder engine data for ECN**
3. **SNL – Develop/demonstrate in-cylinder surface heat transfer diagnostic capability**
4. **SNL – Improve computer-model simulation/analysis tools to complement experimental measurements**

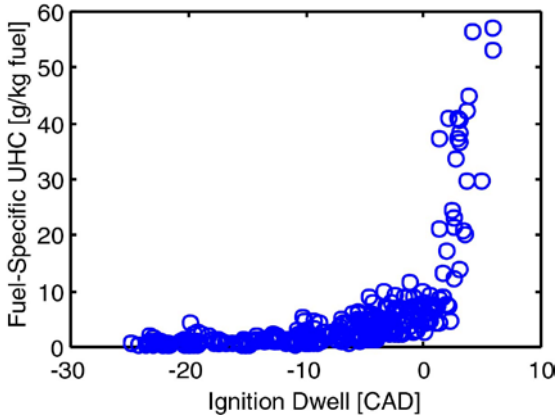
① Previous work on post- and single-injections point to importance of end-of-injection mixing

- FY13: Post-injections can reduce emissions & BSFC
- FY14: post-jet interacts with end-of-injection residual of main-injection jet
- ④ FY15: developing CFD analysis tools for insight into post-injection mechanisms
  - FY16: exp'ts to confirm
  - FY15: exp'ts on main inj.
- FY07: high UHC at long IDs for single (main) injections
  - Cause: over-mixing near injector
- FY14: PIV data confirms "entrainment wave" of increased mixing







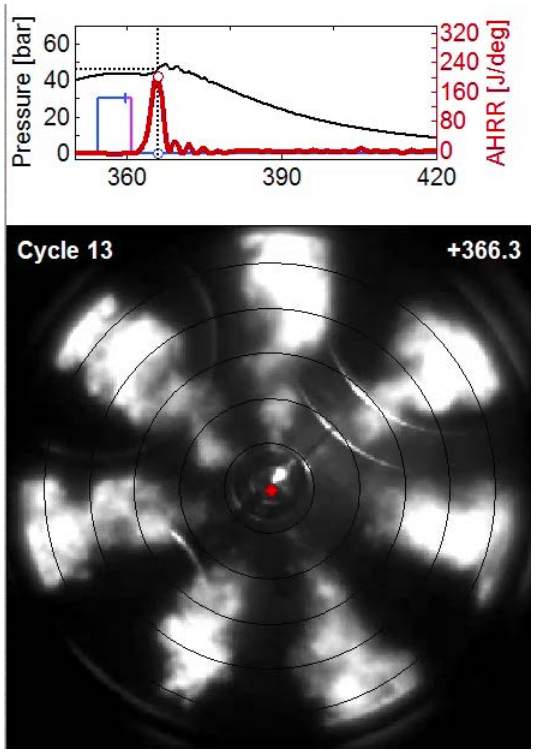


Post injections penetrate into residual mixing fields created by main injections; post-injection mechanisms depend on this residual field

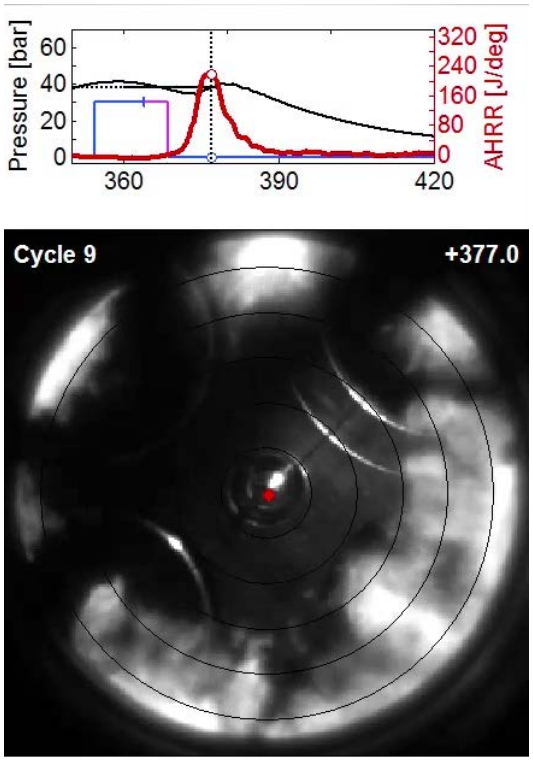
① Some conditions have gradual progression of ignition that allows higher loads at a given AHRR

- Enhanced premixing (PCI, PCCI, MK, HCCI, etc.) is interesting for reducing emissions and improving efficiency, but load is limited by peak heat-release rates (AHRR)
- Some conditions show gradual progression of ignition in the residual mixing field of the main injection, allowing higher loads at a given AHRR

800 K TDC, 1 bar gIMEP, 210 J/º peak AHRR



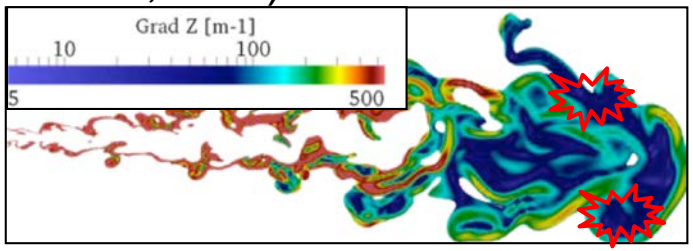
760 K TDC, 3.5 bar gIMEP, 220 J/º peak AHRR

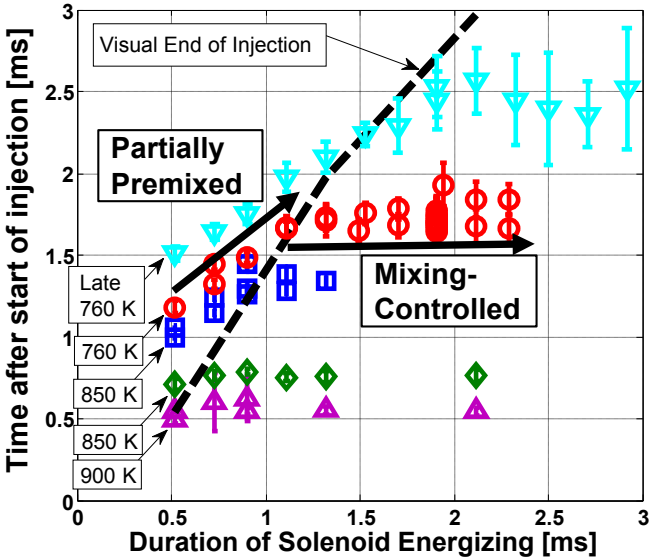


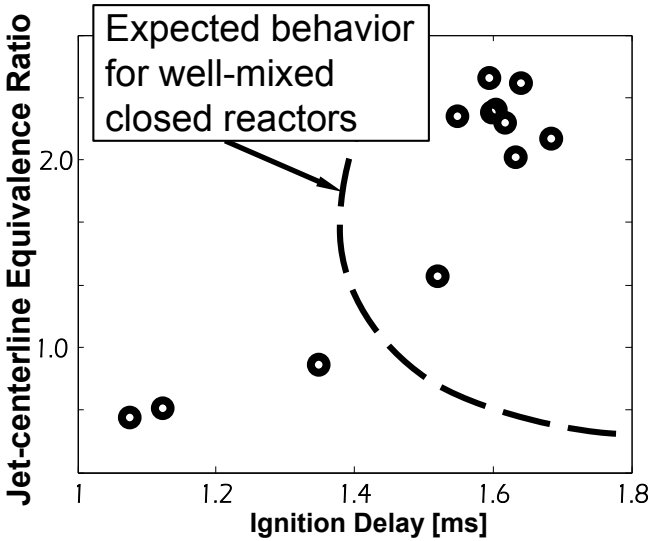
Can we tailor the mixing field created by the main injection, either for heat-release-rate control, or for better coupling with post injections?

① Partial premixing: ID increases with injection duration; can't be explained by mixture fraction

- At lower TDC temperature, ID is longer
  - For mixing controlled combustion, ignition delay is flat with injection duration
  - But, for partial premixing, increasing injection duration can delay ignition
  - Ind. partner: 2nd inj. at ignition can delay too
- Mixing correlations: igniting mixtures are richer with longer injection duration & ID
  - Counter to well-mixed ignition kinetics expectations –scalar dissipation effect?
- Simulations (Oefelein, SNL): low scalar dissipation at experimental ignition sites (Skeen, SNL)





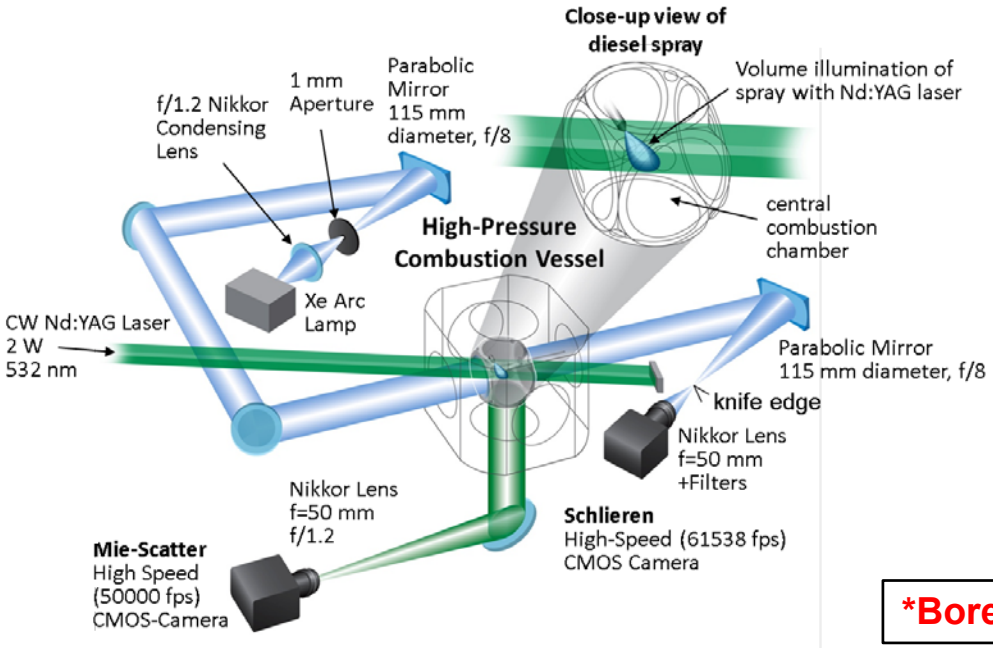


Future work: what is role of scalar dissipation with partial premixing? Can it be controlled for ignition/post-inj.?

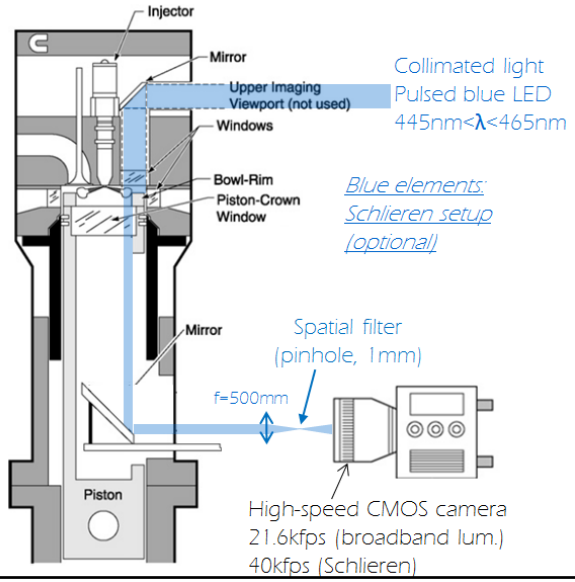
② Vapor penetration is of critical importance for ECN fuel-jet data, but requires extensive optical access

- Engine Combustion Network is a forum and database for collaboration on engine combustion
  - Initial ECN data: single-hole, constant-volume combustion vessels
  - Now adding data for multi-hole injectors and engines
  - First engines step: generate single-injection data; Next: multi-injection
- Vapor jet penetration is a critical measurement, but standard schlieren techniques require pass-through optical access

Constant volume vessel: Full pass-through optical access



Optical engine: Partial pass-through

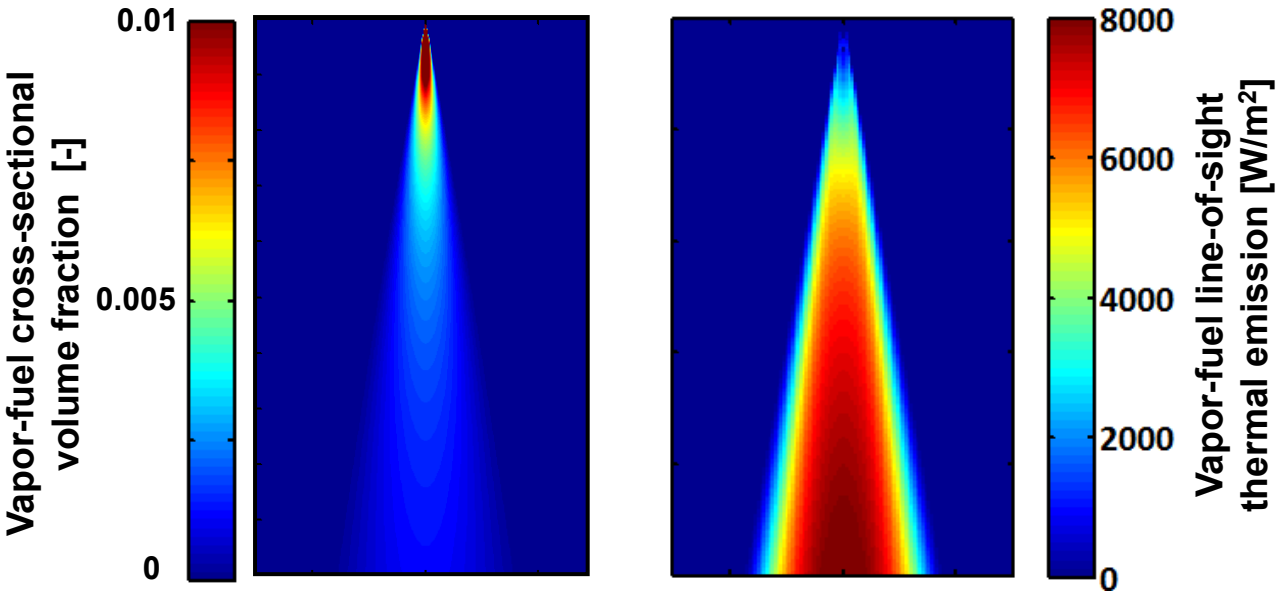


***Borescope engine: Little/no pass-through**

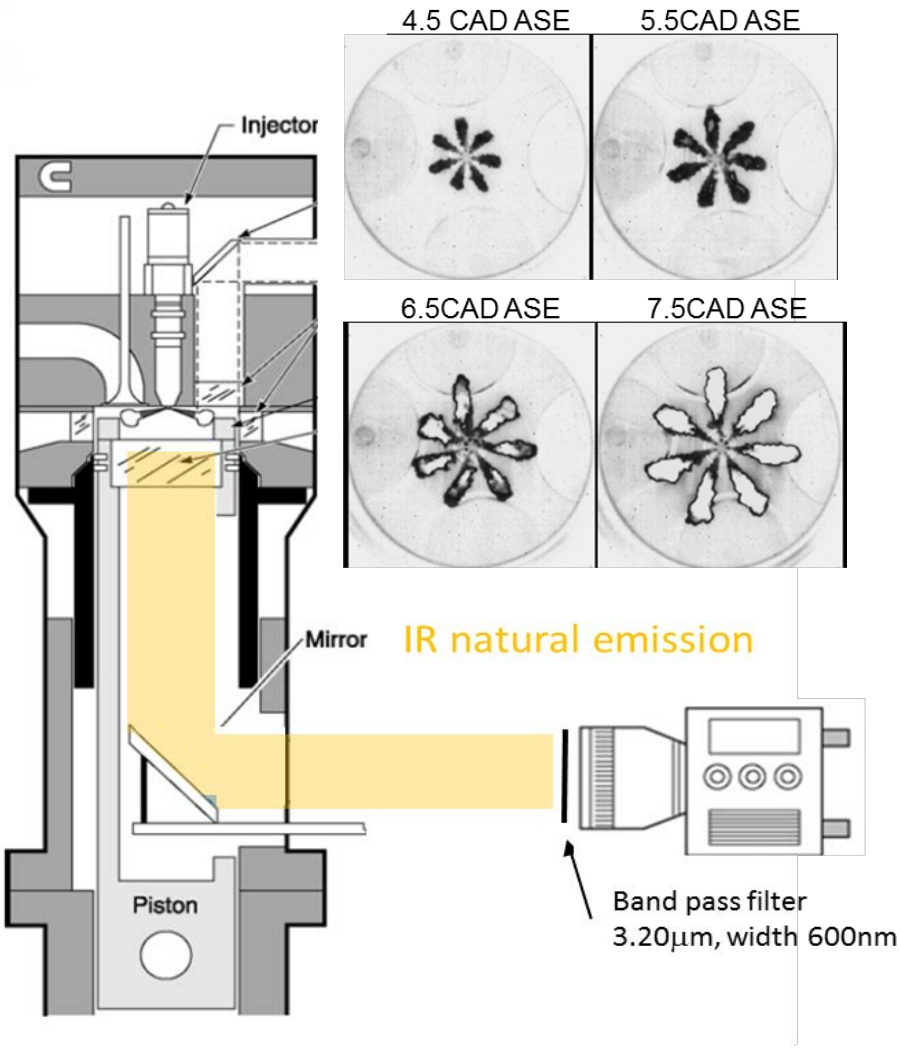
② Thermal (infrared) imaging can provide vapor-fuel penetration data with simpler optical access

- Injected fuel is quickly heated as it vaporizes and mixes with compression-heated in-cylinder gases ⇨ IR emission near 3.4 μm
- Well-established jet-mixing and absorption / emission models (e.g., soot) can predict line-of-sight thermal emission of hot fuel
  - Vapor-fuel concentration profile is diffuse, but line-of-sight and adiabatic heating effects yield sharp-edged IR emission images
- Single window/endoscope is sufficient for vapor-fuel penetration; fused silica transmits @ 3.4 μm (expensive sapphire not req'd)

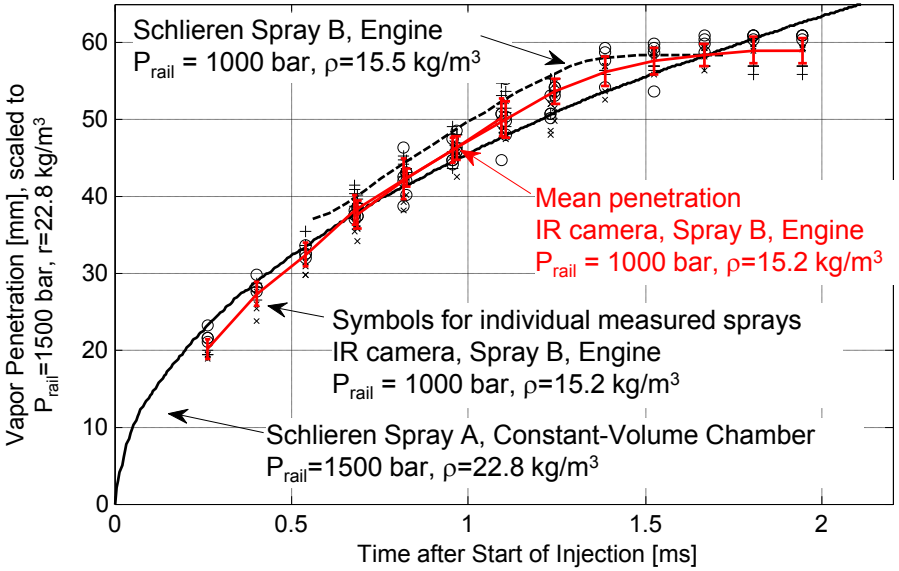
Injection of initially liquid hydrocarbon fuel into 900K ambient through 0.14 micron orifice using Naber/Siebers diesel-jet correlation and assuming adiabatic mixing



② Simple 1-camera IR penetration agrees well with schlieren; engine and chamber data comparable



- Single IR-camera setup yields well-defined vapor-jet boundaries
- IR penetration agrees with conventional pass-through schlieren measurements, and with scaled const.-vol. chamber data
- Also acquired liquid length, lift-off length, and ignition location data



③ Heat transfer is important for efficiency and/or exh. enthalpy for turbocharging/WHR, esp. LTC

- Heat transfer losses can be over 30% of input fuel energy
  - 1980's adiabatic engines using conventional combustion yielded hotter exhaust with little/no efficiency increase[1]
  - Low-temperature combustion engines can benefit much more from reduced heat transfer, both increased efficiency and higher exhaust enthalpy for turbocharging, catalysts, and/or waste heat recovery[2]
  - Post injections can improve fuel efficiency, and one mechanism may be redistribution of combustion that reduces wall heat transfer[3]
- Heat transfer models need improvement/validation data
  - Predictions from cycle-simulation heat-transfer models (e.g., Woschni) vary by an order of magnitude[4]

Heat-transfer data correlated with optical flow/combustion measurements can provide better understanding and prediction of heat transfer for conventional/LTC and/or single/multiple injections

[1]"Low heat rejection engines - an overview," S. Jaichandar and P. Tamilporai, SAE 2003-01-0405, 2003.

[2]"Thermodynamic advantages of low temperature combustion (LTC) engines using low heat rejection (LHR) concepts," J. Caton, SAE 2001-01-0312.

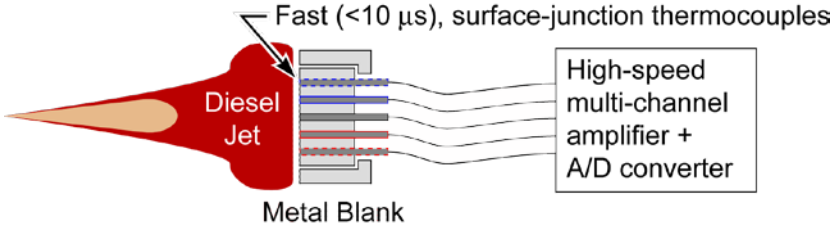
[3]" Reexamination of multiple fuel injections for improving the thermal efficiency of a heavy-dutydDiesel engine," H. Osada et al., SAE 2013-01-0909.

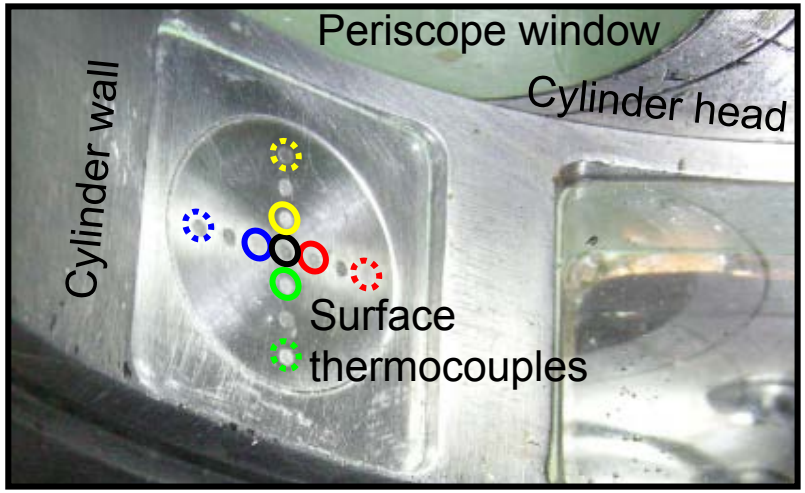
[4]"Heat transfer characteristics of conventional and high efficiency reciprocating engines," J. Caton, Paper IC10, 7th US Nat'l Comb. Meeting, 2011.

③ Two new heat transfer diagnostic developments: Conventional thermocouple and IR thermometry

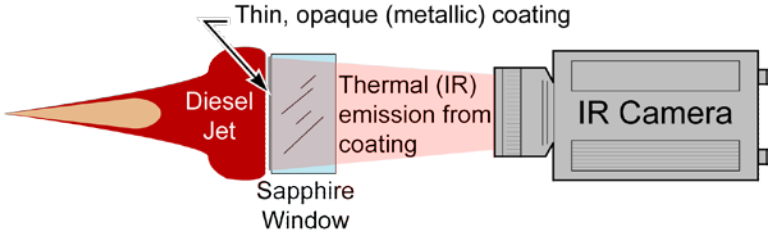
Conventional Thermocouple	IR Thermometry
Collab. w/ Terry Hendricks, Sandia NM	Collab. w/ Marcis Jansons, Wayne State

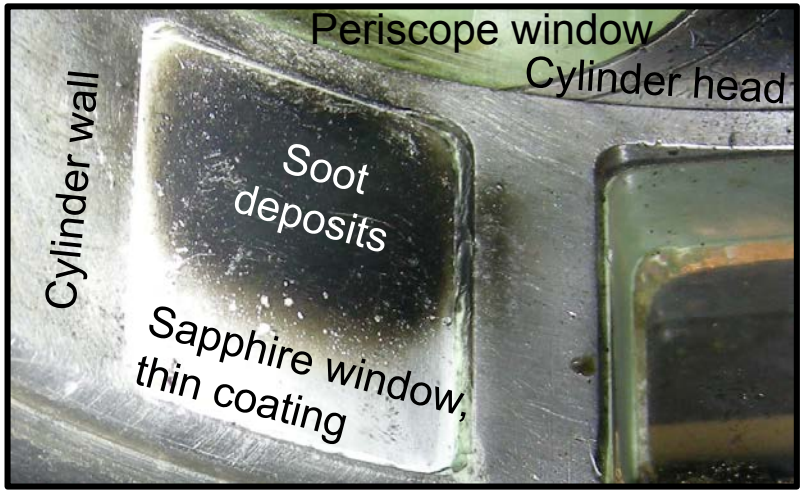
- Surface-junction thermocouple array with fast (10 μs) time response provide multiple point measurements of temperature & heat transfer





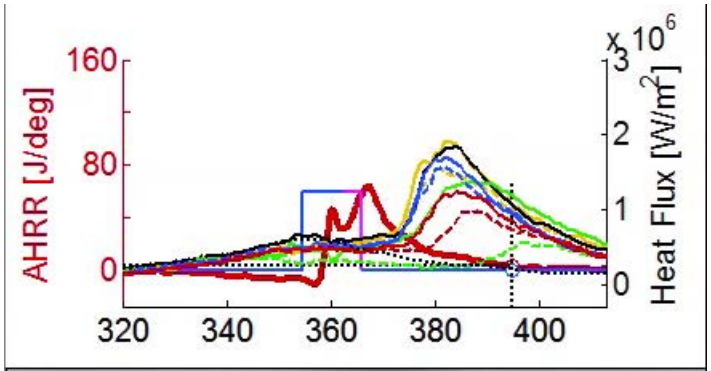
- Thin, opaque (metallic) coating on combustion side of window, IR camera views surface through window for 2-D temperature & heat transfer

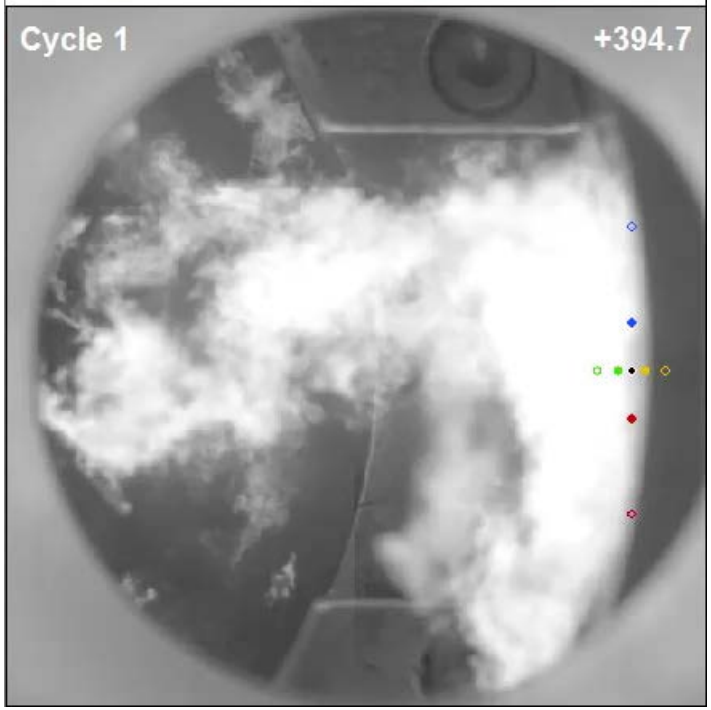


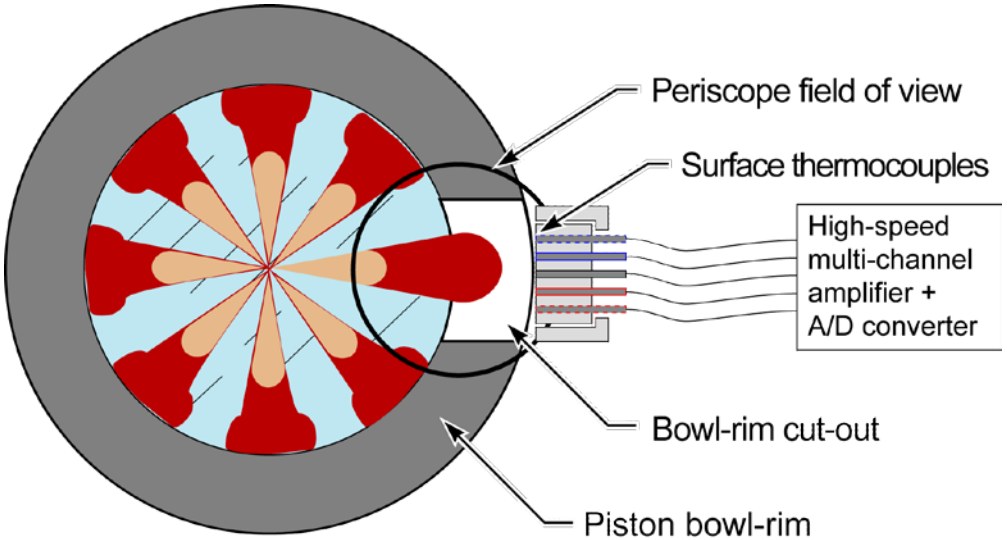


③ Preliminary thermocouple data: jet-impingent heat transfer quantified, not in phase w/ cyl. pressure

- Initial wall heat flux measurements use piston bowl-rim cut-out to allow jet to impinge on cylinder wall, with simultaneous combustion imaging
  - Multiple thermocouples quantify heat transfer at jet arrival, not in phase with cylinder press. (contrast to Woschni)

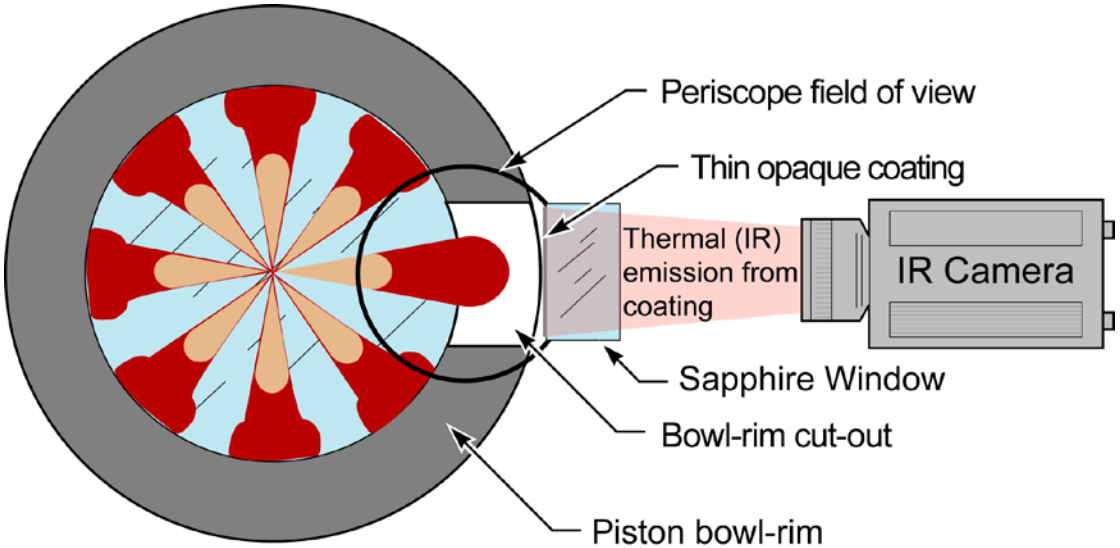


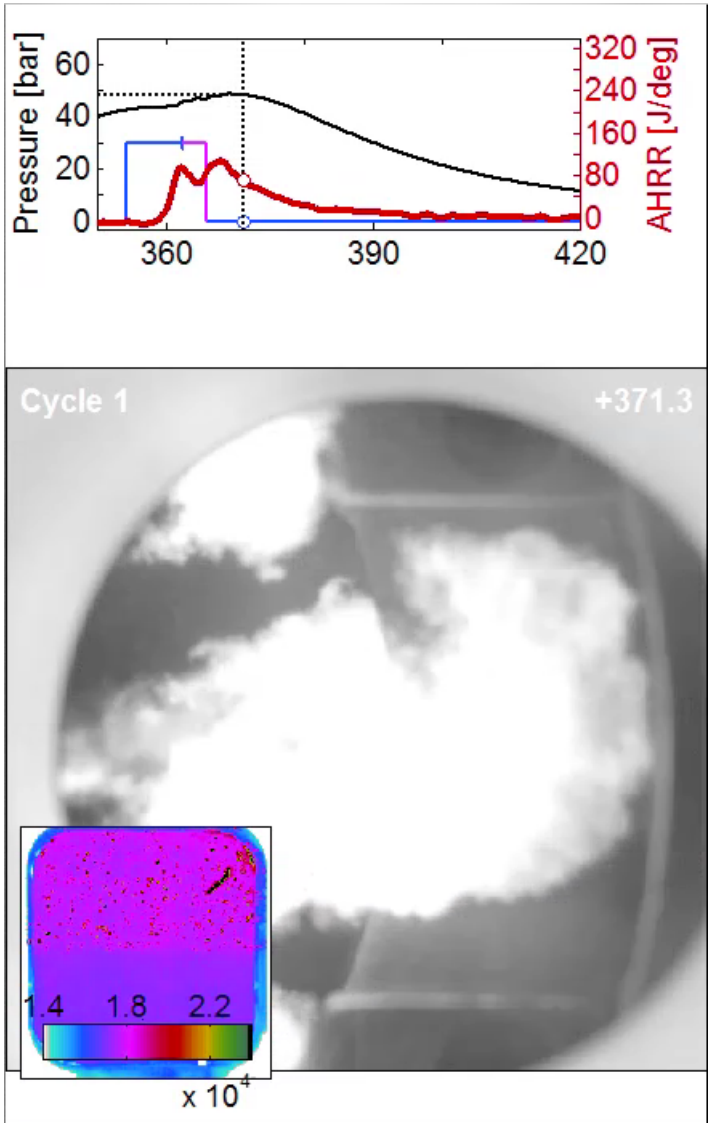




③ Preliminary IR thermometry data: sufficient signal, but pinholes in coating; needs more development

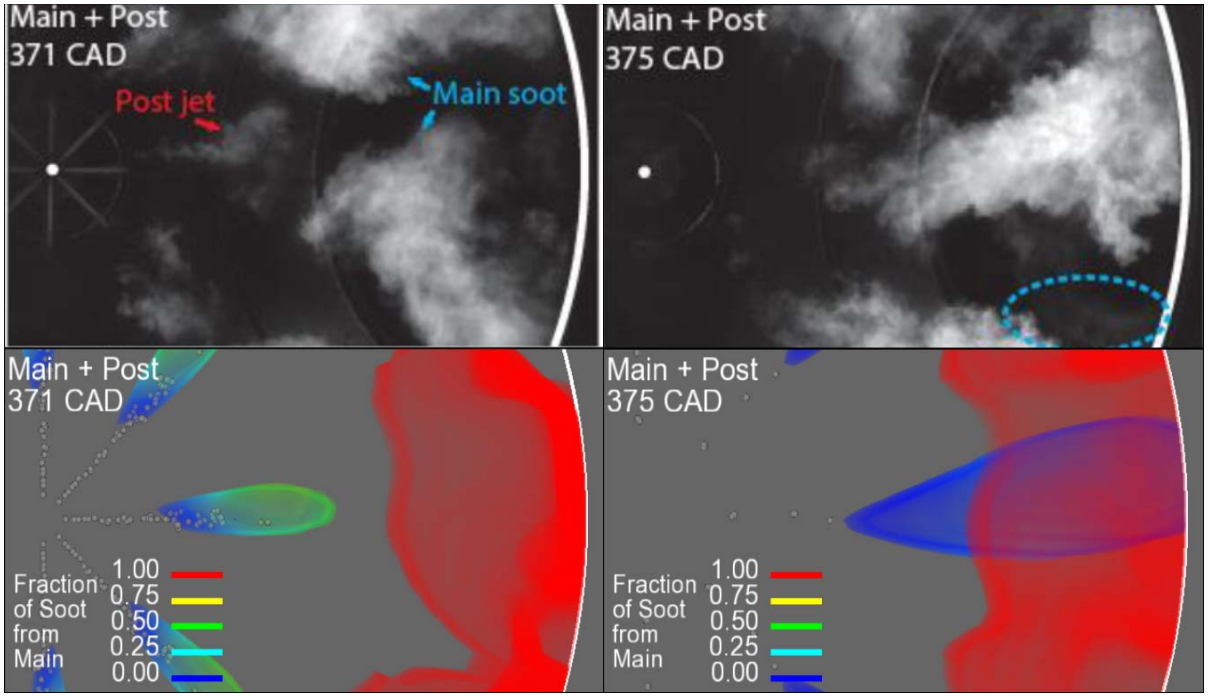
- Initial IR imaging: signal is strong even with fast exposure (10 μs)
  - Good S/N even before jet impingement on the window
- Many pinholes in coating transmit IR emission from combustion
  - More development needed to maintain adhesion (thin) and opacity (thick)



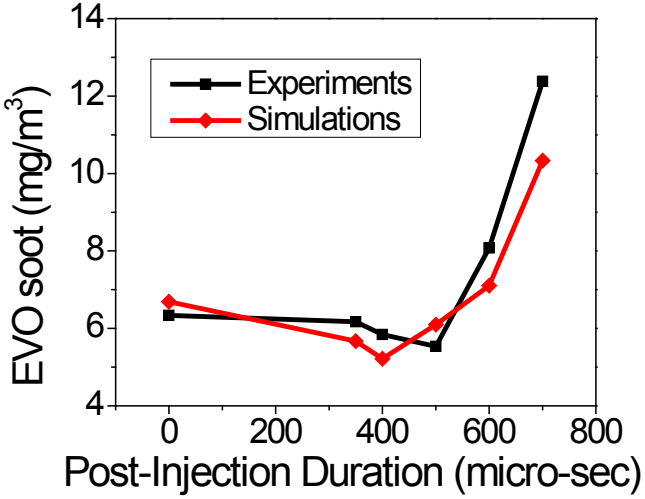


④ Satisfactory agreement between model and exp't soot distributions supports analysis of predictions

- Model-predicted spatial and temporal distributions of soot agree well with experimental images of luminous soot and measured engine-out soot
  - Appearance of post-injection soot is timed well (U. Wisc., R. Hessel)
  - Model captures interaction with residual main-injection soot and reduction of engine-out soot (U. of Wisconsin, Zongyu Yue)



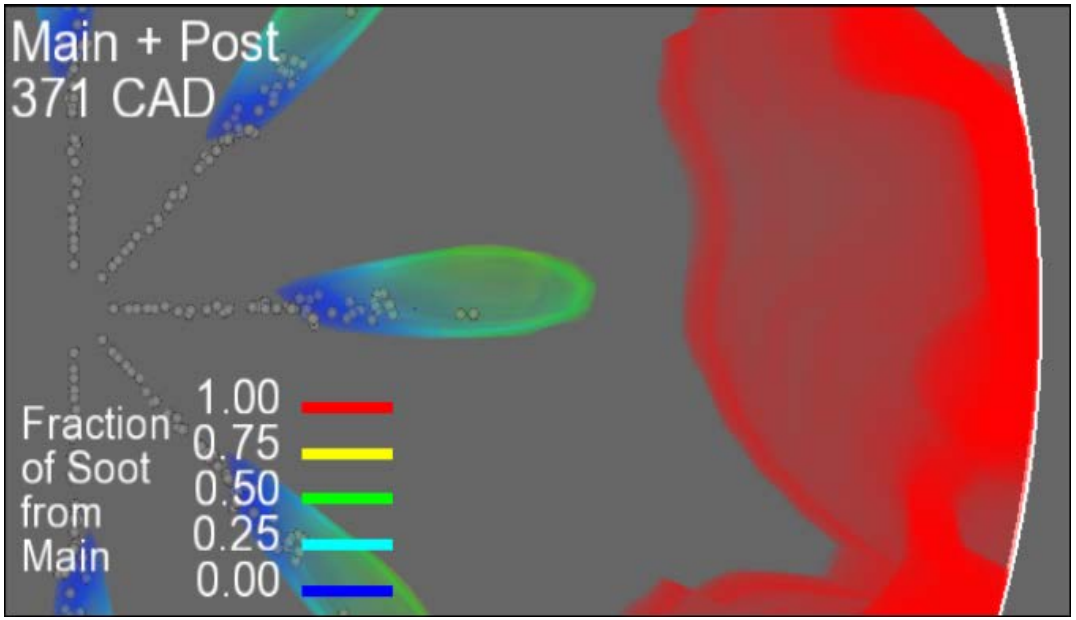
*Images from characteristic time combustion model with 2-step soot model (Hessel)



*Engine-out soot predictions from detailed chemistry combustion model with semi-detailed soot model (Yue)

④ In exp'ts, difficult to separate soot formation/ oxidation, main/post soot ⇨ analyze model results

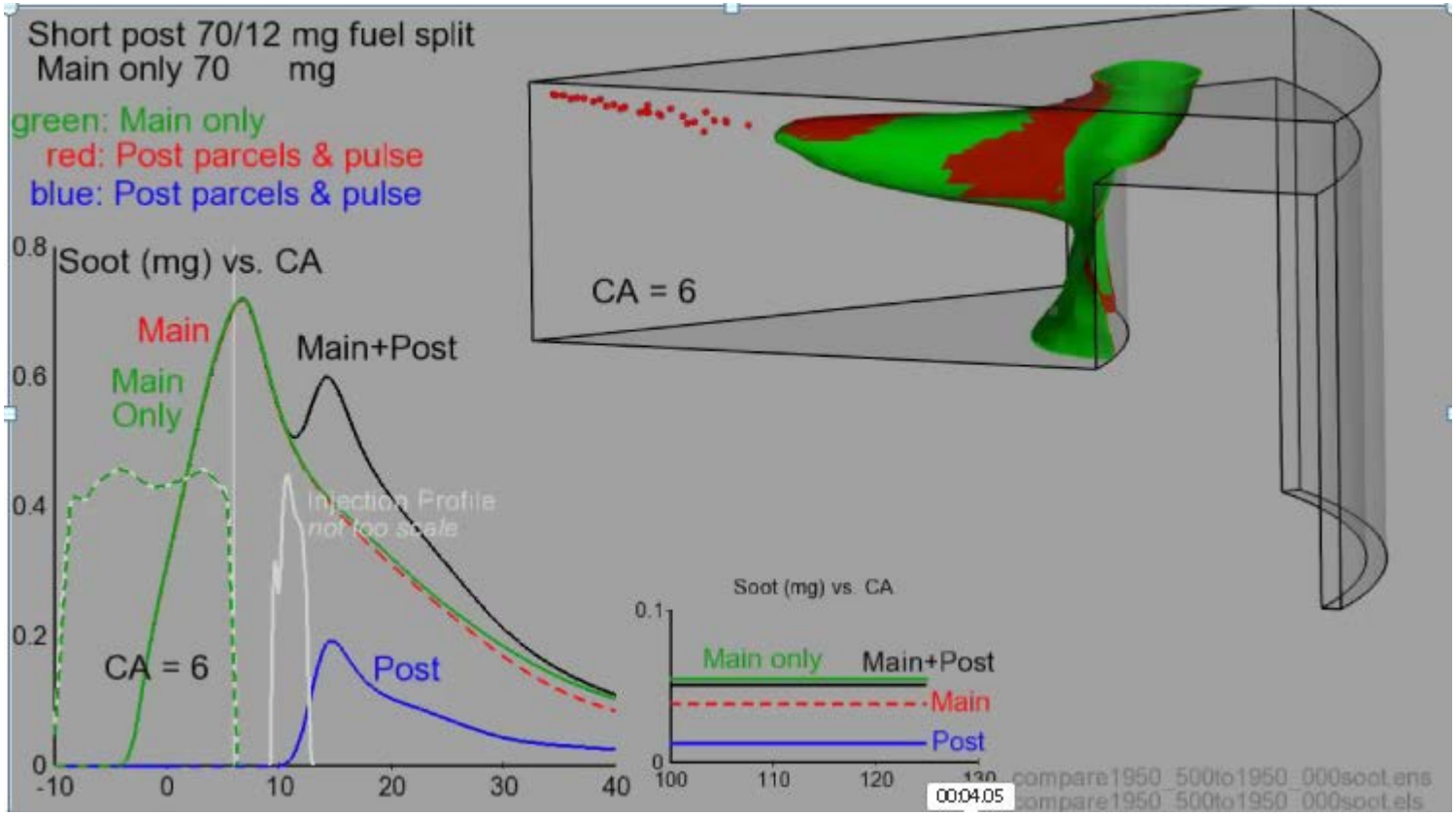
- Experiments can reveal total soot, but formation/oxidation rates are hard to separate, but models can help (FY14 report, or SAE 2014-01-1256)
- Also need model to discriminate soot contributions of main- and post-fuel
- Main- and post-injected fuel in the model can be tagged and tracked separately to quantify their contributions to the total in-cylinder soot
- Rendering shows predicted soot, color coded according to the carbon source, either main (red) or post (blue) injected fuel
- Post-soot forms partly from residual main fuel (blue + red = green)



Can 3-D analysis of the model predictions provide insight into the mechanisms by which the post-injection affects main-injection soot?

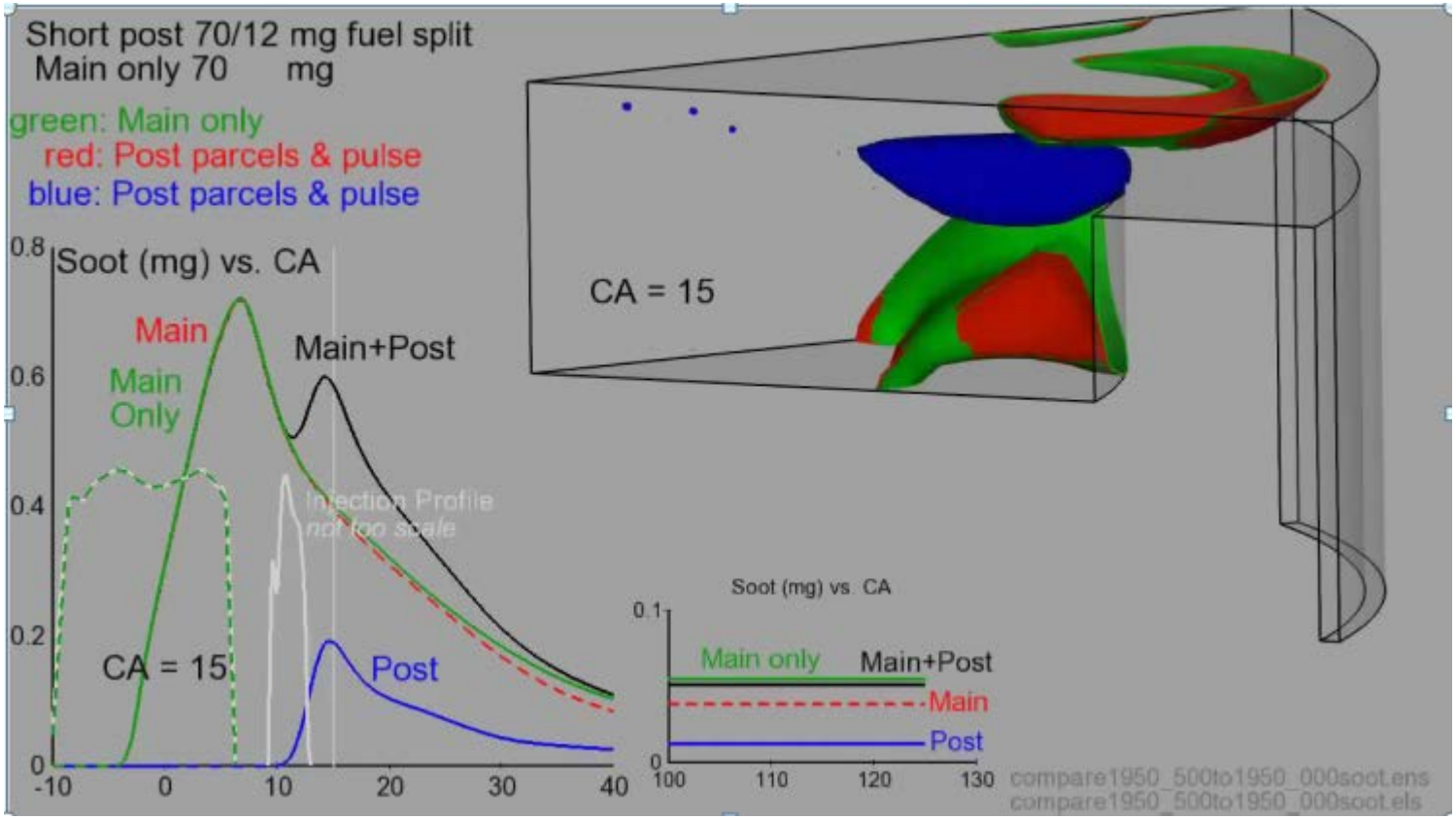
④ Prior to the addition of a post-injection, predicted soot resides near bowl wall, as in experiments

Case	New Color Scheme
Main-injection-only	green = soot from single injection (main)
Main+post injection	red = soot from main injection fuel
	blue = soot from post-injection fuel
	black = soot from main+post injection fuels



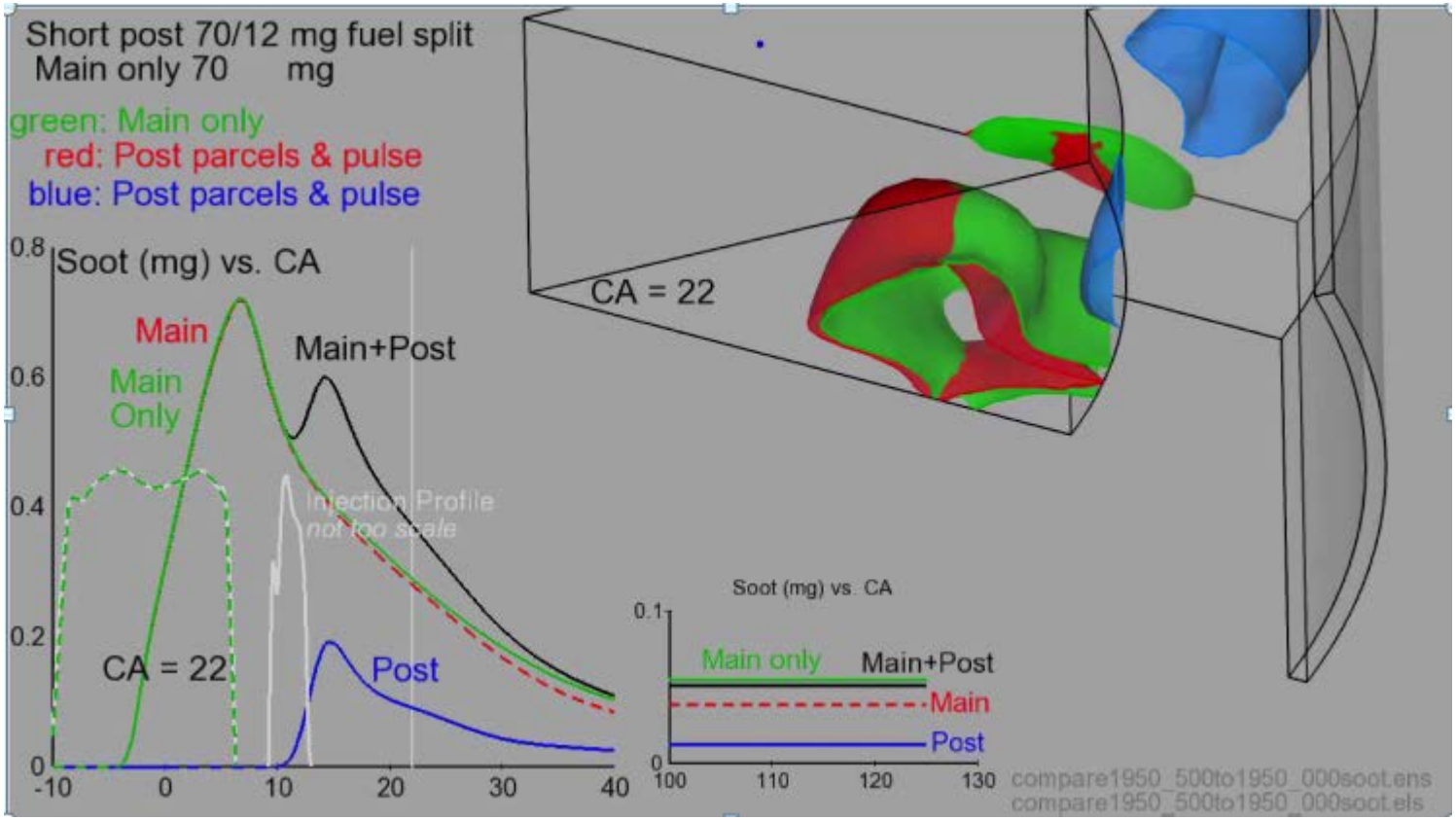
④ As post-injection penetrates, it reduces the main soot primarily by consuming main fuel

- Post injection adds fuel, so total soot (black curve) increases relative to main-injection only (green curve)
- Main soot (red curve) decreases due to lower main-fuel concentration as post-injection promotes faster combustion



④ Post-injection displaces main-injection soot cloud (red) from where it would have been (green)

- Post injection redistributes main-injection soot (red) back toward center of chamber relative to where it would have been without a post injection (green) – is this redistribution essential?
- FY16: Confirm redistribution in experiments and explore role



Remaining Barriers/Future Plans: Multi-injection conceptual model, heat-transfer, fuel-injectors

- Continue building a conceptual-model understanding of multiple-injection processes for both conventional diesel and LTC
  - Multi-injection schedules (pilot, post, split) deployed by industry
  - Identify mechanisms and critical requirements (injector rate-shaping, dwell, duration, etc.) to improve emissions and efficiency
  - Quantify the role of scalar dissipation in ignition/combustion and pollutant-formation/destruction processes
- Determine how combustion design affects heat transfer and efficiency
  - Measure spatial and temporal evolution of heat transfer across range of combustion modes and in-cylinder geometries; correlate to progression of in-cylinder combustion processes
- Gain fundamental insight from both experiments and models
  - Continue to refine 3-D analysis tools and apply them to end-of-injection mixing/ignition processes, multiple injections, heat transfer

Responses to Previous Year Reviewers' Comments

Comment: *"Improvements possible regarding the connection between the work here at a fundamental level with more real-world operation ... with respect to overall engine and power-plant efficiency"*

Response: This year's work to develop quantitative heat transfer measurements opens the door for more explicit connections to efficiency beyond only using high-efficiency conditions.

Comment: *"Would like to have seen one topic fully investigated" "how simulations were improved and validated"*

Response: We focused our work this year on injection processes and efficiency (through heat transfer), and the simulation validations and improvements on post injection soot modeling were addressed.

Comment: *"Would like to hear a hypothesis as to why [post injections reduce soot], then to see a test plan to prove (or disprove) it"*

Response: This year, we used analysis of model predictions to start generating hypotheses about critical features of the post-injection interactions with soot, and have experimental plans to validate them.

Comment: *"Greater focus going forward on end-of-injection mixing should be valuable" "[spend time] understanding the sensitivity of this advanced combustion process (to control variables so that a multi-cylinder engine could find a way into production)"*

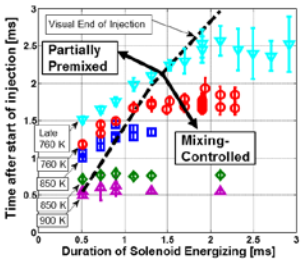
Response: Experiments this year focused on end-of-injection mixing as evidenced by ignition delay dependence on injection duration, which has fundamental implications for post-injection interactions with the main-injection field, as well as practical implications for combustion phasing control.

Comment: *"Continue building the conceptual model", "how many injection events were to be considered. The current approach appeared to focus on a main plus post injection strategy"*

Response: Developing the conceptual model is a multi-year task that will continue, and will include other multiple injection strategies as experimental and computational data are generated.

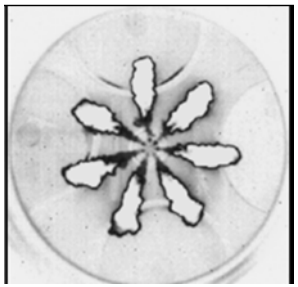
Heavy-Duty Combustion and Modeling Summary

1



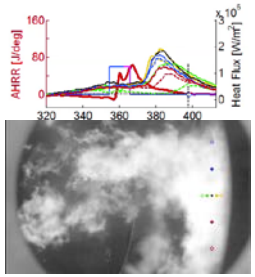
(SNL) Ignition in the residual mixtures of the main injection affected by more than mixing state – scalar dissipation (gradients)? ⇨ Likely affects how post injections interact with residual main injection.

2



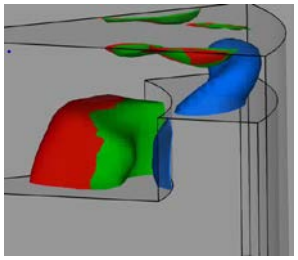
(SNL) Generated Spray-B engine data for ECN including liquid length, lift-off length, ignition/ combustion luminosity, and developed new single window/camera IR vapor-fuel penetration diagnostic.

3



(SNL) Developed conventional thermocouple and IR-thermometry diagnostics for quantitative heat-transfer measurements correlated with in-cylinder phenomena for model and efficiency improvements.

4



(UW) Achieved good agreement with experimental in-cylinder and exhaust soot so that analysis of CFD predictions can add insight and help guide experiments for multiple injection conceptual model.