ACE001: 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, May 15, 2012

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

ACE001

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 fuel injection, mixing, thermodynamic combustion losses, combustion/ emission formation processes
- Inadequate capability to accurately simulate these processes.

Budget

- Project funded by DOE/VT:
  FY11-SNL/UW: $700/115K
  FY12-SNL/UW: $700/115K

Partners

- University of Wisconsin, Delphi
- 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:

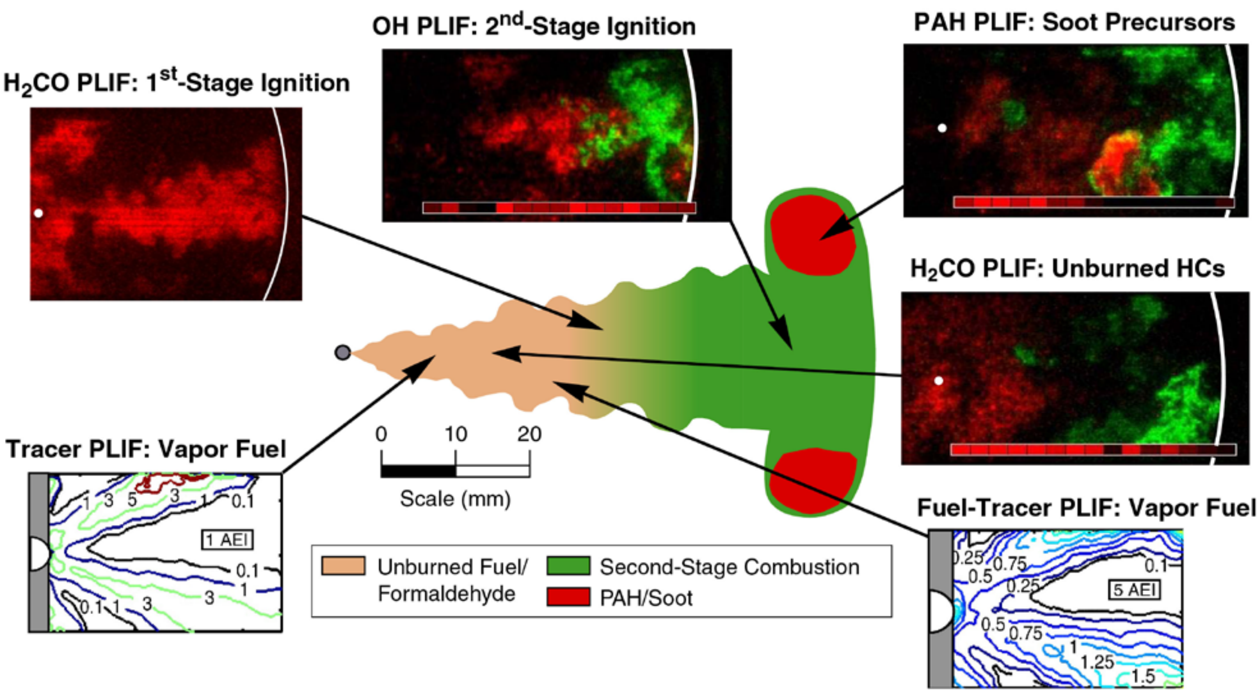
1. SNL – Distill observations spanning years of optical and computational research into conceptual model for LTC
2. SNL – Implement and demonstrate new high precision fuel system for multiple injections in optical engine
3. SNL – Explore close-coupled post injections for mitigating PM emissions and improving fuel efficiency
4. UW - Compare the multi-mode model predictions to exp. data and identify directions for improving thermal efficiency

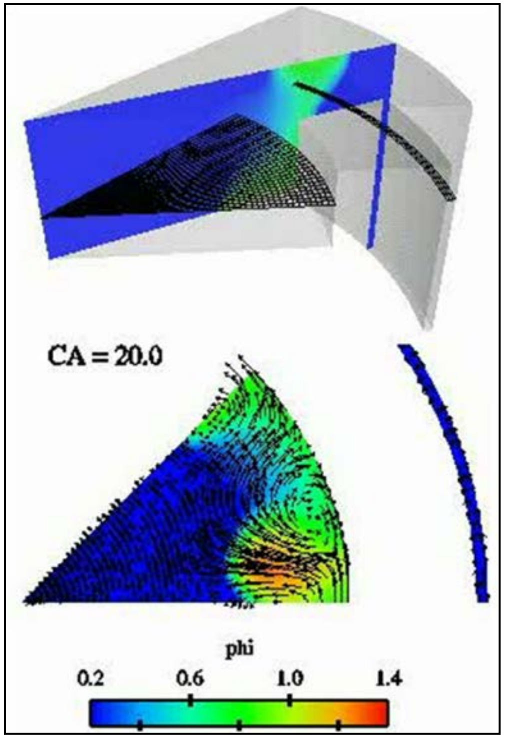
Heavy-duty in-cylinder combustion milestones

1. (SNL) Demonstrate new common-rail fuel injection system for controlled multiple injections.
2. (SNL) Evaluate small post injections for mitigating pollutant emissions and improving fuel efficiency
3. (UW) Compare multi-mode combustion model predictions to measurements of combustion propagation from FY 2011
4. (UW) Compare the multi-mode combustion model predictions to experimental data spanning conventional diesel to advanced LTC combustion taken, and identify directions for thermal efficiency improvements

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
  - FY2012: Delphi provided new injection system with support

Accomplishments (14 slides)

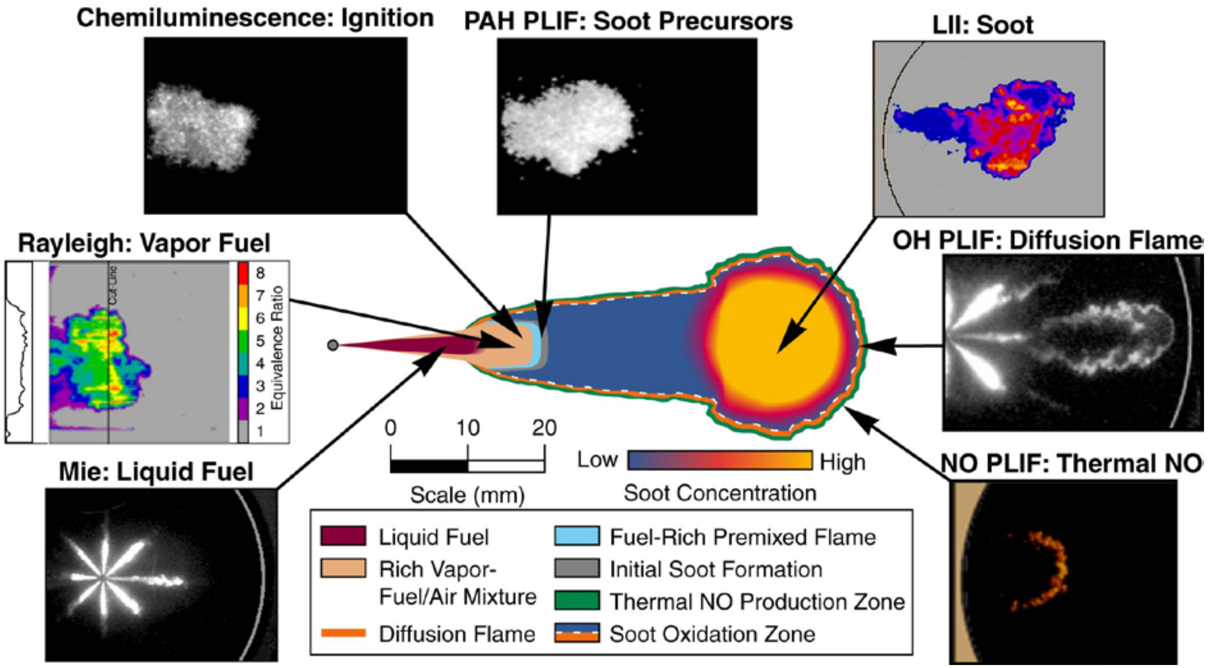
- Accomplishments for each of the four current specific objectives below are described in the following fourteen slides

Current Specific Objectives:

1. **SNL – Distill observations spanning years of optical and computational research into conceptual model for LTC**
2. **SNL – Implement and demonstrate new high precision fuel system for multiple injections in optical engine**
3. **SNL – Explore small post injections for mitigating PM emissions and improving fuel efficiency**
4. **UW – Compare multi-mode model predictions to exp. data and identify directions for improving thermal efficiency**

① Sandia's conceptual model for conventional diesel is cornerstone of understanding

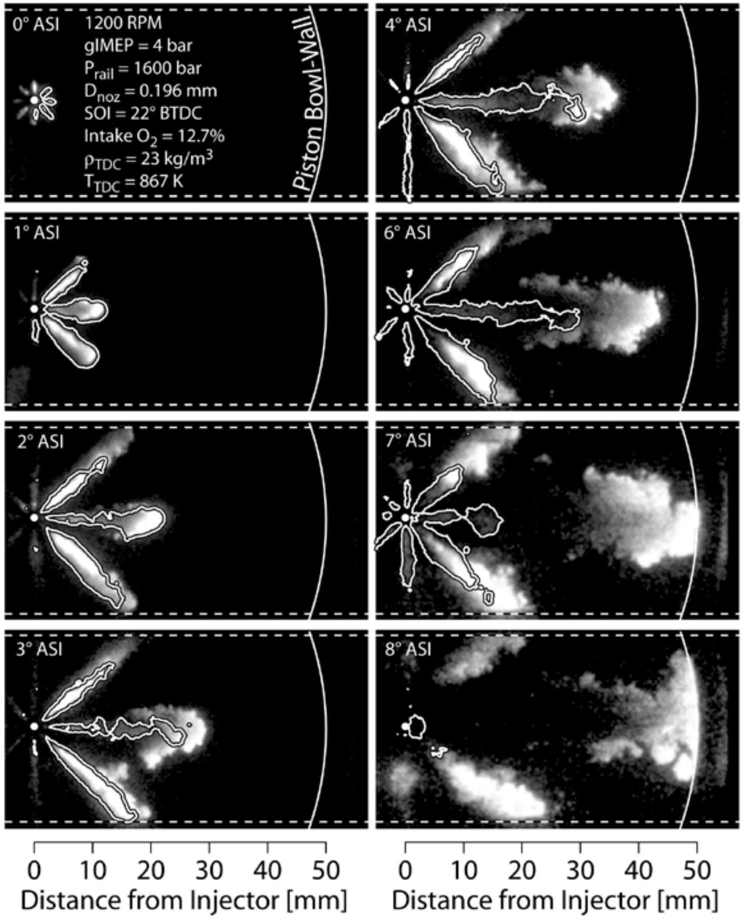
- Sandia's conceptual model of diesel combustion was developed based on observations from multiple laser/imaging diagnostics over many years of optical engine research

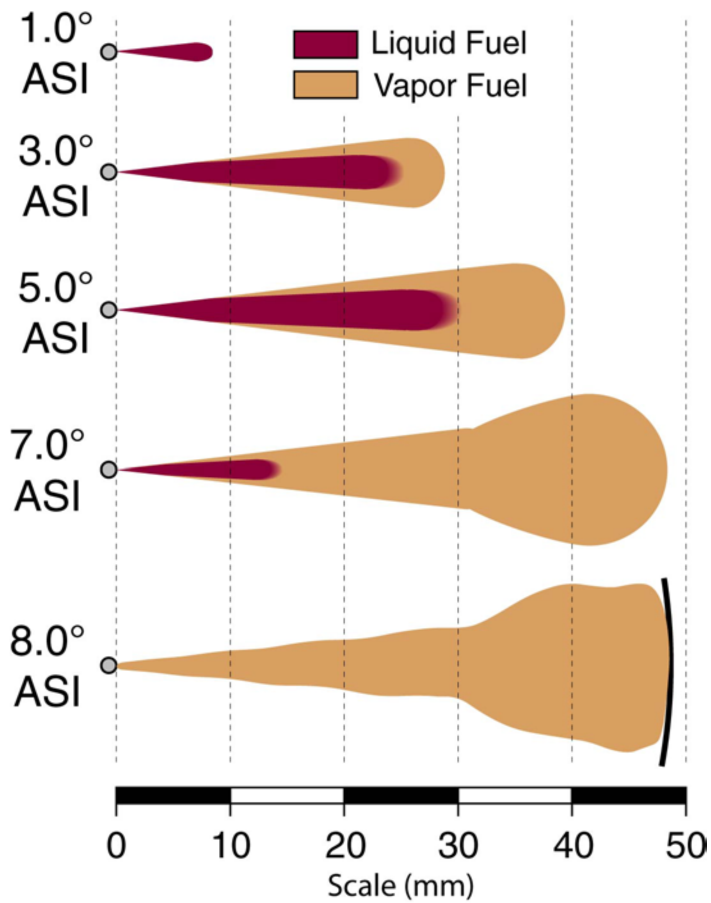


With many years of LTC optical engine research under our belt, can we develop a conceptual model for diesel LTC?

LTC spray penetrates more quickly + longer liquid; liquid recedes after EOI, before SOC

- Injection into lower density: faster spray penetration, longer liquid length
- Liquid recedes before SOC as vapor hits piston wall

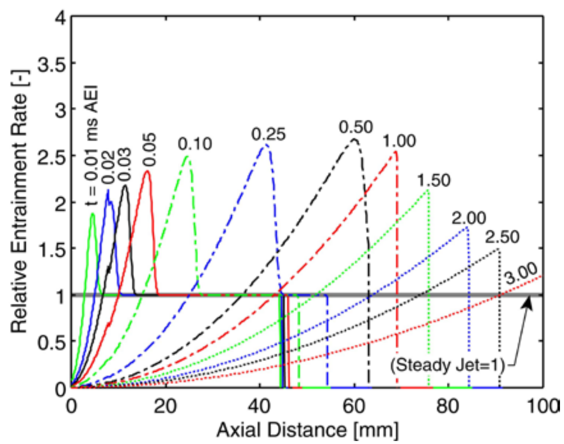




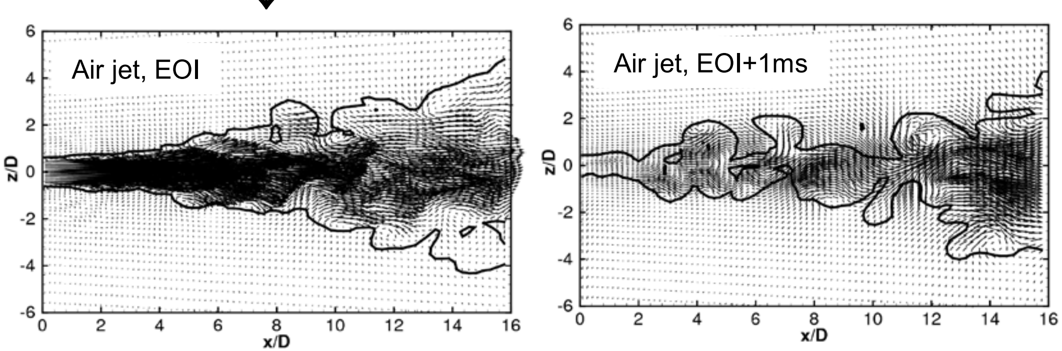
1-D analytic, KIVA RANS, and Sandia LES models predict wave of increased entrainment after EOI

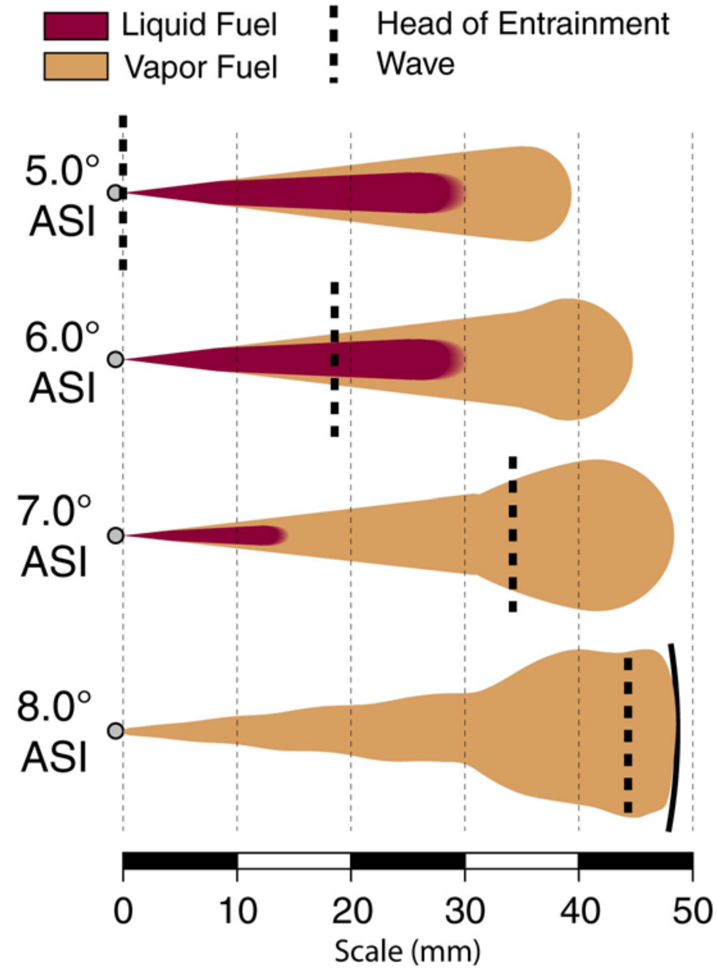
- Reduction in upstream jet velocity draws in more entrainment, which reduces velocity further, driving more entrainment, etc.
- LES (Oefelein, Hu): EOI ramp-down causes large flow structures to separate rather than collide; ambient fluid is entrained into gaps

1-D model →



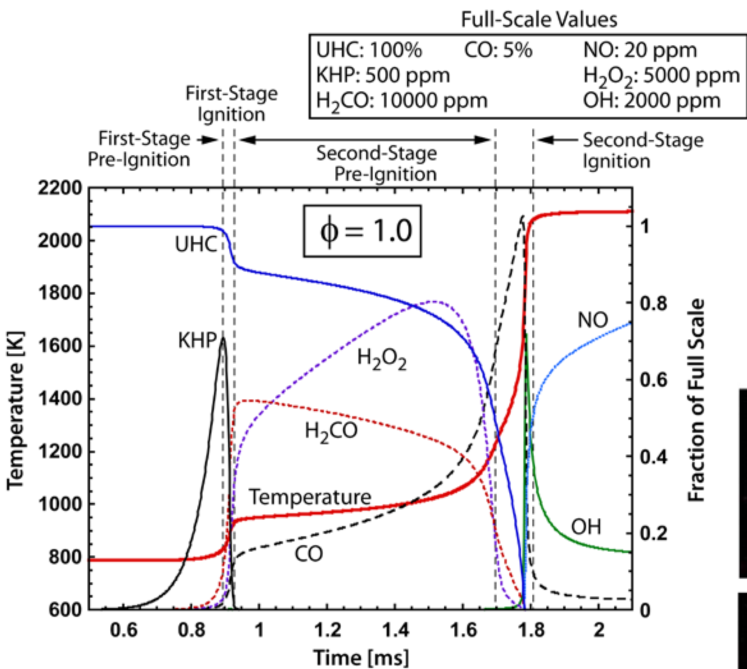
LES model ↓



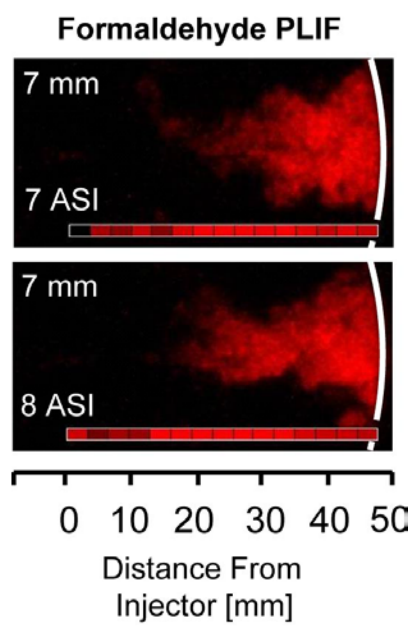


First-stage ignition in downstream vapor fuel, partially burned fuel (UHC, CO) throughout jet

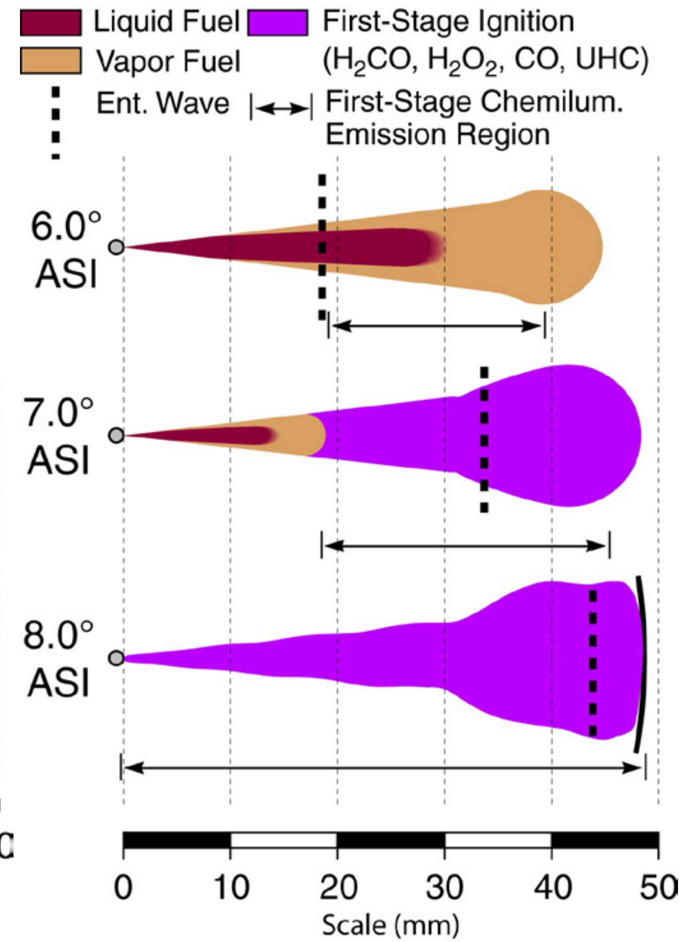
- LLNL chemical kinetics model: formaldehyde at 1st-stage ignition
- Experiments: Formaldehyde fluorescence at 1st stage, throughout jet



← Model

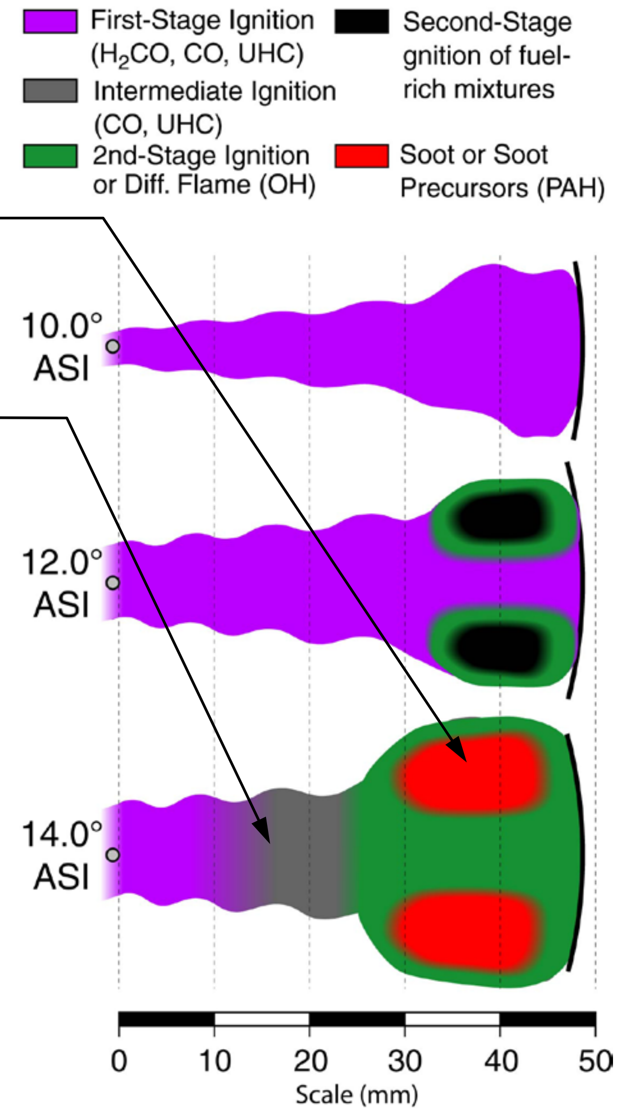


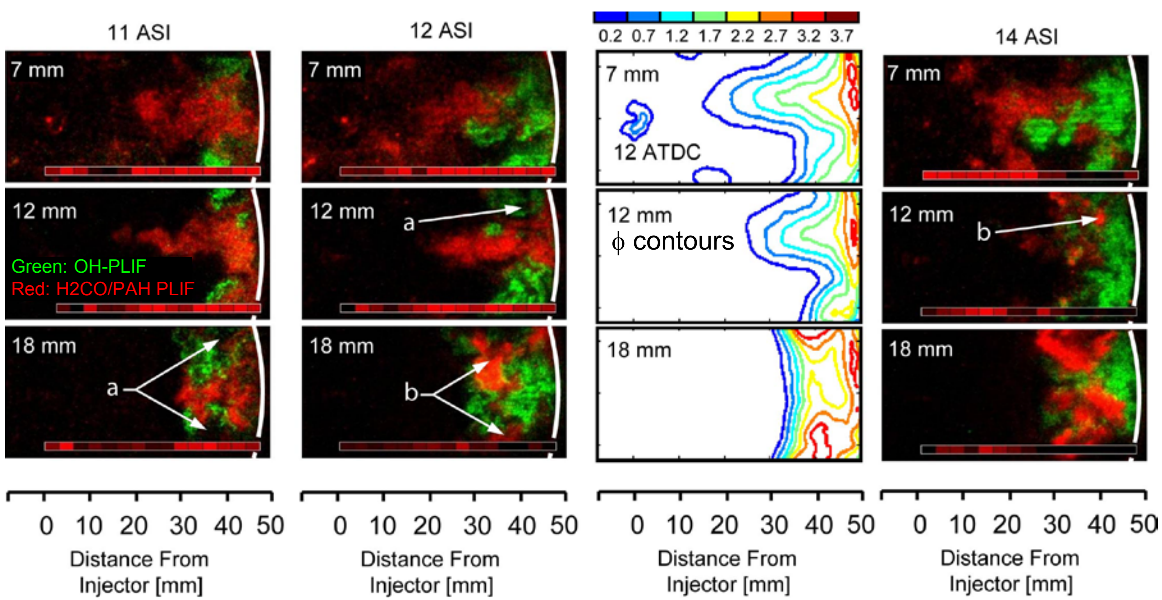
Experiment →



Second-stage ignition downstream where ϕ~1, followed by soot in rich pockets at head of jet

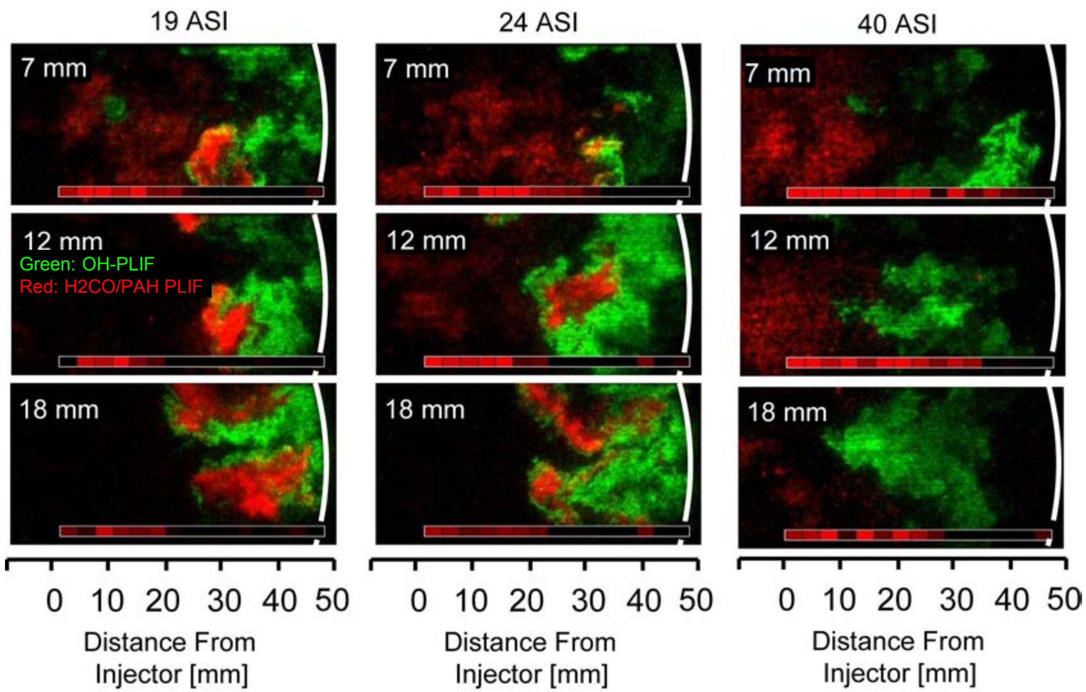
- Simultaneous PLIF of OH (green) and formaldehyde/PAH (red) show 2nd-stage ignition across most of downstream ϕ~1 jet
- Soot and PAH form in ϕ>2 pockets
- In lean upstream regions, experiments and LLNL kinetics simulations show partially burned fuel (CO, UHC, formaldehyde)

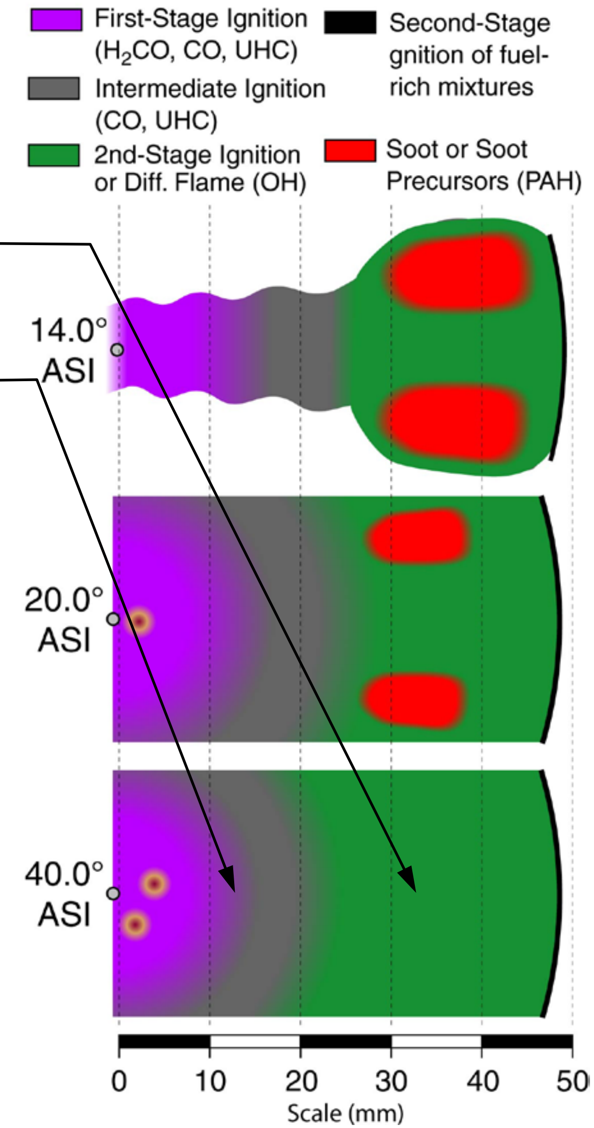




Late cycle: soot pockets largely oxidize, formaldehyde, CO, UHC remain upstream

- Late in cycle, simultaneous PLIF of OH (green) and formaldehyde/PAH/soot LII (red) show soot pockets surrounded OH
- Soot pockets are mostly oxidized by 40º ASI
- Partially burned fuel (CO, UHC, formaldehyde) remain late in cycle



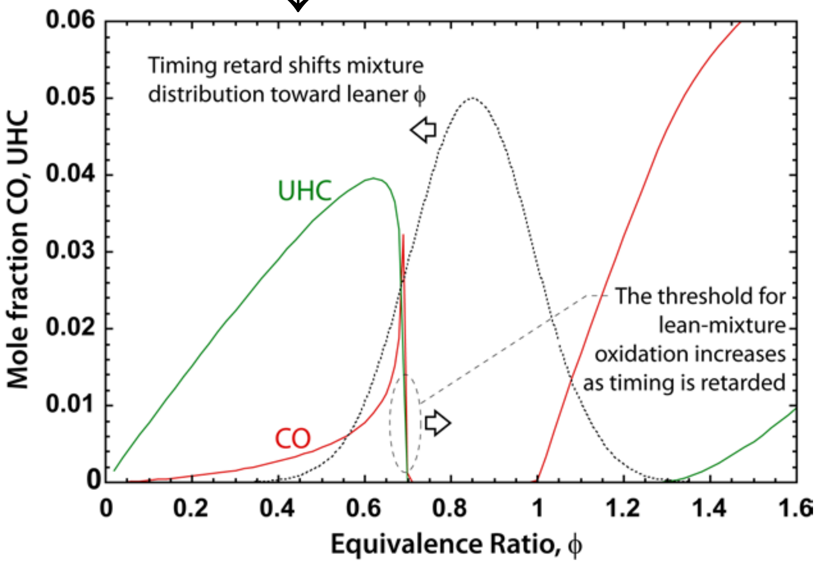


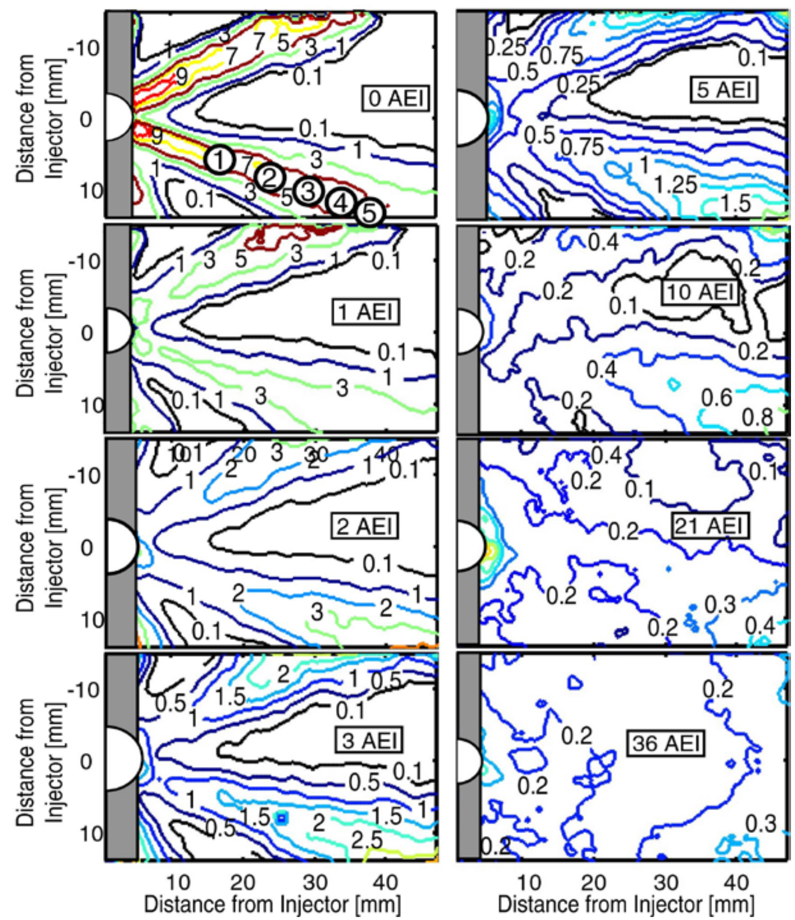
① Experiments show over-lean regions near injector, where kinetics models predict partial combustion

- Experiments: vapor-fuel tracer-PLIF shows lean mixtures near injector where combustion-PLIF shows late-cycle formaldehyde and CO
- LLNL kinetics models: Lean mixtures have long dwell between first- and second-stage ignition, with UHC and CO persisting to exhaust

Kinetics Model ↓

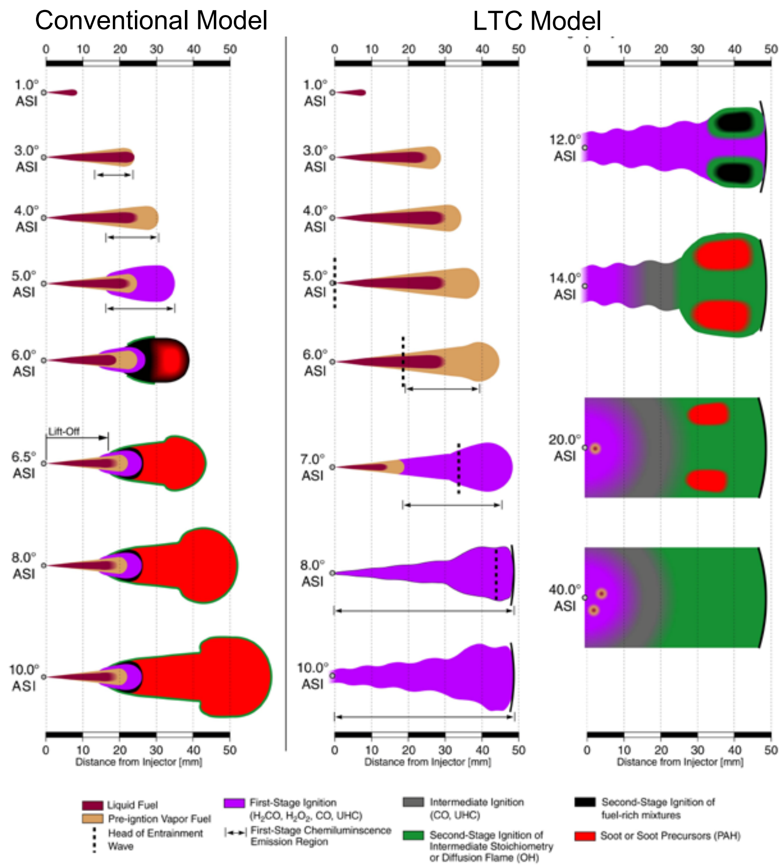
ϕ from experiment →





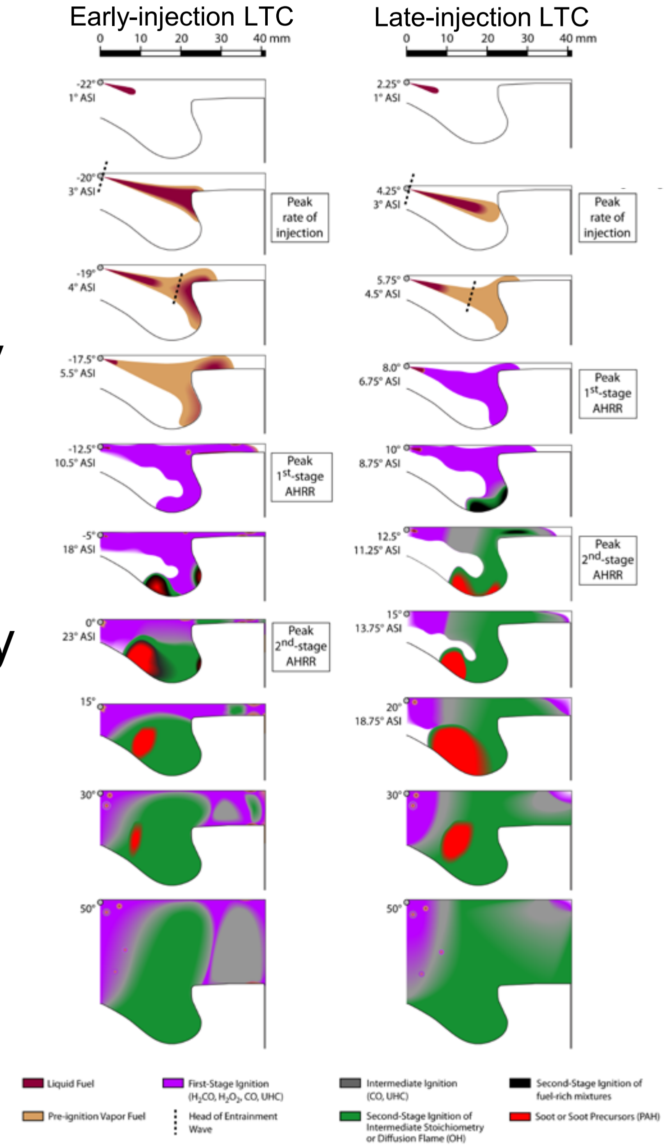
LTC conceptual model review article includes both heavy- and light-duty perspectives

- Team effort with Lyle Pickett and Paul Miles
- March 2012: LTC conceptual model in review (PECS), publication pending



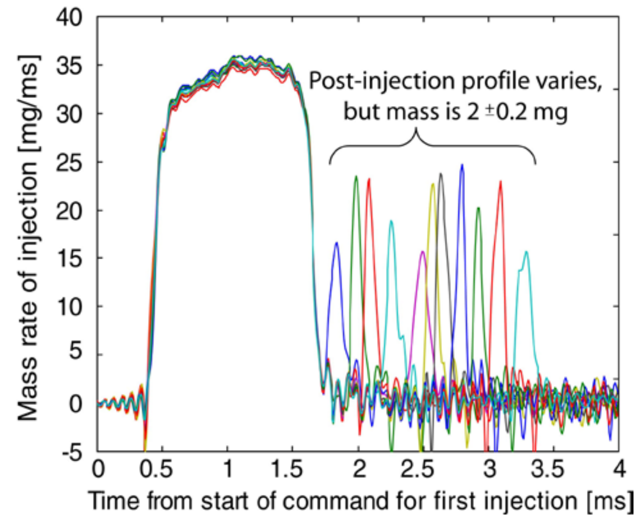
light-duty →

heavy-duty ←



② New fuel injector/system implemented for new effort requiring precise multiple injections

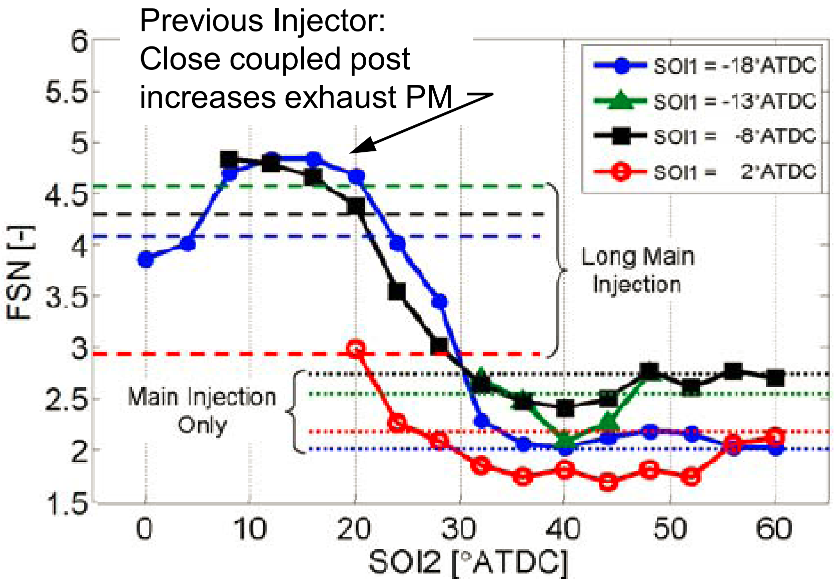
- Optical cylinder head modified to accept Delphi DFI-1.5 injector
- New 0.2 liter accumulator (rail) close to injector to minimize rail dynamic effects
- Delivers close-coupled post-injections down to ~1-2 mg with IMEP COV <1%
- This injector is first step; may follow with other injectors (e.g., direct piezo, fast heavy-duty)

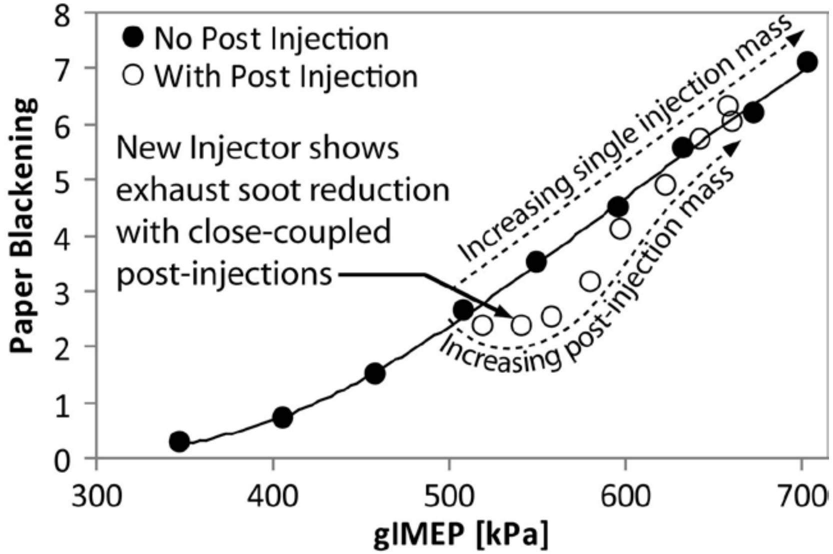


(click movie to play)

PM reduced by close-coupled post injections for wide range of EGR, + good combustion phasing

- Previous work with LTC post-injections showed a benefit only at late timings
  - Soot-free post injection oxidized main-injection soot, but only in squish
  - Significant efficiency penalty for late injections
- New injector shows benefit for close-coupled post injections
  - Similar effect realized at 21%, 18%, 15% and 12% intake O_2
  - Minimum-PM post-injection (7-15 mg) adds 50-100 kPa IMEP
  - Post-injection is close-coupled, so combustion phasing is favorable for efficiency

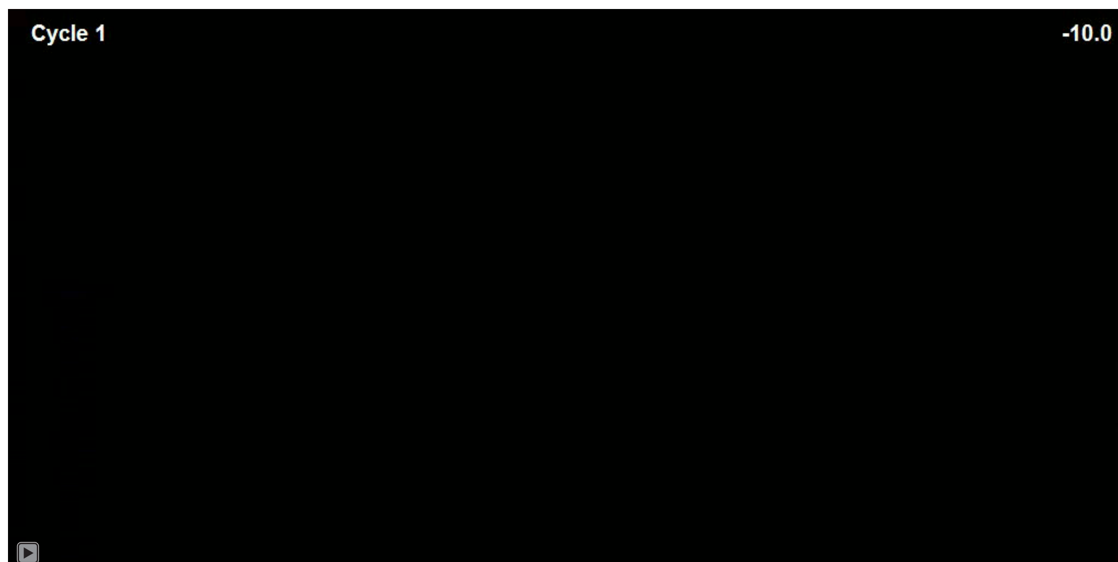




③ Initial results shows how interaction between main and post injections needs proper post penetration

- Small post-injection
  - Luminous soot from post-jet penetrates only half of piston-bowl radius
  - Exhaust soot is similar to main-injection only, implying little interaction between injections
- Larger post-injection
  - Post-jet penetrates across bowl and impinges on bowl-wall
  - Post injection helps to oxidize main injection soot within bowl

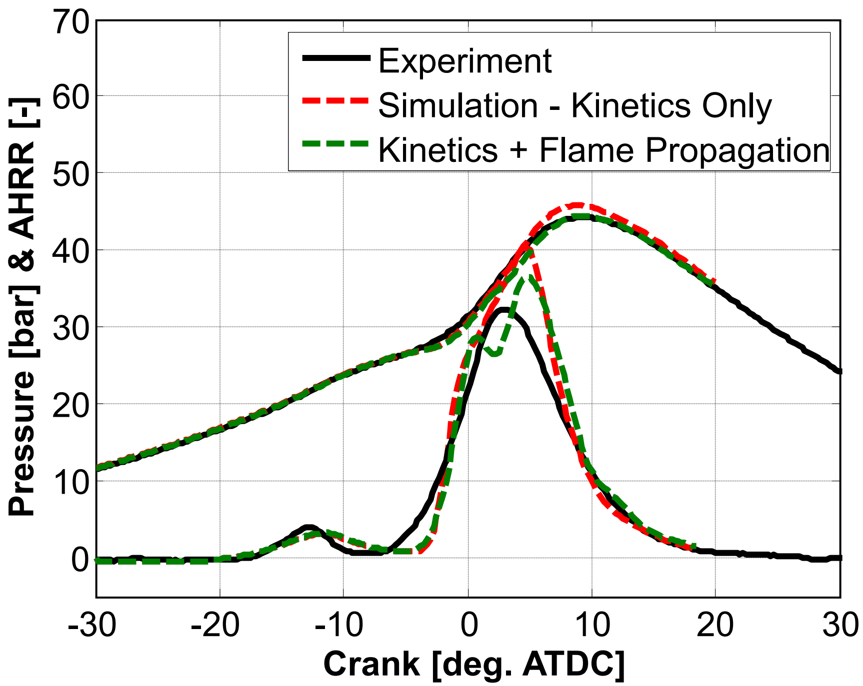
Interaction details to be probed with laser diag.

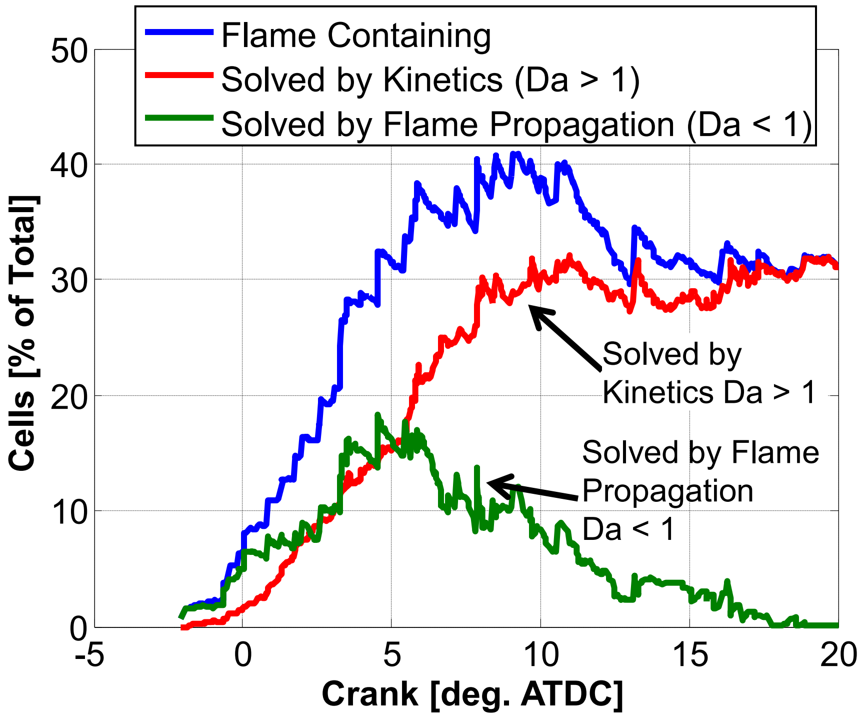


(click movies to play)

CFD for RCCI predicts early flame propagation, but effects on global heat release is small

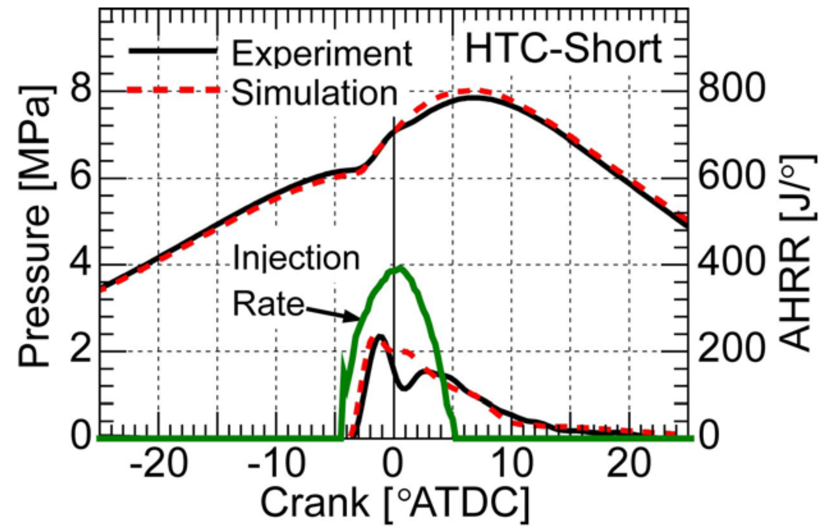
- FY11 laser-ignition experiments showed potential for flame propagation in dual-fuel (gasoline+diesel) Reactivity-Controlled Compression Ignition (RCCI) combustion (e.g., near piston bowl)
- Using a G-equation model with Damköhler number criterion predicts many cells initially dominated by flame propagation
- Predicted heat release similar to no flame propagation model

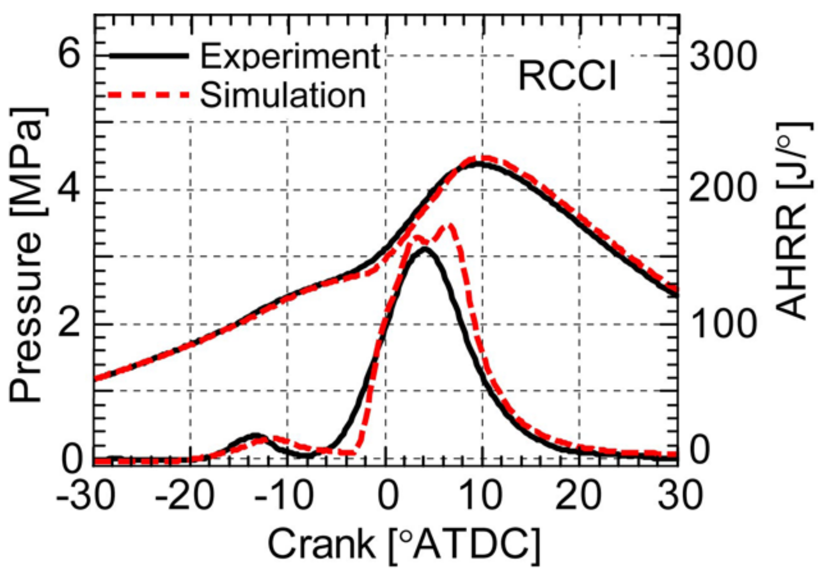


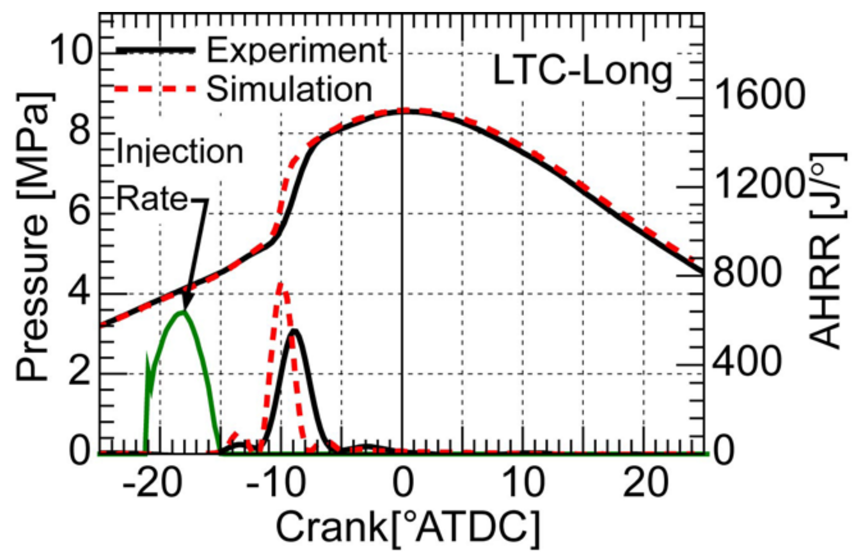


④ Global combustion characteristics captured by single UW-Kiva code across wide mode range

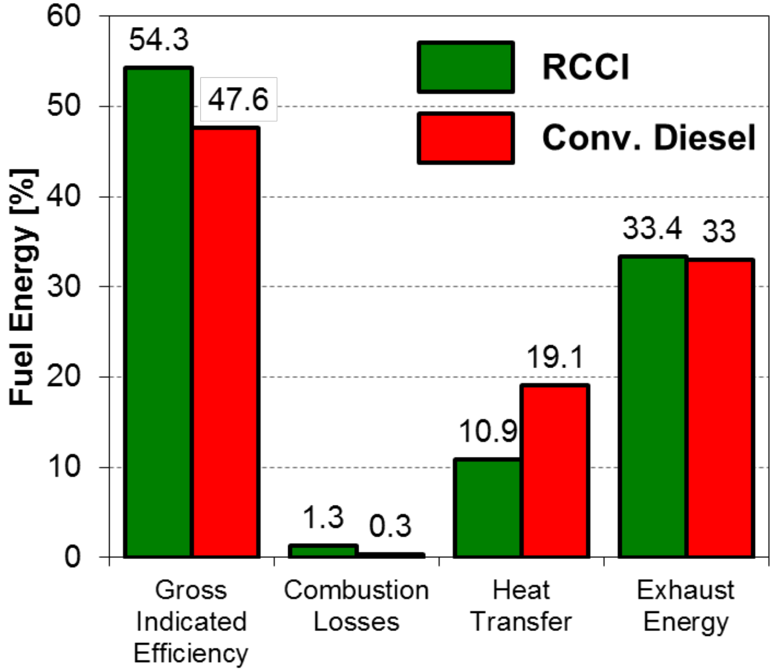
- Model cylinder pressure agrees with multi-mode experiments
  - Conventional high-temperature diesel combustion with short ignition delay (HTC-Short)
  - Low-temperature diesel combustion with long ignition delay (LTC-Long)
  - Dual-fuel RCCI combustion

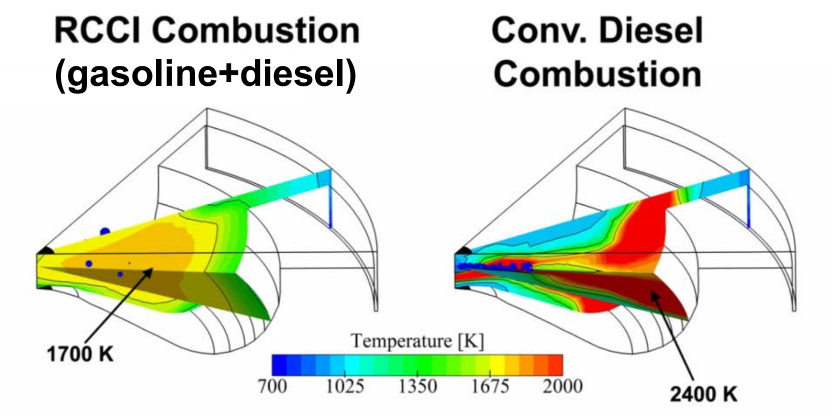






Simulations point to heat transfer & combustion design for further efficiency improvements





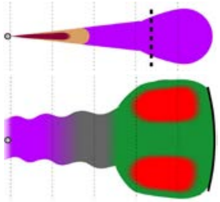
- Model energy balance analysis shows RCCI efficiency improvements are primarily due to reductions in heat transfer
- Heat transfer is reduced by lowering peak temperature
  - Highly premixed operation results in peak equivalence ratio near 0.5
  - Additional temperature reductions are due to EGR
- Further reductions in heat transfer are achieved by keeping high-temperature regions away from surfaces

Future Plans: Build multi-injection conceptual model, heat transfer diag., and LTC PAH/soot

- Start building a design-level conceptual-model understanding of multiple injection processes
  - Explore fuel-injection schedules using multiple pilot, post, and split injections that are currently deployed by industry
  - Identify mechanisms and critical requirements (injector rate-shaping, dwell, duration, etc.) to achieve emissions and efficiency improvements across wide parameter space
- Determine how combustion design affects heat transfer and efficiency
  - Measure spatial and temporal evolution of heat transfer across range of combustion modes; correlate to progression of in-cylinder combustion processes
- 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

Heavy-Duty Combustion and Modeling Summary

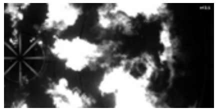
Improved understanding of in-cylinder LTC spray, combustion, and pollutant-formation to help industry build cleaner, more efficient engines

① 

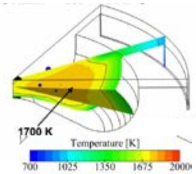
(SNL) Distilled recent years of optical LTC research into conceptual model for both heavy- and light-duty

② 

(SNL) New injector and delivery system provides repeatable, precise close-coupled multiple injections

③ 

(SNL) Close-coupled post-injections reduce soot over range of EGR; images show multi-injection interactions

④ 

(UW) Model predictions show efficiency is improved by combustion design to reduce heat transfer