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

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FY 2009 DOE Vehicle Technologies Program Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
8:30 – 9:00 AM, Tuesday, May 19, 2009

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:
  FY08-SNL/UW: $580/115K
  FY09-SNL/UW: $580/115K

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:

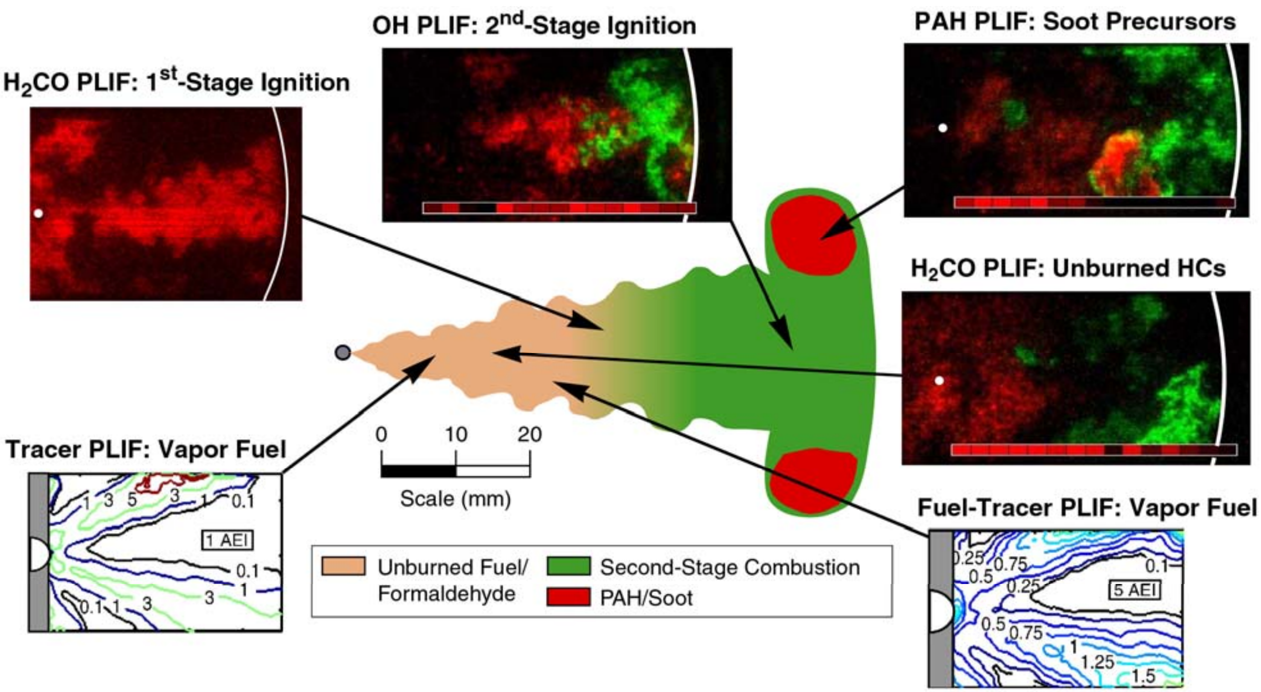
- ② (SNL) Extend diesel conceptual model to LTC
- ④ (SNL) Understand multiple injection effects on LTC
- ② (SNL) Develop wall temperature diagnostic for studying liquid film dynamics
- ② (UW+SNL) Improve computer modeling for LTC/diesel sprays and study piston geometry effects on LTC

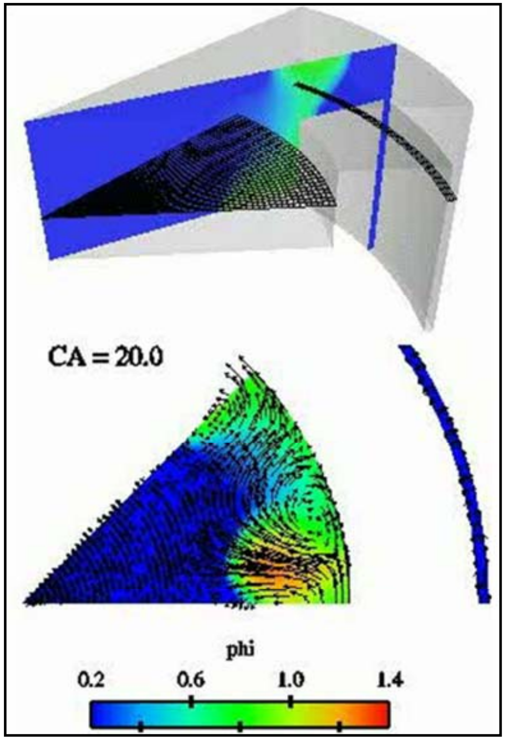
Heavy-Duty In-Cylinder Combustion Milestones

- ② (SNL-June 2009) Complete conceptual model extension for EGR-diluted, low-load, single-injection, low-temperature combustion.
- ④ (SNL – June 2008) Show how interactions between post- and main-injections affect soot LTC conditions.
- ④ (SNL – Feb 2009) Demonstrate a wall temperature diagnostic using coherent-light interference in windows
- ④ (UW+SNL – Sept. 2008) Understand how combustion chamber design parameters affect mixing and emissions.

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





Accomplishments (9 slides)

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

<u>Current Specific Objectives:</u>

➍ **(SNL) Extend diesel conceptual model to LTC**

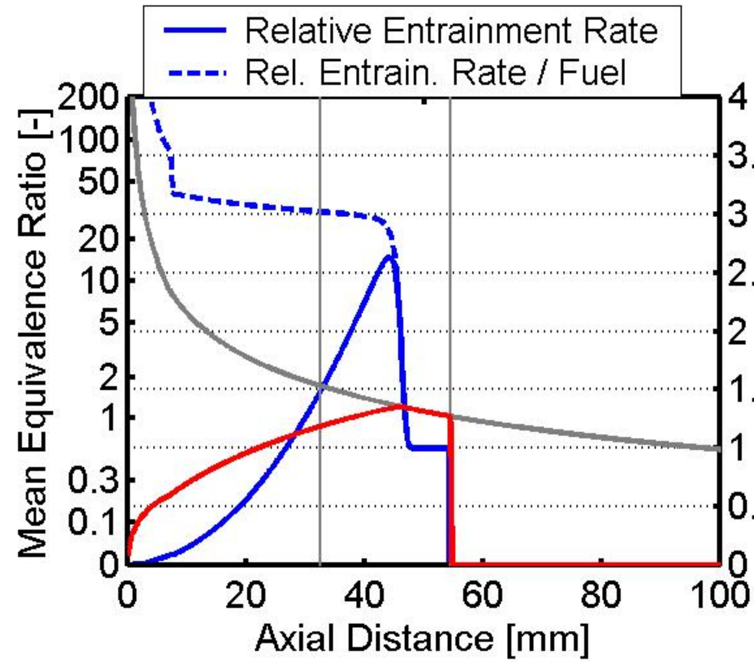
➋ **(SNL) Understand multiple injection effects on LTC**

➍ **(SNL) Develop wall temperature diagnostic for studying liquid film dynamics**

➍ **(UW+SNL) Improve computer modeling for LTC/diesel sprays and study piston geometry effects on LTC**

① Entrainment Wave found to be important for many LTC (and diesel) combustion and emissions phenomena

- <u>Last year:</u> Used simple 1-D CFD to analyze mixing after end of injection
  - Revealed "**Entrainment Wave**" (EW)
- <u>This year:</u> Showed EW causes:
  - i. over-mixed regions (HC & CO)
  - ii. rapid stagnation near injector
  - iii. *spatial distribution of soot formation
  - iv. *increased soot oxidation after EOI
  - v. less penetration of short injections
  - vi. liquid fuel vaporization distribution

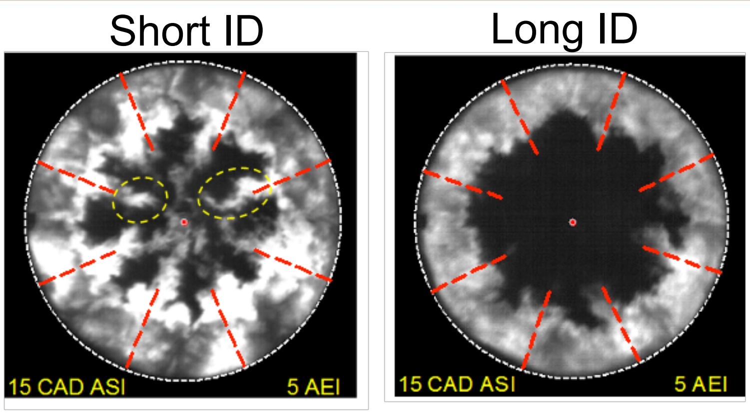


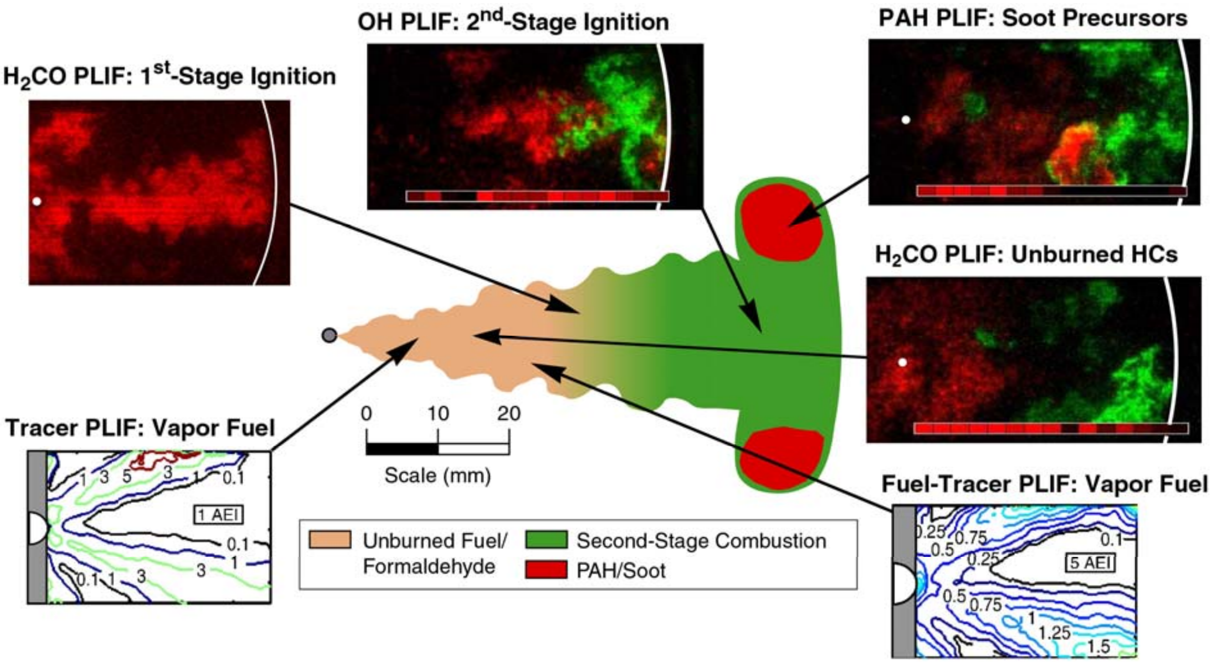
$$\sqrt{\dot{M}} = \sqrt{\left(\frac{t}{2t_{1/2}}-1\right)^2 \frac{\dot{M}_0}{4} - \tan\left(\frac{\theta}{2}\right)\sqrt{\frac{\pi\rho\dot{M}_0}{\beta}}\,\frac{(z_0)^2-(z')^2}{8t_{1/2}}} - \left(\frac{t}{2t_{1/2}}-1\right)\frac{\sqrt{\dot{M}_0}}{2}$$

- <u>New:</u> Analytical solution confirms CFD predictions and defines limits of mixing
- **<u>Tech. Transfer:</u> (1) Cummins used EW knowledge to develop low-HC injection strategy, (2) GM modeling EW in KIVA**

① EW reduces soot formation and increases soot oxidation after end of injection

- Soot behavior after end of injection (EOI) depends on ignition delay (ID)
  - Short ID: Soot races back to injector
  - Long ID: No soot forms near injector
  - After EOI: EW rapidly oxidizes soot



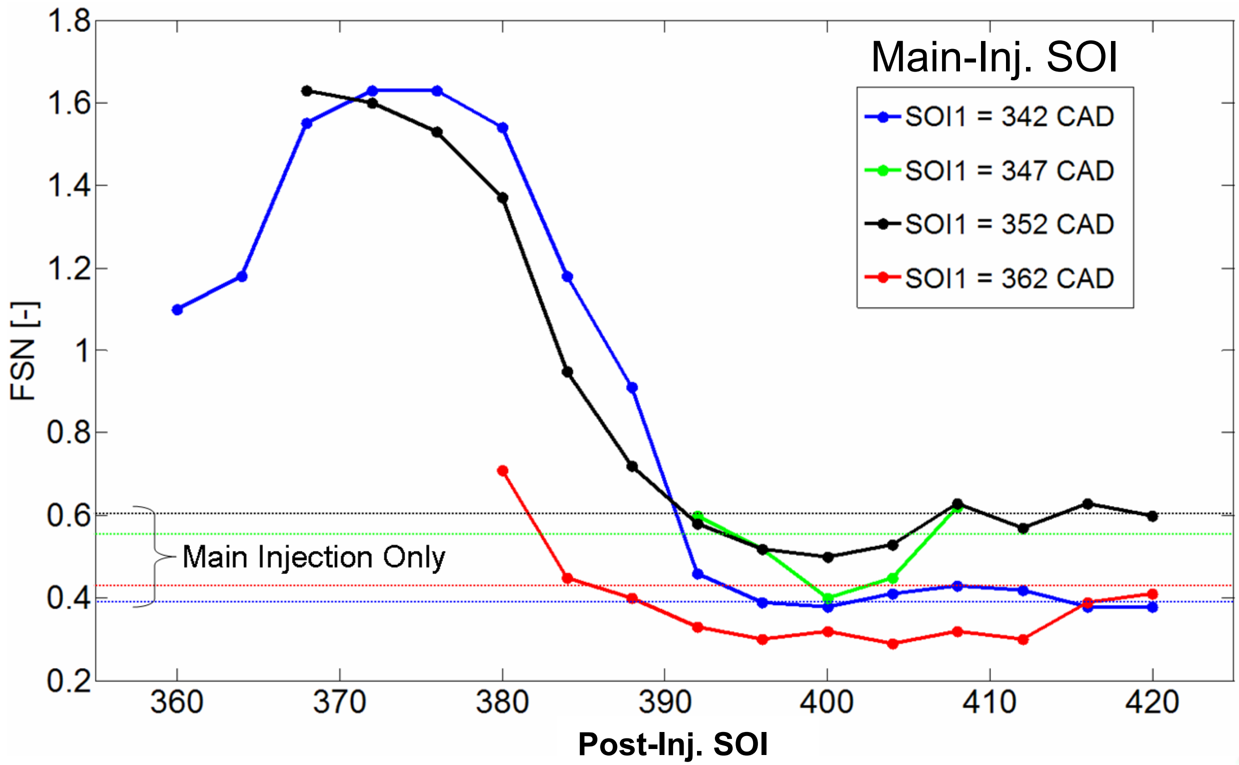


Conceptual Model Extension for LTC:

Many of the necessary building blocks now in place, and development is in progress

② Adding a post-injection can reduce soot from the original, unchanged main injection

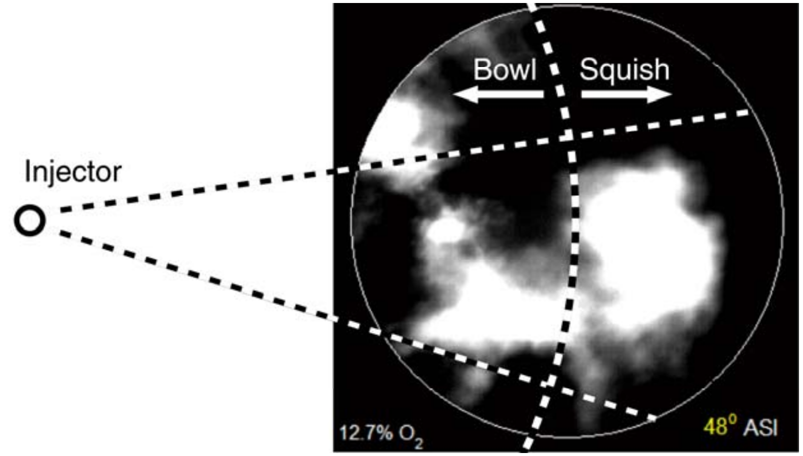
- Post- or split-injections are a well-known strategy to reduce soot emissions, but in-cylinder mechanisms are in dispute
- Distributing fuel into two injections can reduce soot, but can adding a post-injection reduce soot? → YES



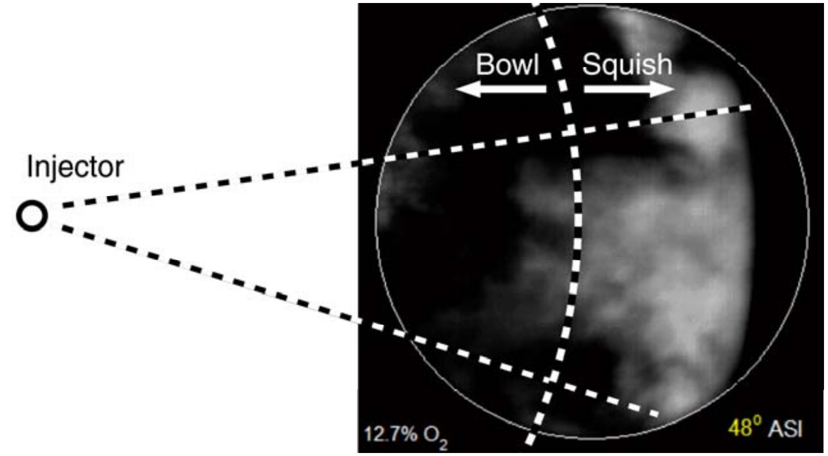
- With constant main injection, adding a post increases soot at small spacing, but decreases soot at larger spacing.
- **Clear evidence of injection interactions**

② Soot luminosity images show interaction occurs in the squish region

- With a single main injection only, soot remains late in the cycle in the wake of the jet, distributed between squish and bowl regions



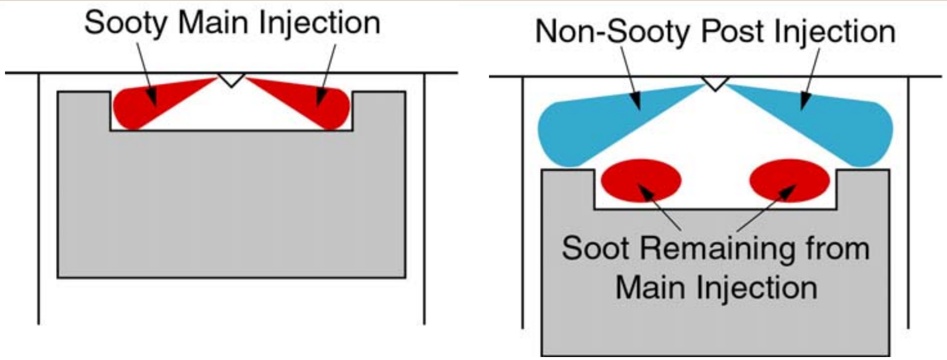
- When a post-injection is added, the soot is pushed back into the squish region, where it oxidizes more quickly



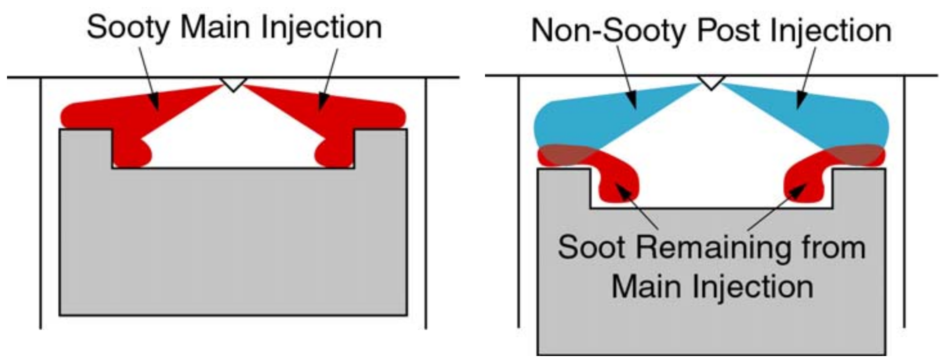
For these late-post conditions, the post-injection seems to primarily increase oxidation of soot in the squish region

② Effectiveness of post injections increases with more interaction with main-injection soot

- (A) For <u>early</u> main-injection conditions, most of the soot is in the bowl
- A late post-injection creates very little soot, but also does not interact with main-injection soot, so main-inj. soot is not reduced



- (B) For <u>late</u> main-injection conditions, the soot is split between bowl and squish regions
- A late post-injection creates little soot of its own but also helps to oxidize soot in the squish region

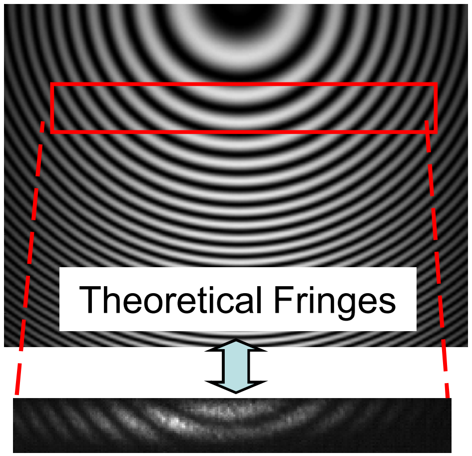


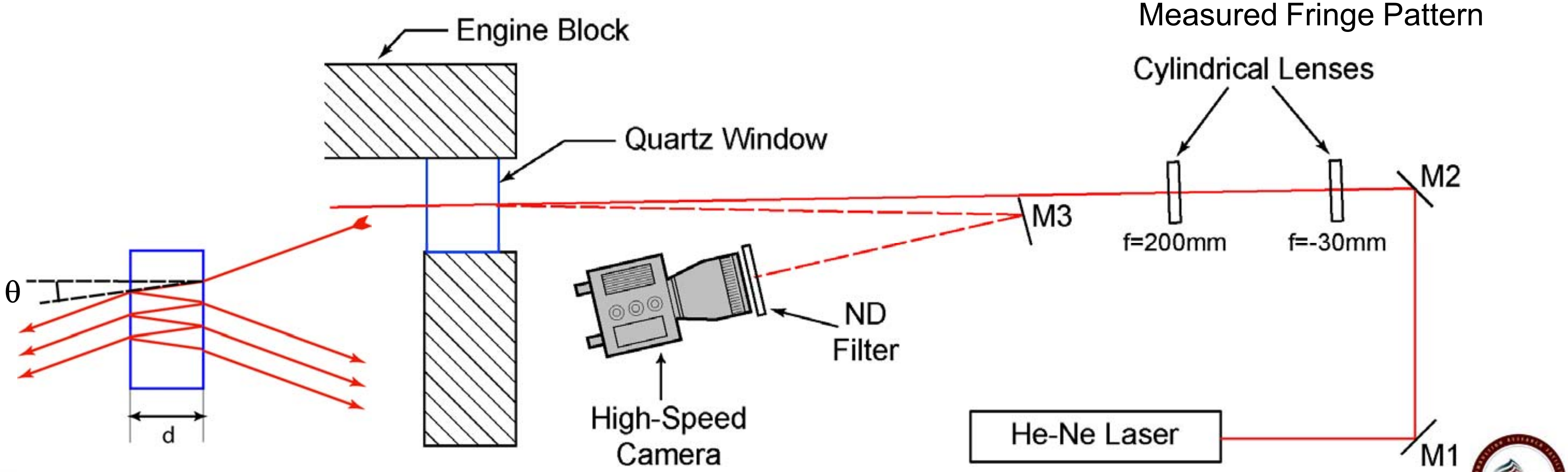
For the most benefit, the post-injection should be targeted to interact with remaining soot from main-injection

③ Developing wall-temperature diagnostic for liquid fuel-film studies

- For LTC, fuel wall-wetting can be troublesome; wall T is important
- Windows offer measurement opportunity
- Previous work → interference T diagnostic
  - Fringe movement is a function of window temperature (and cylinder pressure!)

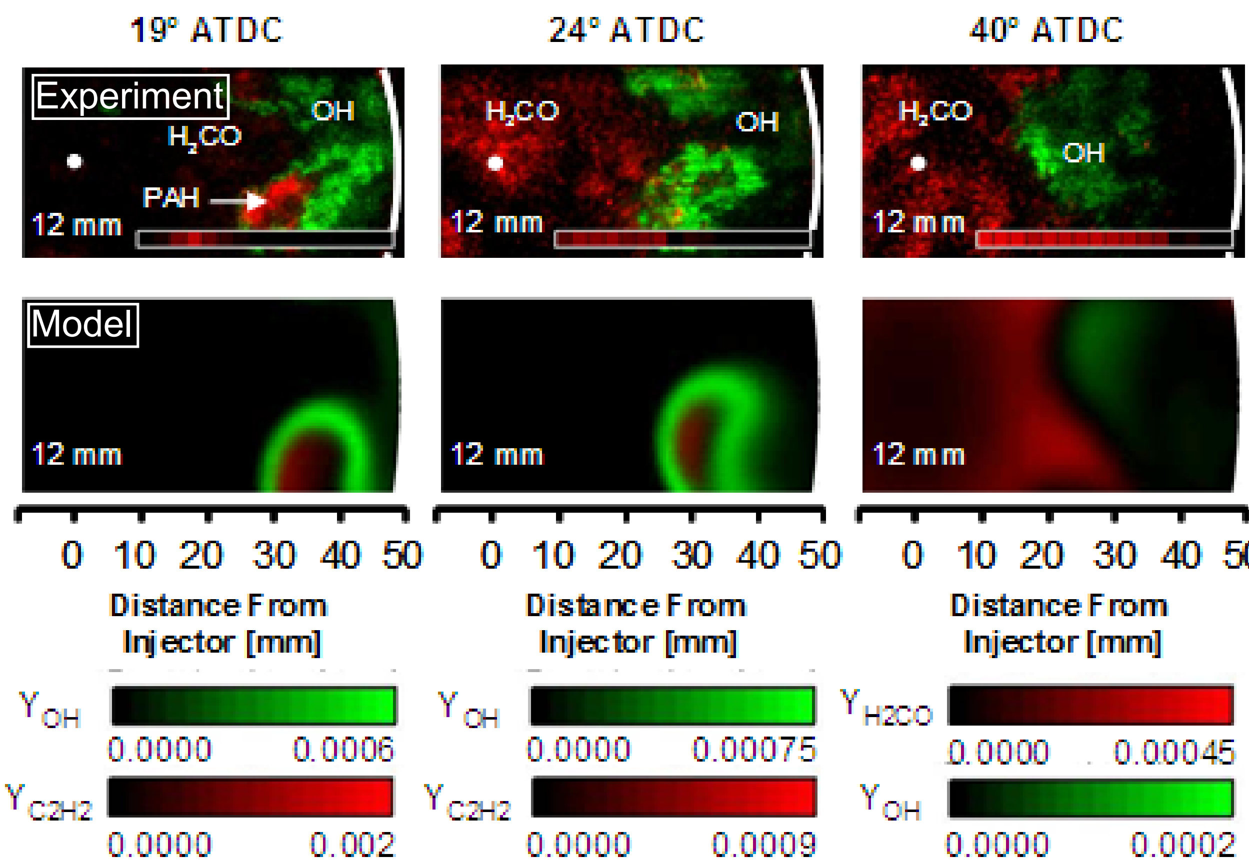
$$I = f\{n(T), d, \cos\theta\}$$





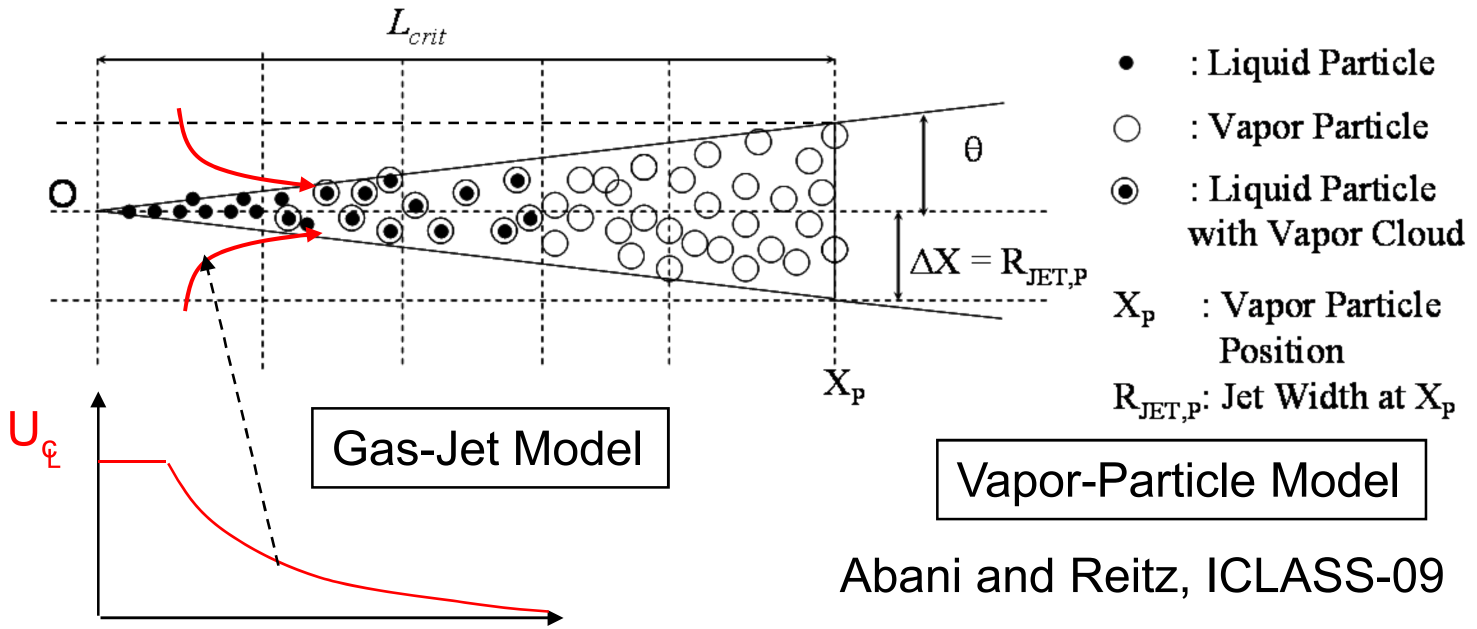
④ Models & experiments show most UHC arises from over-lean regions for late-injection LTC

- Late-Injection LTC: Model C_2H_2 soot precursor and measured PAH distributions agree
- Model vapor-fuel distributions also agree well with experiments (not shown)



Both models and experiments show smaller bowls help to direct hot combustion into over-lean regions to reduce UHC

④ New gas-jet and vapor-particle sub-models reduce grid dependency for diesel sprays

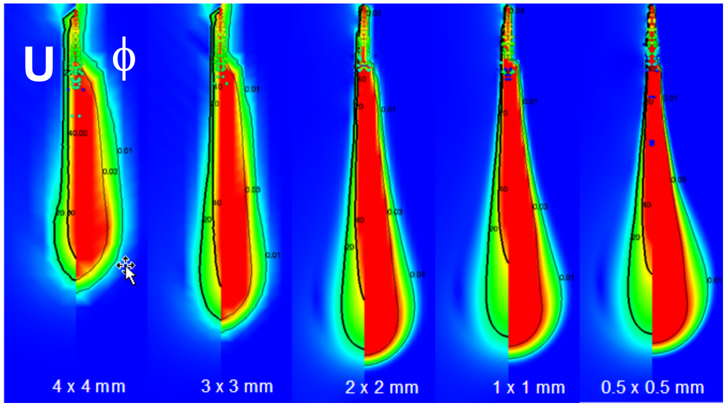


Abani and Reitz, ICLASS-09

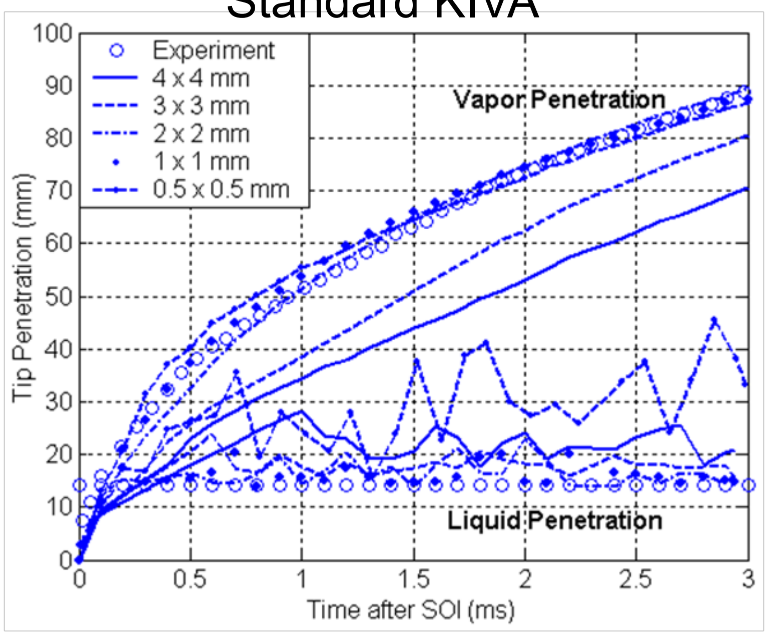
- Theoretical gas-jet velocity solution near the nozzle
- Vapor-particle model downstream to minimize numerical diffusion

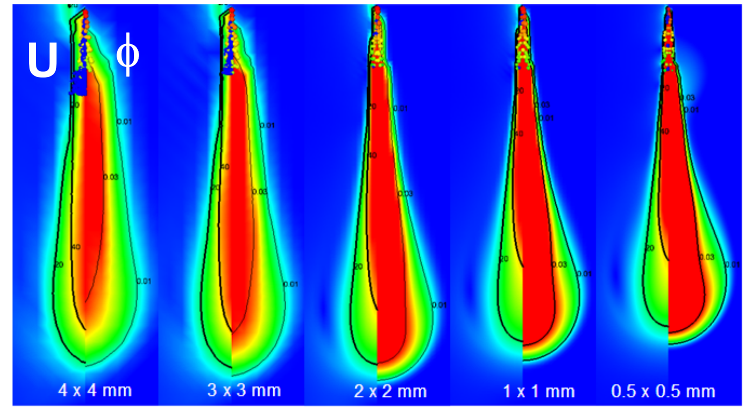
- Grid-independent spray models developed for standard and group-hole nozzles (SAE 2008-01-0970, 2009-01-0701)

④ Liquid and vapor penetration predictions much less grid-dependent with new models for KIVA

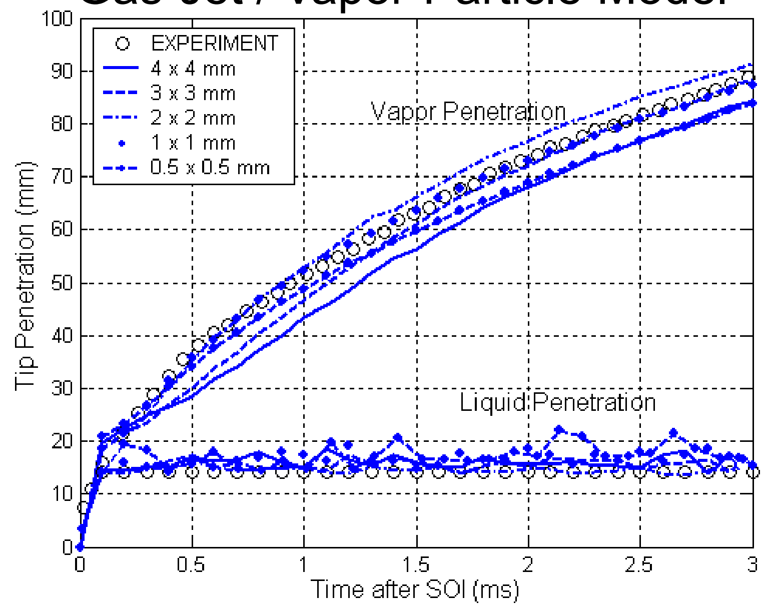


Standard KIVA





Gas-Jet / Vapor-Particle Model



Future Plans: Multiple injections and LTC conceptual model development

- Current results show that diesel jet interactions are critical for soot reductions with multiple injections
  - Use planar laser diagnostics (LII, OH PLIF) to learn how soot formation dynamics can be controlled
  - Use planar-laser diagnostics (fuel tracer PLIF, formaldehyde PLIF) to understand mixing, ignition, and combustion dynamics of multiple injections
  - Understand how post-injection interactions with main-injection soot are affected by targeting: vary the injection spray angle and/or swirl
  - Use other injections schemes (split-main, pilot, three or more injections)
- Continue to develop and refine conceptual model extension for LTC
  - Consolidate insights from multiple institutions and try to build a consensus on the chemical and mixing processes of LTC

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

- ④ (SNL) Entrainment wave concept explains many LTC phenomena, and is helping industrial partners to address practical engine issues
- ② (SNL) Interaction between post-injection and residual soot from main injection is critical for soot reductions
- ④ (SNL) Wall temperature diagnostic demonstrated
- ④ (UW+SNL) Improved computer models with reduced grid dependency agree with and supplement experiments