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

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Program Manager: Gurpreet Singh

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### 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


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.

**Current Specific Objectives:**

1. **(SNL)** Extend diesel conceptual model to LTC
2. **(SNL)** Understand multiple injection effects on LTC
3. **(SNL)** Develop wall temperature diagnostic for studying liquid film dynamics
4. **(UW+SNL)** Improve computer modeling for LTC/diesel sprays and study piston geometry effects on LTC
Entrainment Wave found to be important for many LTC (and diesel) combustion and emissions phenomena

- **Last year:** Used simple 1-D CFD to analyze mixing after end of injection
  - Revealed “Entrainment Wave” (EW)
- **This year:** 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
- **New:** Analytical solution confirms CFD predictions and defines limits of mixing
- **Tech. Transfer:** (1) Cummins used EW knowledge to develop low-HC injection strategy, (2) GM modeling EW in KIVA

\[
\sqrt{M} = \left( \frac{t}{2t_{1/2}} - 1 \right)^2 \frac{M_0}{4} - \tan\left( \frac{\theta}{2} \right) \sqrt{\frac{\pi \rho M_0 (z_0)^2 - (z')^2}{8t_{1/2}}} 
\]
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
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
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.
Effectiveness of post injections increases with more interaction with main-injection soot

- (A) For **early** 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 **late** 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
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!)

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

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Theoretical Fringes

Measured Fringe Pattern

Engine Block

Quartz Window

ND Filter

High-Speed Camera

He-Ne Laser

Cylindrical Lenses

M1, M2, M3
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.
New gas-jet and vapor-particle sub-models reduce grid dependency for diesel sprays

- 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)

\[ \Delta X = R_{\text{JET},P} \]

\[ L_{\text{crit}} \]

\[ U_{\text{g}} \]

Abani and Reitz, ICLASS-09

• Liquid Particle
• Vapor Particle
• Liquid Particle with Vapor Cloud

\[ X_p \]: Vapor Particle Position
\[ R_{\text{JET},P} \]: Jet Width at \( X_p \)
Liquid and vapor penetration predictions much less grid-dependent with new models for KIVA
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.

1. (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.
3. (SNL) Wall temperature diagnostic demonstrated.
4. (UW+SNL) Improved computer models with reduced grid dependency agree with and supplement experiments.