Fuel Effects on Advanced Combustion: Heavy-Duty Optical-Engine Research

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Overview

Timeline
- Project provides fundamental research to support DOE/industry fuel-technologies projects
- Project directions and continuation are evaluated annually

Budget
- Project funded by DOE/VT:
  FY08 – $670K
  FY09 – $600K

Barriers*
- “Lesser-known combustion and emission-formation characteristics of non-petroleum-based fuels”
- “Lack of adequate combustion understanding and simulation capability, especially for new combustion regimes”
- “Need better understanding of composition range of fuels and impacts on advanced combustion”
  * Source: 21st Century Truck Partnership Roadmap

Partners
- Project lead: Sandia – C.J. Mueller (PI)
  B.T. Fisher (post-doc), A.S. Cheng (visitor)
- 15 industry partners in Advanced Engine Combustion Working Group
- Coordinating Research Council (CRC)
- Caterpillar Inc.
Objectives

Develop the fuel-effects and engine-combustion science-base required for maximum petroleum displacement

- Specific objectives of work since FY08 Annual Merit Review
  - Identify underlying cause(s) of NO\textsubscript{x} increase when fueling with biodiesel
  - Study effects of fuel volatility on CI engine efficiency and emissions when using an early direct-injection strategy
  - Establish capability to measure in-cylinder liquid-phase fuel penetration under early direct-injection operating conditions
  - Contribute to development of surrogate diesel fuels for use in combustion modeling studies
Milestones

- **September 2008**
  Demonstrate capability to make in-cylinder liquid-phase fuel penetration measurements under early direct-injection conditions with single-component, low-cetane fuel

- **March 2009**
  Complete publication summarizing origins of biodiesel NO\textsubscript{x} increase
  - **August 2009**
    Complete publication summarizing fuel-volatility effects on efficiency and emissions under early direct-injection conditions
  - **September 2009**
    Complete publication summarizing in-cylinder liquid-phase fuel penetration results for two single-component, low-cetane fuels
  - **October 2009**
    Co-lead AVFL-18 team to formulate a surrogate for #2 diesel that has been validated to match certain desired fuel properties
Use optical engine and advanced diagnostics to understand fuel effects on in-cylinder processes
Technical Accomplishments

- Identified mechanisms explaining $\text{NO}_x$ increase when fueling with biodiesel
- Showed how increasing diesel-fuel volatility can dramatically increase efficiency and decrease emissions under early direct-injection operating conditions
- Established capability to quantitatively measure in-cylinder liquid-phase fuel penetration under early direct-injection operating conditions
- Helped form and lead working group to develop surrogate diesel fuels for use in combustion modeling studies
Technical Question #1: What Causes the Biodiesel NO\textsubscript{x} Increase? (1 of 2)

• Reacting mixtures closer to stoichiometric during ignition

- Higher temperatures, faster reaction rates, less subsequent mixing-controlled combustion required for complete oxidation, shorter combustion duration, longer residence time at high temperature
- Consistent with biodiesel NO\textsubscript{x} increase at lower loads

\[
\phi = \frac{\left( \frac{m_A}{m_F} \right)_{st}}{\left( \frac{\dot{m}_A}{\dot{m}_F} \right)} > 1
\]

- Smaller for biodiesel (fuel contains oxygen)
- Approx. constant regardless of fuel

See SAE 2009-01-1792 for details
Technical Question #1: What Causes the Biodiesel NO\textsubscript{x} Increase? (2 of 2)

- Reacting mixtures closer to stoichiometric in the standing premixed autoignition zone (AZ) near the lift-off length
  
  - Effects similar to those at ignition, plus less soot → less radiative heat loss → higher temperatures
  - Consistent with biodiesel NO\textsubscript{x} increase at higher loads

See SAE 2009-01-1792 for details
Technical Question #2: Does Increasing Fuel Volatility Benefit Early-DI Operation?

- Yes. Avoiding fuel-film formation enables significantly higher efficiency with lower emissions.

HVx = x vol% high-volatility fuel blended with #2 ULSD
SOI = start of injection
Tech. Question #3: How Does Liquid Length Vary under Unsteady In-Cylinder Conditions?

- **Good agreement with steady-state model** (D.L. Siebers, SAE 1999-01-0528)
  - Strong dependence on instantaneous density and temperature
  - Relatively independent of injection pressure
- “Memory” of conditions earlier in injection event is short

*In-cylinder elastic-scattering image of liquid-phase fuel*
Technical Question #4: How to Better Understand and Predict Fuel-Composition Effects?

• Develop more accurate diesel surrogate fuels
  – Team assembled under Coordinating Research Council as AVFL-18
  – Led by Chuck Mueller (Sandia) and Bill Cannella (Chevron)

• Goal is to produce a surrogate for a full-boiling-range #2 diesel fuel with matched:
  – Ignition quality (derived cetane number)
  – Adiabatic flame temperature and EGR composition (C/H ratio)
  – Sooting tendency (% of fuel carbon in aromatic structures)
  – Distillation curve

• 4-component blending model created in FY09
  – Used linear blending to match ignition quality, C/H ratio, and aromatic content
Future Work

• Quantify and model liquid-phase fuel penetration for pure compounds under unsteady in-cylinder conditions
  – Heptamethylnonane and iso-octane

• Study mixing-controlled high-efficiency clean combustion using diesel and an oxygenated fuel, < 40% EGR, and small injector orifices
  – Relies on implementation of new high-pressure common-rail fuel-injection system

• Investigate biodiesel feedstock effects on in-cylinder processes
  – Liquid-phase fuel penetration
  – Combustion and emissions

• Continue diesel surrogate fuel development (AVFL-18)

• Continue other active collaborations
  – Advanced Engine Combustion Working Group, Fuels for Advanced Combustion Engines, Caterpillar
Summary

- This fundamental fuel-effects research effort is tightly focused on a primary DOE goal of petroleum displacement, with close collaboration and guidance from industry stakeholders.

- Significant technical accomplishments have been made during this reporting period, including:
  - Identified mechanisms explaining NO\textsubscript{x} increase when fueling with biodiesel.
  - Showed how increasing diesel-fuel volatility can dramatically increase efficiency and decrease emissions under early-DI operating conditions.
  - Established capability to quantitatively measure in-cylinder liquid-phase fuel penetration under early-DI operating conditions.
  - Helped form and lead working group to develop surrogate diesel fuels for use in combustion modeling studies.