Fuel Effects on Advanced Combustion Engines

Charles J. Mueller
Combustion Research Facility
Sandia National Laboratories

Research Supported by
US DOE Office of Vehicle Technologies
Program Manager: Kevin Stork

FY 2008 DOE Vehicle Technologies Program Annual Merit Review Meeting
Bethesda North Marriott Hotel, Bethesda, MD
Wednesday, Feb. 27, 2008 (Salon G, 9:20 a.m.)

Note: this presentation does not contain any proprietary or confidential information
Outline

- Purpose of work
- Previous review comments addressed
- Technical barriers
- Approach to overcoming technical barriers
- Performance measures and accomplishments
- Technology transfer
- Publications and presentations
- Plans for FY 2009
- Summary
Purpose of Work: Develop the Engine-Combustion Science-Base Required for Maximum Petroleum Displacement

- Facilitate use of domestic, non-petroleum-based diesel fuels → >0.02 Mbdp
  - Investigate the magnitude and origin(s) of the biodiesel NO\(_x\) increase when operating under conventional and advanced combustion modes

- Develop advanced combustion strategies to enable high-efficiency, clean-combustion (HECC) engines → 0.4 to ~3 Mbdp
  - Overcome barriers to achieving early-direct-injection HECC

- Establish fundamental understanding of fuel effects necessary for computational optimization of HECC engines
  - Assist in efforts to provide reference and surrogate fuels for the diesel-engine research community

Potential to reduce petroleum consumption by millions of barrels per day
Responses to Recommendations from FY07 Review

- “This work is one of the most outstanding DOE funded efforts and should be maintained or expanded to enable advanced combustion... for heavy-duty engines.”

- All noted weaknesses addressed:
  - “Intake oxygen mole fractions of 8% aren’t realistic.”
    - Used 16.5% $O_2$ for biodiesel work, 15.0% for early-DI HECC study
  - “Not sure how much value was gained from testing fuels such as TPGME/water blends.”
    - TPGME/water blend study has been completed and published
  - “Citation of external interactions was not supported in the described tasks.”
    - Recent research results are shared with all members of Advanced Engine Combustion (AEC) Working Group at meetings twice a year
  - “Need more focus on testing of fuels that have a reasonable chance of being available in the marketplace.”
    - Increasing responsibilities in Fuels for Advanced Combustion Engines (FACE) Working Group
Technical Barriers* and Relationship to FY08 Activities

- "Lesser-known combustion and emission-formation characteristics of non-petroleum-based fuels" and "efficiency typically reduced by measures to reduce NO\textsubscript{x} emissions"
  - Biodiesel NO\textsubscript{x} research

- "Apparent lack of cost-effective and innovative advanced engine concepts"
  - Early-direct-injection HECC experiments, hardware upgrades

- "Need better understanding of composition range of fuels and impacts on advanced combustion regimes"
  - Development of FACE reference fuels

- "Lack of adequate combustion understanding and simulation capability, especially for new combustion regimes"
  - Development of surrogate fuels

Approach: Understand Fuel Effects on In-Cylinder Processes Using Optical Engine and Advanced Diagnostics

- Modern Engine Hardware
- Advanced Fuels
- Guidance from Industry, Academia, Nat’l Labs

Science-Base to Enable HECC Engines
Performance Measures

1. Investigate NO\textsubscript{x} increase when fueling with biodiesel
   - Magnitude of NO\textsubscript{x} increase in conventional and HECC operating modes
   - Effects of radiative heat transfer on NO\textsubscript{x} emissions
   - Insight into origins of biodiesel NO\textsubscript{x} increase (relevant for all fuels)

2. Identify limiting processes in early-direct-injection HECC
   operation with diesel-boiling-range fuels
   - Origin of increased smoke and NO\textsubscript{x} when injection timing is advanced

3. Assist with design of reference and surrogate fuels
   - To establish an intelligent foundation for fuel-effects studies in advanced
     combustion regimes (experimental and computational)

4. Upgrade engine peak cylinder pressure capability by 50%
   (from 8.0 to 12.0 MPa)
   - Complete fabrication of upgraded spacer ring and cylinder liner
Accomplishment #1: Quantified Magnitude of Biodiesel NO$_x$ Increase under HECC Mode & Showed Role of Radiative Heat Transfer

- Biodiesel NO$_x$ increase is larger in HECC mode
- Changes in radiative heat transfer correlate with NO$_x$ changes for B100 and B94, but CN45 doesn’t show same trend
- Radiative heat transfer effects important (but not only) factor

SINL = spatially integrated natural luminosity (crank-angle resolved measure of radiative heat transfer)
Accomplishment #2: Determined Cause of High Smoke and NO\textsubscript{x} in Early-DI HECC Strategies with Diesel Fuel

- Pool fires = burning films of liquid fuel
  - Emissions correlate with high SINL
  - High SINL occurs after AHRR ends
  - Origin of high SINL is pool fires

- $\phi \geq 1$ pool-fire combustion produces soot and NO\textsubscript{x}

- Increasing volatility of fuel could help avoid pool fires

15-hole, dual-included-angle nozzle: 5 x 35° plus 10 x 70°, all orifices 105-μm diam.

1450 bar peak inj. pressure
Start of injection = -69.5°

1200 rpm
15.0% O\textsubscript{2} (50% EGR)
4.82 bar gross IMEP
$\phi = 0.39$
Accomplishment #3: Continuing to Assist Researchers Studying Fuel Effects on HECC Operating Modes

- Developing common, publicly available, well-characterized reference fuels for experimental and computational studies
  
- FACE fuels for experimental research
  - Reference fuels blended from actual refinery streams
  - 8 of 9 fuels have been produced, all will be available soon

- Surrogate fuels for computational engine design and optimization
  - I am team leader of FACE chemical-kinetics activity, also active member of Diesel Surrogates Working Group
  - Create/evaluate diesel surrogates
  - Active teaming with experts in kinetic modeling (W. Pitz et al. at LLNL)
Accomplishment #4: Increased Peak Cylinder Pressure Capability of the Optical Engine by 50% (from 8.0 to 12.0 MPa)

- 20-MPa-capable upgrades to spacer ring and cylinder liner are complete
- New custom hydraulics for liner-support system fabricated
- Also: in-cylinder, orifice-specific injection rate meter completed and tested
Collaborations and Tech Transfer (1 of 2)

- **Advanced Engine Combustion (AEC) Working Group:**
  - OEMs: Caterpillar, Cummins, DaimlerChrysler, Deere, Detroit Diesel, Ford, General Electric, General Motors, International, Mack/Volvo
  - Energy Companies: British Petroleum, Chevron, ConocoPhillips, ExxonMobil, Shell Global Solutions
  - National Laboratories: Lawrence Livermore, Oak Ridge, Argonne, Los Alamos, National Renewable Energy Laboratory

- **Fuels for Advanced Combustion Engines (FACE) Working Group:**
  - Labs: Battelle, Coordinating Research Council, LLNL, National Centre for Upgrading Technology (Canada), NREL, ORNL, PNNL
  - Energy/petrochemical companies: British Petroleum, Chevron, ConocoPhillips, ExxonMobil, Marathon-Ashland
  - Engine OEMs: Cummins, Ford, General Motors, International
  - Academia: West Virginia University
Collaborations and Tech Transfer (2 of 2)

- **Diesel Surrogates Working Group:**
  - US Dept. of Defense, Caterpillar, Drexel University, ExxonMobil, NIST, Princeton University, Stanford University

- **DOE HECC Research:**
  - David Milam and Michael Radovanovic, Caterpillar
  - Chris Wright, ExxonMobil
  - Not part of DOE Fuels R&D Program but collaboration adds value

- **Biodiesel Combustion and Emissions:**
  - Prof. André Boehman, Pennsylvania State University
  - Prof. A.S. (Ed) Cheng, San Francisco State University
  - Bill Pitz, Lawrence Livermore National Laboratory
Publications and Presentations Since Last Merit Review Meeting


11 presentations (including 3 invited plenary) since last review
FY09 Research Directions

- Study effects of fuel volatility on transient liquid-phase fuel penetration for time-varying in-cylinder conditions and injection rate
  - Single-component fuel

- Investigate fuel-volatility effects on early-direct-injection HECC
  - Are pool fires still limiting factor for efficiency and emissions compliance?

- Explore mixing-controlled HECC using diesel fuel and < 40% EGR
  - Small (< Ø110-µm) orifices are essential

- Engine hardware upgrades
  - Finish design and fabrication of 20-MPa-capable optical piston, connecting rod, and balancing masses
  - Work with Caterpillar to design 20-MPa-capable, variable-swirl cylinder head with new common-rail fuel system

- Continue active collaborations
  - AEC, FACE, and Diesel Surrogates Working Groups; also DOE HECC activities
Summary

- Project demonstrates a solid, proven approach to overcoming key technical barriers to achieving HECC → significant petroleum displacement
  - Optical engine + advanced diagnostics + engine-out emissions meas’mts
  - Fundamental understanding of fuel effects on in-cylinder processes governing efficiency and emissions

- Project is a key resource for producing timely results on HECC fuel effects
  - Heat transfer differences play important role in biodiesel NO\textsubscript{x} increase
  - Liquid fuel impingement and pool fires are key barrier to early-DI HECC
  - Assisting with formulation of reference and surrogate fuels
  - Hardware upgrades are essential for studying emerging technologies

- Project builds on past successes, is responsive to reviewers’ feedback, has many active collaborations to facilitate tech. transfer, and has a clear vision for future work
Acknowledgments

Caterpillar (David Milam, Michael Radovanovic) – support, advice

Dr. Glen C. Martin – post-doc

Dr. Brian T. Fisher – post-doc

Dr. Krishna Lakshminarasimhan – former post-doc