Low-Temperature Diesel Combustion Cross-Cut Research

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Sandia National Laboratories

FY 2010 DOE Vehicle Technologies Program Annual Merit Review
Project ACE005, V Virginia C, 11:00 – 11:30 AM, Tuesday, June 8, 2010

Sponsor: DOE Office of Vehicle Technologies
Program Managers: Gurpreet Singh and Kevin Stork

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Overview

Timeline
• Project provides fundamental research that supports DOE/industry advanced engine development projects.
• Project directions and continuation are evaluated annually.

Barriers
• Engine efficiency and emissions
  – Sources of unburned hydrocarbons and CO for LTC combustion
• Load limitations for LTC
• CFD model improvement for engine design/optimization

Partners
• 15 Industry partners in the Advanced Engine Combustion MOU
• Participants in the Engine Combustion Network
  – Experimental and modeling
• Project lead: Sandia
  – Lyle Pickett (PI)

Budget
• Project funded by DOE/VT: FY09- $570K
  FY10 - $660K
Overall Approach

• Facility dedicated to fundamental combustion research for both heavy-duty and light-duty engines (cross-cut research).
  – Well-defined charge-gas conditions
    • Pressure, temperature, EGR level
  – Well-defined injector parameters
    • Injection pressure, fuel, multi-injections

Experiments in CV
  • Well-defined boundary conditions
  • Quantitative diagnostics at engine conditions
  • Improved physical understanding

Computer models
  • “Retain” insights from experiment
  • Adds knowledge about things that are not “measurable”
  • Parametric design optimization
  • Saves time and cost over “hardware” iteration

High-Efficiency, Low-Emissions Engine
Objectives/Milestones

• Aid the development of computational models for engine design and optimization (ongoing).
  – Experimental and modeling collaboration through the Engine Combustion Network: http://www.ca.sandia.gov/ECN

• Determine the factors that cause liquid wall impingement at post-injection (DPF-regeneration) conditions (FY09-FY10).
  – Urgent need to understand oil dilution, inefficiency using diesel/biodiesel fuel.
  – FY10 (2): First vaporization measurements at low-density, high-T conditions.

• Quantitative characterization of soot processes in transient sprays at LTC conditions (FY08-FY10).
  – Emitted soot is an emissions burden, source of inefficiency, expense.
  – FY10 (3): Comparison of biodiesel and diesel soot distributions. Methods to reduce soot even with mixing-controlled (negative-dwell) heat release.
• Operation at the same ambient and injector conditions: “Spray A”
# Experimental participation in the ECN

<table>
<thead>
<tr>
<th>Institution</th>
<th>Facilities</th>
<th>Personnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandia</td>
<td>Preburn CV</td>
<td>Lyle Pickett, Caroline Genzale</td>
</tr>
<tr>
<td>IFP</td>
<td>Preburn CV</td>
<td>Gilles Bruneaux, Louis-Marie Malbec</td>
</tr>
<tr>
<td>CMT</td>
<td>Cold CV, Flow PV</td>
<td>Julien Manin, Raul Payri</td>
</tr>
<tr>
<td>Chalmers</td>
<td>Flow PV</td>
<td>Mark Linne</td>
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<tr>
<td>GM</td>
<td>Flow PV</td>
<td>Scott Parrish</td>
</tr>
<tr>
<td>Argonne</td>
<td>Cold V, X-ray Synchrotron</td>
<td>Chris Powell, Alan Kastengren</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>Flow PV</td>
<td>Tim Bazyn, Glen Martin</td>
</tr>
<tr>
<td>Aachen</td>
<td>Flow PV</td>
<td>Heinz Pitsch</td>
</tr>
<tr>
<td>Meiji U.</td>
<td>Preburn CV</td>
<td>Tetsuya Aizawa</td>
</tr>
<tr>
<td>Seoul Nat. U.</td>
<td>Preburn CV</td>
<td>Kyoungdoug Min</td>
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## Past/future modeling participation in the ECN

<table>
<thead>
<tr>
<th>Institution</th>
<th>Lead</th>
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<tbody>
<tr>
<td>Sandia</td>
<td>Joe Oefelein</td>
</tr>
<tr>
<td>IFP</td>
<td>Christian Angelberger</td>
</tr>
<tr>
<td>Chalmers</td>
<td>Fabian Kärrholm</td>
</tr>
<tr>
<td>Polit. di Milano</td>
<td>Tommaso Lucchini</td>
</tr>
<tr>
<td>City Univ.</td>
<td>Manolís Gavaises</td>
</tr>
<tr>
<td>Imperial College</td>
<td>David Gosman</td>
</tr>
<tr>
<td>Univ. Wisconsin-Madison</td>
<td>Rolf Reitz, Chris Rutland</td>
</tr>
<tr>
<td>Doshisha Univ.</td>
<td>Jiro Senda</td>
</tr>
<tr>
<td>Aachen/Stanford</td>
<td>Heinz Pitsch</td>
</tr>
<tr>
<td>Purdue Univ.</td>
<td>John Abraham</td>
</tr>
<tr>
<td>Penn State</td>
<td>Dan Haworth</td>
</tr>
<tr>
<td>Convergent Science</td>
<td>Kelly Senecal</td>
</tr>
<tr>
<td>Many other companies (like Bosch) and institutions</td>
<td></td>
</tr>
</tbody>
</table>
How will focus at “Spray A” conditions advance understanding of spray combustion?

- Quantitative, complete datasets (velocity, species, temperature) still do not exist at engine conditions.
  - Need to move beyond “conceptual model” to more detailed comparison.
  - Follows direction of successful activities using more basic flames (TNF workshop).
- Leveraging of work by many experimental and modeling activities will accelerate research.

### Spray A Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient gas temperature</td>
<td>900 K</td>
</tr>
<tr>
<td>Ambient gas pressure</td>
<td>6 MPa</td>
</tr>
<tr>
<td>Ambient gas density</td>
<td>22.8 kg/m³</td>
</tr>
<tr>
<td>Ambient gas composition</td>
<td>15% O₂, 75.1% N₂, 6.2% CO₂, 3.6% H₂O</td>
</tr>
<tr>
<td>Common rail fuel injector</td>
<td>Bosch solenoid-activated, generation 2.2</td>
</tr>
<tr>
<td>Fuel injector nozzle outlet diameter</td>
<td>0.090 mm</td>
</tr>
<tr>
<td>Nozzle K factor</td>
<td>1.5 ( { K = (d_{inlet} - d_{outlet})/10 \text{ [um]} } )</td>
</tr>
<tr>
<td>Nozzle hydro-erosion</td>
<td>Discharge coefficient = 0.86 with 100 bar ( \Delta P ).</td>
</tr>
<tr>
<td>Spray full included angle</td>
<td>( 0° ) (1 axial hole) or ( 145° ) (3-hole)</td>
</tr>
<tr>
<td>Fuel injection pressure</td>
<td>150 MPa</td>
</tr>
<tr>
<td>Fuel</td>
<td>n-dodecane</td>
</tr>
<tr>
<td>Fuel temperature at nozzle</td>
<td>363 K (90° C)</td>
</tr>
<tr>
<td>Common rail volume/length</td>
<td>22 cm³/28 cm (Use GM rail model 97303659)</td>
</tr>
<tr>
<td>Distance, injector inlet to common rail</td>
<td>24 cm</td>
</tr>
<tr>
<td>Fuel pressure measurement</td>
<td>7 cm from injector inlet / 24 cm from nozzle</td>
</tr>
<tr>
<td>Injection duration</td>
<td>1.5 ms</td>
</tr>
<tr>
<td>Approximate injector driver current</td>
<td>18 A for 0.45 ms ramp, 12 A for 0.345 ms hold</td>
</tr>
</tbody>
</table>

Model comparisons to baseline dataset available on the ECN

![Graph showing mixture fraction vs. radius](image-url)
Careful characterization of vessel boundary conditions (temperature) is required.

Schlieren of preburn and cooldown

Gas temperature measurement

Vessel position for TC
Axial $x = 55$ mm
Horiz. $y = 0$ mm
Vertical $z = 0$ mm

$T_{bulk} = \frac{P \cdot MW}{\rho \cdot R_u \cdot Z}$

Flame arrival
Compression Heating
Ambient gas has uniform, horizontal “core”.

Core gas temperature distribution

Buoyancy induced vertical variation in temperature
Injector boundary conditions characterized at multiple facilities.

n-dodecane
90 C
1 atm back pressure

18 Amps 450 \(\mu\)s +
12 Amps 345 \(\mu\)s

330 \(\mu\)s hydraulic delay

Spray A specification:
1500 \(\mu\)s injection duration
mass = 3.5 mg (here)
Comparison of vapor/liquid penetration at two facilities shows reasonable agreement.

Schlieren visualization. Liquid Mie-scatter border in blue. 0% O₂: non-reacting

Graph showing:
- Maximum Penetration [mm] vs Time ASI [µs]
- Comparison of vapor/liquid penetration at two facilities
- Reacting Penetration
- Vapor Non-reacting
- Liquid
Ignition at 450 µs is followed by a quasi-steady lift-off length at 15-17 mm.

- Ignition/lift-off are examples of other measurements for Spray A.
- Refined, quantitative measurements are being pursued to follow these initial measurements (e.g., mixture fraction, liquid volume fraction).
(2) Liquid penetration for late-cycle post-injections is problematic, uncharacterized.

- One strategy used for DPF regeneration is to implement a late-cycle post-injection to enrich the exhaust stream.

**HOWEVER,**
- These injections typically occur well after TDC (near EVO), when in-cylinder densities are quite low. Wall-wetting, oil dilution are concerns!

1. Very low densities
2. Relatively high temperatures (post-combustion)

**Typical post-injection timing for DPF regeneration**

- \( T_{\text{BDC}} = 313 \text{ K} \)
- \( P_{\text{BDC}} = 100 \text{ kPa} \)
- \( \text{A/F} = 20:1 \)
- \( \text{CR} = 17.5:1 \)
Even though temperature are high, liquid penetration exceeds engine dimensions.

0.108 mm nozzle, 1500 bar injection pressure

**#2 Diesel**

- 2 kg/m³
- 1.2 kg/m³
- 3 kg/m³

**Neat Soy-based Biodiesel:**

15-25% increase in liquid penetration

<table>
<thead>
<tr>
<th>Fuel</th>
<th>#2 Diesel</th>
<th>Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>T90 [°C]</td>
<td>315</td>
<td>351</td>
</tr>
<tr>
<td>ρ at 100°C [kg/m³]</td>
<td>767</td>
<td>793</td>
</tr>
</tbody>
</table>

½ bore: light-duty engines
Short injections can limit the maximum liquid penetration, but fuel quantities are small.

1.2 kg/m³ 800 K

3.0 kg/m³ 1200 K
(3) First measurements of soot distribution within combusting biodiesel sprays.

- Factor of five reduction in total soot formed within reacting spray.
- Long inception time permits soot-free combustion with negative ignition dwell, lower heat release.
(4) Soot sampling from sprays within high-temperature, high-pressure combustion vessel.

TEM probe within the combustion vessel.

Spray direction.

TEM grid.

3 mm diameter TEM grid:
- Copper mesh covered by an amorphous carbon film.

TEM grid held within the probe to protect it from excessive heating.
Restrictive passage quenches reaction and protects the TEM grid.

Soot-laden gas skims past the probe, enters through a 1-mm diameter hole, and deposits on the TEM grid.

TEM image of soot particles.
50 mm collection position
60 mm collection position
86 mm collection position
A key input for soot models, the particle size and shape are now characterized.
Future work

• Outlook for the Engine Combustion Network
  – Measurements (not a complete list, Sandia in blue):
    • Nozzle shape
    • Internal needle movement
    • Discharge and area contraction coefficients
    • Rate of injection
    • Near-nozzle liquid volume fraction
    • Droplet size, velocity, shape
    • Maximum liquid penetration
    • Vapor penetration rate
    • Velocity and turbulence within spray
    • Mixture fraction (non-reacting and reacting)
    • Ignition delay
    • Cool flame position and timing
    • Heat-release rate
    • Quantitative soot, soot precursor distribution
    • Lift-off length

  – Side-hole spray compared to axial hole
  – Liquid volume fraction near the liquid length

• Spray-spray interaction effects on mixing and lift-off length.

• Biodiesel soot processes, including soot particle morphology.

• Gasoline direct injection sprays
  – Isolate ignition processes using laser ignition.
  – Identify regimes with both autoignition and flame propagation.
  – Use diesel and GDI-type injectors.
Presentation Summary

- Project is relevant to the development of high-efficiency, low-emission engines.
  - Observations of combustion in controlled environment lead to improved understanding/models for engine development.

- FY10 approach addresses long term and short term needs.
  - Lead team to develop the ECN Spray A condition.
  - Massive dataset is being generated, which will be a key component for future model improvement.
  - Responding to new problems for DPF regeneration, characterized late-cycle post-injection liquid penetration.
  - Made first measurements of soot distribution in biodiesel sprays.
  - Quantified the soot size and morphology within sprays at engine conditions.

- Collaboration expanded to accelerate research and provide greatest impact (MOU, Engine Combustion Network)

- Future plans will continue effort
  - “Spray A” characterization for the ECN.