Low-Temperature Diesel Combustion Cross-Cut Research

Project ID: ace_05_pickett

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Sponsor: DOE Office of Vehicle Technologies
Program Manager: Gurpreet Singh

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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.

## Budget

- Project funded by DOE/VT: FY08 - $580K
  - FY09 - $570K

## Barriers

- Engine efficiency and emissions
  - Sources of unburned hydrocarbons and CO for LTC combustion
- Low-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)
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
• Sum of many sub-models
• 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

• Determine the factors that cause liquid wall impingement at early-injection LTC conditions (FY07-FY09).
  – Addresses an important source of UHC, oil dilution, inefficiency.
  – FY09 (1): Root causes and limitations for early-injection liquid penetration explained and modeled.

• Characterize liquid vaporization and flame/ignition propagation after the end of injection (FY08-FY09).
  – UHC may remain near the injector when using LTC combustion.
  – FY09 (2): Investigate the controlling parameters that extinguish or permit combustion near the injector after the end of injection.

• 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
  – FY09 (3): Develop a baseline high-temperature, high-pressure condition, attain injector set for experimentation by multiple laboratories.
(1) Characterize liquid wall impingement at early-injection LTC conditions.

- Provide quantitative measurement of liquid penetration using optical techniques.
- Assess the effects of
  - temperature
  - boost (density)
  - fuel
  - nozzle size
  - injection pressure
- Prevention by using short and multiple injections.
- Liquid penetration modeled using mixing-limited vaporization (Siebers 1999).
(1) High-speed imaging of liquid and vapor boundaries of penetrating spray

Chamber dimensions allow extensive visualization before wall impingement.

-40 CAD
$T_a = 600$ K
$d' = 0.108$ mm
diesel

Dur. Inj. 0.2 ms
Mass Inj. 0.7 mg

(click to play movie)
Past research focused on TDC, steady conditions, rather than transient, early-injection.

- Liquid penetration follows vapor until some critical distance (max. liquid length).
- Steady liquid length identified at early-injection conditions.
  - Much longer than TDC liquid length.
  - Liquid wall impingement likely.

Siebers 1999

<table>
<thead>
<tr>
<th>Ambient temperature $T_a$</th>
<th>Ambient density $\rho_a$</th>
<th>Orifice diameter $d$</th>
<th>Injection pressure $P_{inj}$</th>
<th>Fuel 90% boiling point $T_{90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑</td>
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</tbody>
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Liq. length: $↓$
Advanced injection timing increases liquid penetration.

Wall impingement (100 mm) at -40 CAD

- $d = 0.108$ mm
- 110 MPa
- #2 diesel

$\cdot$ Time ASI to attain steady liquid length, $t_{ss}$, increases.
Liquid length model shows ability to capture trends wrt to ambient conditions, fuel, nozzle.

Mixing fuel and ambient to saturated mixture state. Spray spreading angle, fuel/ambient thermodynamic properties used as inputs (Siebers 1999).

- Use of low-boiling-point fuel can significantly lower liquid penetration.
  - T₉₀ is 75 °C less for kerosene than diesel.
- Reducing nozzle orifice size will reduce liquid penetration.
- Low-boiling-point fuel more effective at reducing liquid penetration than use of a small nozzle orifice.
  - Liquid length does not increase as sharply for kerosene compared to diesel when advancing injection.
  - Confirmed by both experiments and modeling results.
- Model overpredicts liquid length at earlier CAD.
Why does injection advancement cause less liquid length increase for kerosene over diesel?

- Mixture thermodynamics show:
  - Lower saturated temperature $T_{sat}$ for kerosene.
  - Higher $(F/A)_{sat}$ for kerosene.

- With earlier CAD, $(F/A)_{sat, kero.}$ progressively increases.
  - Higher saturated F/A ratio $\rightarrow$ shorter liquid length

- Kerosene more resistant to wall-wetting with early injection, even compared to diesel and small nozzle orifice diameter.

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**Conditions**

<table>
<thead>
<tr>
<th>Ambient</th>
<th>Fuel</th>
<th>Diesel</th>
<th>Kerosene</th>
</tr>
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<tbody>
<tr>
<td>600 K</td>
<td>373 K</td>
<td>$T_{sat} = 508$ K</td>
<td>$T_{sat} = 474$ K</td>
</tr>
<tr>
<td>5.2 kg/m³</td>
<td></td>
<td>$(F/A)_{sat} = 0.17$</td>
<td>$(F/A)_{sat} = 0.29$</td>
</tr>
</tbody>
</table>
Boost significantly lowers liquid penetration.

- Boost helps to reduce wall impingement when using early injection.
  - Spray penetration speed also reduced.
- Time to reach steady state $t_{ss}$ depends upon conditions.
  - At early CAD, boost increases $t_{ss}$.
  - At later CAD, boost decreases $t_{ss}$. 
Why does $t_{ss}$ increase or decrease with boost at various injection timings?

Use model jet penetration (Naber and Siebers 1996) and liquid length prediction (Siebers 1999).

- Liquid length $L$ depends upon density and $(F/A)_{sat}$.  
- $L$ decreases with increasing density.  

\[ t_{ss} \propto \frac{L}{U_f} \cdot \frac{1}{(F/A)_{sat}} \]  

- $(F/A)_{sat}$ depends only on mixture thermodynamic properties.  
- $(F/A)_{sat}$ decreases with increasing pressure (boiling point $T$ increases).

- The tradeoff between (1) and (2) determines whether the time to attain a steady liquid length will increase or decrease.
Reducing injection duration/mass produces injections with shorter liquid penetration.

- The injection duration must be shorter than $t_{ss}$ to have maximum liquid penetration less than the quasi-steady liquid length.
Injection duration must be less than \( \frac{1}{2} \) of \( t_{ss} \) to reduce the maximum liquid penetration.

- Increased ambient entrainment must propagate downstream to the jet head to reduce F/A and vaporize liquid fuel.
- Musculus’ jet model shows that the entrainment wave reaches the jet head at 2 times the injection duration.
Relevance of early-injection liquid penetration research to LTC.

- Experiments provide data on the steady liquid length and time of penetration that is critical for spray model validation.
- Knowledge about the critical injection duration to limit liquid penetration ($\frac{1}{2}$ of $t_{ss}$) allows injection rate control optimization.
  - Multiple injections limit the liquid penetration and increase the injected mass.
  - Provides a pathway to increase engine load for LTC.
- New understanding about low-boiling-point fuels and their resistance to wall-wetting (superior to diesel+small nozzles) allows further optimization of LTC using alternative fuels.
- Well-controlled environment (pressure and temperature) reveals the fundamental causes of liquid penetration.
  - Needed to understand spray events in an unsteady engine environment.
- Findings provide comprehensive understanding needed to minimize liquid wall impingement and UHC in LTC engines.
(2) Accomplishment: Flame extinction after EOI affected by fuel/ambient mixture.

- Dataset shows lack of flashback for lower equivalence ratio conditions when $\phi(H) < 3$.
- Flashback determines whether or not near nozzle region produces UHC.
(3) Accomplishment: Development of ECN is accelerating model development.

**Successful LTC Engines**

**Experimental Data**
- Soot volume fraction
- Mixture fraction
- Rate of injection
- Ignition Delay
- Heat-release
- Fuel effects
- Temperature
- Pressure
- Inject. Pressure

**Engine Combustion Network**
http://www.ca.sandia.gov/ECN

**Improved, predictive models**
- SAE 2008-01-1331 Vishwanathan, Reitz
  *University of Wisconsin*
- SAE 2008-01-0968 Campbell, Hardy, Gosman
  *Imperial College*
- SAE 2008-01-0961 Karrholm, Tao, Nordin
  *Chalmers University*
- SAE 2008-01-0954 D’Errico, Ettorre, Lucchini
  *Politecnico di Milano*

(Multiple modeling groups using our spray data!)

**Better physical understanding of LTC.**
- Liquid penetration
- Vapor penetration
- Lift-off length
- EGR effects
- Multi-Injection
- Nozzle size

**Experimental Data**
- Soot distribution
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Future work: Experimental collaboration in the ECN

- Multiple groups to work on the same baseline experimental condition: “Spray A”
  - Repeat experiments at multiple facilities.
  - Accurate models require accurate measurements/b.c.

- Bosch to donate “identical” injectors/nozzles to Sandia.
  - Sandia will distribute to other groups for voluntary experimentation at this condition.

- Acceleration of LTC model development.

Spray A
Ambient: 900 K, 60 bar (22.8 kg/m³)
Injector: 1500 bar, 0.090 mm nozzle, KS1.5/0.86

- Michigan Tech. Univ.
  - Vessel temperature composition

- Argonne (x-ray source)
  - Internal needle movement
  - Near-nozzle liquid volume

- IFP
  - Spray velocity

- CMT
  - Rate of injection
  - Droplet diameter

- Meiji Univ.
  - Soot formation

- Sandia
  - Liquid and vapor mixing
  - Combustion diagnostics
Future work (continued)

- Fundamental study of liquid wall impingement at DPF regeneration conditions (post injection).
  - Oil dilution and increased fuel consumption are problematic!
  - Combustion vessel ideal to investigate high-temperature, low-density conditions typical of post-injection.

- Lift-off (UHC and soot) effects with jet-jet interaction.
  - Addresses the gap in understanding between single-spray combustion and that using a multi-hole, practical fuel injector.

- Mixing measurements of Spray A condition.
  - Past mixing dataset with older injector has proven invaluable for spray and CFD model validation.
  - Mixing measurements also performed as a function of ambient gas density. Needed to quantify “spreading angle” in vaporizing spray environment.

- Velocity measurements of combustion vessel
  - Improved boundary condition information needed for CFD model development.
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.

• FY09 approach addresses critical LTC needs.
  – Measurements and new understanding for spray liquid-phase transients for early-injection LTC where wall-wetting is problematic.
  – Factors that influence liquid vaporization and flame flashback after the end of injection.

• Collaboration expanded to provide greatest impact (MOU, Engine Combustion Network)

• Future plans will continue effort
  – Post-injection liquid wall impingement.
  – Lift-off (UHC and soot) with jet-jet interaction.
  – “Spray A” characterization for the ECN.