Why Fuel-Property Considerations Are Important in the Quest for Improved Combustion Strategies: Lessons Learned from Optical-Engine Experiments

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**Optical Engine Specifications and Schematic**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research engine</td>
<td>1-cyl. Cat 3176</td>
</tr>
<tr>
<td>Cycle</td>
<td>4-stroke CIDI</td>
</tr>
<tr>
<td>Valves per cylinder</td>
<td>4</td>
</tr>
<tr>
<td>Bore</td>
<td>125 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>140 mm</td>
</tr>
<tr>
<td>Displacement per cyl.</td>
<td>1.72 liters</td>
</tr>
<tr>
<td>Conn. rod length</td>
<td>225 mm</td>
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<tr>
<td>Conn. rod offset</td>
<td>None</td>
</tr>
<tr>
<td>Piston bowl diameter</td>
<td>90 mm</td>
</tr>
<tr>
<td>Piston bowl depth</td>
<td>16.4 mm</td>
</tr>
<tr>
<td>Squish height</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Swirl ratio</td>
<td>0.59</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>12.5:1</td>
</tr>
<tr>
<td>Simulated compr. ratio</td>
<td>16.0:1</td>
</tr>
</tbody>
</table>

- **Cameras acquire images through windows in piston and cylinder wall**
Outline

● What causes the NO$_x$ emissions increase when fueling with neat soy biodiesel?
  – Igniting and reacting mixtures that are closer to stoichiometric lead to production of more thermal NO$_x$

● Why don’t early direct-injection HCCI-like strategies work well with #2 diesel fuel?
  – Liquid-fuel films degrade efficiency and emissions

● Which parameters govern the in-cylinder penetration of liquid-phase fuel (i.e., the liquid length) during the cycle?
  – Instantaneous thermodynamic conditions and fuel volatility
  – Injection pressure has negligible effect
Part 1: What Causes NO$_x$ Emissions Increase When Fueling with Neat Soy Biodiesel?

- Previous work has shown NO$_x$ increase can originate from
  - Combustion effects
  - Engine-calibration effects (see SAE 2008-01-0078)

- Combustion effects not well understood – many hypotheses
  - Most based on increased thermal NO$_x$ formation

**Increased in-cylinder temperature and/or residence time at high temperature will increase thermal NO$_x$**

- Other hypotheses focus on increased prompt-NO$_x$ formation
  - Not investigated in this work
**Igniting/Reacting Biodiesel Mixtures Are Closer to Stoichiometric**

- Flame lift-off lengths \((H)\) similar for biodiesel and hydrocarbon ref. fuel
  - Rich mixtures at \(H\)

- Oxygen in biodiesel molecules makes rich mixtures at \(H\) closer to stoichiometric

- Mixture stoichiometry quantified using oxygen equivalence ratio, \(\phi_\Omega\)
  - See SAE 2005-01-3705

- Relatively small \(\phi_\Omega\) changes (~0.5) can lead to large changes (100-400 K) in product-mixture temperature
Igniting/Reacting Mixtures Closer to Stoichiometric → More Thermal NO\textsubscript{x}

- Reacting biodiesel mixtures are closer to stoichiometric during ignition and in the standing premixed autoignition zone near the lift-off length

  - Higher temperatures
    - Faster reaction rates
  - Less mixing-controlled combustion required for complete oxidation
  - Shorter combustion duration
  - Less soot → less radiative heat loss → higher local temperatures
  - Longer res. times at higher Ts

Source: J.E. Dec, SAE 970873
Summary: Biodiesel NO\textsubscript{x} Increase

- **Primary factor** in biodiesel NO\textsubscript{x} increase appears to be igniting/reacting mixtures that are closer to stoichiometric
  - Consequences are: higher temperatures, faster combustion, less radiative heat loss, longer res. times $\rightarrow$ more thermal NO\textsubscript{x}

See SAE 2009-01-1792 for details

- **Nevertheless**, an engine optimized for biodiesel is likely to provide benefits relative to an engine optimized for diesel
  - Some fraction of biodiesel PM, HC, and CO benefits can be traded off to eliminate NO\textsubscript{x} increase (e.g., by adding EGR) and raise efficiency (e.g., by decreasing DPF regeneration frequency)

- Preceding conceptual understanding is consistent with trends observed in current work and in literature, but remains to be rigorously validated
**Part 2: Why Don’t Early Direct-Injection HCCI-Like Strategies Work Well with #2 Diesel?**

- Early-DI strategies with gasoline show very low NO$_x$ and smoke

- Similar results not achieved with #2 diesel

- Primary HCCI focus had been on ignition-quality effects, little research on fuel-volatility effects

*Source: Hwang, Dec, and Sjöberg, SAE 2007-01-4130, Fig. 10*
The Importance of Fuel Volatility and the Formation of Liquid-Fuel Films

- Optical-engine experiments show
  - In-cylinder liquid-fuel films are linked with increased emissions and decreased efficiency in early-DI modes employing #2 diesel fuel
  - See Martin et al., SAE 2008-01-2400

For some timings, pool fires form where liquid fuel impinged...

...while for other timings, no pool fires are observed.
A Hypothesis to Explain How Fuel Films, Emissions, and Efficiency Are Linked

- If a bright, luminous pool fire is formed:
  - Fuel-rich regions are producing soot
  - Near-stoichiometric regions around rich regions are producing NO$_x$
  - Radiative coupling between flame and fuel-film causes film to more completely vaporize and burn, yielding lower HC and CO emissions

- If a bright, luminous pool fire is not formed:
  - Hot soot is not being produced in locally richer regions
  - Lack of radiative heating from flame means slower/incomplete fuel-film vaporization and higher HC and CO emissions

Regardless of the extent to which they burn, fuel films lead to problems with emissions and efficiency
Increased Fuel Volatility Prevents Fuel-Film Formation

- If fuel films are a primary factor, this should lead to higher efficiency and lower emissions for HV100...
Avoiding Fuel-Film Formation Enables Higher Efficiency and Lower Emissions

- HV$x = x$ vol% high-volatility diesel blended with #2 ULSD
- Also tested 3 blends of HV0 (i.e., #2 ULSD) with HV100
- SOI = start of inject.
Part 3: Fuel, Injection-System, and In-Cylinder Condition Effects on Liquid Length

- Liquid length (LL) = distance that liquid-phase fuel penetrates from injector orifice into charge gas

- LL variation should be understood due to importance of avoiding wall impingement and fuel-film formation
  - Fuel on cylinder wall can be blown past the rings into the crankcase, where it can persist

- Questions
  - How does LL vary under unsteady in-cylinder conditions?
  - How do biodiesel LLs compare to those for #2 ULSD?
How Does LL Vary under Unsteady In-Cylinder Conditions?

- **Primary effects**
  - In-cylinder T and $\rho \uparrow$, LL $\downarrow$
  - Fuel volatility $\uparrow$, LL $\downarrow$

- **Secondary effects**
  - Heat losses $\uparrow$, LL $\uparrow$
  - Local charge cooling due to fuel vaporization $\uparrow$, LL $\uparrow$

- **Little to no effect**
  - Injection rate / pressure
  - Unsteadiness / history
    - Residence time of liquid fuel in jet is short relative to in-cyl. $\Delta T$, $\Delta \rho$ timescales
    - i.e., instantaneous local thermo-dynamic conditions determine LL

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Shape asymmetries due to secondary effects

IMAP = 1.65 bar
$P_{\text{inj}} = 142$ MPa

T & $\rho$ increasing, LL decreasing

Residence time of liquid fuel in jet is short relative to in-cyl. $\Delta T$, $\Delta \rho$ timescales

Shape asymmetries due to secondary effects
How Does Fueling with Biodiesel Affect LL Relative to Fueling with #2 ULSD?

- Biodiesel LLs are ~20% longer than those for #2 ULSD
  - Helps explain lube-oil dilution with late post-injections of biodiesel
  - True even for cuphea biodiesel, which has T10 – T70 similar to ULSD

- Least-volatile components appear to determine LL

- History, other effects important for multi-component fuels
Conclusions

• To eliminate soy biodiesel NO\textsubscript{x} increase due to autoigniting/reacting mixtures being closer to stoichiometric, focus on
  – Making igniting/reacting biodiesel mixtures richer (e.g., increase fuel cetane number, lower injection pressure, add EGR)
  – Implementing biodiesel-specific engine calibrations

• A primary barrier to achieving benefits of early-DI, HCCI-like strategies with diesel fuel is the formation of liquid-fuel films
  – An “ideal” fuel for early-DI HCCI will have volatility closer to gasoline than to conventional diesel

• Liquid length (LL)
  – LL models based on instantaneous in-cylinder conditions should accurately predict first-order effects
  – ~20% longer LLs for neat conventional biodiesels likely help explain increased lube-oil dilution
References


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