Fuel Effects in Advanced Combustion
-Partially Premixed Combustion (PPC) with Gasoline-Type Fuels

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SAE Publications:
2009-01-2668
2010-01-0871
2010-01-1471
2010-01-2198
Goals for Advanced Combustion Systems

- Improve engine efficiency/fuel economy and meet CO$_2$ emissions regulations
- Lower engine-out NOx and PM/soot emissions to meet stricter regulations
- Reduce size, costs, and fuel consumption penalties of aftertreatment systems (especially NOx)
- Operate effectively over wide speed/load range
- In Europe: Options for mitigating diesel/gasoline supply/demand imbalance
Partially Premixed Combustion

Characteristics:

- Avoid conditions that cause NOx & soot formation in conventional diesel CI combustion -- form of PCCI
- Fuel/air mixing intermediate between HCCI & conventional CI combustion (“partial premix”)
- Better performance than HCCI due to some fuel/air stratification

Approach:

- One or two fuel injections
- When used, first one placed @ -60 TDC to create homogeneous mixture (Similar to Toyota “Unibus” approach)
- Last injection around TDC (to achieve CA50 @ MBT ~5-10° ATDC)
  - Stratification created by this injection triggers combustion.
- Same energy content injected per fuel
- EGR used to prevent early reaction during compression stroke
Study Objectives

Test effects of properties of different gasoline range blends in HD CI engine operated under Partially Premixed Combustion Mode

Different fuel properties/composition
Different “reactivity”
Different ignition and combustion characteristics
Different effective speed/load operating ranges
Fuel Selection

- Gasoline-type fuels selected based on prior results which suggest gasoline may better achieve goals than diesel fuel in PPC due to higher volatility and longer ignition delay (SAE2006-04-3385, SAE2007-01-0006, SIAT 2009)

- Blends of refinery gasoline range components:
  - Studied fuel property effects by blending streams with different compositions and RON’s
  - RON’s ranging from 69-99
  - Ethanol also tested

<table>
<thead>
<tr>
<th>&quot;Gasoline&quot;Fuel</th>
<th>RON</th>
<th>MON</th>
<th>C</th>
<th>H/C</th>
<th>LHV [MJ/kg]</th>
<th>A/F stoich</th>
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<td>FR47335CVX</td>
<td>99.00</td>
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<td>Ethanol</td>
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<td>89.00</td>
<td>2.00</td>
<td>3.00</td>
<td>26.90</td>
<td>9.00</td>
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</table>
Gasoline-range streams having octane numbers as low as ~50 exist in refineries and are used to make gasoline blends.
Bosch Common Rail

- Prail: 1600 [bar]
- Orifices: 8 [-]
- Orifice Diameter: 0.18 [mm]
- Umbrella Angle: 120° [deg]

Engine / Dyno Spec

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<td>r_c_{geometric}</td>
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<tr>
<td>BMEPmax</td>
<td>15 [bar]</td>
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<tr>
<td>Vd</td>
<td>1951 [cm³]</td>
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<tr>
<td>Swirl ratio</td>
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</tbody>
</table>

* - Standard r_c_{geometric} = 17.1

Issue:
- Old, first generation
- Bosch injector – impacts soot emissions

Scania D12 Heavy Duty Diesel Engine – Single Cylinder

* - Standard r_c_{geometric} = 17.1
Achieving low CO, HC, NOx & soot: -Controlling T through EGR & \( \lambda \)

Preferred PPC operating region:

If lambda is \( \sim 1.5 \) and EGR between 45 – 55 %, combustion should occur in the desired temperature range

\( \Rightarrow \) Low NOx and low HC & CO!!!

In addition, should still be enough O2 to limit soot production.
Base Test Conditions

IMEPg [bar]

Dyno LIMIT

18
15
12
8
5

@ 1300 [rpm]

Tailored Injection Strategy

Tin=f(IMEP,ON)

gasoline fuels

Partially Premixed Combustion

High Efficiency
Low NOx & soot
Acceptable MPRR
Loads up to 18 [bar] IMEPg

1.5 \lambda

50% EGR
Higher ON gasolines & ethanol required significant amount fuel in pilot

Higher ON gasolines & ethanol required high Tin to run lower loads

Pilot Ratio vs. Load

Lower ON gasolines performed best with no pilot
Engine-Out NOx and Soot Emissions

**NOx vs. Load**

- NOx below US10 limit for most fuels/conditions (little to no aftertreatment needed!)
- No correlation with RON/MON

**Soot vs. Load**

- Significant improvement in soot when modern injection system used (but DPF still needed for gasolines)

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- Diesel Fuel (CN=52)
  
  - Low RON

- EtOH

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G. ON 99/97
G. ON 98/88
G. ON 97/86
G. ON 93/85
G. ON 89/80
G. ON 87/81
G. ON 80/75
G. ON 70/66
G. ON 69/66
D. CN 52
PRF20
Efficiencies

Combustion Efficiency vs. Load

Very high combustion and gross indicated efficiencies over entire load range

Gross Indicated Efficiency vs. Load

Approaching 56%!

down to 150g/kwhr!
Maximum Pressure Rise Rate (MPRR)

Lower ON fuels had lower MPRR’s at high loads.
Load Operating Area

If $T_{\text{intake}}$ limited to ~330°K:

- With no $T_{\text{intake}}$ constraints, all fuels tested able to operate at all loads

- With reasonable $T_{\text{intake}}$ constraints:
  - all fuels tested able to operate at the higher loads
  - only the lowest RON fuels able to operate at the lowest loads
CA50 Sweep: NOx – soot-efficiency

- NOx vs. CA50
- Soot vs. CA50
- Gross Indicated Efficiency vs. CA50

Nissan MK type combustion, easier to achieve with fuels with high octane number.

For this engine system and mode of operation, optimal timing appears to be ~5-10°ATDC.
Summary

• Gasoline PPC enabled simultaneous achievement of high efficiency, low emissions and acceptable MPRR’s at all loads tested (5-18 bar gross IMEP) in heavy duty CI engine with EGR~50%, $\lambda = 1.5$, & CA50=5-10°ATDC

• Able to run all gasoline fuels and ethanol at all loads tested
  ➢ Lower ON fuels could be run with reasonable intake T’s & 0% pilot
  ➢ Higher ON fuels (incl. ethanol) required high intake T’s & significant % fuel in pilot to run @ lower loads

• Gross indicated efficiency between 52-56% attained for loads higher than 6 bar gross IMEP. (Gross ISFC’s down to 150 g/kwhr)

• Engine-out NOx below US2010 limits without aftertreatment

• At highest load soot was between 0.2-2 FSN. (<0.5 FSN with modern injection system). Acceptable level with DPF’s

• At high loads, Maximum Pressure Rise Rates (MPRR) were best for the lower ON fuels, with values of ~12 bar/CAD