N-Heptane Micro Pilot Ignition in Methane-Air Mixtures

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Contents

- Large Bore Gas Engines and Pilot Ignition (Background)
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Large Bore Gas Engines – Why?

- Natural gas:
  - Abundant resources and low fuel price
  - High octane number of CH₄ (130) allows for high compression ratios and leads to high engine efficiencies
  - Substantial benefits w.r.t. particulate matter compared to Diesel
  - Reduction in CO₂ compared to Diesel/Gasoline due to low C/H ratio

- Large bore engines:
  - Lean-burn operation ensures low exhaust emissions, reduces knock tendency and improves cycle efficiency
  - Further measures to decrease in-cylinder temperatures (and NOx):
    - EGR
    - Miller/Atkinson valve timing
Why do we need Enhanced Ignition Systems?

- To overcome the reduced reactivity, enhanced ignition systems are applied, which provide:
  - High ignition energies
  - Increased and stable ignition «volumes»
  - Turbulence generation

- Two ignition systems are of main interest:
  - Pilot injection (ignition of the methane/air mixture by means of auto-ignition of a directly injected «micro» liquid pilot spray)
  - Pre-chamber spark plug ignition (ignition in a separate volume, generating flame jets entering the main combustion chamber)
Characteristics of Pilot Ignition

- Provides multiple ignition spots
- Turbulence generation due to spray
- Stable ignition source(s)
- Flexible ignition (injection) timing and ignition energy
- Two fuels needed (with different cetane numbers), conditions must be favourable for auto-ignition of the pilot fuel to occur

Representative OH* chemiluminescence image of pilot ignition in the RCEM (6-hole pilot nozzle)
Motivation for this Work

- Fundamental data is sparse:
  - Most studies focus on engine performance and emission investigations
  - The energy released during ignition and early combustion is too low to draw conclusions from heat release analysis

  In-cylinder data necessary at engine relevant conditions to isolate and understand processes

- Questions addressed:
  - What are the fundamental processes of pilot ignition?
  - What are the influences of operating parameters?

  Optical data generation in the RCEM of pilot ignition with emphasis on separation of effects
The Rapid Compression Expansion Machine (RCEM)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>bore</td>
<td>B=84 mm</td>
</tr>
<tr>
<td>stroke</td>
<td>s=120 – 250 mm</td>
</tr>
<tr>
<td>compression ratio $\varepsilon$</td>
<td>5 - 30</td>
</tr>
<tr>
<td>piston bowl</td>
<td>$d_{\text{bowl}}=52$ mm, 4 mm depth</td>
</tr>
<tr>
<td>piston optical access</td>
<td>$d_{\text{window}}=52$ mm, quartz</td>
</tr>
<tr>
<td>cylinder pressure</td>
<td>$p_{\text{max}}$ up to 200 bar</td>
</tr>
<tr>
<td>cylinder head</td>
<td>flat, highly flexible</td>
</tr>
<tr>
<td>pressure measurement</td>
<td>piezoelectric transducer,</td>
</tr>
<tr>
<td></td>
<td>0 - 250 bar</td>
</tr>
<tr>
<td>heating</td>
<td>head and liner up to 470 K</td>
</tr>
<tr>
<td>injection system</td>
<td>flexible, multiple injectors</td>
</tr>
<tr>
<td>ignition system</td>
<td>pre-chamber, flexible</td>
</tr>
<tr>
<td># of experiments</td>
<td>15-20 per hour (theoretically)</td>
</tr>
</tbody>
</table>

High pressure oil acts on connecting rod

Connecting rod pushes experimental piston to the front

Compressed air
Driving pressure (20 - 35 bar)

Compressed air
Loading pressure (1.1 – 2.0 bar)
Experimental Setup – Arrangement of Injectors and optical accesses

- Investigations with pilot ignition:
  - Methane is injected directly into the combustion chamber (before compression)
  - Pilot injector: single hole nozzle fueled with n-heptane (injection rates and total injected masses measured)
  - Located off-axis
  - Second optical access in cylinderhead → schlieren imaging
  - 2D OH* chemiluminescence
Experimental Setup - Optical Diagnostics

- Chemiluminescence imaging
  - Photomultipliers and 2D OH* chemiluminescence
  - Imaging through piston window

- Schlieren imaging
  - Illumination with pulsed diode laser
  - Imaging through both windows ($\varnothing 52 \text{ mm}$)

Photomultipliers @ 100 kHz
band pass filters 310 (OH), 430 (CH) and 510 nm ($C_2$)
Operating Conditions
Investigations with Pilot Ignition (I)

- Previous investigations related to engine experiments
  - EGR consists of 20% CO\(_2\) and 80% N\(_2\)
  - Multi-hole nozzle
  - Pilot fuel Diesel
  - Simultaneous change in p/T condition
  - Chemiluminescence (but no spray data)

- Extended Investigations with pilot ignition
  - Dilution with 100% N\(_2\) (isolate the effect of O\(_2\) concentration)
  - Single hole nozzle
  - N-heptane pilot fuel
  - Variation in charge temperature only
  - Second optical access allows for schlieren imaging to generate spray data

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Submitted for publication
Operating Conditions
Investigations with Pilot injection (II)

- Three p/T combinations assessed: constant pressure evolution, only variation in T
- Same pressure at the respective SOI
- Variations in $\Phi_{CH4}$ and $O_2$ content (dilution with 100% $N_2$)
- Variation in pilot mass (injection duration)

<table>
<thead>
<tr>
<th></th>
<th>OP1</th>
<th>OP2</th>
<th>OP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ [K] at SOI</td>
<td>732</td>
<td>776</td>
<td>823</td>
</tr>
<tr>
<td>$p$ [bar] at SOI</td>
<td>17.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Phi_{CH4}$</td>
<td>0.0-0.66</td>
<td>0.0-1.0</td>
<td>0.0-0.6</td>
</tr>
<tr>
<td>$O_2$ [%]</td>
<td>21</td>
<td>16.8-21</td>
<td>21</td>
</tr>
</tbody>
</table>
Experimental Results

Investigations with Pilot injection (I)

Influence of increasing ambient temperature (OP1 vs. OP2)
Experimental Results
Investigations with Pilot injection (II)
Influence of decreasing \( \text{O}_2 \) content (OP2)
Experimental Results
Investigations with Pilot injection (III)
Influence of increasing CH$_4$ content and pilot mass (OP2)
Experimental Results
Investigations with Pilot injection (III)

- Optical data, Schlieren vs. OH\* chemiluminescence images:
  - Low-T ignition causes «weakening» of the schlieren effect (due to small local temperature rise)
  - “Reappearance” of schlieren signal at high-T ignition onset
Experimental Results Ignition Delay Investigations with Pilot injection (IV)

- High temperature ignition delays over all operating conditions increase for:
  - Increasing methane content
  - Decreasing temperature
  - Decreasing $O_2$ content

- Higher sensitivity of ignition delay w.r.t. Methane content for OP1 than OP3 (steeper linear trendline)
Conclusions (I)

- Two distinct phases in HRR are observed, characterizing pilot ignition/combustion and premixed combustion phase.
- Schlieren imaging delivers information about the penetration and location of the pilot spray vapor phase and ignition timing/location.
- Additionally, low temperature ignition in the pilot spray was observed, characterized by a weakening or disappearance of the refractive indices.

Supporting observations made in spray flames

- Increasing high-temperature ignition delays with increasing amounts of premixed methane, increasing methane equivalence ratios show a higher impact on ignition delay for “cold” conditions than for higher temperatures.

Inhibiting effect of CH$_4$ on auto-ignition reactions of n-heptane influenced by temperature and mixture.
Conclusions (II)

- Contribution of the presented work:
  - Results from pilot ignited gas engine investigations without optical access don’t allow for model formulation and proper validation thereof

  - Optical in-cylinder data from the RCEM, including spray data to reduce modeling uncertainties

- Literature on ignition behaviour of the pilot spray is sparse and often not in agreement (investigations show different trends depending on setup)

  - Separation of the influences of changing T, equivalence ratio, dilution and multi-component pilot fuel in the RCEM (as opposed to engine investigations)
Outlook and Future Work

- Pilot injection and ignition characterization:
  - Ignition and combustion behaviour of micro pilot sprays largely unknown, but with increasing importance also to Diesel engine applications
  - Specific design of experiment needed for optical investigations of pilot sprays in reacting atmospheres and limited choices of generic test rigs

- Auto-ignition phenomena in dual fuel mixtures:
  - No shock-tube data available for n-heptane/methane mixtures (or other PRF’s for dual fuel) and hence no validated reaction mechanisms
Acknowledgements

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Thank you for your attention