Characterization of Dual-Fuel Combustion Processes

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Dual-fuel principle

- Otto principle (premixed) → lean gas/air charge
- Low-pressure gas admission
- Liquid pilot fuel injection → two stage ignition process
- Combustion transition → auto-ignition → premixed flame

Pilot-fuel ignition

→ various complex processes
→ several injection stages
→ different combustion phases

PhD thesis A. Srna
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Pilot-fuel injection evaporation/mixing
EOI entrainment

2-stage ignition process
Combustion transition
(auto-ignition to premixed flame)
Introduction

Dual-fuel principle

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- Low-pressure gas admission
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- Combustion transition → auto-ignition → premixed flame

DF engine application

31 DF (MEP 27.2 bar)
**Introduction**

**Lean-burn gas engine characteristics**

- \(\uparrow\) high efficiency
- \(\uparrow\) high H/C ratio
- \(\downarrow\) low NO\(_x\) and PM (soot) emissions

- Ignition: knocking vs. misfiring
- Stability: cycle-to-cycle variation
- CH\(_4\) slip \(\rightarrow\) GHG emissions

**Dual-fuel principle**

- Otto principle (premixed) \(\rightarrow\) lean gas/air charge
- Low-pressure gas admission
- Liquid pilot fuel injection \(\rightarrow\) two stage ignition process
- Combustion transition \(\rightarrow\) auto-ignition \(\rightarrow\) premixed flame

**DF engine application**

31 DF (MEP 27.2 bar)
Introduction

DF characterization

- Operation window → knocking vs. misfiring
- Ignition delay/location
- Flame propagation
- Heat release
- Combustion stability → cycle-to-cycle variation

DF engine application

31 DF (MEP 27.2 bar)

(qualitative) DF (gas mode) vs. Diesel

<table>
<thead>
<tr>
<th>Emission values [%]</th>
<th>CO₂</th>
<th>NOₓ</th>
<th>SOₓ</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>80</td>
<td>60</td>
<td>40</td>
<td>20</td>
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</tbody>
</table>

CO₂ > NOₓ > SOₓ > PM
Motivation

DF characterization

- Operation window
  → knocking vs. misfiring
- Ignition delay/location
- Flame propagation
- Heat release
- Combustion stability
  → cycle-to-cycle variation

pre-ignition
Test Facility "Flex-OeCoS"

Features (specifications)

• Optical access: 4 windows optical chamber: $\varnothing 60 \times 20$ mm

• Engine-like compression/combustion pressure/temperature
  $\Rightarrow$ up to 160 bar max. 240 bar / $\leq 800 \ldots \geq 1000$ K

• Variation of flow/turbulence by motor speed
  $\Rightarrow u' \approx 3\ldots6$ m/s @ 400...1000 rpm

• Flexible operation (cycles) in a wide range of air-fuel ratios

• Variability to adapt test rig to a variety of combustion processes

Process conditions

$T$: fine-wire TCs

$p$: sensors

flow: high-speed PIV

instrumented with various probes
(boundary conditions)

Jointly developed and pursued by LAV-ETHZ and ITFE-FHNW

Liebherr D944 (2 l per cyl., $\varnothing 130$ mm, stroke 150 mm)
Characterization DF Combustion Processes

Measurements

Simultaneous Schlieren/OH* chemiluminescence

Investigations

- Ignition delay (location): OH* chemiluminescence
- Flame propagation: Schlieren
- Heat release/cyclic stability: pressure measurements

Spatial resolution: 60×30 mm → full height CC

Temporal resolution:

≤ 600 rpm: 36 kHz (27.8 µs) → 0.1 °CA (!)
≥ 800 rpm: 18 kHz (55.6 µs) → 0.2 °CA
Measurements

Simultaneous Schlieren/OH* chemiluminescence

Investigations

- Ignition delay (location): OH* chemiluminescence
- Flame propagation: Schlieren
- Heat release/cyclic stability: pressure measurements

Parameter variation

<table>
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<tr>
<th>CH\textsubscript{4}/air charge: (T\textsubscript{in}=50°C)</th>
</tr>
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<tbody>
<tr>
<td>• Air-fuel ratio (\lambda): inf. / 3.0 / 2.5 / 2.0 / 1.5</td>
</tr>
<tr>
<td>• Compression pressure: 70 / 100 / 130 [bar]</td>
</tr>
<tr>
<td>• Flow conditions: 400 / 600 / 800 [rpm]</td>
</tr>
</tbody>
</table>

Injection:

- Pilot fuel: Dodecane / OME (polyoxymethylene dimethyl ether)
- Nozzle diameter: 90 / 120 [\mu s]
- Injection pressure: 600 / 1000 / 1400 [bar]
- Start of injection (SOI): -30 / -25 / -20 / -15 / -10 / -5 / 0 / +5 [°CA]
- Injection duration (ET): ... < 300 ... 500 ... 800 < ... [\mu s] (25 \mu s steps)
Variation CH₄/air charge (λ)

- Methane defers the ignition delay
- \( \uparrow \frac{c_p}{c_v} \Rightarrow \downarrow T \), energy absorption
- Pilot fuel auto-ignition suppressed (chemistry – micro-mixing interaction)
- Heat release depending on \( \lambda \) (gas dynamics, acoustic resonator)

Dodecane / p=70 bar / 600 rpm / p_{inj}=1000 bar / ET=500 µs / SOI=-15 °CA

Air (\( \lambda = \text{inf.} \)) \hspace{1cm} \lambda = 3.0 \hspace{1cm} \lambda = 2.5 \hspace{1cm} \lambda = 2.0 \hspace{1cm} \lambda = 1.5

\( \lambda = 3.0 \) \hspace{1cm} \lambda = 2.5 \hspace{1cm} \lambda = 2.0 \hspace{1cm} \lambda = 1.5

in preparation to be published
Variation SOI

Dodecane / $p=70$ bar / 600 rpm / $p_{\text{inj}}=1000$ bar / ET=500 $\mu$s / $\lambda=2.0$

- Ignition delay strongly temperature dependent (density $\neq \emptyset$)
  - rapid spreading of first-stage reactivity towards fuel-richer conditions
  - $\text{CH}_4$ deferring the cool-flame reactivity (low-T ignition) $\Rightarrow$ $\uparrow$ ID
- Heat release
- Combustion stability
- Soot formation (!)

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Start of Injection (SOI)

Variation SOI / pilot fuel: OME\textsubscript{3-5} (polyoxymethylene dimethyl ether, mixture n=3-5)

- Dodecane
- OME

Error bars: Confidence level 90%

SOI = -25 °CA
SOI = -20 °CA
SOI = -15 °CA
SOI = -10 °CA
SOI = -5 °CA
SOI = 0 °CA

SOI = -25 °CA
SOI = -20 °CA
SOI = -15 °CA
SOI = -10 °CA
SOI = -5 °CA
SOI = 0 °CA

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Variation DOI (energizing time ET)

Dodecane / p=70 bar / 600 rpm / p_inj=1000 bar / SOI=-15/-20/-25 °CA / λ=2.0

- ET = 300 µs
- ET = 450 µs
- ET = 600 µs
- ET = 750 µs

DOI < ID: "enhanced mixing" (due to end-of-injection transient)

Error bars: Confidence level 90%

- ET = 300 µs
- ET = 450 µs
- ET = 600 µs
- ET = 750 µs

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**Variation pilot fuel: OME$_{3-5}$ (polyoxymethylene dimethyl ether, mixture n=3-5)**

- **Dodecane vs. OME$_{3-5}$ / p=70 bar / 600 rpm / $p_{\text{inj}}$=1000 bar / SOI=-15 °CA / ET=450 μs / $\lambda=2.0$**

- **DOD SOI=-15°CA**
- **OME SOI=-15°CA, $d = 90$ μm**
- **-11.3 °CA**
- **-9.9 °CA**

- **ET = 450 μs**
- **∅ 90 μm**
- **stability**
- **soot (misfiring)**

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Duration of Injection (DOI)

Variation pilot fuel: OME$_{3-5}$ (polyoxymethylene dimethyl ether, mixture n=3-5)

Dodecane vs. OME$_{3-5}$ / p=70 bar / 600 rpm / $p_{\text{inj}}$=1000 bar / SOI=-15 °CA / ET=450 µs / $\lambda=2.0$

- Ignition delay trend
- Ignition location
- Soot: ↓ formation  ↑ oxidation
- LHV$_{\text{OME}} = 19.1$ [MJ/kg]
  vs. LHV$_{\text{DOD}} = 44.1$ [MJ/kg]
- Adapted LHV$_{\text{OME}}$ by:
  ↑ injection
- Combustion stability

- ET = 450 µs
- $\emptyset$ 90 µm
- ET = 450 µs
- $\emptyset$ 120 µm

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Conclusions & Outlook

Conclusions

• Test facility operation (engine relevant loads) ➔ acquisition of operation/boundary conditions
google ➔ pressure, temperature, flow/turbulence (PIV)

• Tunable DF combustion process conditions ➔ from misfiring to knocking
  ➔ variation of operation/injection parameters
  ➔ pilot fuels: dodecane vs. OME

• Application of optical diagnostics ➔ simultaneous Schlieren/OH\(^*\) chemiluminescence

• Characterization DF combustion process ➔ ignition delay, flame propagation, heat release (stability)

• Comprehensive investigations/analysis ➔ reference data for CFD/CRFD

Outlook

• Further data analysis/quantification (ignition location, flame speed, COV, etc.)

• Additional measurements: \(\uparrow\) pressures, constant density \((T_{\text{in}})\), rpm variation, homogenization

• Alternative gas/pilot fuel: renewable, synthetic, blends, ...

• ....
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Capacity area A2: Chemical energy converters (Ch. Bach, Empa)
Topic A2.2: IC engine powertrain efficiency increase
Task A2.2.1: Multi-mode/minimal emission combustion process