Title: Particulate Emissions Characterization and Combustion Analysis by using Water-Diesel Fuel Emulsions in Heavy Duty DI-Diesel Engines equipped with Common-Rail Injection System

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Abstract:
Measurements are carried out on a heavy-duty four-cylinder diesel engine equipped with turbocharger and common rail fuel injection. The engine investigations are conducted in different operating points in the engine map covering wide load ranges and EGR rates. The injection parameters are thereby set independently. Experiments are conducted with reference diesel fuel and 3 different water-in-diesel-emulsions (13% / 21% / 30% Water). In this contribution we present the impact of engine and fuel technology on the combustion process and on the nanoparticle emissions.

By using diesel-in-water-emulsions particulates and NOx are reduced in a significant way (e.g. at the operating point A25, for the 30% emulsion compared to diesel fuel, we measured 30% NOx and 70% PM reduction). The combustion flame temperature decreases linearly with the added water amount in the fuel, its major effect is on NOx reduction. Lower particulate emissions are due to lower soot formation for the water-diesel fuel emulsions (e.g. improved mixing of the fuel with the combustion air).

The fuel consumption (diesel equivalent) when using diesel-in-water-emulsions is similar to that of the reference fuel.

The number and size of the emitted particles is very sensitive to the added water quantity in the fuel. When using diesel-water emulsion fuels the mean particle diameter of the accumulation mode decreases and, at low load conditions, a nucleation mode is present. The majority of these ultrafine particles could be removed using a thermodesorber, indicating the presence of condensates. The rest of the particles in the size range under 20-30 nm seem to be solid particles (maybe salts or ashes); these are only present when the number of particles in the accumulation mode is very low.

The combination diesel-in-water-emulsions and EGR is very effective to reach lowest NOx and particulate emissions values (but the fulfillment of EUROIV still does not appear to be possible).
Particulate Emissions Characterization and Combustion Analysis by using Water-Diesel Fuel Emulsions in Heavy Duty DI-Diesel Engines equipped with Common-Rail Injection System

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Background & Research Approach

Research project
Technologies for lowest NOx and particulate emissions in DI-diesel engine combustion – influence of injection parameters, EGR and fuel composition

Engine performance & emissions

Particulate emissions

Combustion analysis

Correlations & modeling
Objectives

Effects of water-diesel fuel emulsions on NOx, particulates and relevant combustion parameters

Influence of water content in the emulsions

Combination of w-d emulsions with EGR

Combination of w-d emulsions with modern fuel injection system
**Test Engine at LAV**

- **LIEBHERR 4-Cylinder 4-stroke direct injected diesel engine**
  - Stroke = 142 mm; Bore 122 mm
  - $V_e = 6.64 \text{ l}$; $\varepsilon = 17.2$
  - 183 kW @ 2100 1/min
  - 1060 Nm @ 1540 1/min

- **Common Rail Injection System**
  - ETH Fuel Pump (-2000 bar)
  - BSG Electronic (pilot & post injection)
  - CRT Injectors (-1600 bar), Type P2
  - Nozzle tip 8*0.200 mm

- **Turbocharger**
  - K 27.2 – 15.22

- **EGR-System (preliminar)**
  - Cooled EGR (high pressure side)
  - with Throttle after Turbine
Parameter Variation

- Engine operating condition
  - Engine load
    - A25, A50, A75, A100

- Fuel injection
  - Injection pressure
    - 500 – 1600 bar
  - Start of injection
    - 14°CA BTDC – 5°CA ATDC

- Air management
  - EGR rate
    - 0 – 42%

- Fuel composition

Main properties of the fuels tested

<table>
<thead>
<tr>
<th></th>
<th>Water content [mW/(mD+mA)]</th>
<th>Lower heating value [MJ/kg]</th>
<th>Density [kg/m³]</th>
<th>Air/fuel ratio [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>0</td>
<td>43</td>
<td>820</td>
<td>14.6</td>
</tr>
<tr>
<td>13% W-D emulsion</td>
<td>13</td>
<td>38</td>
<td>850</td>
<td>13.0</td>
</tr>
<tr>
<td>21% W-D emulsion</td>
<td>21</td>
<td>35</td>
<td>860</td>
<td>12.4</td>
</tr>
<tr>
<td>30% W-D emulsion</td>
<td>30</td>
<td>33</td>
<td>870</td>
<td>11.8</td>
</tr>
</tbody>
</table>
Measurement Setup Particulate Emissions

- **Temperatures**
  - Sample line from engine exhaust to dilution unit: 170°C
  - Dilution air of the first ejector: 150°C
  - Thermodesorber: 350°C

- **Dilution ratio ca. 124**

- **SMPS size range 9.82 – 429 nm**

- **Number of scans 2 - 15**
W-D Fuel Emulsions, A25: Water Content Variation

Constant pRail or Constant Inj Duration  SOI 8°C CA BTDC

- Reference Diesel, 500 bar
- Emulsion 13%, 500 bar
- Emulsion 21%, 500 bar
- Emulsion 30%, 500 bar
- Emulsion 13%, 560 bar
- Emulsion 21%, 590 bar
- Emulsion 30%, 650 bar

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Rate of Heat Release [% / deg] vs. Crank Angle [deg]

- 500 bar, -8°C, Diesel
- 580 bar, -8°C, Emulsion 13%
- 590 bar, -8°C, Emulsion 21%
- 630 bar, -8°C, Emulsion 30%

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Constant pRail or Constant Inj Duration  SOI 8°C CA BTDC

- Constant Injection Duration
- Constant Injection Pressure

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Max Temp. Ad. Flame [K] vs. Water Content in Fuel m/(mD+mA) [%]

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Premixed Comb [%] vs. Water Content in Fuel m/(mD+mA) [%]

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Ignition Delay [°CA] vs. Water Content in Fuel m/(mD+mA) [%]

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W-D Fuel Emulsions, A25: Water Content Variation

Constant pRail or Constant Inj Duration SOI 8°CA BTDC

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A25, Constant Injection Duration, SOI -8°CA, Fuel Variation, without TD

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W-D Fuel Emulsions, A25: Influence of Thermodesorber

Constant Injection Duration, SOI -8°CA, Fuel Variation, without/with TD at 350°C

- A25 560 -8 Emulsion 13% no TD
- A25 560 -8 Emulsion 13% with TD
- A25 590 -8 Emulsion 21% no TD
- A25 590 -8 Emulsion 21% with TD
- A25 650 -8 Emulsion 30% no TD
- A25 650 -8 Emulsion 30% with TD

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W-D Fuel Emulsions: A25 Injection Pressure Variation

A25, Reference Diesel & Emulsion 21%, Variation injection pressure, without TD

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W-D Fuel Emulsions, A25: cooled EGR

A25 Constant Injection Duration

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Tot. Particulate Conc. [#/Ncm³] (Size Range 40-429 nm)

NOX [g/kWh] EGR Variation

Emulsion Water Content [%]

Opacity [%]

Air/Fuel Ratio [-] EGR Variation

Emulsion Water Content [%]

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A25 Constant Injection Duration
W-D Fuel Emulsions, A25: cooled EGR
W-D Fuel Emulsions, A25: cooled EGR

**Diesel, EGR Variation**

- A25 1100 -4 Diesel 38% EGR no TD
- A25 1100 -4 Diesel 30% EGR no TD
- A25 1100 -4 Diesel 21% EGR no TD
- A25 1100 -4 Diesel no EGR no TD

**Emulsion with 13% Water, EGR Variation**

- A25 1200 -4 Emulsion 13%, no EGR with TD
- A25 1200 -4 Emulsion 13%, 21% EGR with TD
- A25 1200 -4 Emulsion 13%, 31% EGR with TD
- A25 1200 -4 Emulsion 13%, 39% EGR with TD

**Emulsion with 30% Water, EGR Variation**

- A25 1300 -4 Emulsion 30%, no EGR with TD
- A25 1300 -4 Emulsion 30%, 21% EGR with TD
- A25 1300 -4 Emulsion 30%, 30% EGR with TD
- A25 1300 -4 Emulsion 30%, 36% EGR with TD
Conclusions

Main effects of water-diesel fuel emulsions:

BSFC similar
NOx equal or lower
Ignition delay and premixed combustion higher
Combustion temperature lower, major effect on NOx reduction, no PM increase
Total number of particles (D > 50nm) lower
Mode particle diameter smaller
Accumulation mode always reduced
Nucleation mode present at:
  - low or medium engine load
  - high injection pressure
- moderate EGR rate
- high added water amounts
Nucleation mode eliminated in most cases by using a thermodesorber
By combining d-w fuel emulsions, cooled EGR and high injection pressure, lowest
NOx and particulate emissions can be achieved

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