Particle Size and Composition Measurements at Modern Engines and Aftertreatment Systems

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1. equipment @ CUTC to
   - generate particles
   - measure
     - particle size
     - composition
   - minimize particles

2. test conditions & results
   - engine out
   - filter out

3. summary/conclusion
structure

1. equipment @ CUTEC to
   - generate particles
   - measure
     - particle size
     - composition
   - minimize particles
2. test conditions & results
   - engine out
   - filter out
3. summary/conclusion
equipment @ CUTEC to generate particles

**engine**

VW TDI-PUI 4 cylinder 1.9 L, 85 kW, 285 Nm, EURO 3
equipment @ CUTEC to generate particles

**Engine/Filter test bench**

220 kW Schenk DYNAS engine-dynometer

VW TDI-PUI 4 cylinder 1.9 L, 85 kW, 285 Nm, EURO 3
Questions to be answered within this lecture

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3. summary/conclusion
equipment @ CUTEC to measure particle size & composition

Dilution Tunnel

- filter holder or impactor
- Second injector dilution ratio: 1:5 - 1:30
- heated hose
- dilution ratio: 1:7 - 1:10
- micro dilution tunnel
- injector dilution ratio: 1:5 - 1:30
- flow meter
- pump
equipment @ CUTEC to measure particle size & composition

**particle size measurement**

- Exhaust tube
- **Constant Volume Sampling**
- dilution system
  - T ≤ 52 °C
  - dilution ratio 1 : 300
  - dilution ratio 1 : 10
- TSI - SMPS
- 12 stages Berner - impactor
equipment @ CUTEC to measure particle size & composition

**particle size**

12-cascade impactor

gas entry

φ $D_p$ 16000 nm

Al-foil

gas exit

φ $D_p$ 10 nm

determination of particle mass distribution

particles are collected on Al-foil separated by aerodynamic diameter

chemical analysis of collected classified particles
equipment @ CUTEC to measure particle size & composition

**chemical analysis of soot samples**

- **pallflex-filter**
  - microwave assisted extraction
  - SOF
  - PAH
  - nitro-PAH
  - gravimetric GC
  - HPLC GC-MS

- **quartz fiber filter**
  - OC
  - EC
  - anions
  - cations
  - coulometer
  - IEC
  - ICP
equipment @ CUTEC to measure particle size & composition

state of the art SOF determination

- Filter
- Soxhlet extraction
- Weighing

3 - 5 mg soot

Solvent: 200 mL

0.5 - 1 mg SOF

duration: 8 hours
equipment @ CUTEC to measure particle size & composition

SOF determination @ CUTEC

filter

microwave assisted extraction

1 - 3 mg soot

solvent: 30 mL

peak area

duration: 2 hours

GC
equipment @ CUTEC to measure particle size & composition

Comparison of SOF determination by GC or gravimetry

R² = 0.9908
equipment @ CUTEC to measure particle size & composition

Determination of gaseous PAH

- coil condensers
- PU-plugs
- PAH Adsorbens
- flow meter
- condensed liquid fraction
- inlet
- $T \ll 52 \, ^\circ\text{C}$
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equipment @ CUTEC to minimize particles

Particle emission reduction

- primary
  - fuel quality (sulfur 50 ppm - 10 ppm)
- secondary
  - aftertreatment systems
    - DOC
    - DPF, CCF
equipment @ CUTEC to minimize particles aftertreatment systems

- DOC/CCF

DOC 5.66” x 3.54”
cordierite

CCF 5.66” x 6”
silicon carbide
Experimental setup
DOC/CCF

Sampling points:
1 engine out
2 DOC/CCF out

Temperature:
- a engine out
- b upstream DOC/CCF
- c DOC
- d inside CCF
- e downstream DOC/CCF
1. equipment @ CUTEC to
   - generate particles
   - measure
     - particle size
     - composition
   - minimize particles

2. test conditions & results
   - engine out
     - OC/EC = f (T, particle size)
     - PAH = f (T)
     - fuel quality (50 ppm - 10 ppm S)
   - filter out

3. summary/conclusion
results engine out (50 ppm S)

**OC + EC emissions = f (temperature)**

![Bar chart showing OC and EC emissions at different temperatures.](chart)

- Temperature [°C]: 330, 360, 370, 410, 470
- Emissions [mg/m³]: Organic Carbon (yellow), Elemental Carbon (blue)

Overall, as temperature increases from 330°C to 470°C, the emissions of both organic and elemental carbon show a trend of increase and decrease.
results engine out (50 ppm S)

OC/EC - ratio = f (temperature)
results engine out (50 ppm S)

PAH = f (temperature)

[Graph showing PAH emissions at different temperatures and pressures]
TPM = f (fuel quality)

2000 rpm 12 bar ; T = 430 °C
Particle size distribution = f (fuel quality)
2000 rpm 12 bar 430 °C cold dilution
1. equipment @ CUTEC to
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     - particle size
     - composition
   - minimize particles
2. test conditions & results
   - engine out
   - filter out
3. summary/conclusion
Questions to be answered within this lecture

1. equipment @ CUTEC to
   - generate particles
   - measure
     - particle size
     - composition
   - minimize particles

2. test conditions & results
   - engine out
   - filter out
     - TPM filtration efficiency
     - OC/EC = f (T, particle size, filter)
     - PAH = f (T, soot loading)
     - TPM = f (fuel quality)

3. summary/conclusion
results filter out (50 ppm S)

**TPM filtration efficiency**

2000 rpm 5 bar; T = 360 °C; CCF 1

**filter efficiency : 99.98 %**

![Graph showing engine out and filter out particle size distribution](image)
OC & EC = f (temperature, CCF)

Results filter out (50 ppm S)

Engine out CCF 1 CCF 2 CCF 3 CCF 4

Temperature [°C]

Total carbon concentration [mg/m³]

- Organic carbon
- Elemental carbon
OC / EC - ratio = f (temperature, CCF)

- Engine out
- prototype 1
- prototype 2
- prototype 3
- prototype 4
results filter out (50 ppm S)

OC & EC = f (particle size)

2000 rpm 5 bar (360 °C)

![Graph showing organic carbon and elemental carbon content versus particle size](chart.png)
OC / EC - ratio = f (particle size)

results filter out (50 ppm S)

2000 rpm 5 bar (360 °C)

ratio OC/EC [-]

particle size [nm]
Comparison OC/TC @ engine out & CCF out
2000 rpm 5 bar 340 °C

<table>
<thead>
<tr>
<th></th>
<th>Engine out [µg/m³]</th>
<th>CCF 1 out [µg/m³]</th>
<th>Reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic carbon</td>
<td>1307</td>
<td>768</td>
<td>41</td>
</tr>
<tr>
<td>Elemental carbon</td>
<td>5873</td>
<td>822</td>
<td>86</td>
</tr>
<tr>
<td>OC/TC [-]</td>
<td>0.18</td>
<td>0.49</td>
<td></td>
</tr>
</tbody>
</table>

TC = OC + EC
1. equipment @ CUTEC to
   - generate particles
   - measure
     - particle size
     - composition
   - minimize particles

2. test conditions & results
   - engine out
   - filter out
     - TPM filtration efficiency
     - OC/EC = f (T, particle size, filter)
     - PAH = f (T, soot loading)
     - TPM = f (fuel quality)

3. summary/conclusion
results filter out (50 ppm S)

Σ PAH = f (temperature, soot loading)

Σ PAH [ng/m³]

soot mass [g/l]²

temperature °C
results filter out (50 ppm S)

PAH conversion = f (temperature, soot loading)

PAH conversion cleaned filter [%]

PAH conversion [%]

clean filter

filter with 2 g/L soot

filter with 3 g/L soot
PAH reduction = f (temperature)

<table>
<thead>
<tr>
<th>PAH</th>
<th>2000 rpm 2 bar</th>
<th>2000 rpm 5 bar</th>
<th>2000 rpm 12 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenanthrene</td>
<td>98 %</td>
<td>98 %</td>
<td>97 %</td>
</tr>
<tr>
<td>Pyrene</td>
<td>95 %</td>
<td>92 %</td>
<td>85 %</td>
</tr>
<tr>
<td>Benzo(a)anthracene</td>
<td>82 %</td>
<td>77 %</td>
<td>85 %</td>
</tr>
</tbody>
</table>

engine operations point
2g/L soot load CCF 1
PAH reduction = f (soot loading)

<table>
<thead>
<tr>
<th>PAH</th>
<th>clean</th>
<th>2 g/L soot</th>
<th>3 g/L soot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenanthrene</td>
<td>97 %</td>
<td>98 %</td>
<td>97 %</td>
</tr>
<tr>
<td>Pyrene</td>
<td>96 %</td>
<td>95 %</td>
<td>99 %</td>
</tr>
<tr>
<td>Benzo(a)anthracene</td>
<td>81 %</td>
<td>82 %</td>
<td>72 %</td>
</tr>
</tbody>
</table>

engine operations point
2000 rpm 2 bar 280°C CCF 1
structure

1. equipment @ CUTCET to
   - generate particles
   - measure
     - particle size
     - composition
   - minimize particles
2. test conditions & results
   - engine out
   - filter out
     - TPM filtration efficiency
     - OC/EC = f (T, particle size, filter)
     - PAH = f (T, soot loading)
     - TPM = f (fuel quality)
3. summary/conclusion
results filter out (50 ppm S)

$\text{SO}_4^{2-} = f (\text{temperature, CCF})$

**Graph:**
- Y-axis: $\text{SO}_4^{2-}$ [µg/m$^3$]
- X-axis: temperature [°C]
- Lines representing different prototypes (prototype 1, prototype 2, prototype 3, prototype 4, Engine out)

**Legend:**
- Green square: prototype 2
- Blue circle: prototype 1
- Orange triangle: prototype 4
- Purple diamond: prototype 3
- Red circle: Engine out
SO$_4^{2-}$ & TC = f (temperature, particle size)

results filter out (50 ppm S)

**Particle Size [nm]**

<table>
<thead>
<tr>
<th>Particle Size</th>
<th>Mass Concentration [mg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5</td>
<td>0</td>
</tr>
<tr>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>138</td>
<td>0</td>
</tr>
<tr>
<td>405</td>
<td>0</td>
</tr>
<tr>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>1545</td>
<td>0</td>
</tr>
<tr>
<td>6000</td>
<td>0</td>
</tr>
</tbody>
</table>

**Conditions & Temperatures**

- **1500 rpm/ 2 bar**
  - $T_{\text{filter}}$: 240°C
- **1500 rpm/ 5 bar**
  - $T_{\text{filter}}$: 360°C
- **2000 rpm/ 12 bar**
  - $T_{\text{filter}}$: 420°C
SO$_4^{2-}$ / TC -ratio = f (temperature, particle size)

Results filter out (50 ppm S)

Graph showing the ratio of SO$_4^{2-}$ to total carbon as a function of particle size, with data points for different temperature and pressure conditions.
results filter out CCF 1
TPM = f (fuel quality)

2000 rpm 12 bar ; T = 430 °C
Particle number distribution = \( f \) (fuel quality)
cold dilution

results filter out

<table>
<thead>
<tr>
<th>Particle size [nm]</th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>dN/d\log Dp [1/cm³]</td>
<td>0.0E+00</td>
<td>5.0E+07</td>
<td>1.0E+08</td>
</tr>
<tr>
<td></td>
<td>1.5E+08</td>
<td>2.0E+08</td>
<td>2.5E+08</td>
</tr>
</tbody>
</table>

2000 rpm 12 bar 430 °C

50 ppm S

10 ppm S
Sulphur effect on the emissions engine out

<table>
<thead>
<tr>
<th>S [ppm]</th>
<th>TPM [mg/m$^3$]</th>
<th>SOF [mg/m$^3$]</th>
<th>TPM [mg/m$^3$]</th>
<th>max. particle number (nuclei range) [1/cm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>7.5 ± 1.8</td>
<td>3.3 ± 0.6</td>
<td>3.5 ± 0.49</td>
<td>3*10$^8$</td>
</tr>
<tr>
<td>10</td>
<td>8.7 ± 0.6</td>
<td>3.4 ± 0.8</td>
<td>1.3 ± 0.35</td>
<td>5*10$^6$</td>
</tr>
<tr>
<td>80 %</td>
<td>0</td>
<td>0</td>
<td>63 %</td>
<td>98 %</td>
</tr>
</tbody>
</table>
Questions to be answered within this lecture

1. equipment @ CUTEC to
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   - minimize particles

2. test conditions & results
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     - TPM filtration efficiency
     - OC/EC = f (T, particle size, filter)
     - PAH = f (T, soot loading)
     - TPM = f (fuel quality)

3. summary/conclusion
# Summary/Conclusion

Particle Size and Composition Measurements at Modern Engines and Aftertreatment Systems

<table>
<thead>
<tr>
<th></th>
<th>Engine Out</th>
<th>DOC+CCF Out</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OC + EC = f(T)</strong></td>
<td>maximum</td>
<td>effected by CCF</td>
</tr>
<tr>
<td><strong>OC/EC-ratio = f(T)</strong></td>
<td>no tendency</td>
<td>CCF minimum (360 °C)</td>
</tr>
<tr>
<td>OC + EC = f(particle size)</td>
<td>maximum</td>
<td>no tendency</td>
</tr>
<tr>
<td>OC/EC-ratio = f(particle size)</td>
<td>OC/EC &lt; 1 30 nm &lt; TPM &lt; 10000 nm</td>
<td>no tendency</td>
</tr>
<tr>
<td>PAH = f(T)</td>
<td>strong</td>
<td>minimum (clean, soot load)</td>
</tr>
<tr>
<td>TPM = f(sulfur)</td>
<td>no effect</td>
<td>strong</td>
</tr>
<tr>
<td>SO$_4^{2-}$ = f(T)</td>
<td>low effect</td>
<td>strong (360 °C)</td>
</tr>
<tr>
<td>particle size / number = f(sulfur)</td>
<td>weak</td>
<td>98 %</td>
</tr>
<tr>
<td>filtration efficiency</td>
<td>99.98 %</td>
<td></td>
</tr>
</tbody>
</table>
summary/conclusion
Particle Size and Composition Measurements at Modern Engines and Aftertreatment Systems

- R & D
  - filter material
  - catalytic coating
  - filtration characterisation / -kinetics
  - regeneration strategies / - kinetics
summary/conclusion

Particle Size and Composition Measurements at Modern Engines and Aftertreatment Systems

Thank you for your attention!
Particle Size and Composition Measurements at Modern Engines and Aftertreatment Systems

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