Real time measurement of the effective density and fractal dimension of diesel exhaust particles

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Motivation

• **Density and fractal dimension carry information:**
  - particle properties
  - origin of particles
  - structure of particles

• **Existing methods for density measurement**
  - DMA and Impactor in series (Kelly and McMurry, 1992)
  - DMA and APM in series (McMurry et al., 2002)
  - Accurate but slow (single mobility size at a time)

• **SMPS and ELPI used in several engine labs**
  - Parallel data in abundance
**Effective density**

- **SMPS**: distribution as a function of mobility diameter

- **ELPI**: classification according to aerodynamic diameter

- Mobility and aerodynamic diameter linked through effective density:

\[
d_a^2 C_c(d_a) \rho_0 = d_b^2 C_c(d_b) \frac{[C_c(d_m)]^3 \rho_p}{[C_c(d_b)]^3 \chi^3} = d_b^2 C_c(d_b) \rho_e
\]
Description of the method

• Simultaneous measurement with SMPS and ELPI

• Number distribution measured by SMPS is converted to ELPI “current distribution”

• Calculated and measured ELPI current distributions compared
  - Cost = difference between simulated and measured currents

• Cost minimization
  => Repeated with varying density until minimum difference between simulated and measured currents
Description of the method

- SMPS size distribution
- Charger efficiency

Calculated $i'(db)$
Measured ELPI current

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Description of the method

Integral transform

$k(d_b)$
$i'(d_b)$

Normalized Current $I$ vs. $d_a / \mu m$

Fitted $I'$ ($da$)

Measured ELPI current distribution
Constant density test particles

- **Liquid particles:**
  - density 0.912 (DOS) - 1.9 g/cm³ (Fomblin)

- **Solid particles:**
  - density 2.17 (NaCl) - 10.49 g/cm³ (Ag)

- Size range 40–280nm (peak diameter)
Constant density test results

![Graph showing measured density vs. bulk density for various materials. The graph includes points for DOS 0.912, Santovac 1.2, Fomblin 1.9, NaCl 2.17, Zn 7.14, and Ag 10.49. The graph has a linear trend line.]
Constant density results

<table>
<thead>
<tr>
<th>ρ (fitted)</th>
<th>DOS</th>
<th>Santovac</th>
<th>Fomblin</th>
<th>NaCl</th>
<th>Zn</th>
<th>Ag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of scans</td>
<td>22</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Standard dev.</td>
<td>0.05</td>
<td>0.07</td>
<td>0.09</td>
<td>0.10 / 0.06</td>
<td>0.01</td>
<td>0.93 / 0.86</td>
</tr>
<tr>
<td>Standard dev. %</td>
<td>5.4 %</td>
<td>6.0 %</td>
<td>4.5 %</td>
<td>3.97 / 2.28</td>
<td>0.2 %</td>
<td>7.74 / 8.14</td>
</tr>
<tr>
<td>min</td>
<td>0.72</td>
<td>1.06</td>
<td>1.71</td>
<td>2.42 / 2.42</td>
<td>7.39</td>
<td>11.33 / 9.81</td>
</tr>
<tr>
<td>max</td>
<td>0.90</td>
<td>1.23</td>
<td>1.84</td>
<td>2.67 / 2.54</td>
<td>7.42</td>
<td>13.09 / 11.51</td>
</tr>
<tr>
<td>Average</td>
<td>0.85</td>
<td>1.11</td>
<td>1.91</td>
<td>2.57 / 2.48</td>
<td>7.40</td>
<td>12.04 / 10.58</td>
</tr>
<tr>
<td>Bulk value</td>
<td>0.912</td>
<td>1.2</td>
<td>1.9</td>
<td>2.17</td>
<td>7.14</td>
<td>10.49</td>
</tr>
<tr>
<td>error %</td>
<td>-6.5 %</td>
<td>-7.2 %</td>
<td>0.4 %</td>
<td>18.2 / 14.5</td>
<td>3.7 %</td>
<td>14.7 / 0.9</td>
</tr>
</tbody>
</table>
Diesel soot: fractal like agglomerates

- Fractal dimension $d_f$ defines the scaling of $\rho_e$ and $d_b$:

$$\rho_e \propto d_b^{d_{fm} - 3}$$

20-50 nm
Agglomerates: density vs $d_b$

$slope = 3 - d_f$

$\rho_0$

$\rho_i$

$\rho_e (g/cm^3)$

$d_{b0}$

$d_{bi}$

$d_b (\mu m)$
Agglomerates: silver particles

- reference method: DMA (monodisperse particles) + impactor
Diesel vehicle tests

- Audi A4 1.9 TDI (Euro II)
  - Direct injection
  - EGR + oxidation catalyst

- Euro II fuel (EN590)

- Steady state tests on chassis dyno

- Dilution methods
  - Porous tube diluter (+ thermo denuder)
  - 2 stage ejector diluter: 1st at 180°C, 2nd at room temperature
Example results

\[ \rho ( \text{g/cm}^3 ) \]

\[ \text{Norm. } dN/d\log_{db} \]

- Red: Without TD, df~2.9
- Black dashed: With TD, df~2.7
- Orange: SMPS without DT
- Blue dotted: SMPS with DT
Discussion 1: soot particles

• **Effective density**: 0.4 – 1.3 g/cm³ (soot)
  - Comparable to other methods.

• **Fractal dimension**: 2.6–3
  - Higher than most other studies
  - We obtain average over the size distribution
    • Higher $d_f$ for small particles (monomer-cluster agglomeration)
    • Lower $d_f$ for larger particles (cluster-cluster)
Discussion 2: method

• **Positive**
  - Simple, no time loss from distribution measurement
  - Fast enough for on-line operation
  - Old data can be re-evaluated

• **Negative**
  - Less accurate than serial methods
  - Inaccuracy increases for low fractal dimension values

• **Further development**
  - Search method development
  - Multi-mode distributions

Presentation based on: