The microstructure of soot fractal aggregate deposits

Evdoxia Kladopoulou and Athanasios G. Konstandopoulos
Aerosol & Particle Technology Laboratory, CERTH/CPERI

Abstract

In the literature it has been common practice to assume that the soot layer grown on DPF walls can be described by a uniform density (equivalently porosity), surface area and permeability, which are parameters that have to be tuned according to experiments, leading to widely varying values among different publications. We have shown that during DPF loading the microstructure of the soot cake is determined by the convective-diffusive transport of the soot aggregates towards the deposit and it was also demonstrated that soot cake packing density and permeability are related to the local value of the dimensionless mass transfer Peclet number. In addition these parameters can be related to the porosity and primary particle properties of the soot aggregates. Further insight into soot cake properties has been obtained by model experiments with soot aggregates generated by a Combustion Aerosol Standard (CAST) burner (Matter Engineering, Switzerland). The CAST is a quenched diffusion flame gas (propane) burner that allows the stable and controlled generation of soot aggregates over a much larger size range than that found in diesel exhaust. The model experiments performed with the CAST burner involved the loading of flat disk shaped glass-fiber filters at a wide range of Peclet numbers (0.05-30)-which was achieved by changing the sampling flow for each case- and for soot aggregate sizes between 95 and 200 nm (as measured with the Scanning Mobility Particle Sizer). The results presented show that the porosity of soot deposits depends strongly on the Peclet number, as well as on the aggregate mobility diameter. When soot loaded filters are exposed to a critical pressure drop, soot layer compaction occurs. The microstructure of the resulting deposits, is shown to be well represented in terms of universal power-law functions with respect to the Peclet number and the deposit yield pressure drop.
The Microstructure of Soot Fractal Aggregate Deposits

Evdokia Kladopoulou & Athanasios G. Konstandopoulos

Aerosol & Particle Technology Laboratory
CERTH/CPERI, Thessaloniki, Greece
Motivation

Structure of soot aggregate deposits is important for a number of applications:

- Pressure drop of diesel particulate filters
- Health effects of soot particles/deposits (contact/interaction with tissues)
Methodology

Study the microstructure of soot aggregate deposits using:

- Reference soot size distributions collected on glass fiber absolute filters
- Measurements of filter pressure drop at different Peclet numbers by varying the filtration velocity
- Analysis of results to extract the flow resistance $1/(\text{packing density} \times \text{permeability})$ of the collected deposits
- Appropriate dimensionless numbers and correlations to describe the results
Combustion Aerosol STandard (CAST, Matter Engineering)

Quenched Flame Burner provides reference soot size distributions
CAST soot size distributions

Nominal CAST size

- 30 nm
- 60 nm
- 91 nm
- 106 nm
- 128 nm
- 143 nm
- 190 nm

AEROSOL AND PARTICLE TECHNOLOGY LABORATORY
Nominal (CAST) vs. measured (SMPS) diameter

<table>
<thead>
<tr>
<th>CAST nominal (nm)</th>
<th>SMPS D median (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>51</td>
</tr>
<tr>
<td>60</td>
<td>95</td>
</tr>
<tr>
<td>91</td>
<td>115</td>
</tr>
<tr>
<td>106</td>
<td>129</td>
</tr>
<tr>
<td>128</td>
<td>145</td>
</tr>
<tr>
<td>143</td>
<td>161</td>
</tr>
<tr>
<td>190</td>
<td>197</td>
</tr>
</tbody>
</table>

Note: The table shows the nominal values for CAST and the corresponding measured values for SMPS. The graph illustrates the comparison between the two methods.
CAST Primary vs. Aggregate particle size

\[ d_p = A \cdot d_{ag}^B \]
Experiments were performed using the CAST to load small glass fiber absolute filters with raw exhaust using 6 different size distributions and varying the filtration velocity.
## Experimental test matrix

<table>
<thead>
<tr>
<th>Filtration velocity (cm/s)</th>
<th>Particle mobility diameter $d_p$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>95</td>
</tr>
<tr>
<td>40</td>
<td>■</td>
</tr>
<tr>
<td>33</td>
<td>■</td>
</tr>
<tr>
<td>26</td>
<td>■</td>
</tr>
<tr>
<td>25</td>
<td>■</td>
</tr>
<tr>
<td>20</td>
<td>■</td>
</tr>
<tr>
<td>17</td>
<td>■</td>
</tr>
<tr>
<td>13</td>
<td>■</td>
</tr>
<tr>
<td>10</td>
<td>■</td>
</tr>
<tr>
<td>7</td>
<td>■</td>
</tr>
<tr>
<td>3</td>
<td>■</td>
</tr>
<tr>
<td>1.7</td>
<td>■</td>
</tr>
<tr>
<td>1.2</td>
<td>■</td>
</tr>
<tr>
<td>0.7</td>
<td>■</td>
</tr>
<tr>
<td>0.5</td>
<td>■</td>
</tr>
<tr>
<td>0.4</td>
<td>■</td>
</tr>
<tr>
<td>0.2</td>
<td>■</td>
</tr>
<tr>
<td>0.1</td>
<td>■</td>
</tr>
<tr>
<td>0.07</td>
<td>■</td>
</tr>
</tbody>
</table>

Nominal (CAST setting)

Measured (SMPS)
Soot cake flow resistance

\[ \Delta P = \frac{1}{(\rho \times k)_{soot}} \mu u_f \left( \frac{m_{soot}}{A} \right) \]

\[ (\rho \times k)_{soot} = \tilde{\rho} \cdot (1 - \varepsilon) \times f(\varepsilon) \cdot d_p^2 \cdot SCF \]

\[ f(\varepsilon) = \frac{2}{9} \cdot \left[ 2 - \frac{9}{5} (1 - \varepsilon)^{\frac{2}{3}} - \varepsilon - \frac{1}{5} (1 - \varepsilon)^2 \right] \]

\[ SCF = 1 + Kn \left( 1.257 + 0.4e^{-\frac{1.1}{Kn}} \right) \]

\[ Kn = \frac{2\lambda}{d_p} \quad \lambda = \sqrt{\frac{\pi \cdot MW}{2 \cdot R \cdot T}} \]
Flow resistance vs. filtration velocity

- Axis labels:
  - Flow resistance $\rho x k$ (soot) (kg/m)
  - Filtration velocity (cm/s)

- Data points for different soot sizes:
  - 95 nm
  - 115 nm
  - 129 nm
  - 145 nm
  - 161 nm
  - 197 nm

- Graph shows the relationship between flow resistance and filtration velocity for different soot sizes.
Peclet number effect on soot cake microstructure

\[ Pe = \frac{u_f \cdot d_p}{D} \]

\[ D = \frac{k_B \cdot T}{3\pi \cdot \mu \cdot d_{ag}} \cdot SCF_{ag} \]

Low Pe

High Pe

Diffusion (Diffusion Limited deposition)

Convection (Ballistic deposition)

Porosity $\varepsilon$ vs. Peclet number

![Graph showing the relationship between porosity and Peclet number for different particle sizes. The graph includes data points for 95 nm, 115 nm, 129 nm, 145 nm, 161 nm, and 197 nm particles.](image-url)
Porosity $\varepsilon$ vs. Peclet number correlation

$$\varepsilon(Pe) = 1 - (1 - \varepsilon_\infty) \cdot (1 + \frac{Pe_0}{Pe})^{-n}$$
Flow resistance vs. Peclet number

\[(\rho \times k)_{soot} = \tilde{\rho} \cdot (1 - \varepsilon) \cdot f(\varepsilon) \cdot d_{pr}^2 \cdot SCF\]

\[\varepsilon(Pe) = 1 - (1 - \varepsilon_\infty) \cdot (1 + \frac{Pe_0}{Pe})^{-n}\]
Soot deposit compaction

Deposit compaction model

\[ \frac{\phi}{\phi_0} = \left( \frac{\Delta P - \Delta P_{cr}}{\Delta P^*} \right)^{\delta} \]

- \(\phi\): solid fraction of deposit (1-\(\varepsilon\))
- \(\phi_0\): \(\phi\) in the uncompacted stage
- \(\Delta P_{cr}\): deposit compaction sets in
- \(\Delta P^*\): scaling constant

\(d_{ag} = 129 \text{ nm}\)
Effect of $\Delta P$ on soot deposit compaction

![Graph showing the effect of pressure drop on soot deposit compaction for different particle sizes.](image)

- $95\,\text{nm}$
- $115\,\text{nm}$
- $129\,\text{nm}$
- $145\,\text{nm}$
- $161\,\text{nm}$
- $197\,\text{nm}$
Conclusions

✓ The microstructure of soot aggregate deposits was studied using reference soot from CAST on glass fiber absolute filters

✓ The CAST primary particle size was found to scale with the aggregate size with a power law: \[ d_p = A \cdot d_{ag}^B \]

✓ The flow resistance of soot deposits was calculated varying the Peclet number for 6 different size distributions

✓ The porosity of soot deposits was linked to the Peclet number through a power law correlation: \[ \varepsilon(Pe) = 1 - (1 - \varepsilon_\infty) \cdot \left(1 + \frac{Pe_0}{Pe}\right)^{-n} \]

✓ Soot deposit compaction occurs after a critical pressure drop is reached and the solid fraction of the compacted deposit can be described by a Bingham-like behavior: \[ \phi / \phi_0 = \left[(\Delta P - \Delta P_{cr}) / \Delta P^*\right]^\delta \]
Acknowledgements

- Partial support for the work has been provided by the IST program of the European Commission through the IMITEC project
- We thank our colleague G. Moustakas for contributions in the experimental part