Steady-state and transient effective density of cigarette smoke

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Introduction

• **The density of a smoke droplet:**
  • related to volume and mass
  • may reflect known chemistry differences at product or puff level
  • may influence the mobility properties of the droplet
  • may influence regional deposition in the lung

• **Limited published data**
  • Lipowicz (1988) : UK 1R3F : density = 1120 ± 40 kg.m\(^{-3}\)
    : limited to aerosol aged over 1 hour & > 1000 nm diameter
  • Chen (1990) : UK 2R1F : density = 1120 ± 40 kg.m\(^{-3}\)
Methods
Mobility – Volume measurement
• Balance of electrostatic and centrifugal forces allows correct mass:charge ratio
• Differential cylinder speed allows transit, irrespective of entry radius
- Balance of electrostatic and centrifugal forces allows correct mass:charge ratio
- Differential cylinder speed allows transit, irrespective of entry radius
Steady state density measurements
Steady state density measurements
Transient density measurements
Transient density measurements
Samples

Research / reference cigarettes
• University of Kentucky 3R4F & 1R5F
• CORESTA Monitor CM6

Commercial cigarettes used in consumer and research mouth level exposure and deposition studies
• 1, 4 and 7 mg ISO tar (pack tar)
• Standard King Size (KS) versus King Size Super Slim (KSSS)
• Cellulose acetate (NC) versus carbon / CA (C) filter
Results
Steady state density versus aerosol diameter (3R4F)

- Effective density = 1187 ± 111 kg.m⁻³
- Peak mobility diameters and concentrations at ~230 nm
- Consistency of response with size and with coagulation present implies no fractal dimension and that the smoke aerosol is spherical
Steady state density (3R4F)

Density versus aerosol concentration and age

\[ \rho_{\text{eff}} = 0.0512 \cdot t + 1208.6 \]

\[ \rho_{\text{eff}} = -4e-5 \cdot N_I + 1183.6 \]
Transient density (3R4F)

Puff by puff
Transient density (3R4F)

Base measurements
## Transient density - summary

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Variable</th>
<th># of Samples</th>
<th>Mean ± SD (kg/m$^3$)</th>
<th>Tukey Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Cigarettes</td>
<td>1R5F</td>
<td>15</td>
<td>1346 ± 185</td>
<td>A B C</td>
</tr>
<tr>
<td></td>
<td>CM6</td>
<td>18</td>
<td>1221 ± 176</td>
<td>C D</td>
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<td></td>
<td>3R4F</td>
<td>56</td>
<td>1090 ± 79</td>
<td>D</td>
</tr>
<tr>
<td>Puff Profile</td>
<td>-2 s</td>
<td>36</td>
<td>1101 ± 101</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>0 s</td>
<td>56</td>
<td>1090 ± 79</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>+2 s</td>
<td>51</td>
<td>1059 ± 73</td>
<td>A</td>
</tr>
<tr>
<td>Mouth Hold</td>
<td>8 s</td>
<td>22</td>
<td>1388 ± 156</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>1 s</td>
<td>18</td>
<td>1377 ± 255</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>2 s</td>
<td>56</td>
<td>1090 ± 79</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>4.03</td>
<td>52</td>
<td>1090 ± 73</td>
<td>A</td>
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<tr>
<td>Dielectric Constant</td>
<td>8.72</td>
<td>56</td>
<td>1090 ± 74</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>13.5</td>
<td>55</td>
<td>1077 ± 78</td>
<td>A</td>
</tr>
<tr>
<td>Inhaled Volume</td>
<td>500 ml</td>
<td>56</td>
<td>1090 ± 79</td>
<td>P-Value≤0.001</td>
</tr>
<tr>
<td></td>
<td>1000 ml</td>
<td>17</td>
<td>1311 ± 172</td>
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</tr>
<tr>
<td>Mouth Cast</td>
<td>Yes</td>
<td>56</td>
<td>1090 ± 79</td>
<td>P-Value≤0.001</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>16</td>
<td>1306 ± 156</td>
<td></td>
</tr>
<tr>
<td>Puff Regime</td>
<td>ISO</td>
<td>56</td>
<td>1090 ± 79</td>
<td>P-Value=0.010</td>
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<tr>
<td></td>
<td>HCI</td>
<td>21</td>
<td>1170 ± 123</td>
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</tbody>
</table>
Transient density – commercial cigarettes

Mean ± SD: Letters denote Tukey grouping
Transient density

- Density for smoke from commercial cigarettes > 3R4F reference cigarette
  - Puff to puff density relatively consistent
    - no difference within puff (data not shown)
    - puff 1 differences related to lighting consistency
  - No effect of format, or Carbon versus standard cellulose acetate filter
  - Trend of increasing density with ISO tar yield but within measurement uncertainty
Summary – Smoke particle density

- Support hypothesis of smoke aerosol as spherical droplets
- Independent of particle mobility size
- Small trends observed for different cigarettes, particularly ISO pack tar but within measurement uncertainty.
- Observed difference between commercial and reference cigarettes
- Minimal impact on range of modelled lung particle deposition
Acknowledgements & Bibliography

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