Emissions Report: Ultrafine particles (UFPs) and volatile organic compounds (VOCs) from desktop 3D printers

Filament: BambooFill Brown
Printer: LulzBot Mini

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Summary:
The goal of this work is to experimentally characterize the emissions of ultrafine particles (UFPs, or particles <100 nm) and speciated volatile organic compounds (VOCs) when printing a standardized test part with a desktop 3D printer and polymer filament following manufacturer recommended settings.

Methods:
We conducted controlled environmental chamber testing following methods described in Azimi et al. (2016) Environ Sci Technol 50(3):1260-1268. All measurements were conducted inside a well-mixed 3.6 m³ stainless steel chamber. The 3D printer bed was prepared for printing before sealing the chamber by applying small amounts of adhesive from glue sticks following manufacturer recommendations. We printed a 10×10×1 cm standardized sample from the National Institute of Standards and Technology (NIST), as shown in Figure 1.

Results:
UFP emissions
Figure 2a shows time-varying total UFP concentrations resulting from the single print test and Figure 2b shows estimates of time-varying total UFP emission rates. The left guideline in Figure 2a shows the moment that the printer began warming up prior to printing, which we considered part of the printing emissions period. The second guideline shows the moment that the printer stopped printing. The data smoothing method (SM) that was used and the corresponding coefficient of determination (SM-R²) are shown in Figure 2a. The error bars in Figure 2b show an estimated ~45% uncertainty in the UFP emission rate estimates. The solid line and the upper and lower dashed lines in Figure 2b demonstrate the median and interquartile range of the estimated UFP emission rates. The number of negative estimated emissions (NNEE) is also provided in Figure 2b.
Figure 2. a) Time-varying UFP concentrations inside the chamber during background, printing, and decay time periods, and b) estimates of time-varying UFP emission rates during the printing period.

Table 1 summarizes the estimated UFP emission rate results. The UFP concentration in the chamber increased slightly once the printing period began and then stayed approximately constant during the printing period. The UFP emission rate was very low compared to other tested filaments (e.g., a median UFP emission rate of \(~5.8 \times 10^7 \, \#/\text{min}\) compared to an average of \(~2 \times 10^{10} \, \#/\text{min}\) from 15 printer and filament combinations reported in Azimi et al. 2016).

**Table 1. Summary of total UFP emission rate results**

<table>
<thead>
<tr>
<th>Average (±SD) (#/min)</th>
<th>Median (#/min)</th>
<th>Max (#/min)</th>
<th>Min (#/min)</th>
<th>Total UFPs emitted (#)</th>
<th>Emission per mass of filament (#/g)</th>
<th>Printing duration (mins)</th>
<th>Printing temperature (°C)</th>
<th>Nozzle</th>
<th>Bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8 \times 10^7 (±2.9 \times 10^7)</td>
<td>5.8 \times 10^7</td>
<td>1.3 \times 10^8</td>
<td>2.5 \times 10^6</td>
<td>8.9 \times 10^9</td>
<td>2.0 \times 10^8</td>
<td>184</td>
<td>190</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

**Speciated VOC emission rates**

Table 2 summarizes estimates of individual speciated VOC and ΣVOC emission rates (i.e., the sum of the emission rates of the top 5 speciated VOCs with the highest individual emission rates) from the tested filament. "Acetic Acid", "2-Propanone, 1-hydroxy-", and "Furfural" had the highest individual VOC emission rates from the tested filament. ΣVOC emissions from this filament and printer combination (~4.0 µg/min) were low relative to an average of ~67 µg/min from 15 printer and filament combinations reported in Azimi et al. (2016). The uncertainty in individual VOC emission rates is estimated to be ~36%.

**Table 2. Summary of top-five individual speciated VOC emission rates**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Acetic acid</th>
<th>2-Propanone, 1-hydroxy-</th>
<th>Furfural</th>
<th>Ethylamine</th>
<th>Butanoic acid, butyl ester</th>
<th>ΣVOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (µg/min)</td>
<td>1.57</td>
<td>0.81</td>
<td>0.66</td>
<td>0.48</td>
<td>0.45</td>
<td>3.96</td>
</tr>
</tbody>
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