Cambustion Aerosol Measurement Consultancy Report	
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Characterisation of 3D Printer Nanoparticle Emissions and Filtration Performance of BOFA 3D PrintPRO 3

Introduction

Three aerosol instruments were used to measure nanoparticle emissions from an enclosed desktop 3D printer (operated with PLA or ABS filaments) and characterise the filtration performance of the BOFA 3D PrintPRO 3 extraction system:

- The Differential Mobility Spectrometer (DMS) 500 is a real-time particle sizing instrument that is well suited to measuring 3D printer particle emissions, since its very fast response (a fraction of a second) means it can capture rapid variations in particle size and number, and its integrated dilution system offers a wide dynamic range.
- The Scanning Mobility Particle Sizer (SMPS) usually takes more than 1 min to accurately record a particle size distribution, since it proceeds through the size channels consecutively and sends the classified particles to a counter. However, its high sensitivity means it is best suited to capture size information on any particle penetration through the filter in the PrintPRO 3.
- A separate Condensation Particle Counter (CPC) was employed that reports total particle number concentration without size information, but combines a fairly fast response (<2 sec) with high sensitivity. This would accurately capture the rapid reduction in particle concentration downstream of the filter after the extraction system has been switched on. (It may also be valuable in tracking any filter breakthrough that could be linked to short-lived spikes in particle emissions at a particular size that would be resolved by the DMS, but not by the SMPS.)

Equipment & Method

Apparatus

3D printer: Intamsys Funmat HT

(www.intamsys.com/funmat-ht-3d-printer)

The model printed for all tests was the **3DBenchy** (www.3dbenchy.com). Two filament materials were tested:

- **Polylactic acid (PLA)**
  - Chamber temperature = 23°C, bed temperature = 60°C, extruder temperature = 210°C
- **Acrylonitrile butadiene styrene (ABS)**
  - Chamber temperature = 23°C, bed temperature = 100°C, extruder temperature = 250°C

Extraction system under test: BOFA 3D PrintPRO 3

- Three identical filter boxes were supplied ("P0301003 without carbon and filter pads"), one to use for each filament material and one spare
- The air flow was set to the maximum (setpoint = 150 m^3/hr, indicated by six green lights on the front panel)
- Plenums were provided to connect the 50 mm diameter PrintPRO 3 hoses to the Funmat HT (replacing the snap-in handles on either side):
  - The inlet hose (withdrawing particle-laden air from the printer) was 1 m long.
  - The outlet hose (returning filtered air to the printer) was 5 m long.

Aerosol instruments:

- **Cambustion DMS500 Mk2 fast aerosol sizer** (www.cambustion.com/products/analytical-instrumentation/dms500-aerosol-size-spectrum-measurements):
    - The DMS operates by passing the aerosol sample through a unipolar corona charger, followed by simultaneous parallel detection of particles over a range of electrical mobilities using electrometers. This provides real-time measurement of the particle size spectrum with a data rate up to 10 Hz and a time response ($T_{10\text{-}90\%}$) down to 200 ms. The size range used in these experiments was 5 nm—1000 nm and the sample flow rate was approx. 8 l/min. For tests requiring less rapid response and higher sensitivity (e.g., when sampling the ambient air surrounding the printer), the DMS data were averaged over 5 samples (2 Hz) or 20 samples (0.5 Hz).

- **TSI SMPS 3938** (https://tsi.com/products/particle-sizers/scanning-mobility-particle-sizer-spectrometers/general-scanning-mobility-particle-sizer-(smps)-3938):
    - Particles were classified by their electrical mobility diameter using an Electrostatic Classifier 3082 with a Differential Mobility Analyser 3081A and detected using a CPC 3775. Each particle size spectrum was produced from a 2 min scan, with automatic software corrections applied for multiple charges and particle diffusion. Scans were run consecutively during each test, either in low flow mode (= 0.3 l/min sample flow and 3 l/min sheath flow) for a size range of 6 nm—229 nm, or in high flow mode (= 1.5 l/min sample flow and 15 l/min sheath flow) for a size range of 15 nm—649 nm.

- **TSI CPC 3752** (https://tsi.com/products/particle-counters-and-detectors/condensation-particle-counters/high-concentration-condensation-particle-counter-3752):
    - A second, stand-alone CPC was used to measure total particle number concentration between 4 nm (D50) and >3000 nm with a time response ($T_{10\text{-}90\%}$) of 1.5 sec for 1.5 l/min sample flow. It operates in single particle counting mode (accuracy: ±10%) for number concentrations up to 10^5 /cm^3 and photometric mode (accuracy: ±20%) for concentrations of 10^5—10^7 /cm^3.

Test schedule

For both PLA and ABS filaments:

1. The Intamsys Funmat HT was set up next to a mixing fan under a ducted fume hood (with the valve to the extraction duct closed), as shown in Fig. 1:
    a) During a single 3DBenchy print, ambient air surrounding the printer was sampled beside the top door of the printer with the DMS, SMPS and CPC. Upon completion of the print, the top door was opened (using a wire around the latch, pulled through a hole in the roof of the fume hood) while instrument logging continued.
    b) Test 1a) was repeated with the top door to the printer open throughout the print.

2. The fume hood was removed and the BOFA PrintPRO 3 extraction system was connected to the Funmat HT in a re-circulating loop, as shown in Fig. 2:
    a) During a single 3DBenchy print, particle-laden air from the PrintPRO 3 inlet was sampled using the DMS and filtered air from the outlet was sampled using the SMPS and CPC.
        - The PrintPRO 3 was left off for the first 15 min of the print (to allow the particle concentration to build up within the hoses), then switched on to capture the filtration process.
    b) Test 2a) was repeated with the aerosol instruments exchanged between the sample ports either side of the PrintPRO 3.

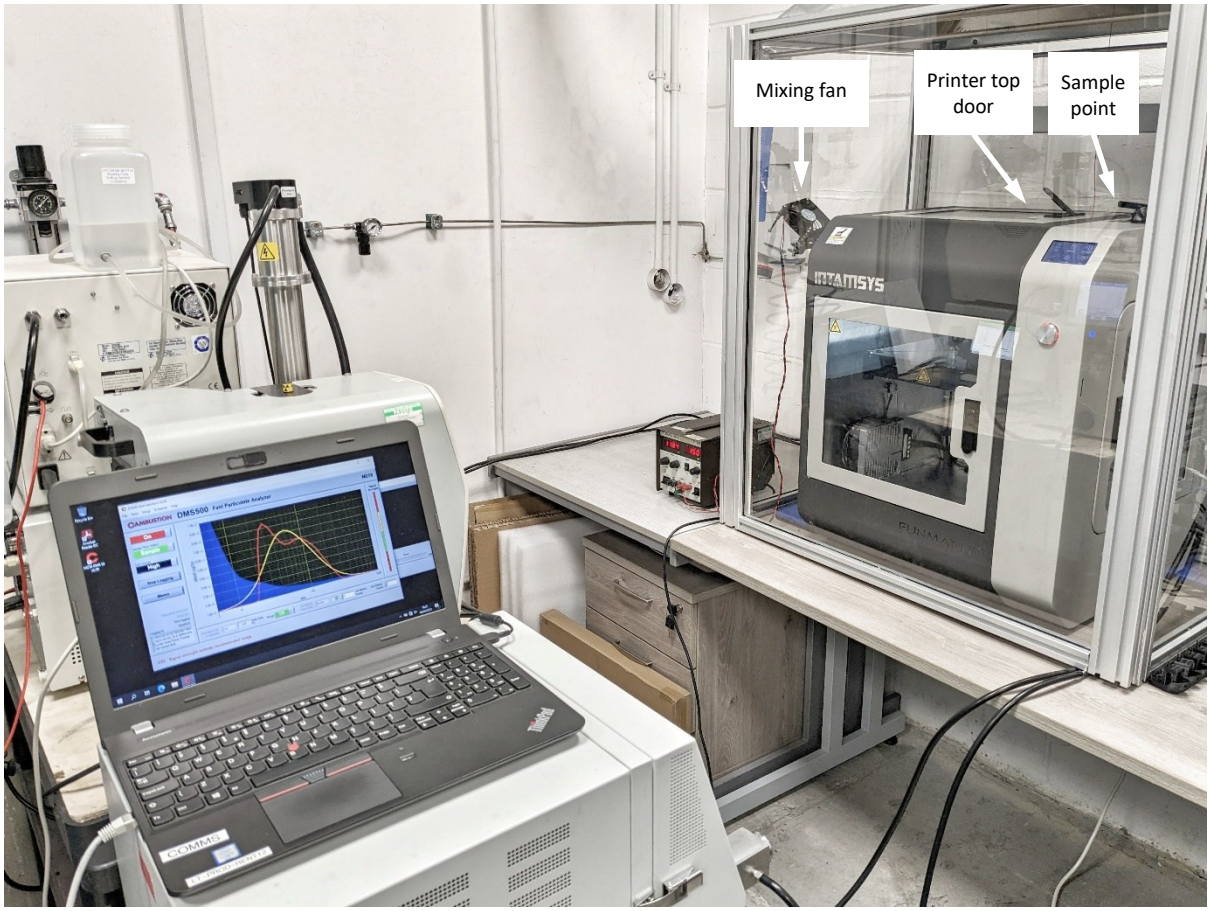

Fig. 1: The Intamsys Funmat HT 3D printer alongside a mixing fan within the fume hood. The aerosol instruments are sampling the air close to the top door of the printer.

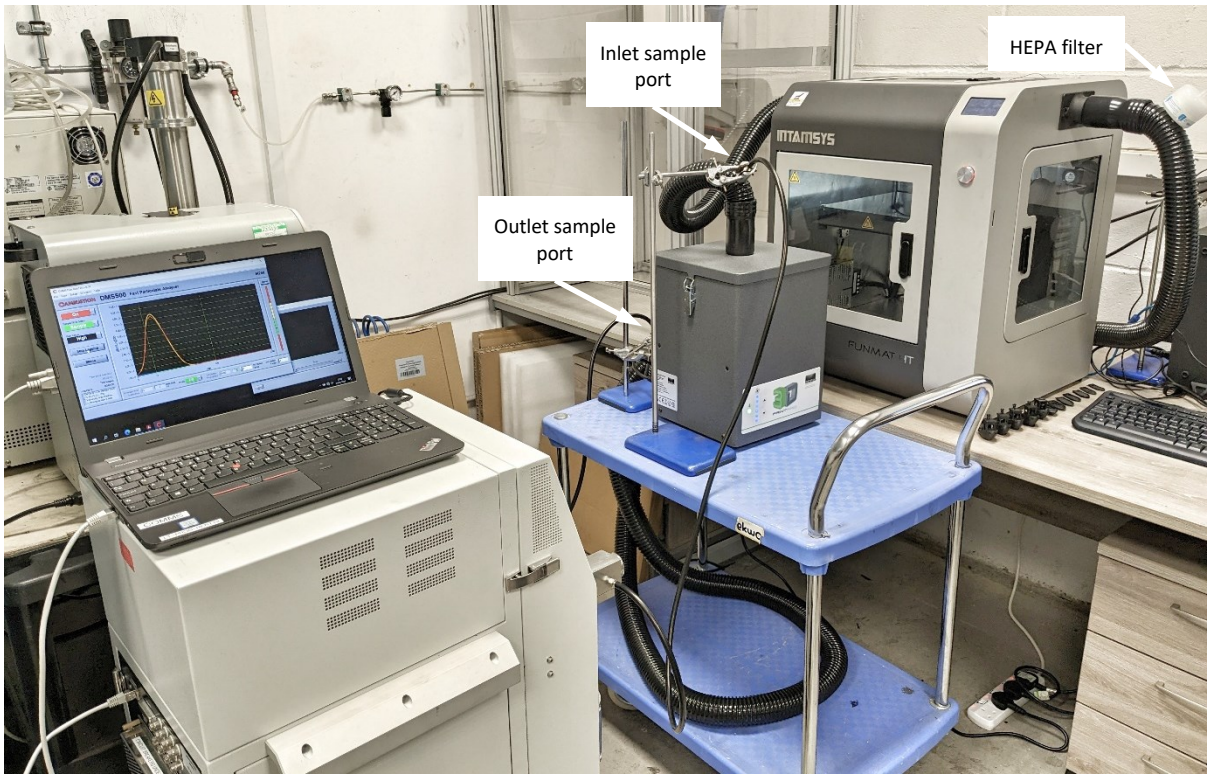

Fig. 2: The BOFA 3D PrintPRO 3 extraction system attached to the Intamsys Funmat HT 3D printer via plenums on the left and right sides. The aerosol instruments are sampling the air at the inlet and outlet of the PrintPRO 3.

Notes on experimental set-up

- The PrintPRO 3 withdrew air directly from the Funmat HT printer bed chamber (left side shown in Fig. 2); the filtered air flow to the printer returned air to the compartment containing the printer electronics (right side in Fig. 2), which is thermally insulated from the bed chamber and air would have been flowing through the gaps in-between. When measuring air flow velocities in and out of the PrintPRO 3 using an anemometer, the indicated inlet flow corresponded to approx. 115 m^3/hr (at the unit's maximum air flow setting), but the outlet flow was as low as half of this figure. Outwards flow of air from the bottom of the PrintPRO 3 was apparent (between all four sides of the base and the outer casing). No further investigation was carried out due to time constraints and the need to break the seal between the pump unit and the casing. No concern about particle exposure is implied, since the air emerging from the base was downstream of the filter.

- 5 mm diameter holes were drilled in the flexible hoses for the sample ports, approx. 50 mm away from the edge of the inlet/outlet tubes of the PrintPRO 3 (to avoid damaging the extraction unit itself). Stainless steel barbs were inserted and sealed in these holes. Aerosol samples were transported to the instruments in 5.5 mm i.d. conductive silicone tubes (which varied between 1.5 m and 2.5 m in length, depending on the test configuration); a correction for particle losses by diffusion in these tubes was applied to the data from the SMPS in low flow mode (0.3 l/min sample flow).

- A High Efficiency Particle Air (HEPA) filter was installed on a port at the air inlet to the printer (see top right of Fig. 2) to equalise the pressure inside the system with the ambient level (since the three aerosol instruments together withdraw up to 11 l/min flow, which is not returned to the recirculating loop). This measure was intended to reduce the inwards flow of ambient air through gaps in the printer enclosure (that may contain particles generated by other processes in the laboratory) and instead encourage the filtration of inwards leaking air to remove potential artefacts in the data.

- The filter box in the PrintPRO 3 was changed between the two filament materials. After testing was complete, the used filters were labelled as loaded with particles generated by PLA or ABS printing, in case further analysis (e.g., electron microscopy) is to be carried out on the collected particles.

- There were difficulties to overcome when configuring the Funmat HT to produce repeatable 3DBenchy prints (i.e., both in terms of print quality and the measured particle emissions), particularly with the supplied ABS material. For any future testing (especially with PEEK, which requires significantly higher bed and extruder temperatures), additional preparation time would be required to optimise the calibration of the printer for each filament material specification.

Results

3D printer nanoparticle emissions measured in fume hood

CPC data for the total particle number concentration throughout all four prints in the fume hood are plotted in Fig. 3. The valve in the duct was closed so that particle emissions were largely retained under the hood, while a mixing fan circulated the air inside. The sample points were positioned beside the opening end of the printer top door. Particle number emissions during printing with ABS were generally an order of magnitude higher than with PLA, and as the print commenced (just before 300 sec in Fig. 3) there was a substantial breakthrough of ABS particles even through the closed door, which peaked at 7.7×10^4 /cm^3. Then the ABS particle concentration gradually settled to a level of approx. 10^4 /cm^3, which doubled when the door was opened at the end of the print (before the valve in the extraction duct was opened, to scavenge the particles from the fume hood). With the top door left open during the following print, the ABS particle number concentration rapidly reached a peak of 2.7×10^6 /cm^3, then settled to a level of approx. 8×10^4 /cm^3. The corresponding features in the PLA data are much less prominent, with total number concentrations generally around 4000 /cm^3 and 9000 /cm^3 in the tests with the printer top door closed and open respectively.

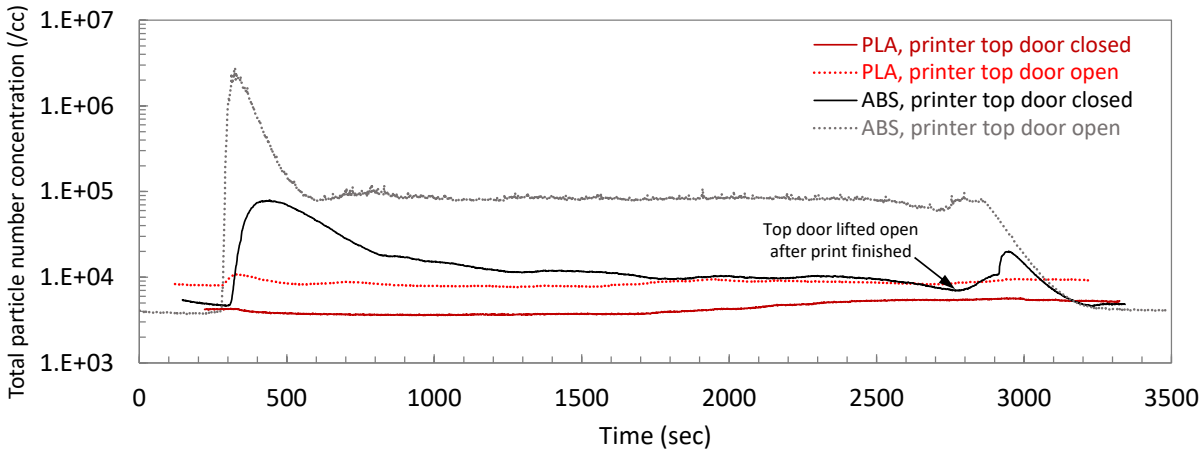

Fig. 3: CPC total number concentration for both PLA and ABS particle emissions measured above Funmat HT with top door closed (solid lines) and opened at the end of the print (approx. 2750 sec), then repeated with top door open throughout the print (dotted lines).

SMPS data from 2 min scans recorded at approximately halfway through each print (when the particle emissions were relatively steady) are plotted in Fig. 4, revealing that the modal sizes of particles in the air above the open door were 60 nm for PLA and 40 nm for ABS. When the printer top door was closed, the PLA particle size distribution was bimodal, with one mode at 55 nm and the other (probably aged) mode at 125 nm. The single mode of the ABS particles shifted upwards to 105 nm. These findings imply agglomeration of the particles over time in the air around the printer.

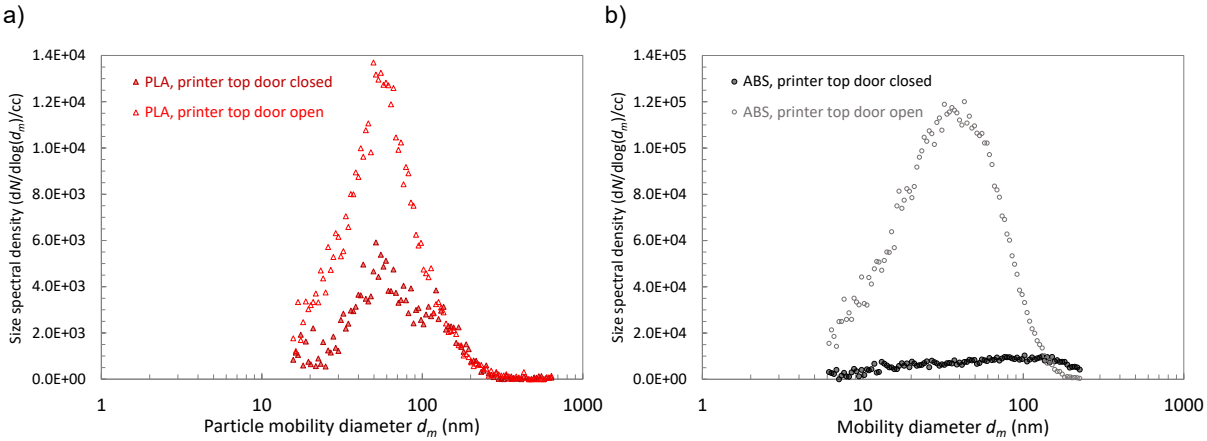

Fig. 4: SMPS spectra for a) PLA particles and b) ABS particles measured halfway through the print (note: the spectral density axis is an order of magnitude higher for ABS than for PLA).

The DMS contour plots shown in Fig. 5 provide a useful snapshot of size-resolved nanoparticle measurements during an entire test. A logarithmic scale of particle mobility diameter is plotted on the y-axis, with the timescale on the x-axis. The spectrum of colours represent a logarithmic scale of particle spectral density (i.e., the number concentration of particles in each size channel divided by its logarithmic width).

The DMS size information is consistent with the SMPS data in Fig. 4; the PLA particle spectra show relatively small temporal variations during the two prints, with the highest spectral densities generally at 50—60 nm. In contrast, prominent transients are captured in the DMS measurements of the ABS particle emissions. Two particular events are shown in more detail in the dynamic particle spectra plotted in Fig. 6: the opening of the top door at the end of the print (corresponding to the region of the contour plot beginning at 2750 sec in Fig. 5c) and the start of the subsequent print with the door held open (corresponding to the distinct red region beginning at 150 sec in Fig. 5d). In the latter case, the surge of the most freshly generated ABS particles had a count median diameter of 15 nm, then it steadily increased in particle size and decreased in number.

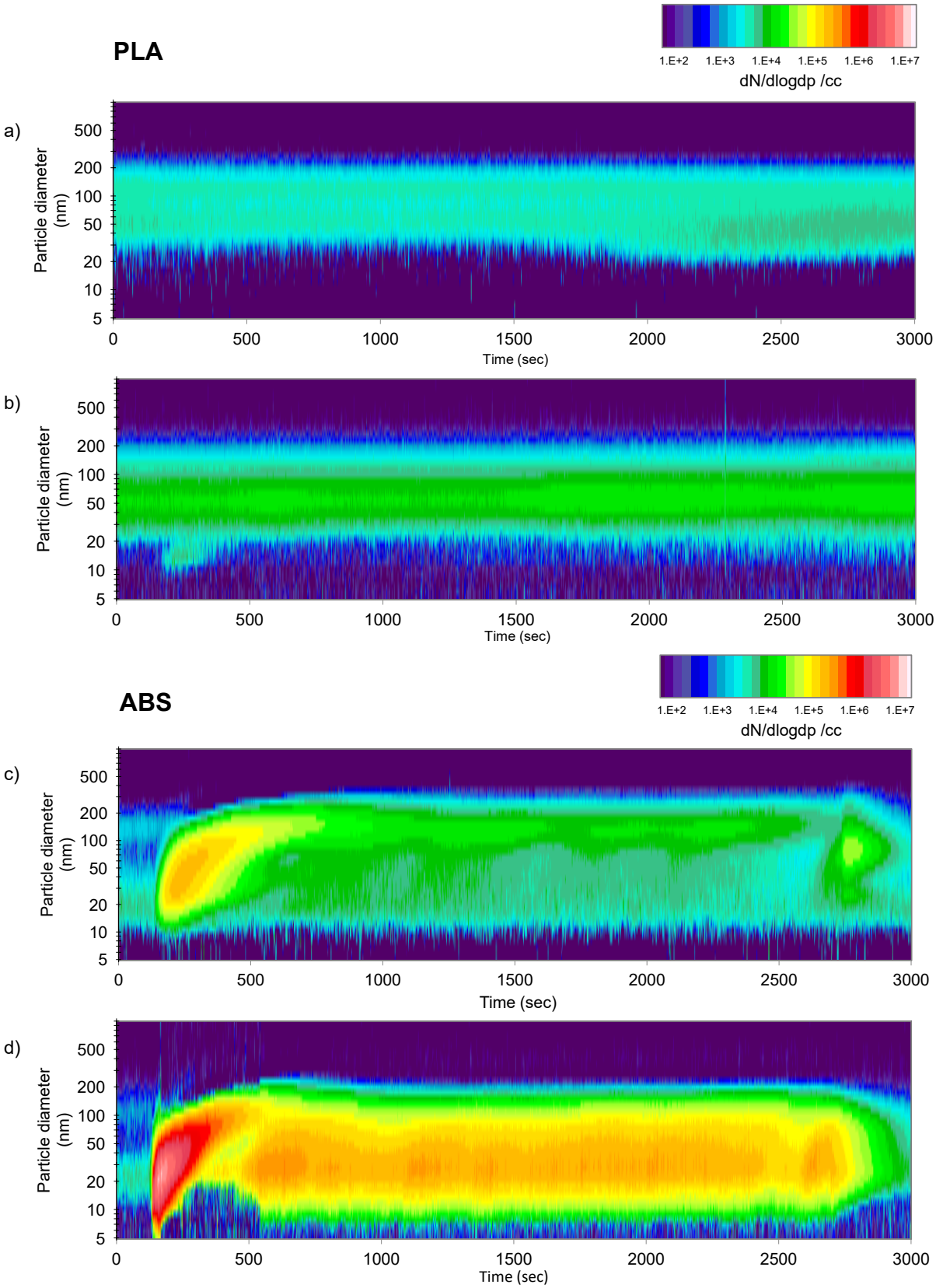

Fig. 5: DMS contour plots of particle emissions measured above Funmat HT for a) PLA with top door closed, then opened at the end of the print (approx. 2750 sec), b) PLA with top door open throughout printing, c) ABS with top door closed, then opened at the end of the print (approx. 2750 sec), and d) ABS with top door open throughout printing.

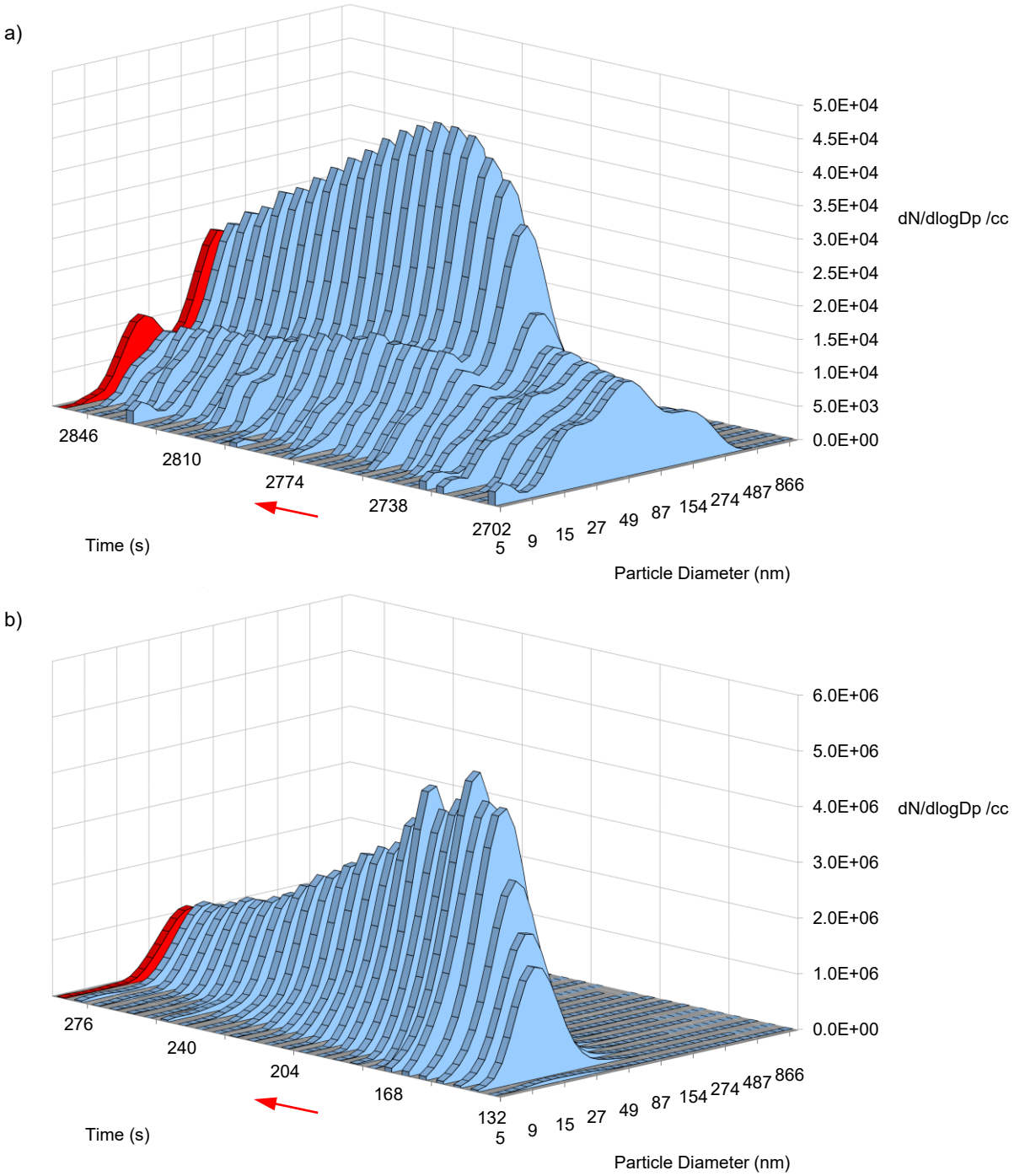

Fig. 6: DMS dynamic particle spectra during a) opening of top door after ABS print was complete and b) beginning of subsequent ABS print with door kept open (note: the spectral density axis is two orders of magnitude higher for plot b than for plot a).

3D printer nanoparticle emissions measured at inlet and outlet of PrintPRO 3

PLA filament

CPC data for the total particle number concentration measured throughout both PLA prints with the PrintPRO 3 connected are plotted in Fig. 7. The PrintPRO 3 was switched on at approx. 15 min (900 sec), which caused the upstream particle number to decrease by approx. 30%. The downstream particle number dropped to <1 /cm^3 within 12 sec, yielding an average filtration efficiency over the following 15 min of 99.985% for PLA particle number emissions. The corresponding DMS contour plots are shown in Fig. 8.

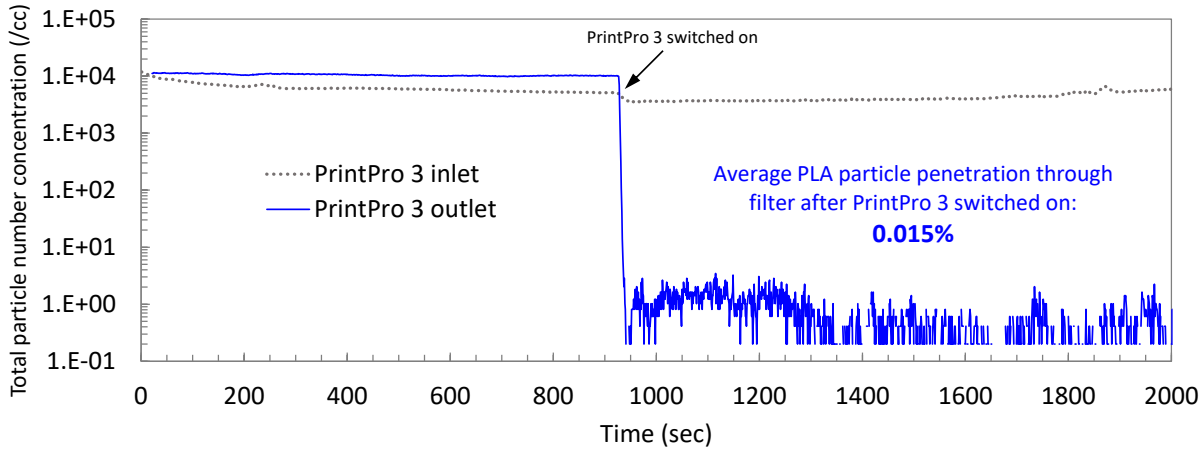

Fig. 7: CPC total number concentration for PLA particle emissions measured at the PrintPRO 3 inlet and outlet during two separate prints, with the extraction flow activated at approx. 900 sec.

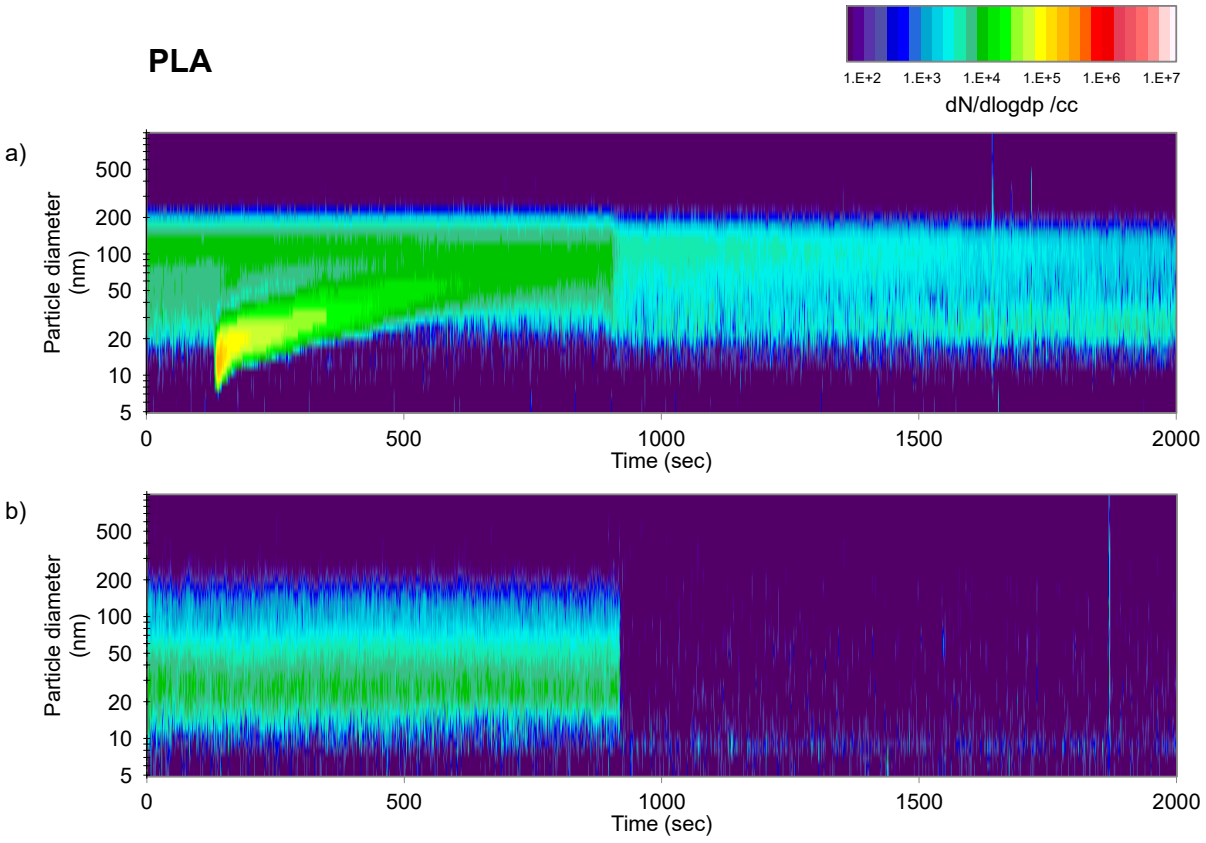

Fig. 8: DMS contour plots for PLA particle emissions measured during two separate tests at a) the inlet of the PrintPRO 3 and b) the outlet. In both cases the PrintPRO 3 was powered on at approx. 900 sec.

The start of the print at 150 sec in Fig. 8a generated a mode of PLA particles with an initial count median diameter of 13 nm; as the particles accumulated in the static air in the inlet hose, they agglomerated causing a gradual increase in size and decrease in number. After the recirculating flow of filtered air was established, relatively little temporal variation in the particle spectra was measured at the PrintPRO 3 inlet. At the outlet, the rapid reduction in particle concentration at all sizes downstream of the filter is captured in Fig. 9.

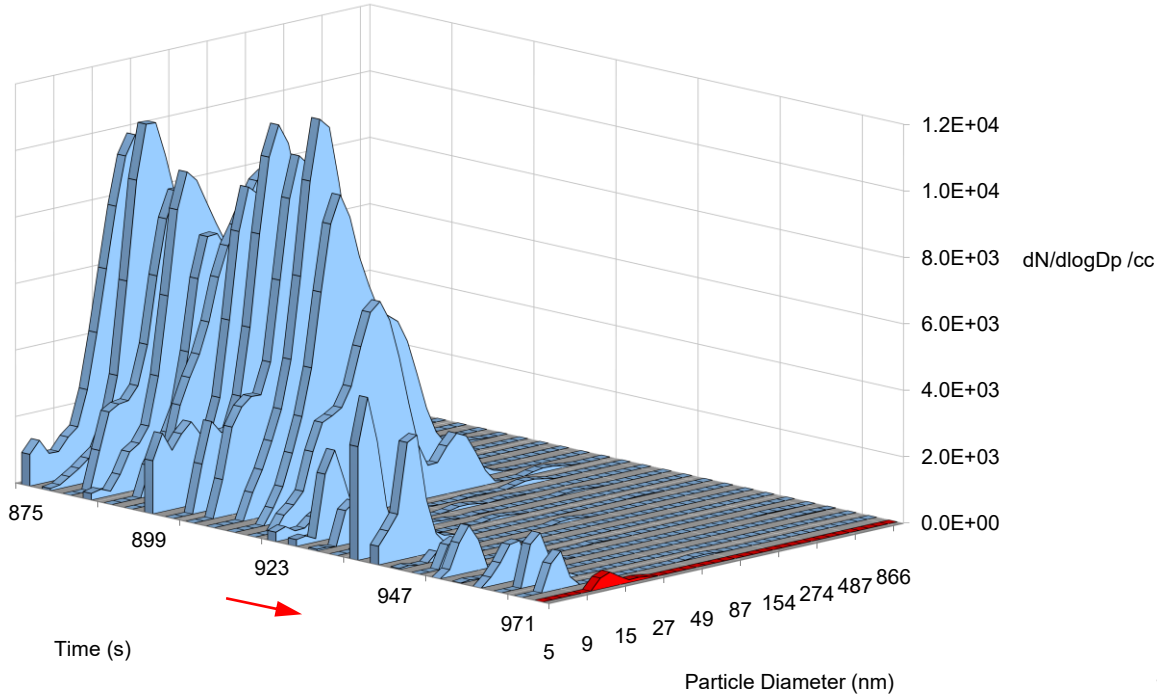

Fig. 9: DMS dynamic particle spectra of PLA particles downstream of the PrintPRO 3, shortly before and after it was switched on.

ABS filament

Following manual recalibration of the Funmat HT for the supplied ABS material (to ensure the base of the 3DBenchy adhered to the printer bed), a longer print duration of 55 min was required; during the same single print, both the inlet and outlet of the PrintPRO 3 were sampled by the three aerosol instruments before and after the extraction system was switched on. The CPC data compiled from the periods up- and downstream of the filter are shown in Fig. 10. For the smaller ABS particles, the reduction in upstream number concentration was far more pronounced than seen with PLA, with a drop of approx. 98% after the PrintPRO 3 was switched on. The downstream particle number dropped to <2 /cm^3 within 12 sec, yielding an average filtration efficiency over the following 15 min of 99.975% for ABS particle number emissions. The corresponding DMS contour plots are shown in Fig. 11.

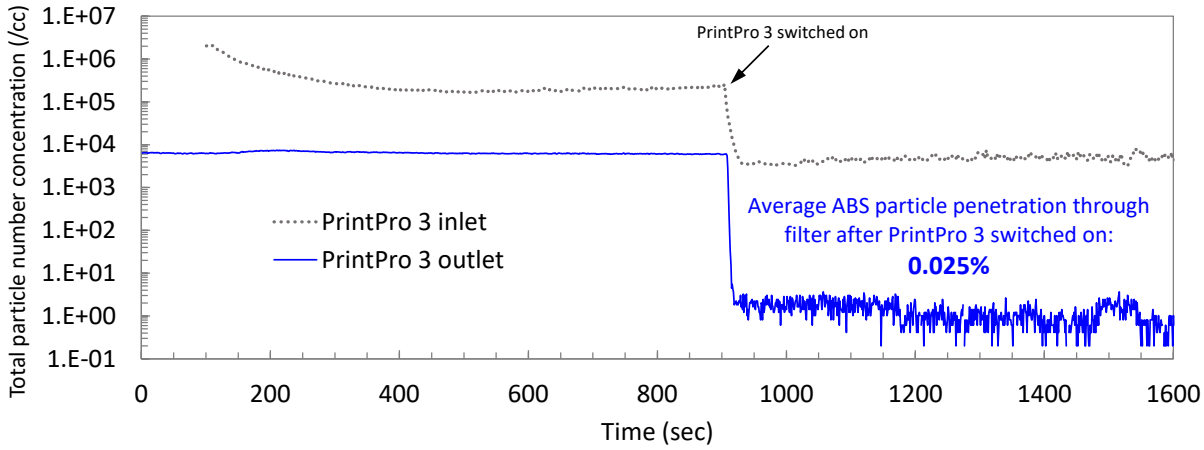

Fig. 10: CPC total number concentration for ABS particle emissions measured at the PrintPRO 3 inlet and outlet during two separate prints, with the extraction flow activated at approx. 900 sec.

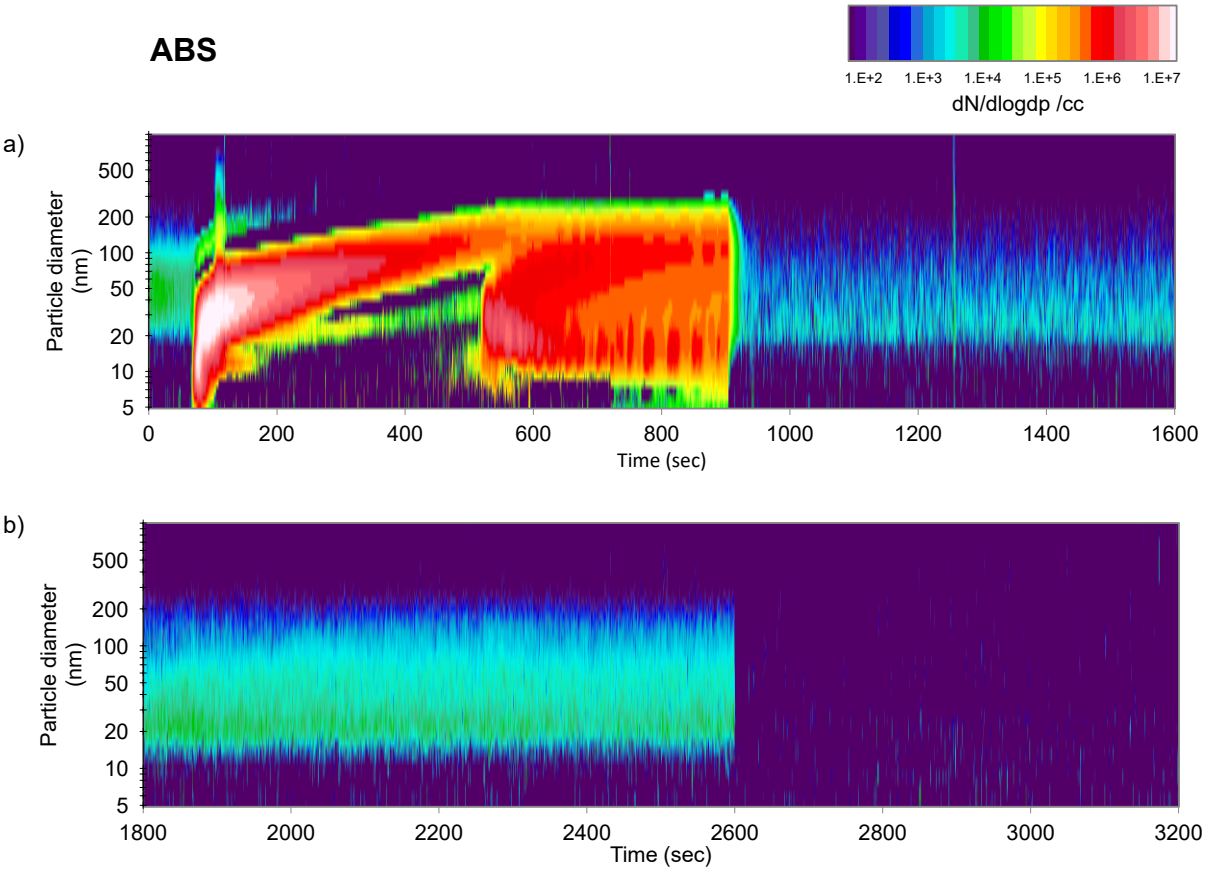

Fig. 11: DMS contour plots for ABS particle emissions measured during the same test at a) the inlet of the PrintPRO 3, which was powered on at approx. 900 sec, and b) the outlet, with power applied at approx. 2600 sec.

The start of the print at 60 sec in Fig. 11a generated a mode of ABS particles with an initial count median diameter of 12 nm; the corresponding dynamic spectra are plotted in Fig. 12a. This was followed by agglomeration in the inlet hose, which caused the peak of the distribution to increase to over 100 nm during the following 8 min. Then a freshly generated population of 25 nm particles joined the gradually agglomerated mode, an event that is captured in the DMS dynamic spectra in Fig. 12b.

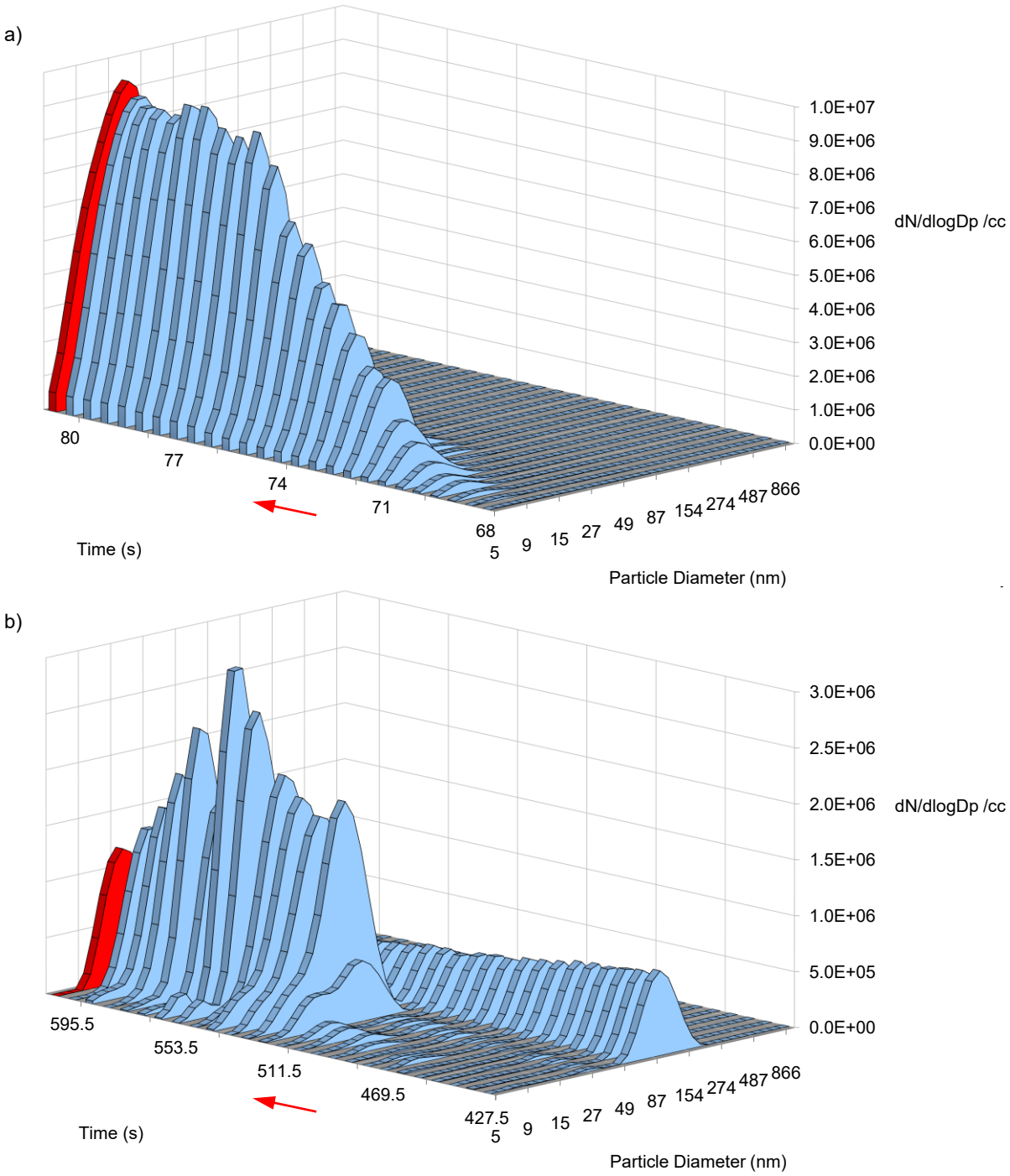

Fig. 12: DMS dynamic particle spectra from PrintPRO 3 inlet hose at a) beginning of ABS print and b) later generation of a high concentration of 25 nm ABS particles joining an aged mode of 135 nm particles.

With DMS sampling switched to the PrintPRO 3 outlet hose and the extraction system powered on, the swift reduction in ABS particle concentration at all sizes is plotted in Fig. 13.

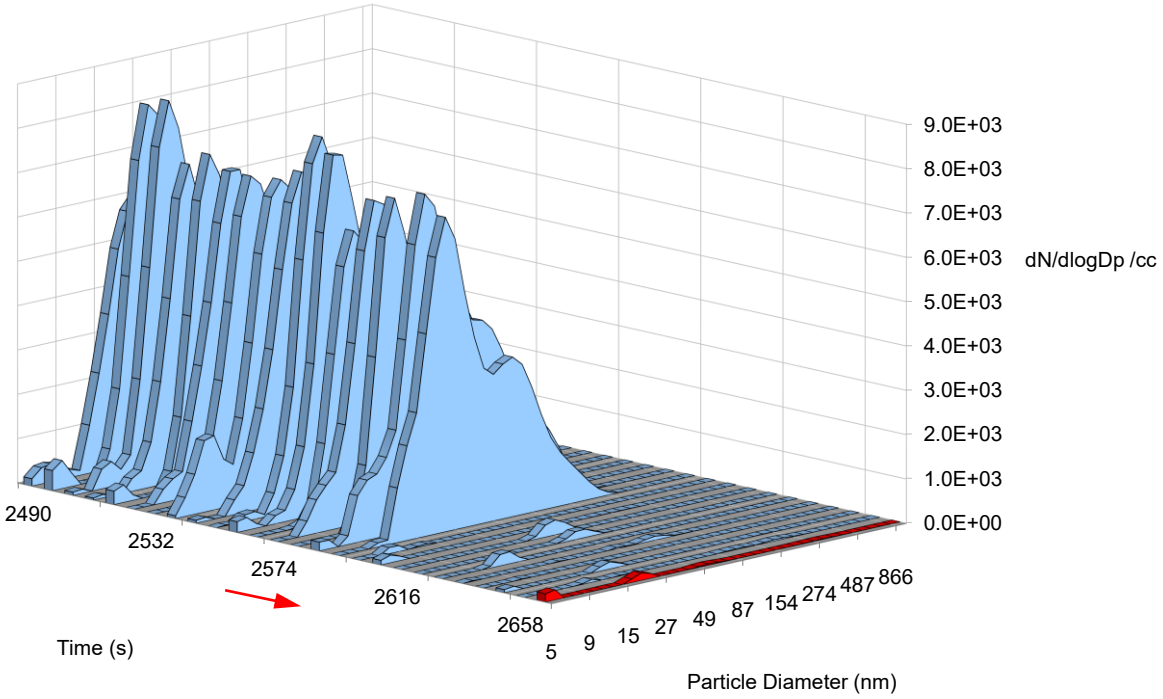

Fig. 13: DMS dynamic particle spectra of ABS particles downstream of the PrintPRO 3, shortly before and after it was switched on.

Comments on SMPS data recorded downstream of filter in PrintPRO 3

The filter installed in the PrintPRO 3 was reported as being certified to EN 1822 grade H14, meaning the penetrations limits are an integral value of 0.005% and a local value (i.e., at the most penetrating particle size) of 0.025%. Measurements have been made previously at Cambustion of size-classified particle penetration through H13 and U15 filter samples (i.e., the grades below and above what is installed in the PrintPRO 3); the data are available to view on slides 7 and 8 of the following presentation delivered at the 2023 Nordic Society for Aerosol Research Symposium:

- www.researchgate.net/publication/369378122_Measurements_of_particle_capture_in_PPE_and_HVAC_filters_using_aerosols_classified_by_aerodynamic_diameter

In order to resolve particle size information downstream of the filter in those tests, the upstream number concentrations were in the 10^7—10^8 /cm^3 range, which is a few orders of magnitude above what was observed upstream of the PrintPRO 3 on its maximum air flow setting. In particular, the dilution of high ABS particle emissions from the printer bed by the recirculated filtered air reduced the number concentration measured upstream of the filter to a level that was too low for resolving any size information on penetrating particles. Instead, the CPC data successfully captured the high filtration efficiency and rapid scavenging of both PLA and ABS particle emissions in terms of total number concentration.

Conclusions

- The processes of 3D printer aerosol generation and evolution involve significant transients that are well captured using the DMS. Particle number emissions during printing with ABS were generally an order of magnitude higher than with PLA, and the concentration of ABS particles in the air around the enclosed printer exceeded 10^6 /cm^3 shortly after printing started.

- When sampling static air in the PrintPRO 3 inlet hose, freshly generated particles from both filament materials were mostly <15 nm in mobility diameter, which appear to agglomerate over the following minutes. Aged and agglomerated particles of various sizes were measured in the air surrounding the printer; generally, printing with PLA led to evolution of larger particles than with ABS.

- It was not possible to obtain size-resolved particle penetration through the PrintPRO 3 filter using the SMPS, due to efficient scavenging of the upstream particle concentration by the recirculating air flow. It was for this reason that the PrintPRO 3 was left off for the first 15 min of the print and then switched on to capture the rapid decrease in particle number downstream of the filter using the CPC; subsequently, the reduction in particle concentration upstream also became evident (generally decreasing by an order of magnitude in number for ABS printing) as the recirculating loop of filtered air was established.

- The total particle number concentration measured by the CPC showed that after powering on the PrintPRO 3 on its maximum flow setting, the particle concentration downstream of the filter fell to <2 /cm^3 within seconds. The PrintPRO 3 removed 99.985% of PLA particles and 99.975% of ABS particles by number over the following 15 min.

Line-up of 3DBenchy pieces printed during particle emissions measurement.