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Investigating Particle Emissions from a Consumer Fused Deposition Modeling 3D Printer with a Lognormal Moment Aerosol Dynamic Model

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Introduction

- Fused deposition modeling (FDM) 3D printers are popular with general public and usually used in indoor environments not designed for manufacturing[1]
- High levels of nanoparticles and gases from 3D printers were reported, depended on printer and filament properties[2,3], which may cause adverse health effect[4]
- Particle formation mechanism and aerosol dynamic processes involved have not been systematically investigated

Objective

- Examine 3D printer particle emission and evolution mechanism with a lognormal moment model using chamber experiment data
- Investigate key factors that influence particle emissions
- Potential mitigation method

Method

Chamber experiment

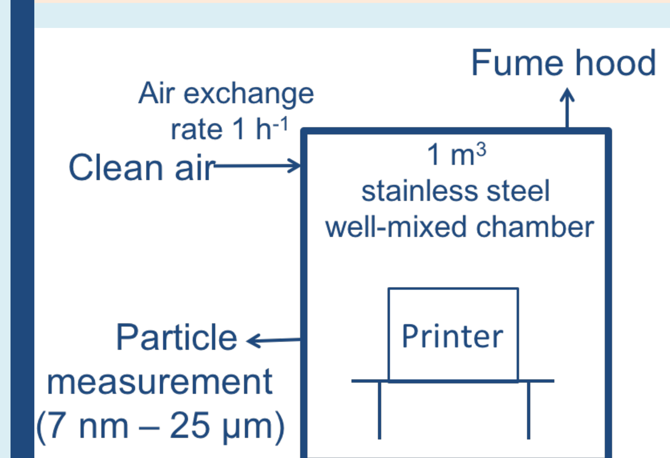

Fig.1 Experimental chamber system

- Chamber condition[5]
  - Temperature 23 ± 1 °C; Relative humidity 3.0 ± 0.2%
- Print condition

Expt.	1	2	3	4
Material	acrylonitrile butadiene styrene (ABS)			nylon
Filament	a	d	d	-
Temp.	270	270	243	243

- Aerosol measurement
  - Particle number distributions as a function of time

Lognormal moment model

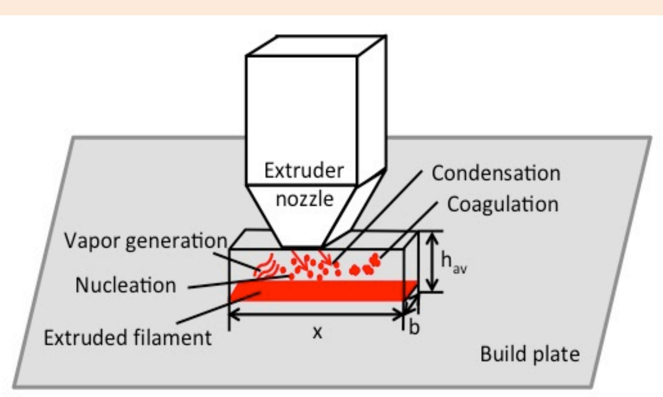

Fig.2 Schematic of the control volume and aerosol dynamic processes that are modeled within the control volume

- Control volume (CV) defined by x, h_{av}, b
- Assumptions
  - No external processes at/across CV boundaries
  - Neglect particle losses to chamber surfaces
  - Particles were chemically homogeneous
  - No chemical reactions
  - Temperature (T) in CV uniform and constant
  - Out of CV only dilution
- Governing equations[6]
  - 0th moment: $\frac{dN'}{d\theta} = I' - \xi N'^2$
  - 1st moment: $\frac{dV}{d\theta} = I'k^* + f\eta(S-1)N'$
  - 2nd moment: $\frac{dV_2}{d\theta} = I'k^{*2} + 2f\epsilon(S-1)V + 2\zeta V^2$
  - Vapor balance: $\frac{dS}{d\theta} = R' - I'k^* - f\eta(S-1)N'$
- Key parameters

Model (vapor property)	Observation (particle property)
R (vapor generation rate)	N (total number concentration)
f (condensation coefficient)	D_{pg} (geometric mean diameter)
P_s (saturation vapor pressure)	σ_g (geometric standard deviation)

- Input (R, f, P_s, T, x) → Output (steady state N, D_{pg}, σ_g)

Results

Observation

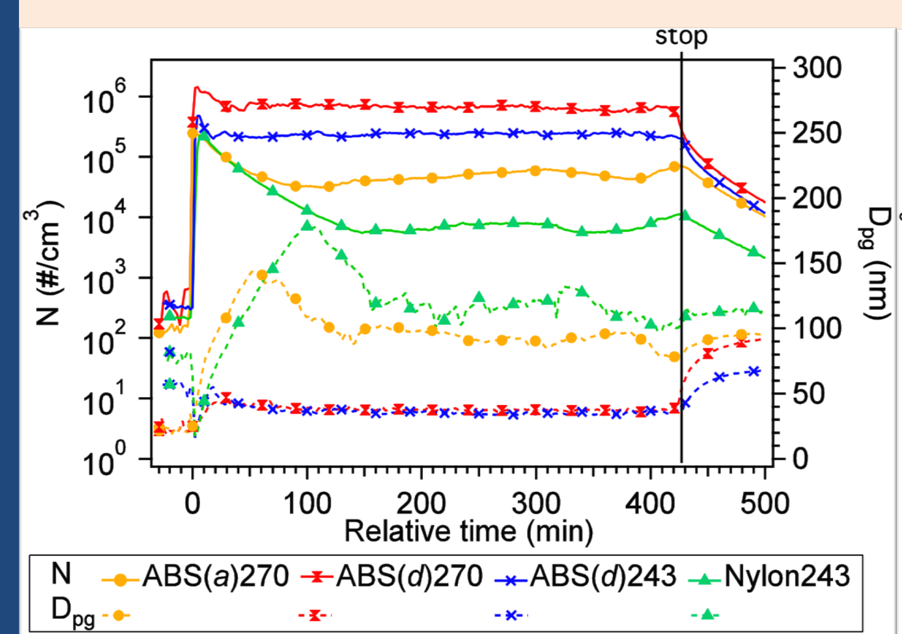

Fig.3 Total particle number concentrations and geometric mean diameters measured in chamber

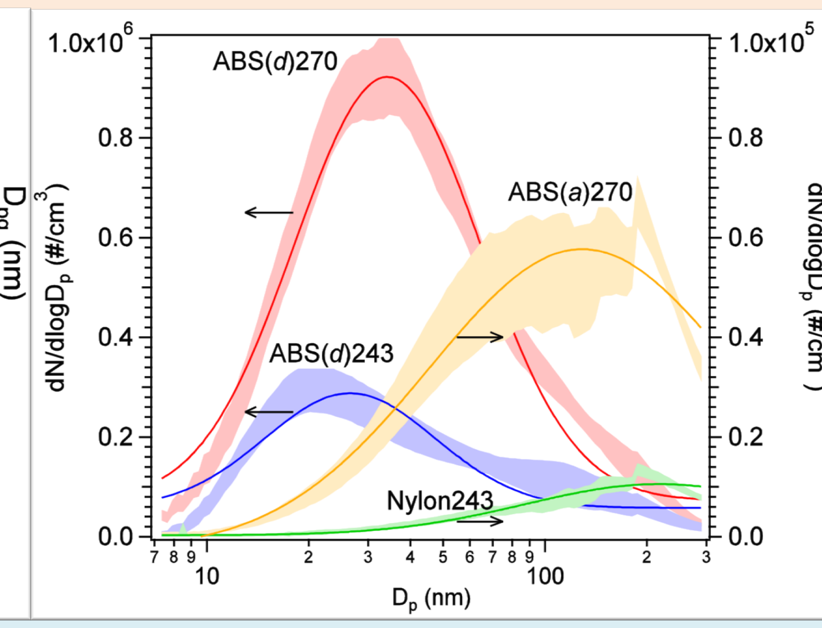

Fig.4 Average particle size distributions at steady state

- Particle concentration time series and size distribution
  - Similar trend for different filaments on the same printer
  - Concentration peaked consistently at the beginning; reached approximate constant after 1–2 h into printing
  - Particles were generally lognormal distributed
- Aerosol dynamic processes
  - New particle formation (NPF) from semi-volatile vapors at beginning (initial peak)
  - NPF, vapor condensation, particle coagulation and dilution reached steady state

Sensitivity analysis

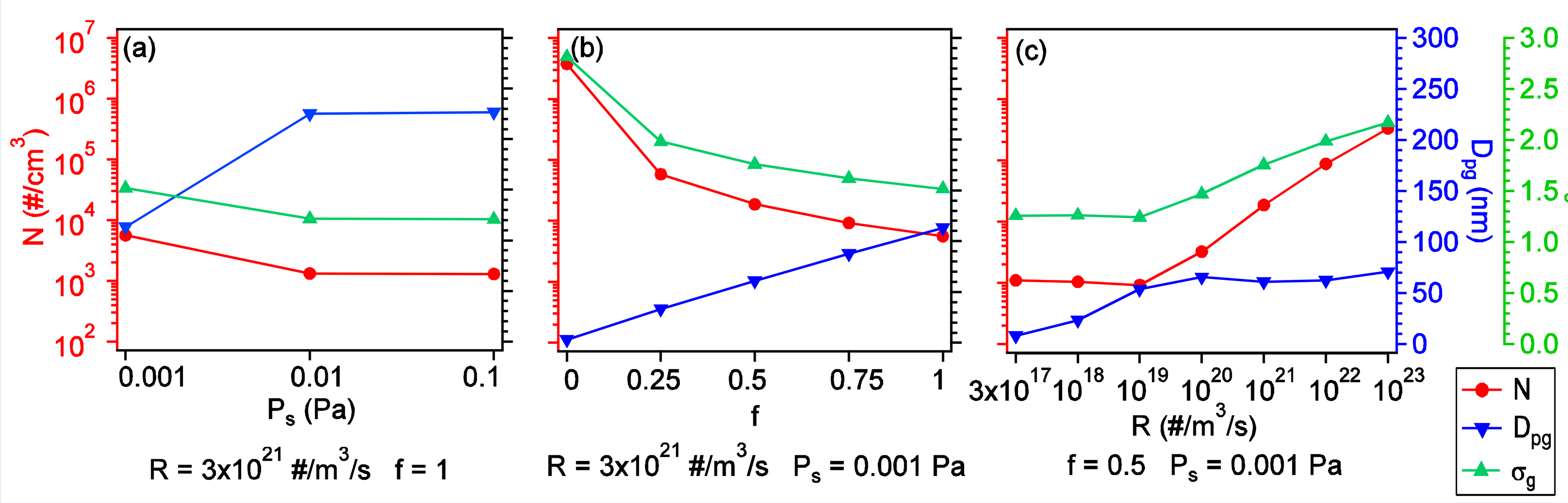

Fig.5 The simulated steady state particle characteristics (N, D_{pg}, σ_g) as a function of each vapor property (P_s, f, R) separately when controlling the other two

- Smaller P_s → higher NPF → larger N and smaller D_{pg}
- Larger f → vapor condensation on existing particles favors than NPF → smaller N and larger D_{pg}
- R larger than inflection point → larger R → higher NPF → larger N

Simulation

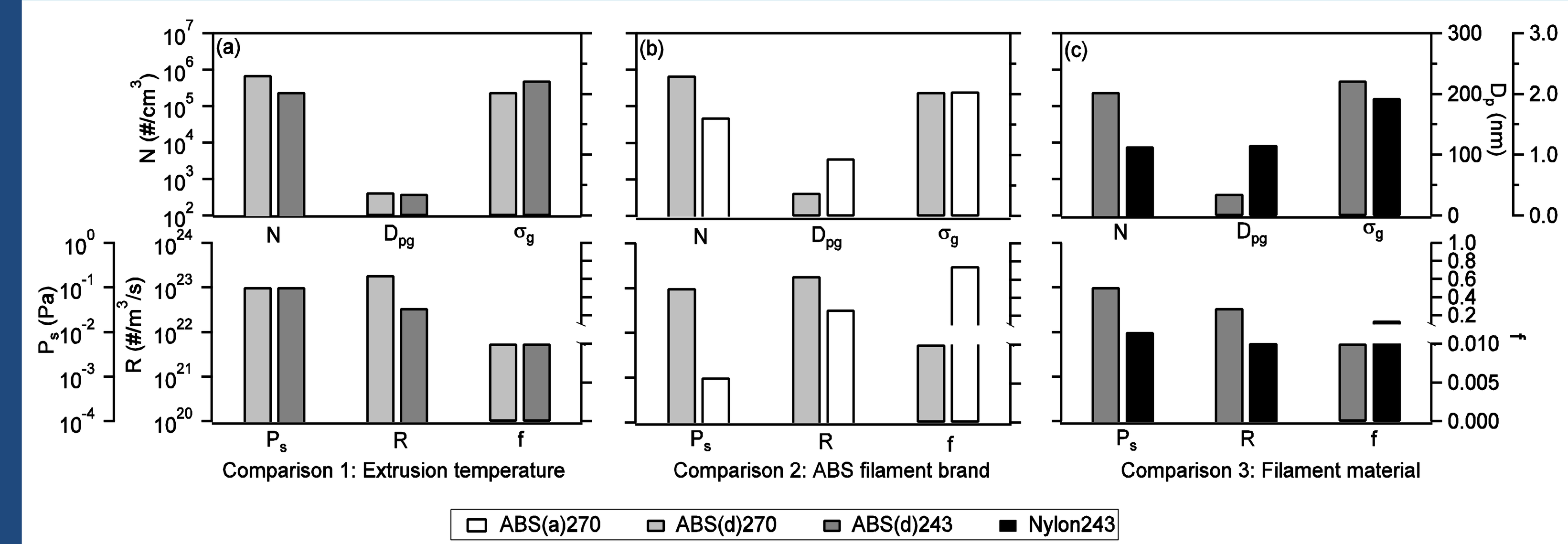

Fig.6 Observed steady state particle size characteristics (upper panel) and model simulated condensing vapor properties (lower panel), grouped by 3 sets of comparisons

- Higher extrusion temperature → higher R, same P_s and f → emit more of the same condensing vapors
- Similar trend for changing filament brand and material: high emitting case has higher P_s and R, lower f → R mainly drives emissions
- Vapor properties for different filament brands differed → particles form from species other than bulk material

Discussion & Conclusion

- A lognormal aerosol moment model is capable of capturing the particle characteristics at steady state during printing phase
- Modeled aerosol processes: particles are formed from nucleation of semi-volatile vapors emitted from the heated filament, and then grow by vapor condensation and particle coagulation in a small control volume close to extrusion nozzle
- These dynamic processes were interrelated and depended on some key properties of the condensing vapors (R, f, P_s)
- Printing conditions (filament material, filament brand and extrusion temperature) influenced the steady state particle characteristics and could be related to the differences in the model predicted properties
- Particles are formed from semi-volatile compounds associated with additives in filaments (i.e., different from bulk filament)
- Vapor generation rate from the filament largely drove the particle emissions and linked to printer extruder temperature
- Possible mitigation strategy: remove the newly formed small particle near the extruder nozzle by thermophoresis

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