Evaluation of Uncertainties in Aircraft Soot Engine Emissions Derived from Engine Smoke Number

Marc E.J. Stettler*, Jacob J. Swanson and Adam M. Boies

Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom.

*Corresponding author. Email: ms828@cam.ac.uk

1. Introduction

Aircraft gas turbine engines emit particles with a geometric mean particle diameter less than 100 nm consisting of non-volatile and volatile particles. The non-volatile component is primarily black carbon soot (*1*). Current regulation is concerned with the visibility of aircraft exhaust, quantified via the engine smoke number (SN) and each engine type is measured according to a standard procedure defined in Aerospace Recommended Practice (ARP) 1179C (*2*) before entering service. The SN is a dimensionless quantity related to the darkening of particle-loaded filters through the transmissions of a given quantity of exhaust gas per unit of filter area (Figure 1).

Aircraft BC emissions are currently estimated from the SN, using a method called the First Order Approximation v3.0 (FOA3) (*3*), which is endorsed by the International Civil Aviation Organization (*4*). Current efforts are directed towards finalising a new standard non-volatile PM mass and number measurement standards, however in the absence of retrospective measurements, BC emissions from engines currently in use will continue to be estimated.

Recent analysis comparing FOA3 estimated emissions indices with published measurements has shown that there is an order of magnitude discrepancy in 40% of cases (Figure 2) (*5*). Such uncertainty in aircraft emissions leads to significant uncertainties in estimates of the air quality impacts of aircraft operations at airports. Figure 1 shows that at London Heathrow Airport, modelled airside concentrations of BC as a result of all airside operations (aircraft, APUs and airside support equipment) are reduced by 35% when using FOA3 compared to an alternative empirical method based on existing measurements of BC emissions indices (*5*). Additionally, the spatial extent of the airport's impact on surrounding communities is significantly reduced (Figure 3).

2. Objectives

The objectives of this study are to investigate whether the deviation of FOA3 compared to measurement is as a result of flexibility within the SN measurement standard. We present a preliminary investigation into the effect of using different filter diameters, which affects incident face velocity. We also present findings from an investigation of the filtration efficiency as a function of incident BC mass and particle size.

3. Methodology

Soot is produced via an inverse diffusion flame supplied with propane, air and N_2. Combustion products are rapidly quenched by a perpendicular flow of N_2 and for all results presented here. A catalytic stripper downstream of the burner removes any volatile PM components. Filter Smoke Number is collected according to ARP 1179 (*2*) using Whatman 4 Qualitative filters. The estimate of loaded mas is obtained by assuming an effective density of ρ_{eff} = 0.6 g/cm^3. Figure 4 shows the experimental set-up.

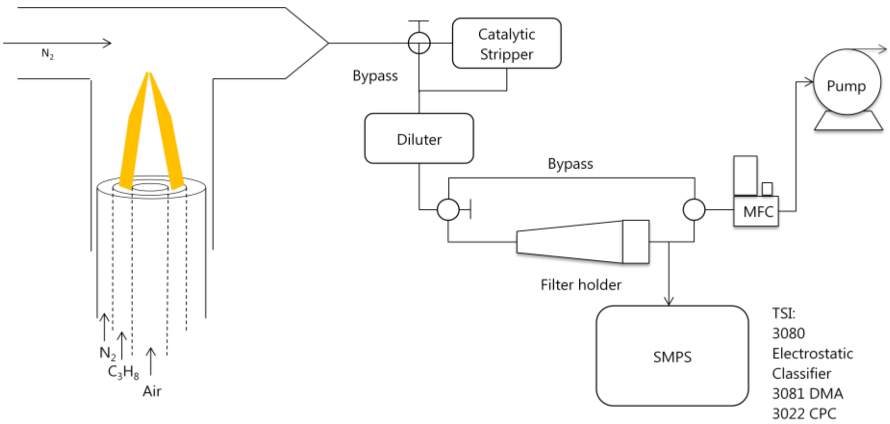

Figure 4: Experimental set-up to produce soot and collect SN and SMPS samples.

4. Results

Number concentration and size distribution of generated soot can be altered by varying the absolute and relative quantities of propane, air and N_2 (Figure 5). For all results presented here, the flow rates of the input gases are constant and lead to a geometric mean diameter of 62 nm and a geometric standard deviation of 1.95.

In order to relate a given SN to a mass emissions index, FOA3 uses an empirical correlation between sample mass concentration, a concentration index (CI) with units mg/m^3, and SN. Measurements from this study show good agreement with this relationship (Figure 6) suggesting that this is not a source of the observed discrepancy between measured and modelled emission indices.

Two filter diameters, 27 and 35 mm corresponding to face velocities of 0.41 and 0.24 m/s were tested and demonstrate that there is no significant effect of filter diameter and on measured SN (Figure 7).

The mass and number filtration efficiency of the Whatman 4 filters increases with increasing SN (Figure 8) and mass loading.

The particle number filtration efficiency as a function of D_p shows that for a clean filter, filtration efficiency at for D_p~60 nm is ~20% less than for smaller or larger particles. For high mass loadings, filtration efficiency shows no significant dependence on particle size (Figure 9).

5. Conclusions

- A diffusion burner that is capable of producing soot with a range of number concentrations and particle size distributions has been developed.
- The CI-SN correlation used in FOA3 is verified for non-volatile soot suggesting that this is not a significant source of discrepancy between measured and modelled soot emission indices.
- There is no observed dependence of the SN on filter diameter.
- Filtration efficiency increases from ~40% to ~90% with increased mass loading and SN.
- Filtration efficiency is a weak function of particle size for the given size distribution.

6. Future Work

- Investigate soot morphology.
- Test the minimum allowed filter diameter (19.5 mm, 0.83 m/s) to investigate whether this affects filtration efficiency.
- Investigate filtration efficiency, and CI-SN relationship with different particle size distributions, of poly- and mono-disperse particles.
- Investigate the effect of volatile components on measured SN as these could affect the mass specific absorption cross section of BC or scattering by the filter material. Volatile organics and sulfates (from sulphur in the fuel) could exist in semi-volatile states due to flexibility with respect to different sampling line temperature in the SN standard procedure.
- Quantify uncertainties associated with estimating aircraft BC from SN.

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1. Introduction

- Aircraft gas turbine engines emit particles with a geometric mean diameter less than 100 nm, primarily black carbon soot (BC).
- Existing regulation is concerned with the visibility of aircraft exhaust, quantified via the smoke number (SN), a dimensionless quantity related to the darkening of particle-loaded filters through the transmission of a given quantity of exhaust gas per unit of filter area.

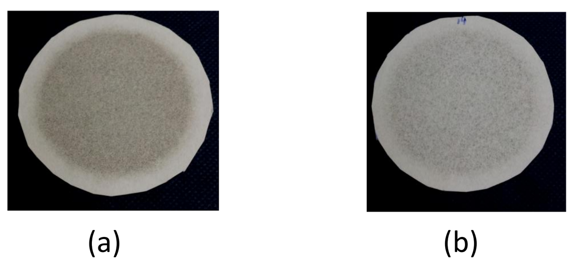

Figure 1: Example of filter Smoke Number samples, (a) the incident face (SN=38), (b) the back of the filter.

- Aircraft BC emissions are currently estimated using the SN. The latest version of this method is called the First Order Approximation v3.0 (FOA3)[1] and is endorsed by the International Civil Aviation Organization (ICAO). Aircraft PM emissions will continue to be estimated as a result of long engine lifetimes.
- Order of magnitude underestimation in 40% of cases when FOA3 is compared with emissions measurements (Figure 2) leading to significant uncertainties in air quality modelling (Figure 3).

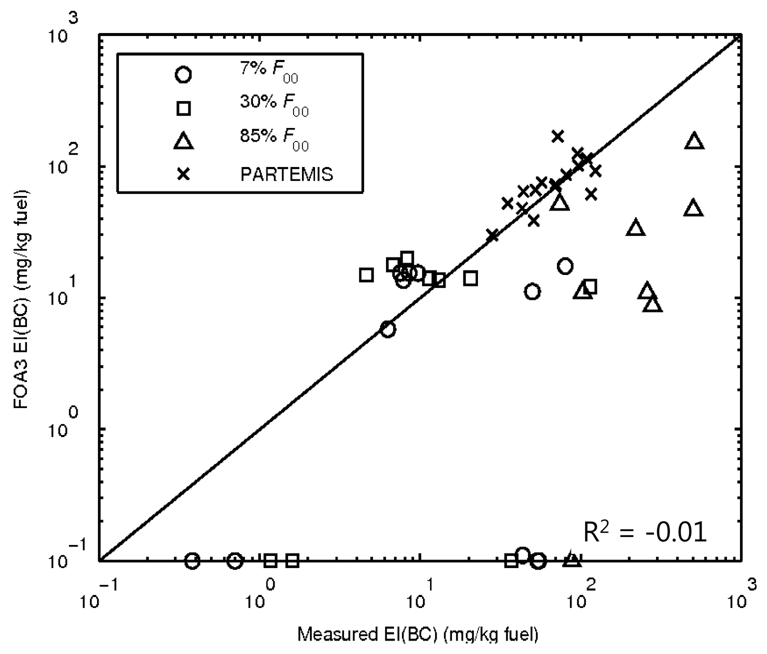

Figure 2: Comparison between estimated (FOA3) and measured EI(BC) for real engines (open) and PARTEMIS combustor experiments (x). Calculated R^2 refers only to the engine data.

- Airside BC concentrations at LHR are reduced by 35% and the extent of the impact of the airport on surrounding communities is reduced significantly when using FOA3 as opposed to a model based on EI(BC) measurements.

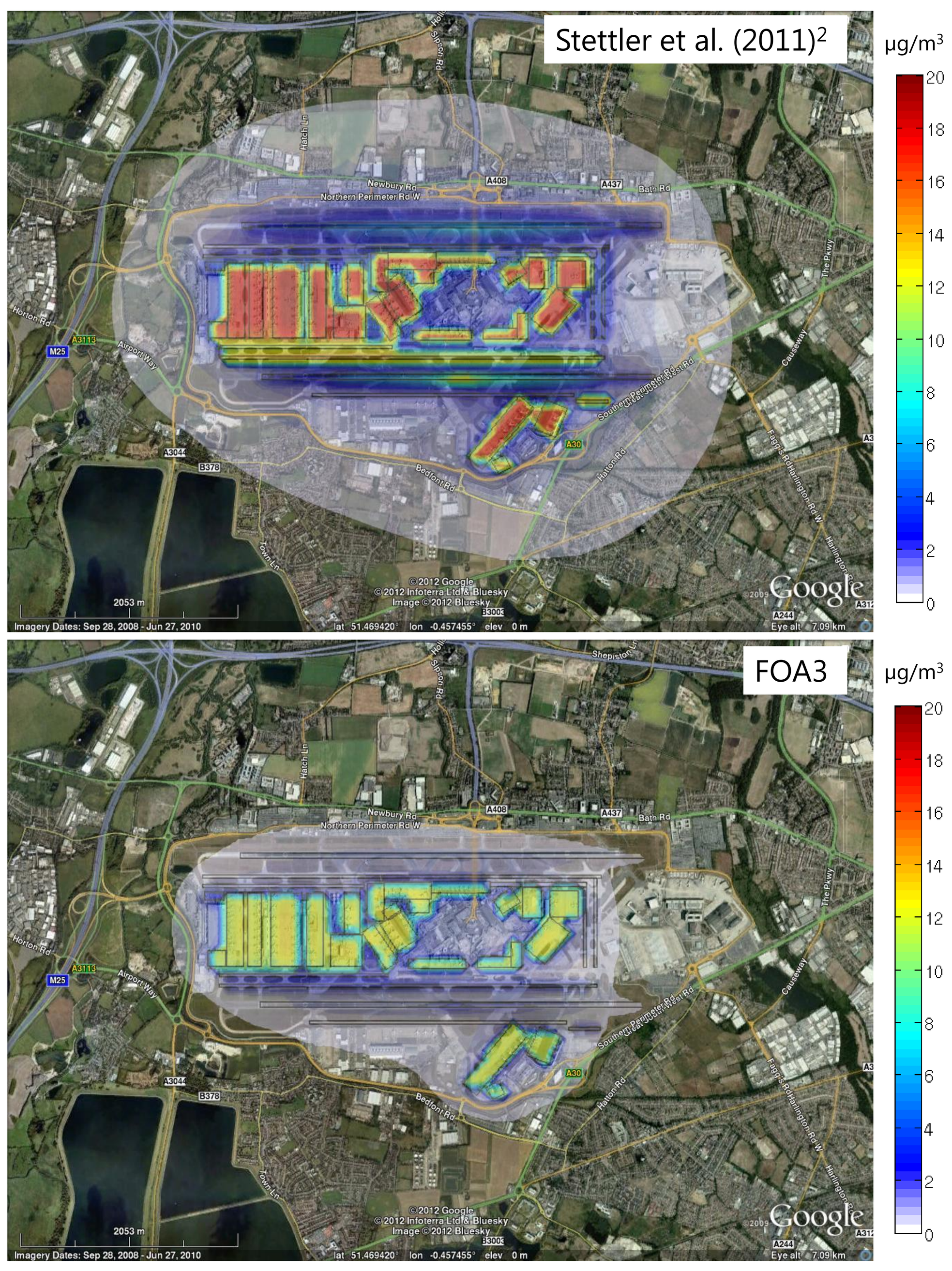

Figure 3: Comparison between modelled local BC concentrations at London Heathrow (LHR) due to different emissions models.

Acknowledgements

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References

1. Wayson, R. et al. (2009). Methodology to Estimate Particulate Matter Emissions from Certified Commercial Aircraft Engines. *J. A&WMA, 59*(1), 91-100. doi:10.3155/1047-3289.59.1.91
2. Stettler, M. E. J. et al. (2011). Air quality and public health impacts of UK airports. Part I: Emissions. *Atmos. Env., 45*(31), 5415-5424. doi:10.1016/j.atmosenv.2011.07.012

2. Objectives

- Investigate deviation of FOA3 due to flexibility within the SN measurement standard. Here, we show preliminary investigation in the effect of using different filter diameters (affecting incident face velocity).
- Investigate the filtration efficiency as a function of incident mass, SN and particle size.

3. Methodology

- Soot is produced by a diffusion burner supplied with propane, air and N_2. An inverse diffusion flame was chosen to give stable soot production rates.
- Combustion products are rapidly quenched by a perpendicular flow of N_2 and a catalytic stripper downstream of the burner removes any volatile components in the results presented here.
- Filter Smoke Number samples have been collected according to ARP 1179C using Whatman 4 Qualitative filters.
- The estimate of the loaded mass is obtained by assuming an effective density of ρ_{eff} = 0.6 g/cm³.

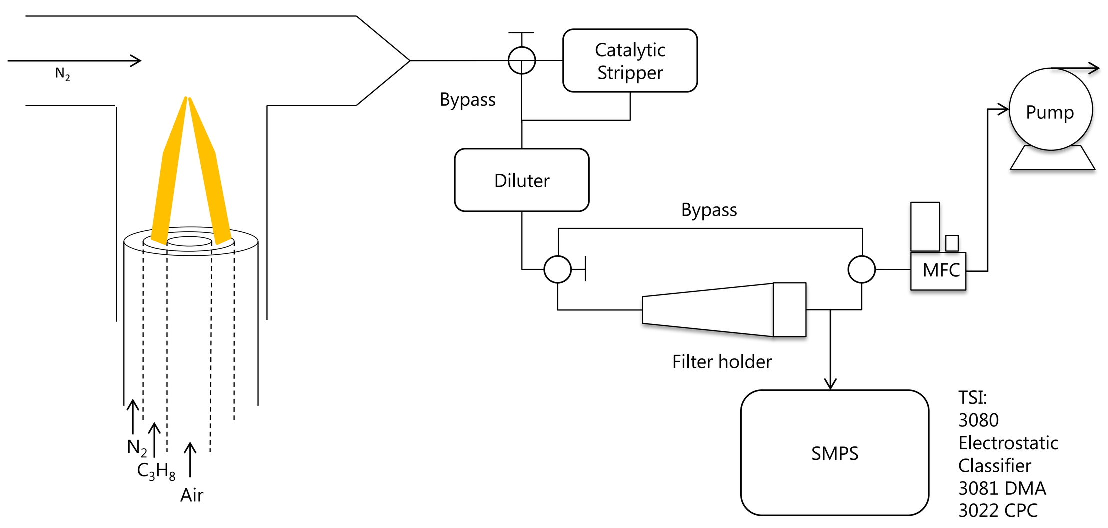

Figure 4: Experimental set-up to produce soot and collect SN and SMPS samples.

4. Results – Generated Soot Size Distribution

- Number concentration and size distribution altered by varying the absolute and relative quantities of propane, air and N_2.
- For results presented here, the flow rates of the input gases have been kept constant and lead to the a geometric mean diameter 62nm and a geometric standard deviation of 1.95 (red line).

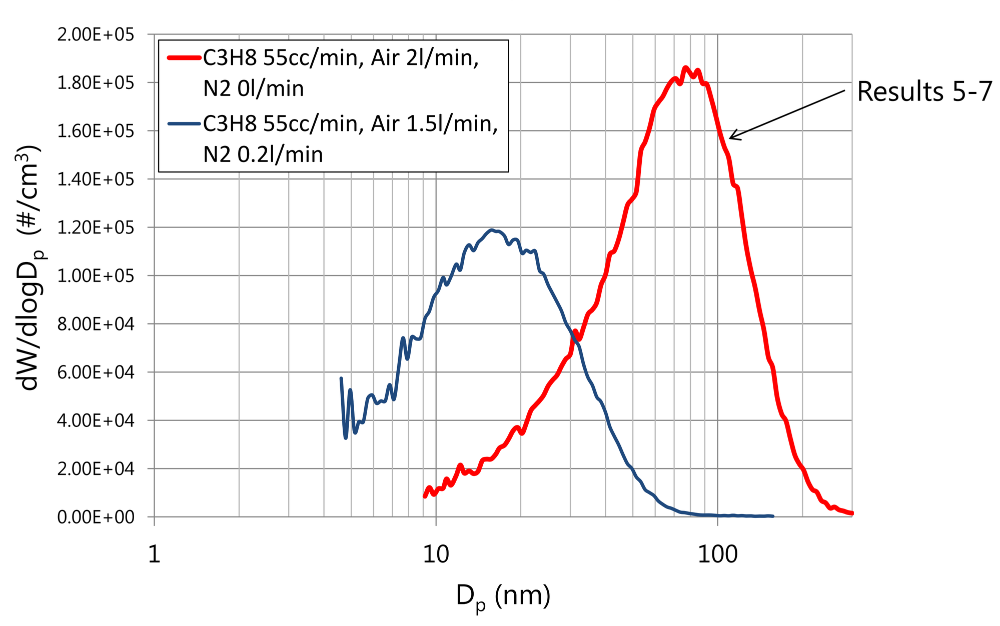

Figure 5: Generated soot size distribution measured by the SMPS.

5. Results – Concentration Index vs SN

- To relate a given SN to a mass emissions index from aircraft engines, FOA3 uses an empirical relationship between sample mass concentration and SN. Measurements from this study show good agreement with this empirical relationship.

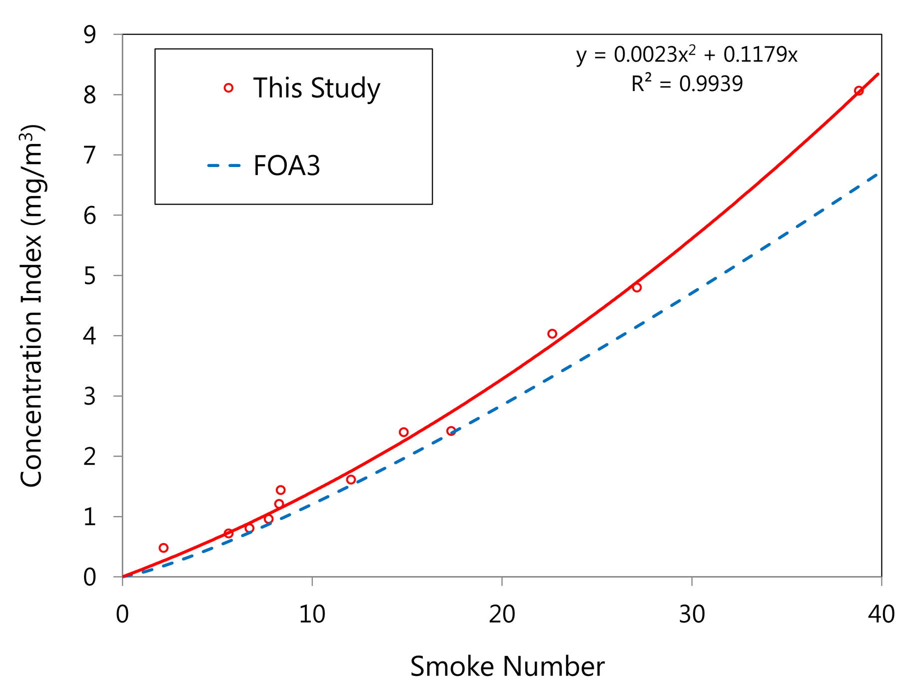

Figure 6: Verification of the empirical relationship used in FOA3 for non-volatile soot.

6. Results – Effect of Filter Diameter

- Results for 27 and 35 mm filter diameters, representing face velocities of 0.41 and 0.24 m/s respectively, demonstrate no significant effect of filter size on measured SN.

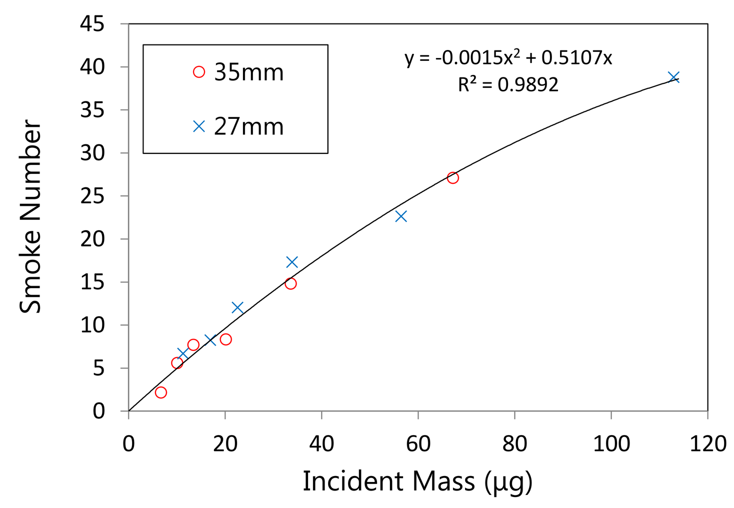

Figure 7: SN versus incident soot mass as for filter diameters of 27 and 35mm.

7. Results – Filtration Efficiency

- The mass and number filtration efficiency as a function of SN shows increasing filtration efficiency with increasing particle loading.

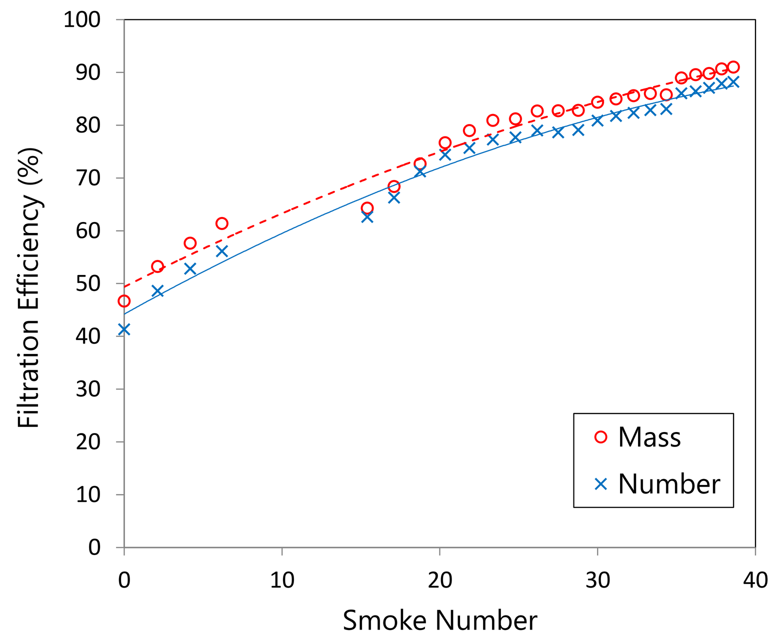

Figure 8: Filtration efficiency versus filter smoke number.

- The particle number filtration efficiency as a function of D_p shows that for a clean filter, filtration efficiency at for D_p~60 nm is ~20% less than for smaller or larger particles. For high mass loadings, filtration efficiency shows no significant dependence on particle size.

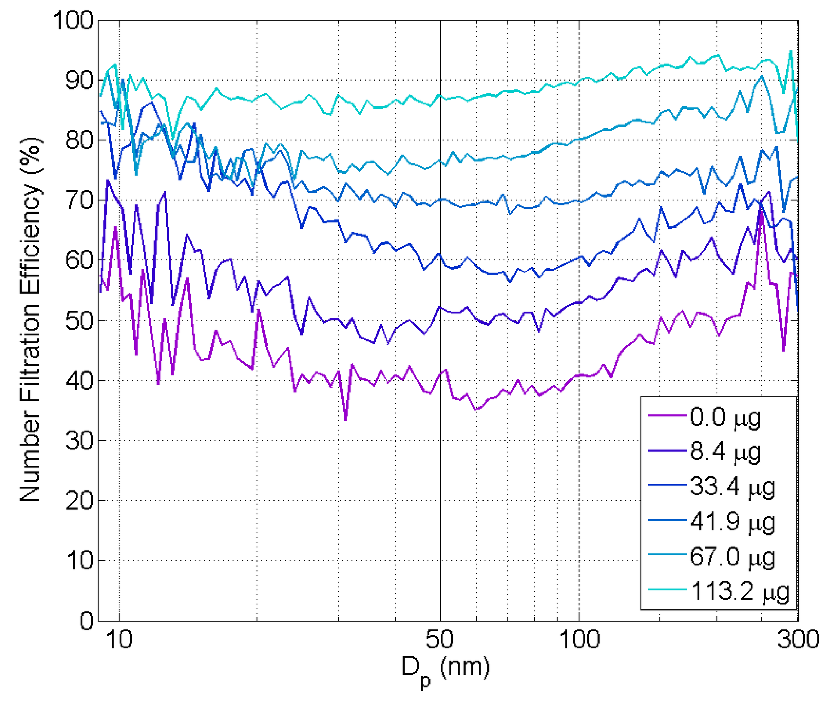

Figure 9: Filtration efficiency as a function of D_p for a range of incident particle masses.

8. Conclusions

- The CI-SN relationship used in FOA3 is verified for non-volatile soot.
- No significant effect of filter diameter on measured SN.
- Filtration efficiency increases from ~40% to ~90% with increased mass loading and SN.
- Filtration efficiency is a weak function of particle size for the given size distribution.

9. Future Work

- Investigate soot morphology.
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