



Aircraft non-volatile particle emissions: estimating number from mass

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1. INTRODUCTION

- Aircraft emissions of non-volatile particulate matter (PM) contribute to anthropogenic climate forcing and degrade air quality.
- Direct radiative forcing (RF) is proportional to emitted mass of particles.
- In-direct RF due to contrails and induced cloudiness is potentially greater than the direct RF, however it is highly uncertain [1].
- The number of ice particles in contrails has been shown to correspond to the number of non-volatile particles, affecting the contrail optical properties [2].
- Estimates of non-volatile PM mass emitted by aircraft have recently been revised [3].
- Estimating particle number emissions is required to accurately estimate global aviation climate impacts.

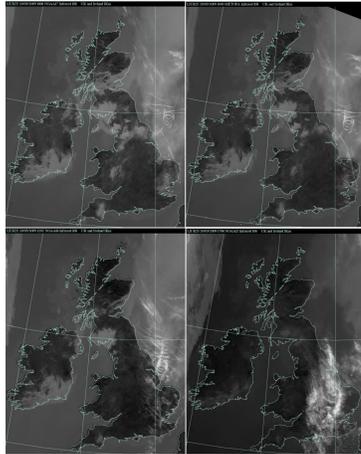


Figure 1: Images of the formation of contrail induced cirrus over seven hours. Images published by Haywood et al. [4].

2. THEORY

In the free molecular regime ($Kn \rightarrow \infty$) for diffusion limited cluster aggregation aggregates, the number, n_{va} , of primary particles of volume-surface equivalent diameter d_{va} in an aggregate of mobility diameter d_m is

$$n_{va} = k_a \left(\frac{d_m}{d_{va}} \right)^{D_m}, \quad (1)$$

where $k_a \sim 1$ is a parameter describing agglomerate structure and D_m is the mass mobility exponent [5,6].

The mass of an aggregate, m , is the sum of the mass of the primary particles and assuming a constant d_{va} within a given aggregate,

$$m(d_{va}) = n_{va} \rho_0 \left(\frac{\pi}{6} \right) d_{va}^3. \quad (2)$$

For non-volatile PM emitted by aircraft engines, Boies et al. [7] have shown that d_{va} is a function of d_m and a power-law fit to experimental data yields $d_{va} = 0.79 d_m^{0.8}$ ($R^2=0.86$). For the same aggregates, Johnson et al. [8] have shown that $D_m = 2.76$. Combining equations (1) and (2) yields

$$m(d_m) = \rho_0 \left(\frac{\pi}{6} \right) 0.79^{(D_m-3)} d_m^{(2.4+0.2D_m)}, \quad (3)$$

where $\rho_0 \sim 1900 \text{ kg/m}^3$ is the material density of soot comprised of elemental carbon. Assuming the number weighted aggregate mobility diameter distribution, $n(d_m)$, is represented by a mono-modal lognormal distribution, the total mass concentration M is the $d_m^{(2.4+0.2D_m)}$ -th moment,

$$M = \int_0^\infty m(d_m) n(d_m) d \log d_m$$

$$M = \rho_0 \left(\frac{\pi}{6} \right) 0.79^{(3-D_m)} N_0 \text{GMD}^\phi \exp\left(\frac{\phi^2 (\log \text{GSD})^2}{2}\right), \quad (4)$$

where N_0 is the particle number concentration, GMD and GSD are the geometric mean and standard deviation of the distribution and $\phi = 2.4 + 0.2D_m$. Aircraft emissions are typically normalized to the mass of fuel burned, to give an emissions index. Re-arranging equation (4) gives

$$\text{EI}_n = \frac{\text{EI}_m}{\rho_0 \left(\frac{\pi}{6} \right) 0.79^{(3-D_m)} \text{GMD}^\phi \exp\left(\frac{\phi^2 (\log \text{GSD})^2}{2}\right)}, \quad (5)$$

3. EXPERIMENTAL

Ground level

Measurements of aircraft engine (GE, CFM56-5B4-2P) PM emissions were conducted as part of the SAMPLE III campaign. Particle number and size distribution were measured using a DMS500 (Cambustion Ltd, UK). Non-volatile particle mass was measured via Laser Induced Incandescence (LII, Artium LII-300) [7].

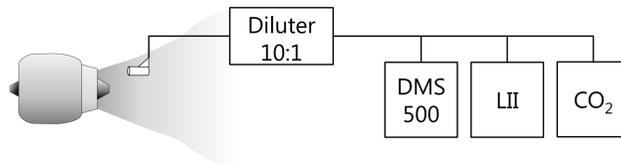


Figure 2. Schematic of sampling system and instruments.

Cruise

Measurements at cruise of particle mass, number and size distribution were conducted during the SULFUR 1-7 measurement campaigns [2].

Emissions indices

Engine emissions are normalised to fuel burn to give an emissions index, EI_m (g/kg-fuel) or EI_n (part./kg-fuel).

4. RESULTS - GROUND LEVEL

- Measured EI_n are compared to EI_n estimated using LII measurements of EI_m and the proposed method. Good agreement ($R^2 = 0.98$) is shown in Figure 2.
- For each data point, EI_n , GMD and GSD were measured with a DMS500 and EI_m with an LII.

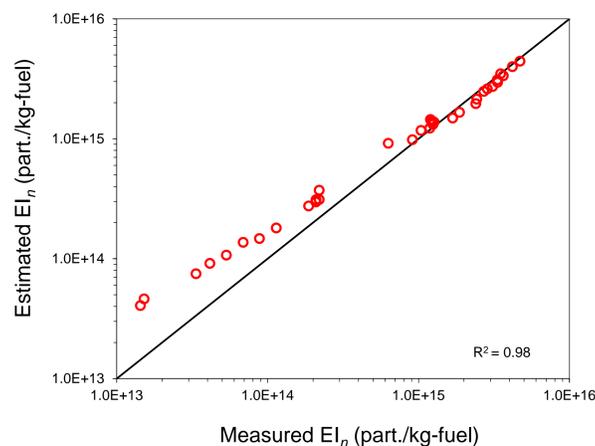


Figure 2: Comparison between measured and estimated EI_n during ground level testing.

5. RESULTS – CRUISE ALTITUDE

- Measured EI_n are compared to EI_n estimated using the proposed method and assumed GMD, GSD and D_m shown in Table 1 from literature [2].
- Good agreement ($R^2 = 0.98$) is shown in Figure 3.

Aircraft	Measurements		Assumptions			Estimate	
	EI_m (g/kg-fuel)	EI_n ($\times 10^{15}$ part./kg-fuel)	GMD (nm)	GSD	D_m	EI_n ($\times 10^{15}$ part./kg-fuel)	
B707	0.5		1.7	60	1.4	2.76	1.7
ATTAS	0.1		1.7	30	1.4	2.76	1.6
A310	0.019		0.6	25	1.4	2.76	0.5
B737	0.011		0.35	25	1.4	2.76	0.3
A340	0.01		0.18	25	1.4	2.76	0.3

Table 1: Aircraft PM measurements, assumptions and estimates at cruise.

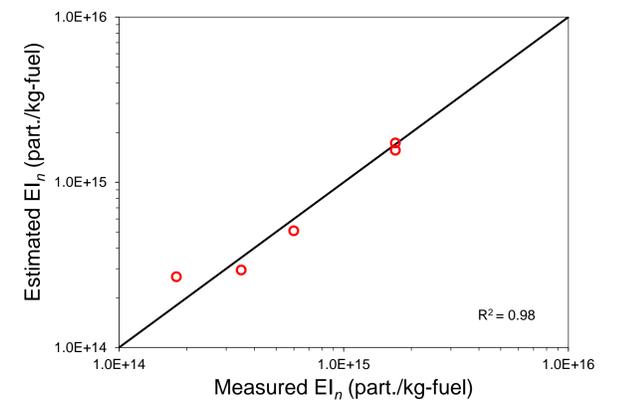


Figure 3: PM measurements, assumptions and estimates at cruise.

6. RESULTS - SENSITIVITY

- Global sensitivity indices [9] indicate that method is most sensitive to input GMD.

Variable	Nominal value (range)	Sensitivity index
GMD	25 (20-40) nm	0.72
GSD	1.4 (1.3-1.5)	0.03
D_m	2.76 (2.5-2.9)	0.29
ρ_0	1900 (1800-1900) kg/m ³	0.01

Table 2: Global sensitivity indices of method to inputs.

7. SUMMARY

- New method to estimate aircraft EI_n from EI_m proposed.
- Estimates show good agreement with measurements ($R^2 \sim 0.98$) at ground level and cruise.
- Sensitivity analysis indicates that GMD is the input parameter with greatest influence on estimates.
- Next steps are to:
 - Develop relationship to estimate GMD as a function of engine operating point
 - Apply method to estimate global aircraft particle number emissions.

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