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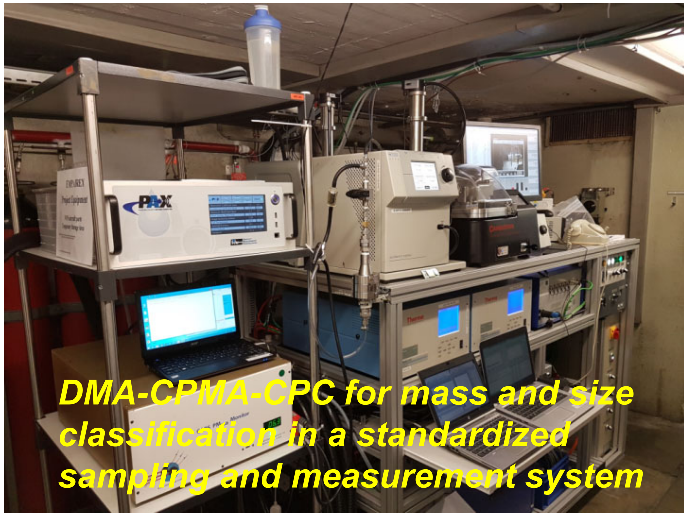

Effective density of aircraft engine PM revisited: Effects of engine thrust, engine type, fuel, and sample conditioning

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Effective density of non-volatile PM from large turbofan engines is useful for modeling and emissions testing. There is very limited good quality data.

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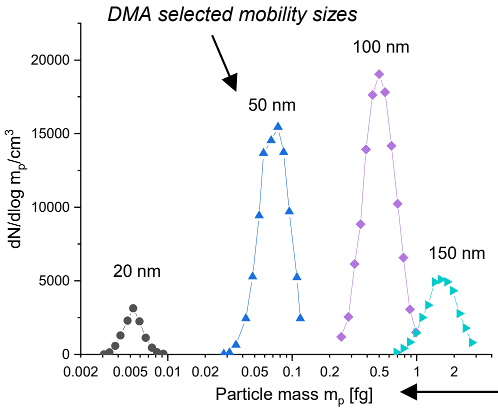
- Applications
  - Estimation of PM number from mass emissions for airport air quality modeling (with modeled particle size distributions)
  - Estimation of PM mass emissions from measured size distributions (especially beneficial at ultra-low concentrations)
  - Correction for paticle losses in standardized sampling systems for aircraft turbine engine emissions
  - Particle morphology information for health effects

Measurements were done on various in-service large turbofans with samples extracted at the engine exit plane and 25 m downstream using the DMA-CPMA-CPC setup

Engine	Test type	Sampling location	Fuel	Eff. density measurement method
5 CFM56 variants 3 PW4000 variants	Short test (pass-off test)	Engine exit plane	Jet A-1	**Fast** - SMPS-CPMA
CFM56-7B	Dedicated testing	Engine exit plane	Jet A-1 and 32% SAF blend	**Fast** - SMPS-CPMA
CFM56-7B	Dedicated testing	~25 m downstream of the exhaust nozzle	Jet A-1	**Slow** - scanning CPMA, with and without a Catalytic Stripper

Slow method – DMA - scanning CPMA

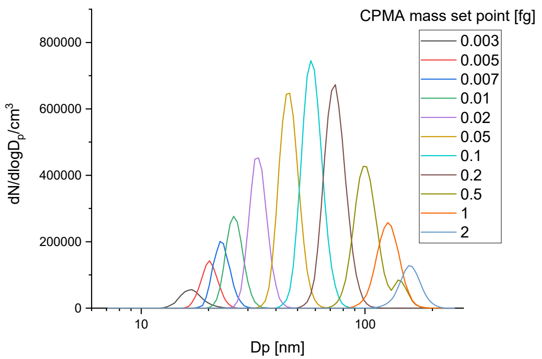


← *Particle mass in femtograms (fg) – 10^{-18} kg*

- CPMA step scan of DMA classified particles at a selected mobility size
- Long stabilization and scan time of up to 10 min for sizes <50 nm
- ← 4 data points took more than 30 minutes (very high engine cost!)

Effective density = GMD of the mass distribution / volume of a sphere with diameter equal to the DMA-selected mobility size

Fast method – SMPS-CPMA



- SMPS scan with CPMA running between the DMA and the CPC at a fixed mass set point
- Delay time for SMPS scan must be determined down to 0.05s
- ← scan time of ~ 1 min per mass set point

Effective density = mass set point / volume of a sphere with diameter equal to the GMD of the size distribution for the mass set point

Results(1/3): Distinct low thrust and medium-to-high thrust density distributions for all engines tested and no effects of the 32% SAF blend found

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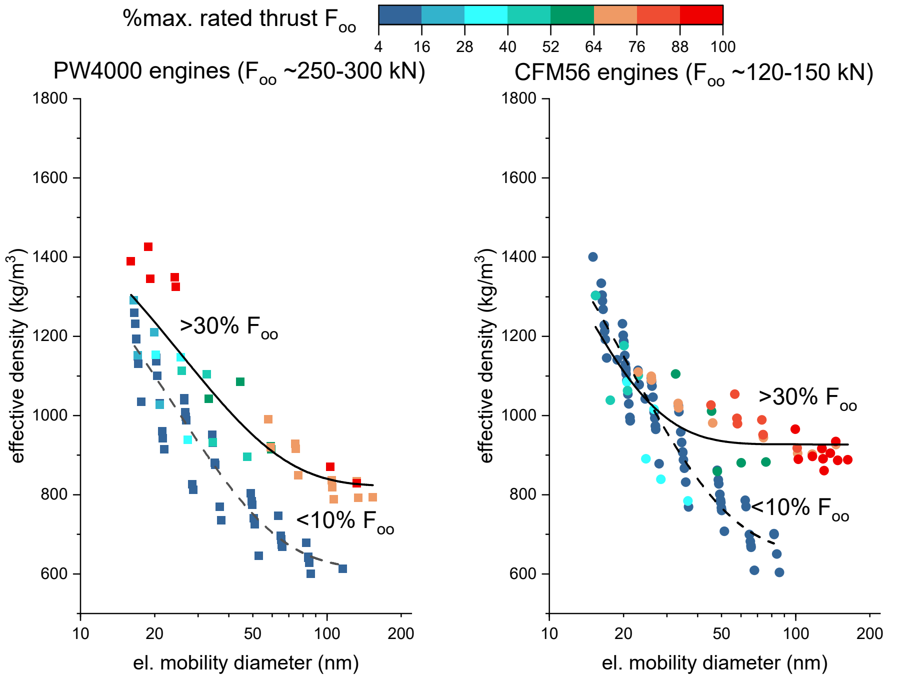
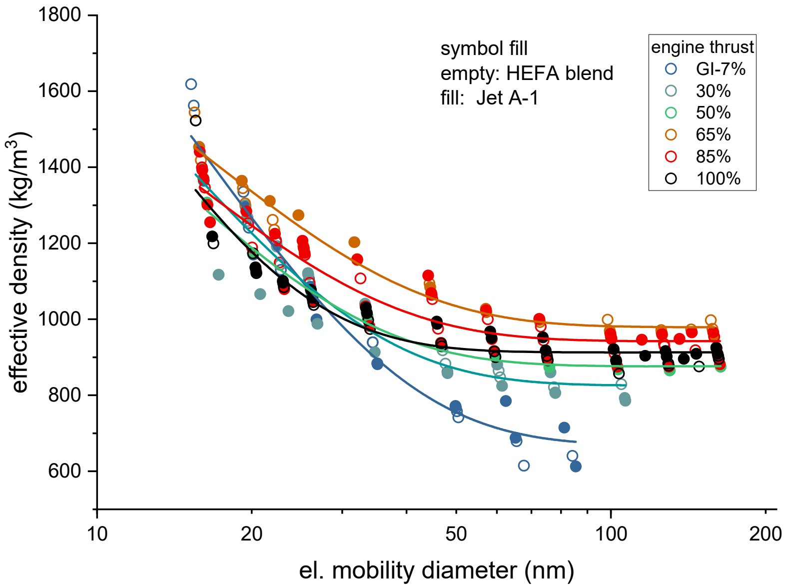
Short engine tests with limited data



PM from CFM56 engines had higher effective density at medium to high thrust at particle sizes >50 nm than PW4000 engines.

Dedicated campaign using a CFM56-7B engine with Jet A-1 and 32% SAF blend



Distinct low and medium-to-high thrust density distributions in agreement with those found during short engine tests. Highest eff. density at 65% thrust. At medium to high thrust, effective density >75 nm constant as a function of size. We did not find any fuel composition effects.

Results(2/3): 25 m downstream of the engine, the volatile mass contribution was highest at low thrust and <10%.

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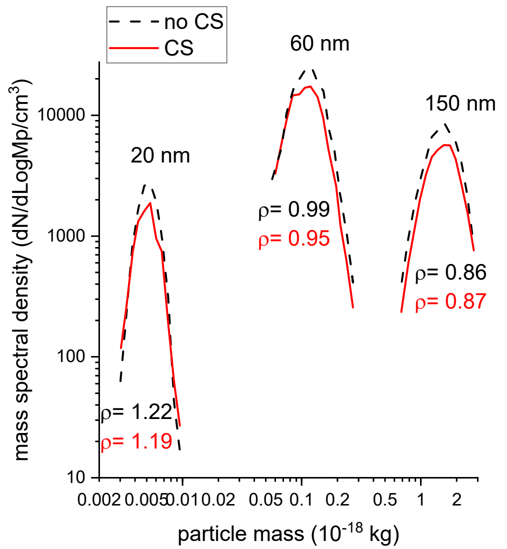
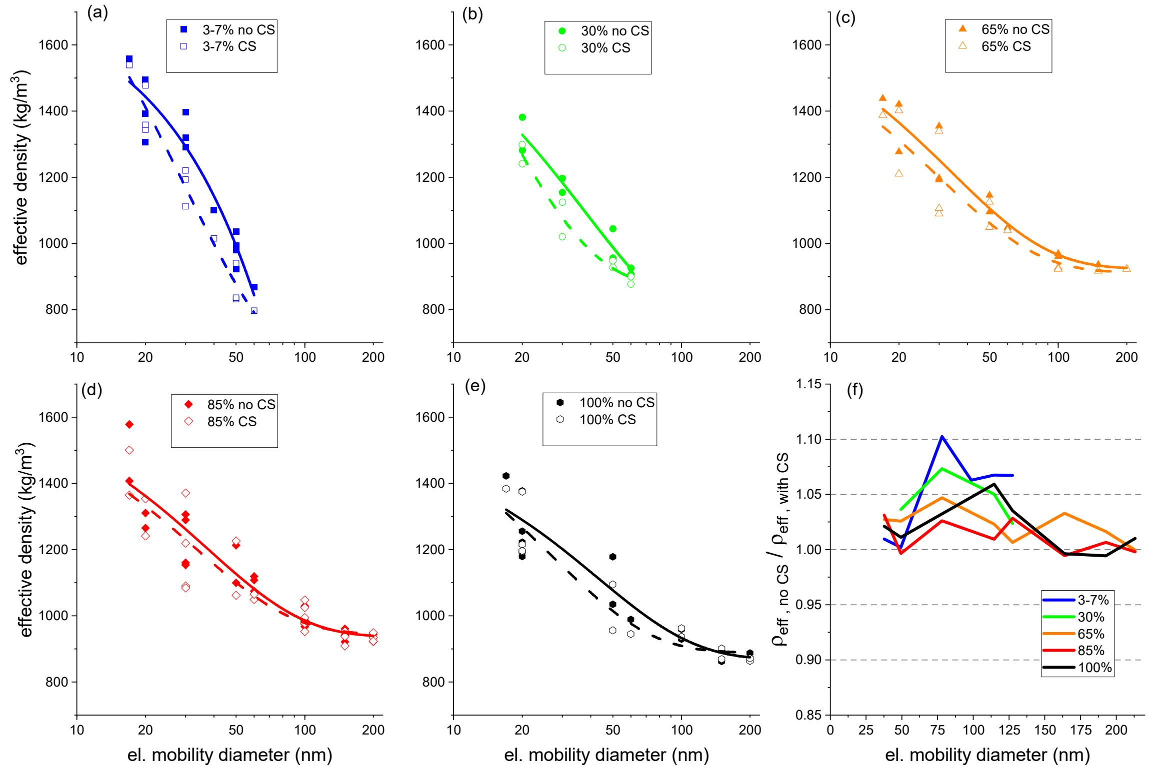
Dedicated campaign using a CFM56-7B engine with Jet A-1 and sampling 25 m downstream of the engine exhaust nozzle



Results of CPMA step-scans at 100% thrust with and without the catalytic stripper. Very little to no measurable volatile fraction. The red curves with CS have lower concentrations due to losses in the CS.



Effective density distributions with and without CS using the slow DMA-scanning CPMA method. At low thrust, the effective densities without CS were higher than samples after CS due to condensation of volatile PM on the soot.

Results (3/3): Density vectors for low and high thrust (exponential fits) and average density of the integrated size distributions.

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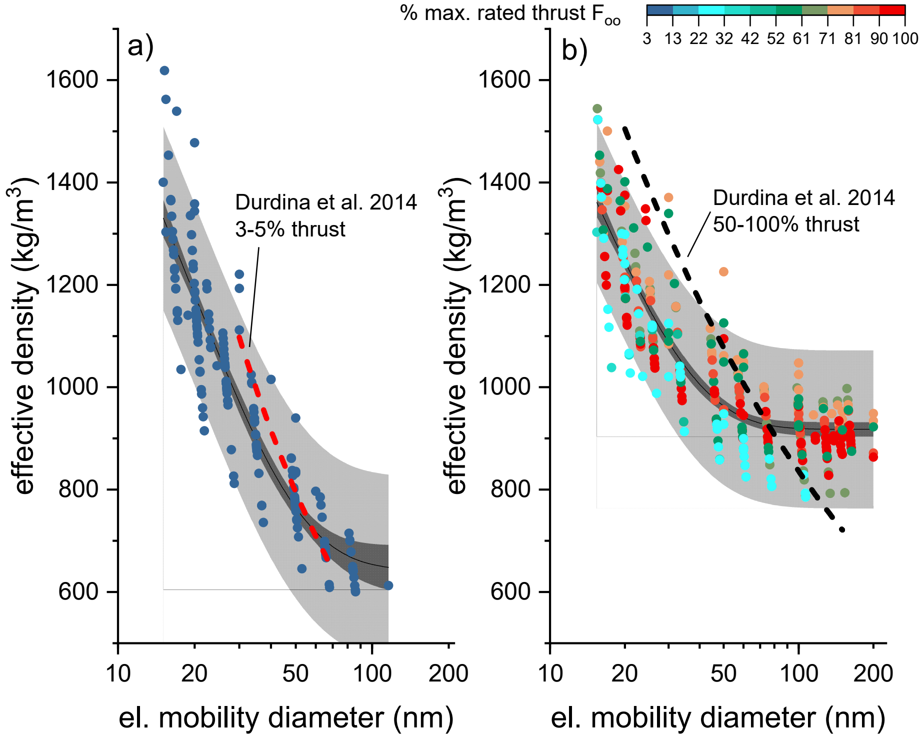

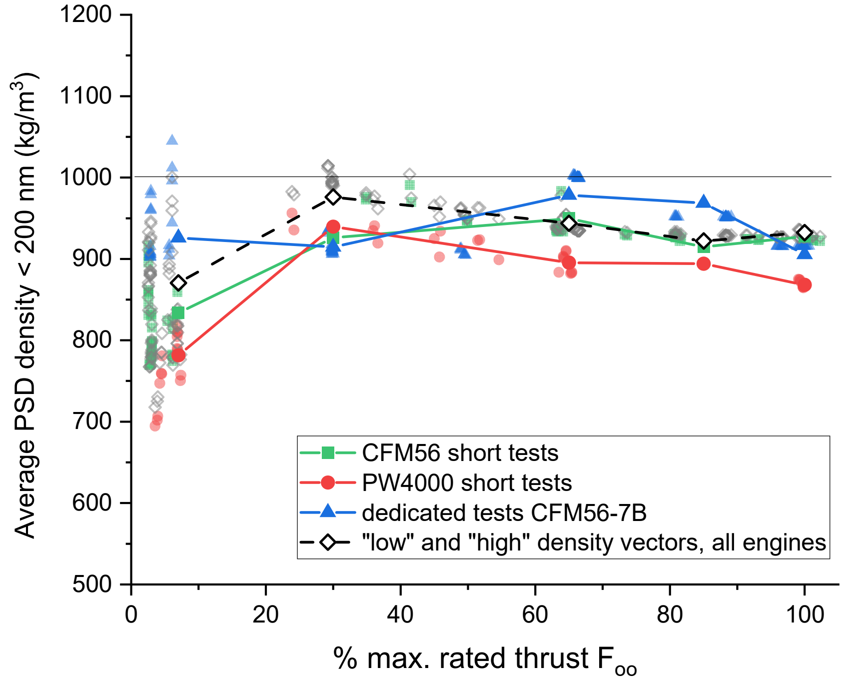

The data shown include all samples at the engine exit plane and the samples taken 25 m downstream with the catalytic stripper.

The average density is the ratio of the integrated SMPS mass using different density vectors to the SMPS volume. The caveat here is the upper limit of ~200 nm. At high thrust, the size distributions are broader and there is a potentially significant mass fraction (~20%) above 200 nm.

Conclusions

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- We provide new data on PM effective density for large turbofan engines
- We confirmed the thrust dependence of effective density distributions for various engine types
- The mass-mobility relationship reported previously underestimated effective densities at high thrust at sizes > 75 nm. *Mass-mobility exponents determined from power law fits depend on the size range of the data available. Thus, the exponent may be meaningless if only data in a very narrow size range is available.*

Additional information

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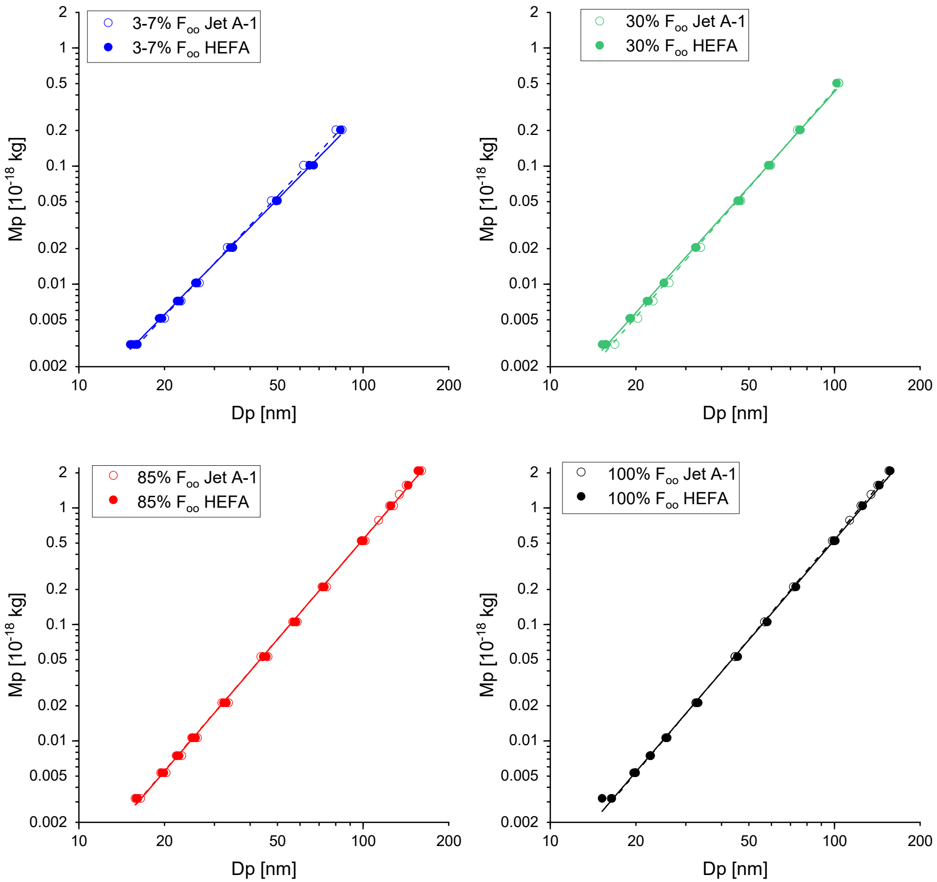
Particle mass vs mobility diameter with Jet A-1 and 32% SAF blend



- Open symbols: Jet A-1
- Filled symbols: 32% HEFA blend
- No fuel effect observed

Comparison of the “slow” and “fast” methods on the same engine in campaigns one year apart. Slow method was used 25 m downstream of the engine with CS. Fast method was used on samples at the engine exit plane without CS.

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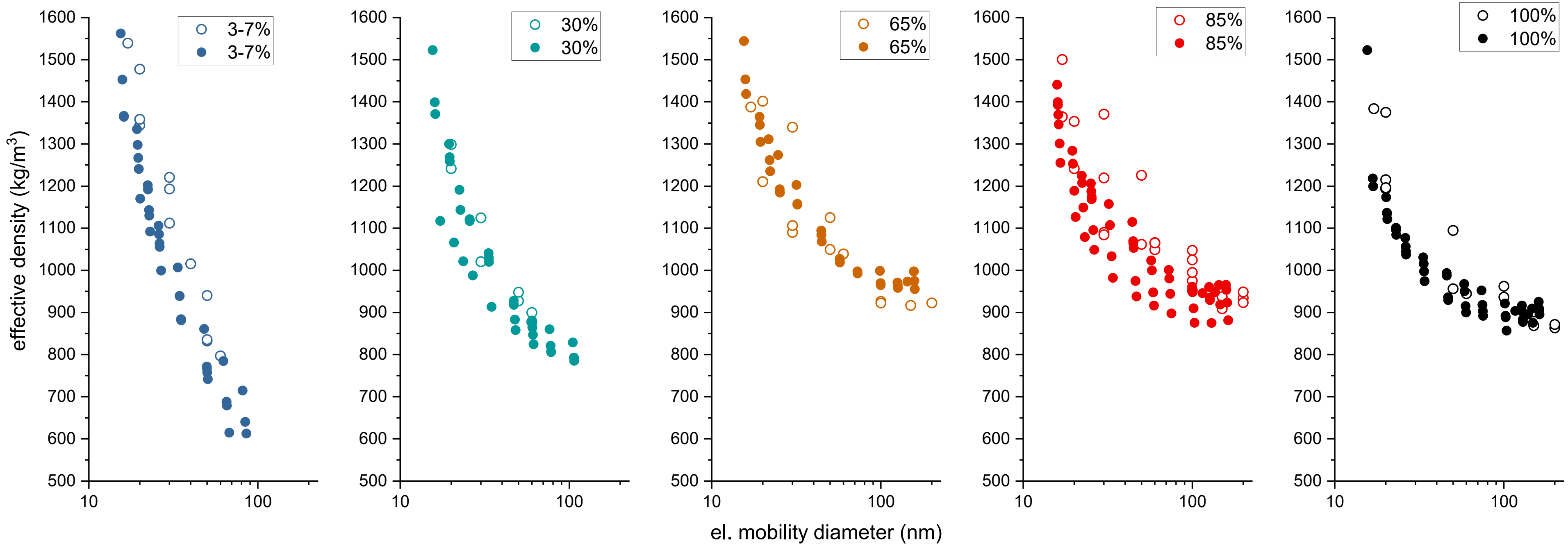
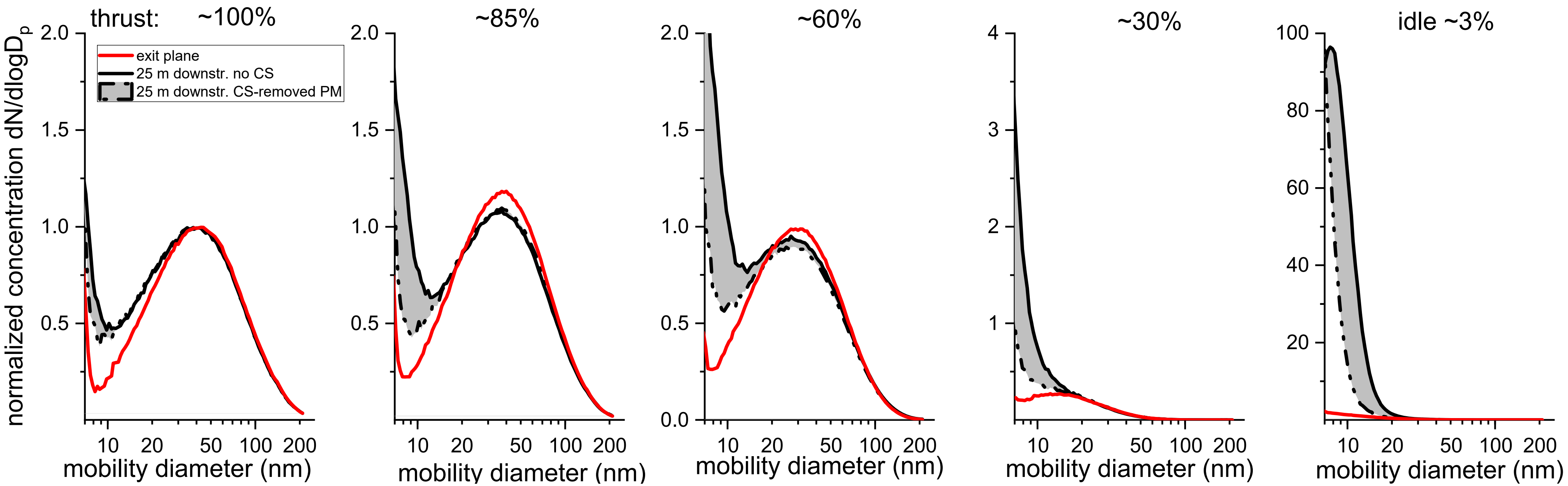
open symbols: sampling 25 m downstream after CS (slow method)

filled symbols: sampling at the engine exit plane without CS (fast method)



Particle size distributions at the engine exit plane and 25 m downstream (corrected for particle losses and dilution) of a CFM56-7B engine. The gray area is the PM fraction removed by the CS. The apparent nucleation mode in the red curves may be a system loss correction artifact.



Comparison of the slow and fast method using miniCAST soot in the lab. Note the effect of the delay time (td) in the fast method. Here, 6 seconds delay time agreed best with the scanning CPMA method.

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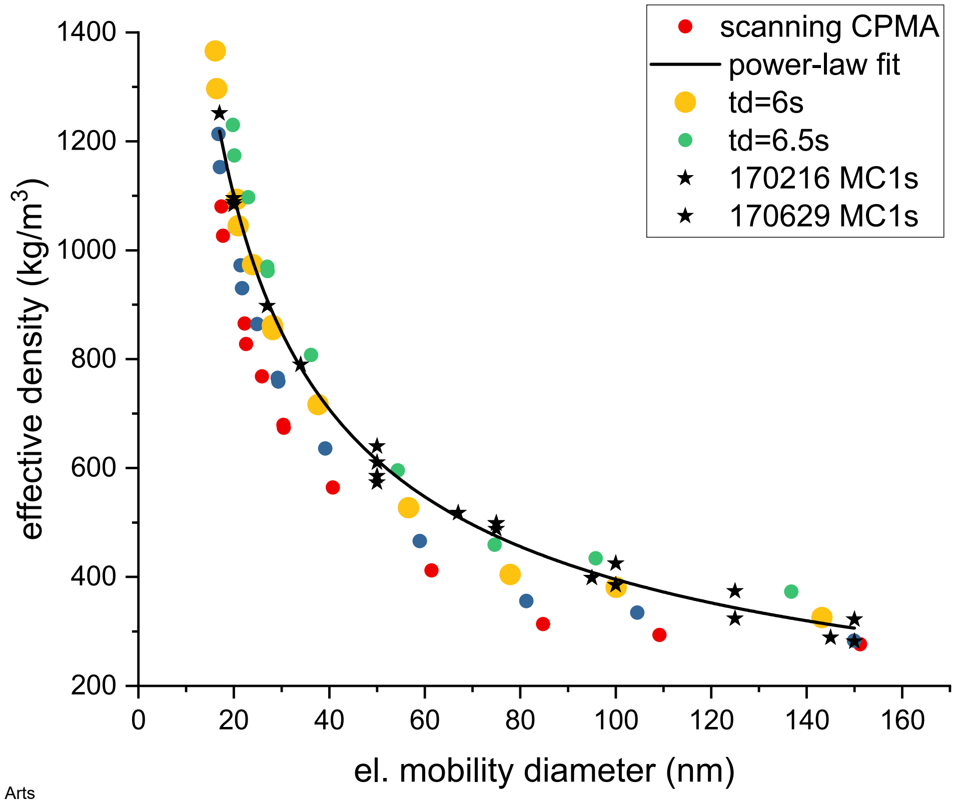

The SMPS measurements and the postprocessing were done using AIM 9.0. In the newer versions of AIM, the delay time cannot be set (AIM 10 allows setting only the tubing lenght up to 100 cm).