Improved Determination of Soot Mass Emissions from Aircraft Turbine Engines Using Particle Effective Density

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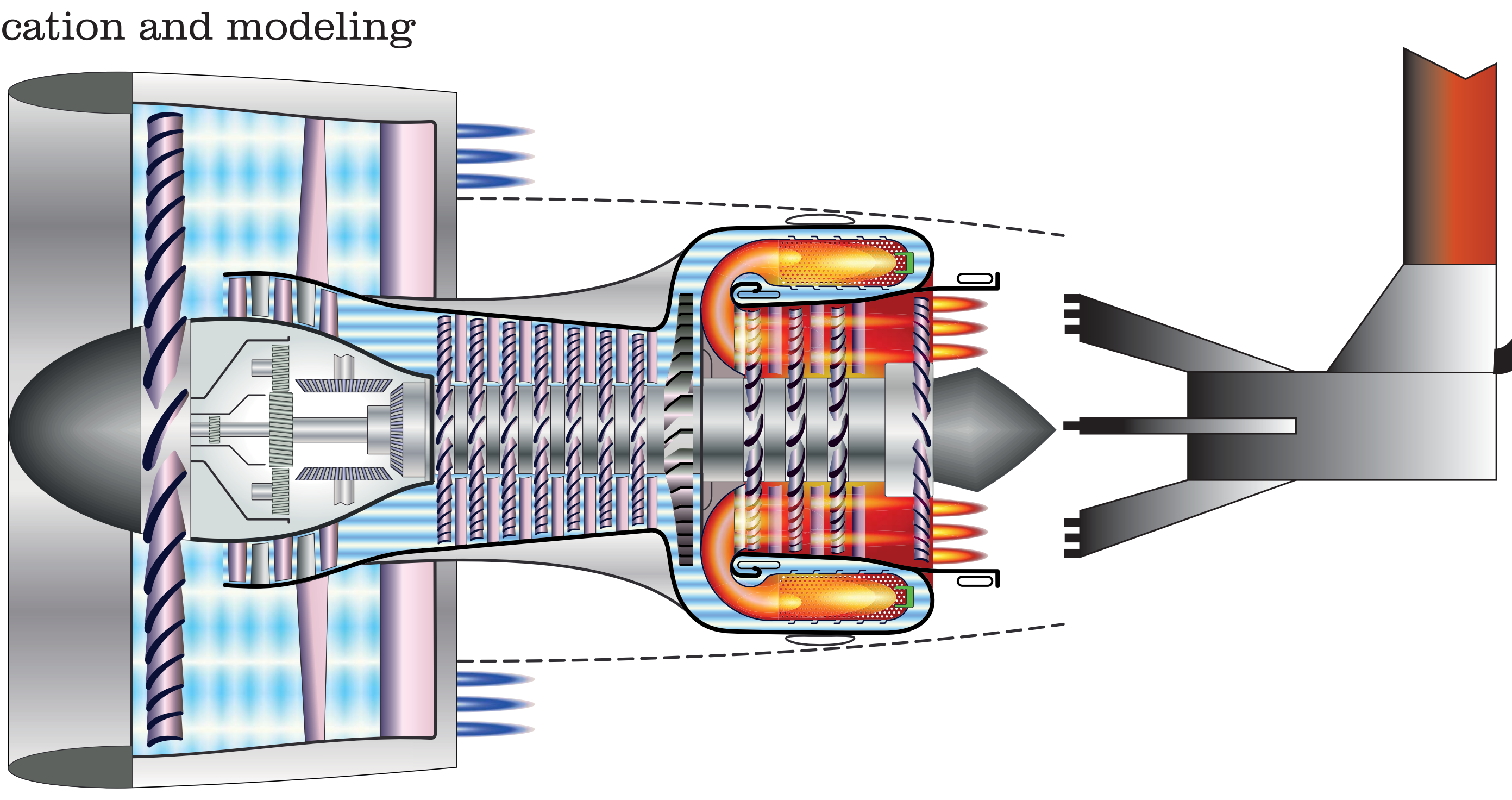
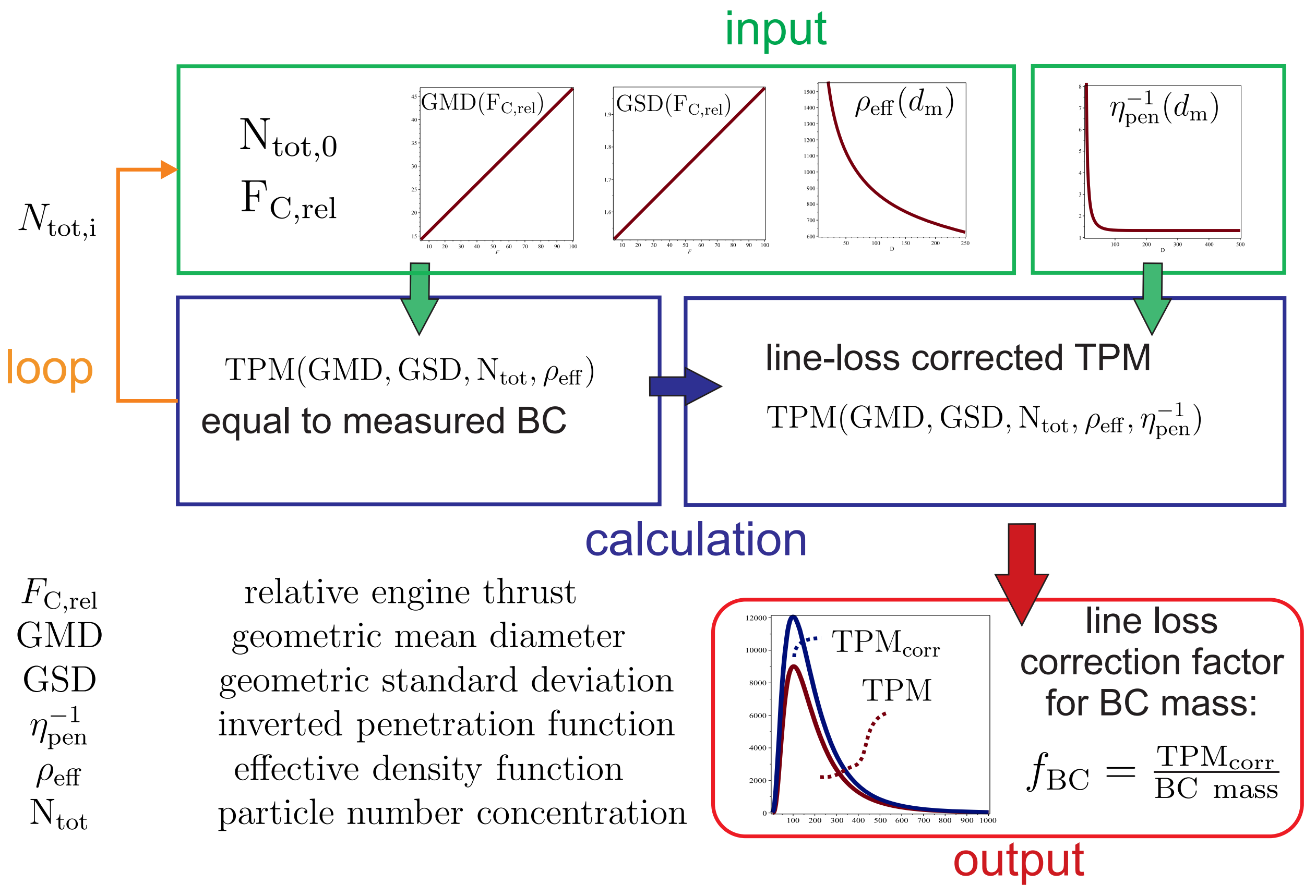
Introduction

- aerosol sample is drawn from the engine exit plane to the instruments through more than 30 m long sample lines
- particles stick to the tube walls due to diffusional and thermophoretic effects
- first principle model predicts well the particle transport efficiency in terms of particle number concentration
- PM mass losses are more complicated - particle effective density changes with size
- a reliable estimate of the PM at the engine plane essential for the emissions quantification and modeling



Method

- measure non-volatile PM mass (equivalent / refractory black carbon; BC)
- measure particle size distributions (PSD)
- fit lognormal distributions and find dependence on engine thrust
- determine effective density distributions from mass-mobility measurements
- model the particle transport efficiency from the probe tip to the instruments
- iterate the PM mass derived from the lognormal PSD model and the effective density distributions until it is equal to the measured PM mass
- correct the model PM mass distribution using the inverted penetration function
- calculate the line loss correction factor as a ratio of the corrected and uncorrected (measured) PM mass



input

$N_{tot,0}$
$F_{C,rel}$

$N_{tot,i}$

loop

$TPM(GMD, GSD, N_{tot}, \rho_{eff})$
equal to measured BC

line-loss corrected TPM
$TPM(GMD, GSD, N_{tot}, \rho_{eff}, \eta_{pen}^{-1})$

calculation

$F_{C,rel}$	relative engine thrust
GMD	geometric mean diameter
GSD	geometric standard deviation
η_{pen}^{-1}	inverted penetration function
ρ_{eff}	effective density function
N_{tot}	particle number concentration

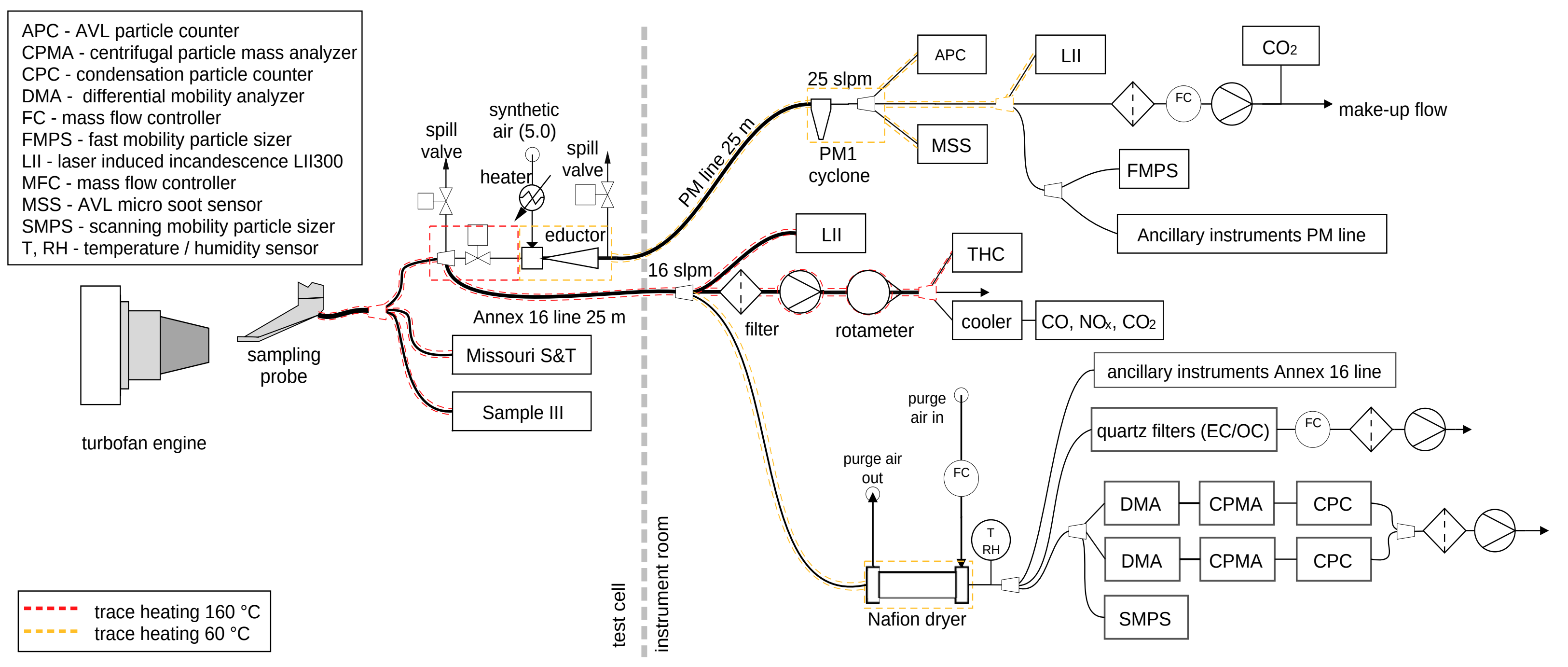
line loss correction factor for BC mass:

$$f_{BC} = \frac{TPM_{corr}}{BC\ mass}$$

output

Sampling and measurement

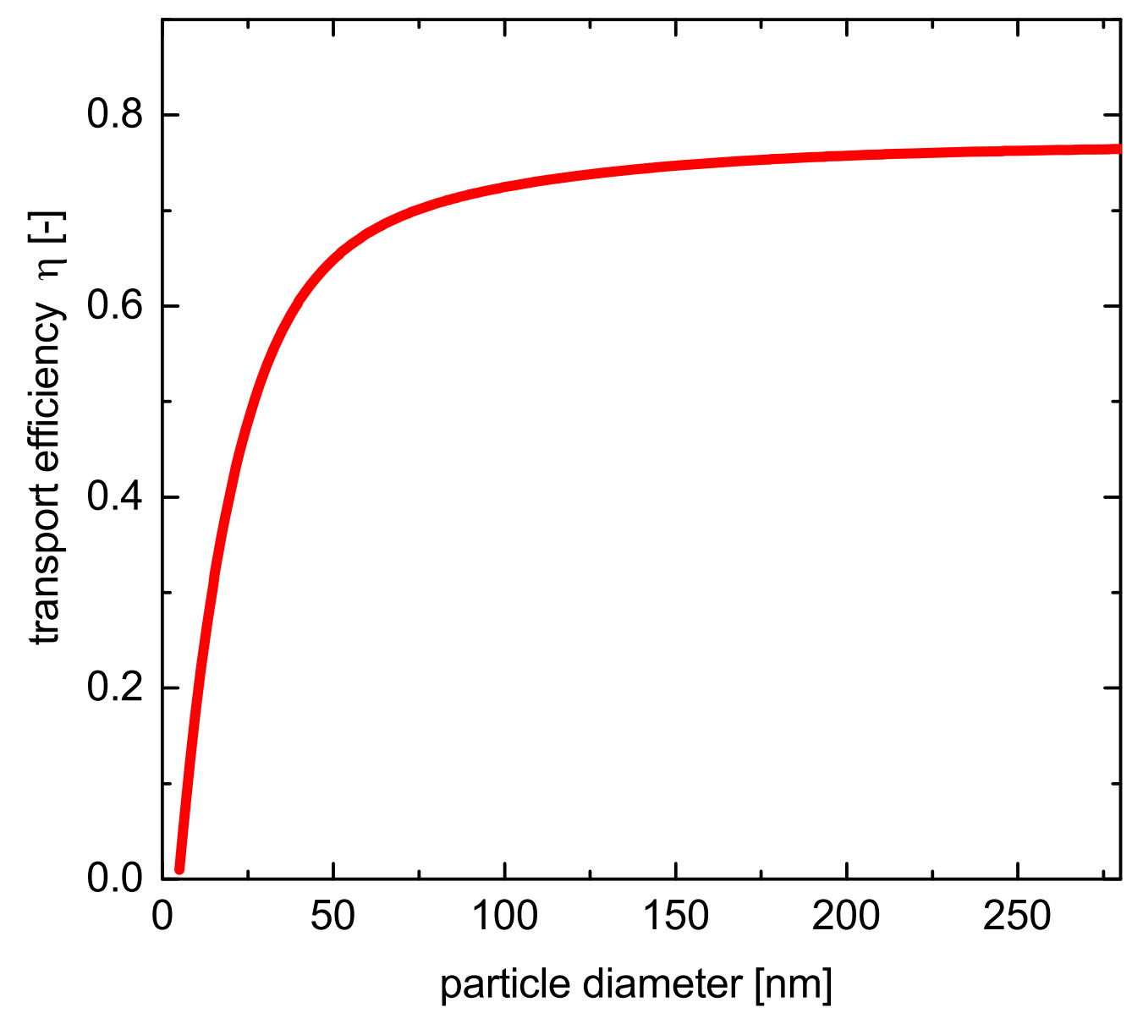
- CFM56-7B26/3 engine (Boeing 737, Airbus A320) tested in an engine test cell over the entire thrust range from idle to maximum power
- primary PM measurements on the diluted line (factor ~10:1; PM line)
- ancillary PM measurements on the undiluted line (Annex 16 line)
- up to 3 systems built to the same standard[1] were deployed in parallel



APC - AVL particle counter
CPMA - centrifugal particle mass analyzer
CPC - condensation particle counter
DMA - differential mobility analyzer
FC - mass flow controller
FMPS - fast mobility particle sizer
LII - laser induced incandescence LII300
MFC - mass flow controller
MSS - AVL micro soot sensor
SMPS - scanning mobility particle sizer
T, RH - temperature / humidity sensor

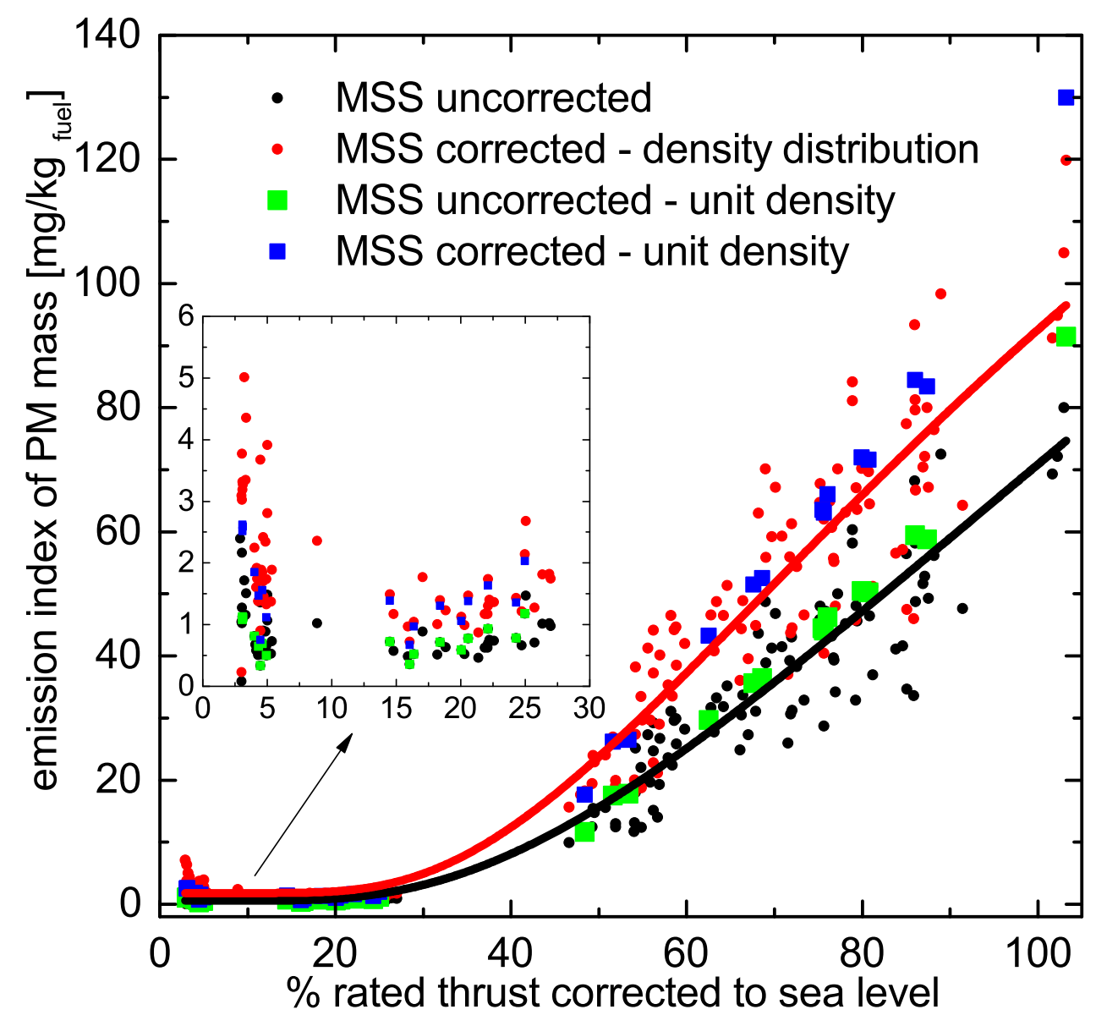
Particle transport model

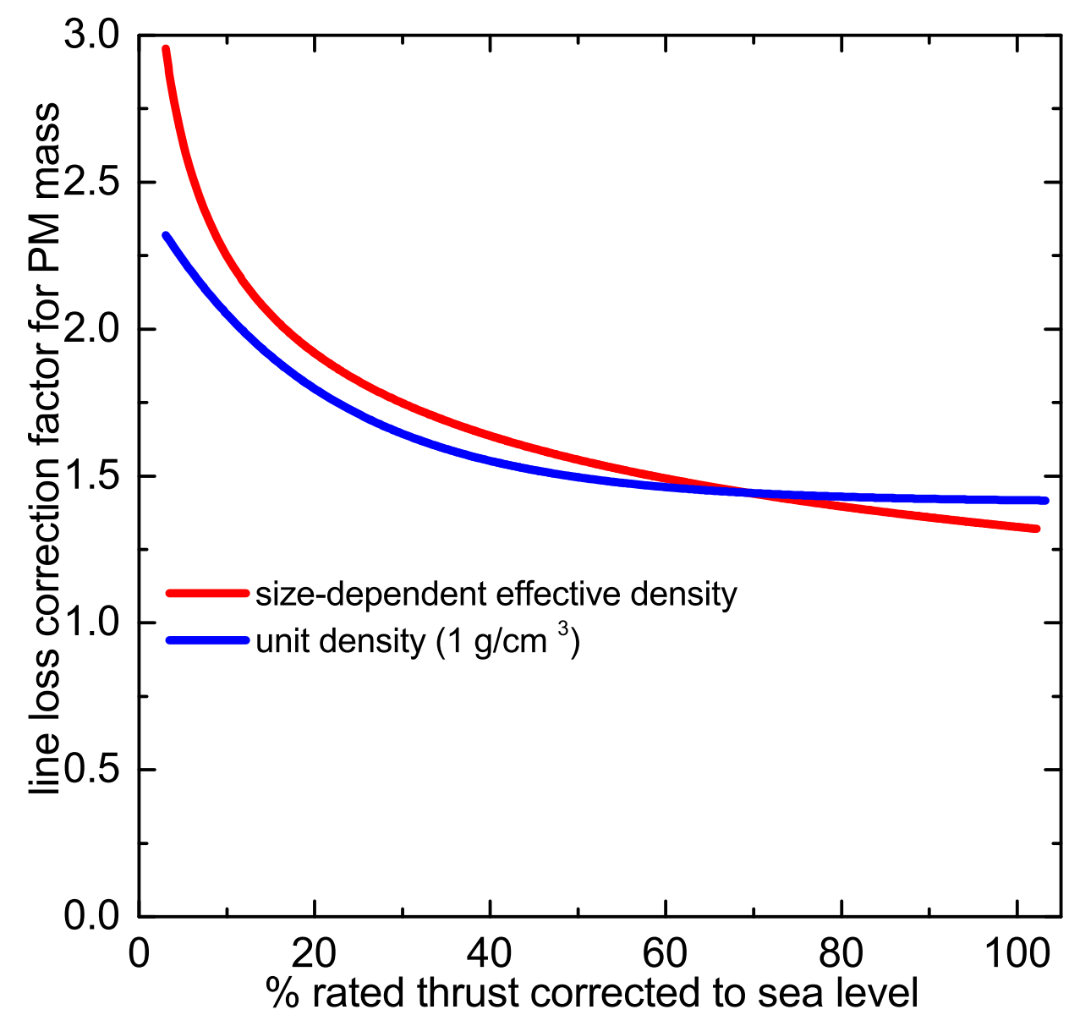
- UTRC particle transport tool[2] uses basic aerosol mechanics theory for particle transport efficiency prediction in the aircraft exhaust sample lines



Results and outlook

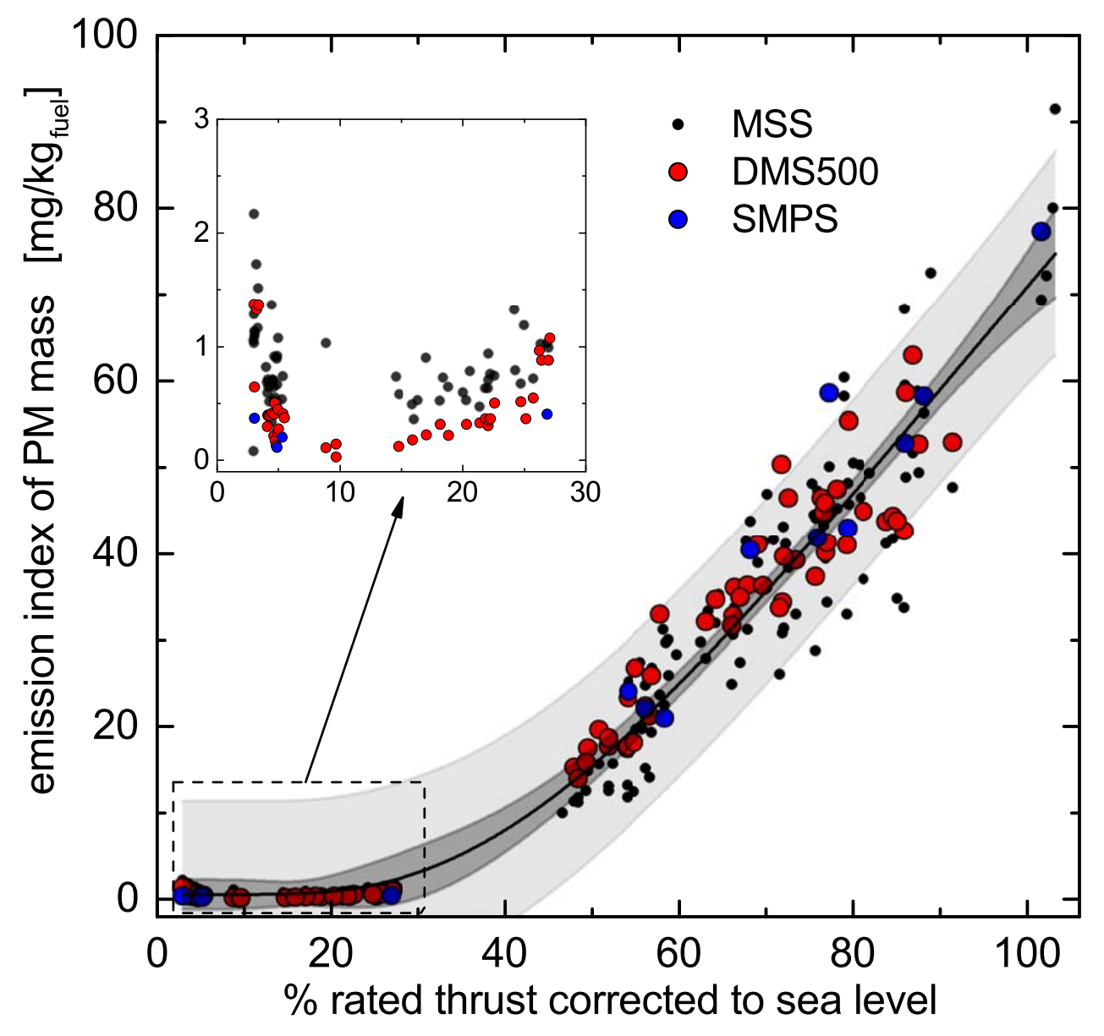
- line loss correction factor for PM mass ranged from 2.75 at engine idle to 1.35 at maximum power conditions using the size-dependent effective density
- the unit density assumption provided a similar range of correction factors, but might have overestimated the losses at high thrust as well as underestimated at low thrust
- probe inlet temperature needs to be measured for a more accurate thermophoretic loss prediction
- future work will focus on intercomparison with models that do not use measured effective density and particle size





Total PM mass (TPM) and measured BC mass

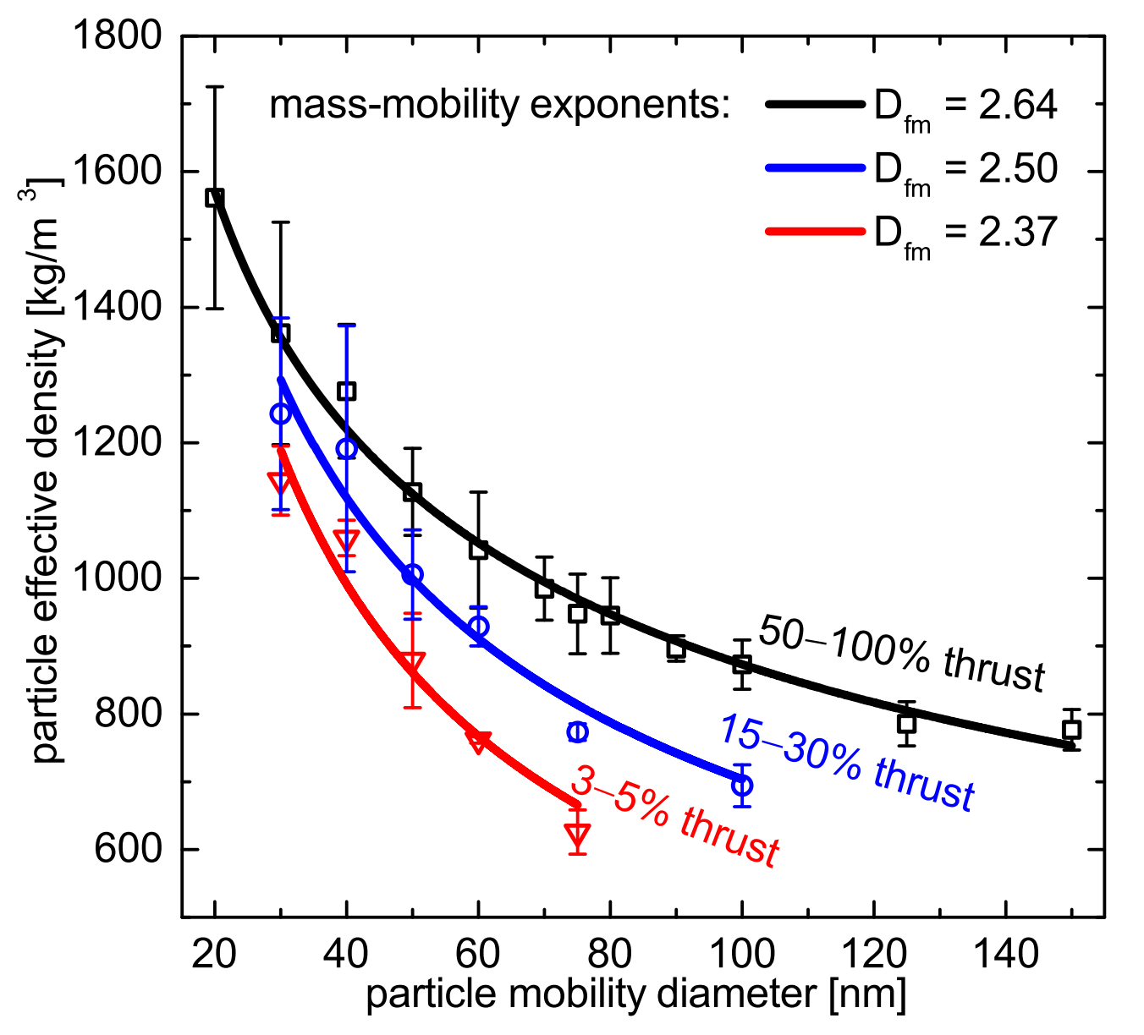
- TPM calculated from the effective density distributions and PSD agreed with the BC mass measured by the MSS



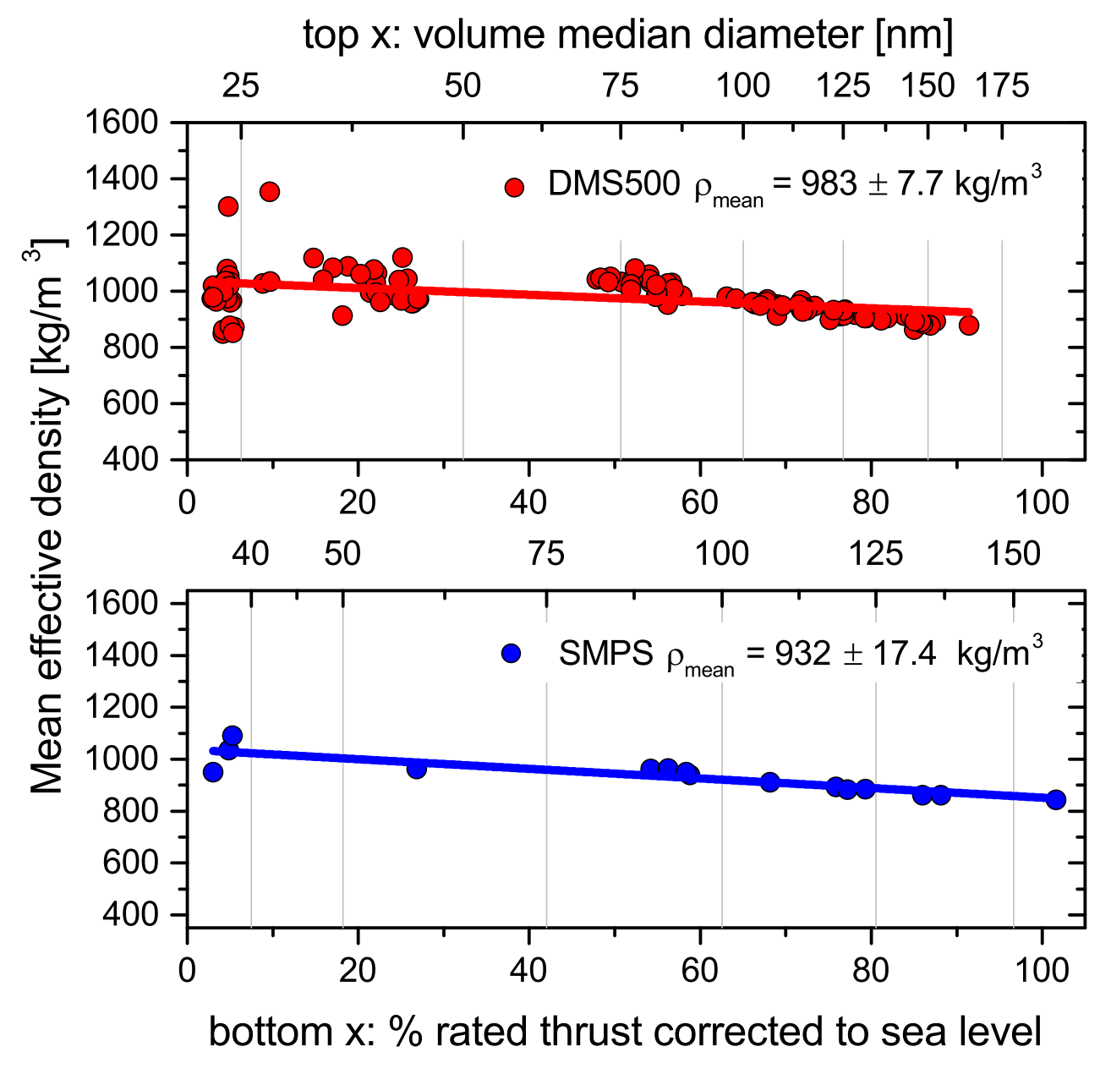
$$TPM_{\text{PSD instrument}} = \sum_{i=1}^{n} n_i \frac{\pi D_{p,i}^3}{6} \rho_{eff}(D_{p,i})$$

Effective density: distributions and mean

- power law fits of experimental data (CPMA mass over mobility equivalent volume)
- increase with engine thrust: primary particle size growth and change of the internal structure from amorphous to crystalline (Liati et al., 2014, submitted to Env. Sci. Technol.)
- mean effective density decreased with engine thrust (GMD shifted to larger diameter particles that have lower effective density)
- could be approximated as unit denisty (1000 kg/m³) for this engine



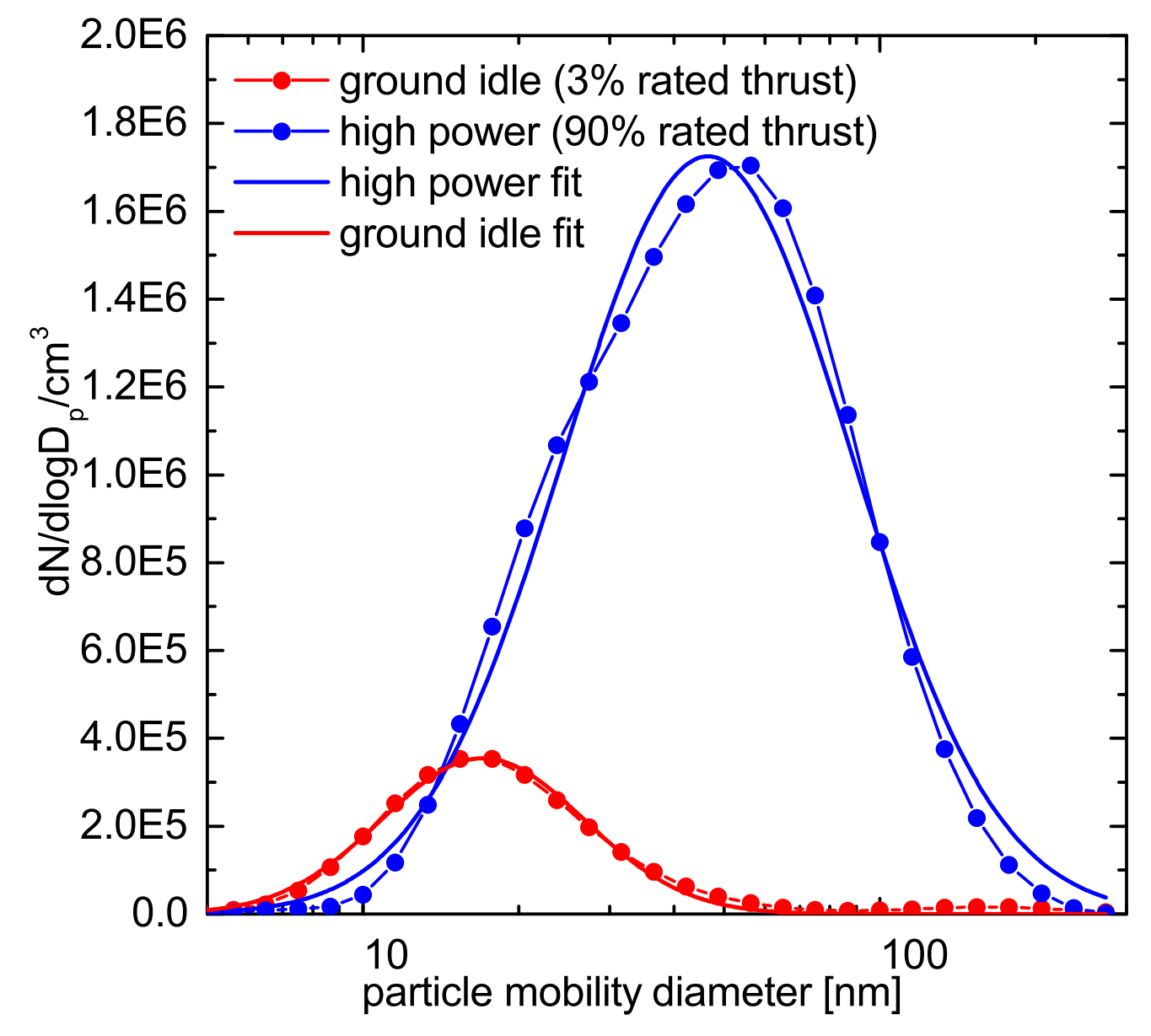
$$\rho_{eff} = C_{\rho} d_m^{(D_{fm}-3)}$$

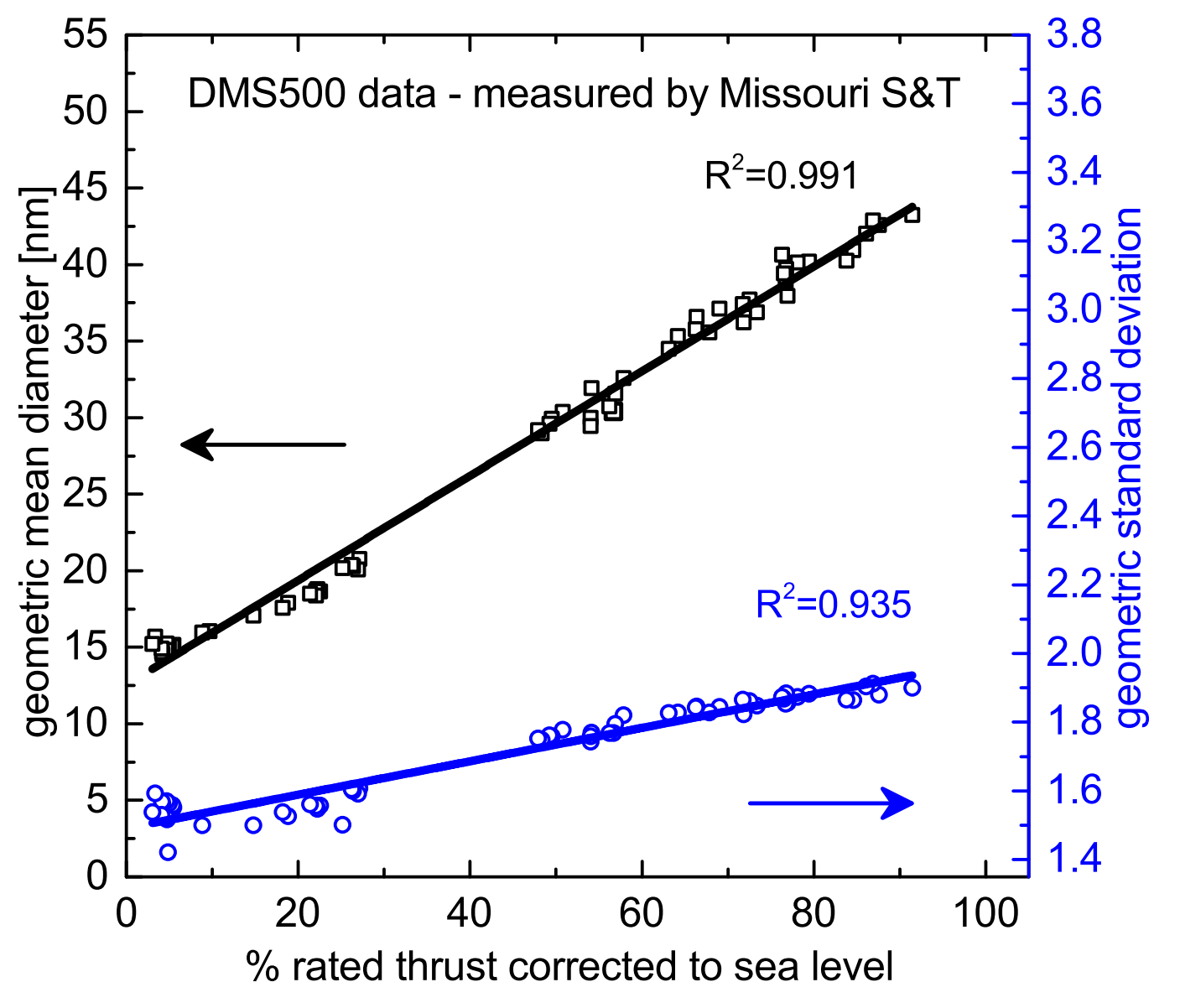


$$\rho_{mean} = \frac{\sum_{i=1}^{n} n_i \frac{\pi D_{p,i}^3}{6} \rho_{eff}(D_{p,i})}{\sum_{i=1}^{n} n_i \frac{\pi D_{p,i}^3}{6}}$$

Particle size distribution

- Geometric mean diameter (GMD) and the geometric standard deviation (GSD) determined from the lognormal fits increased linearly with engine thrust





$$\frac{dN}{d\log D_p} = \frac{N_{tot}\ln 10}{\sqrt{2\pi}\ln GSD} e^{-\frac{(\ln D_p - \ln GMD)^2}{2\ln^2 GSD}}$$

References

Durdina, L. et al., 2014, Improved determination of particle mass emissions from aircraft turbine engines using effective density; submitted to Atm. Environ.
1 SAE, 2013. Aerospace Information Report 6241: Procedure for the Continuous Sampling and Measurement of Non-Volatile Particle Emissions from Aircraft Turbine Engines.
2 Liscinsky, D. et al., 2010. Effect of Particle Sampling Technique and Transport on Particle Penetration at the High Temperature and Pressure Conditions found in Gas Turbine Combustors and Engines: NASA/CR-2010-NNC07CB03C.

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