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Inlet Losses of Nanoparticles in Electric Mobility Analyzers

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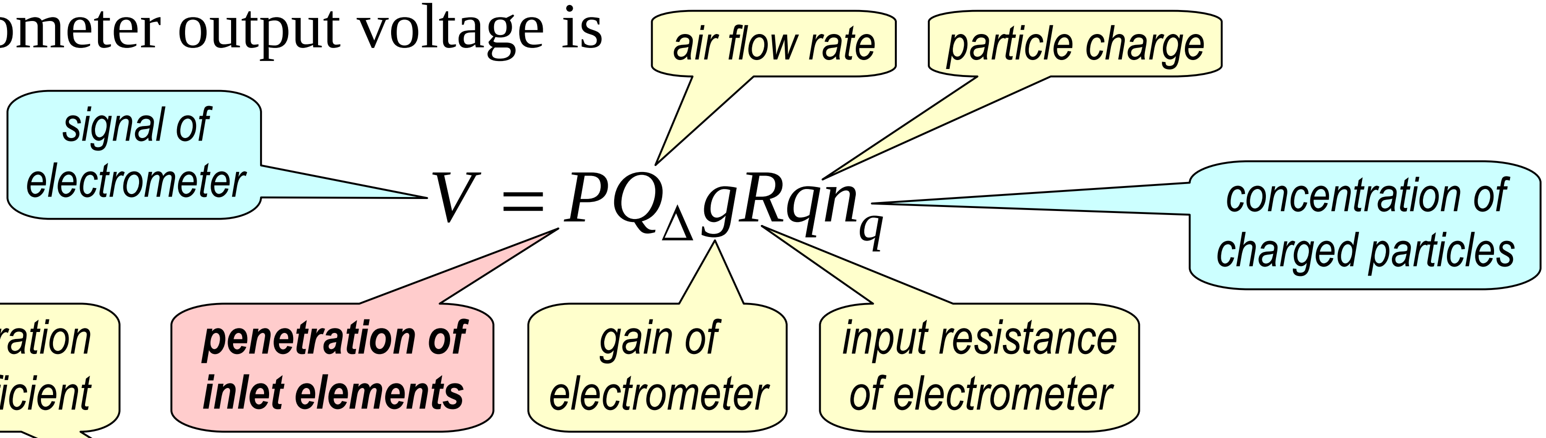
Introduction

- Calibration of instruments is a critical issue in nanoparticle measurement.
- Electric mobility analyzer (e.g. DMA) is a common instrument used to measure and classify nanoparticles.
- If nanoparticles are detected according to the electric current, then DMA could be considered as an absolute instrument. An electric mobility analyzer can be calibrated according to the measurements of geometric dimensions, air flow rate, electrometer gain, input resistance, and voltage.
- The electrometer output voltage is



air flow rate

particle charge

signal of electrometer

$$V = PQ_\Delta gRqn_q$$

concentration of charged particles

penetration of inlet elements

gain of electrometer

input resistance of electrometer

and

calibration coefficient

$$n_q = cV \quad \text{where} \quad c = \frac{1}{PQ_\Delta gRq}.$$

Inlet losses and calibration uncertainty

- Two factors of calibration uncertainty are the uncertainty of the charging probability and the uncertainty of the inlet penetration coefficient.
- Inlet losses can be characterized by the relative adsorption $A = 1 - P$.
- Relative uncertainties δ_A and δ_P can be defined as follows:

$$A_{low} = A_o / (1 + \delta_A) < A < A_{high} = A_o \times (1 + \delta_A) ,$$

$$P_{low} = P_o / (1 + \delta_P) < P < P_{high} = P_o \times (1 + \delta_P) .$$

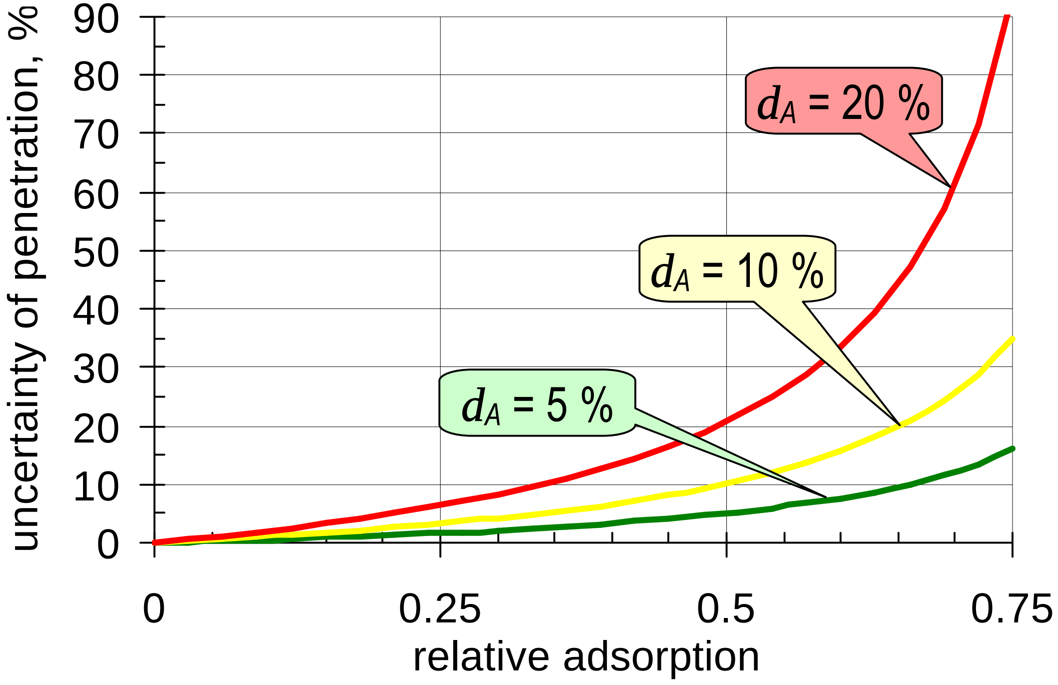
- The limits of the uncertainty interval are matched:

$$P_{low} = 1 - A_{high} ,$$

$$P_{high} = 1 - A_{low} .$$

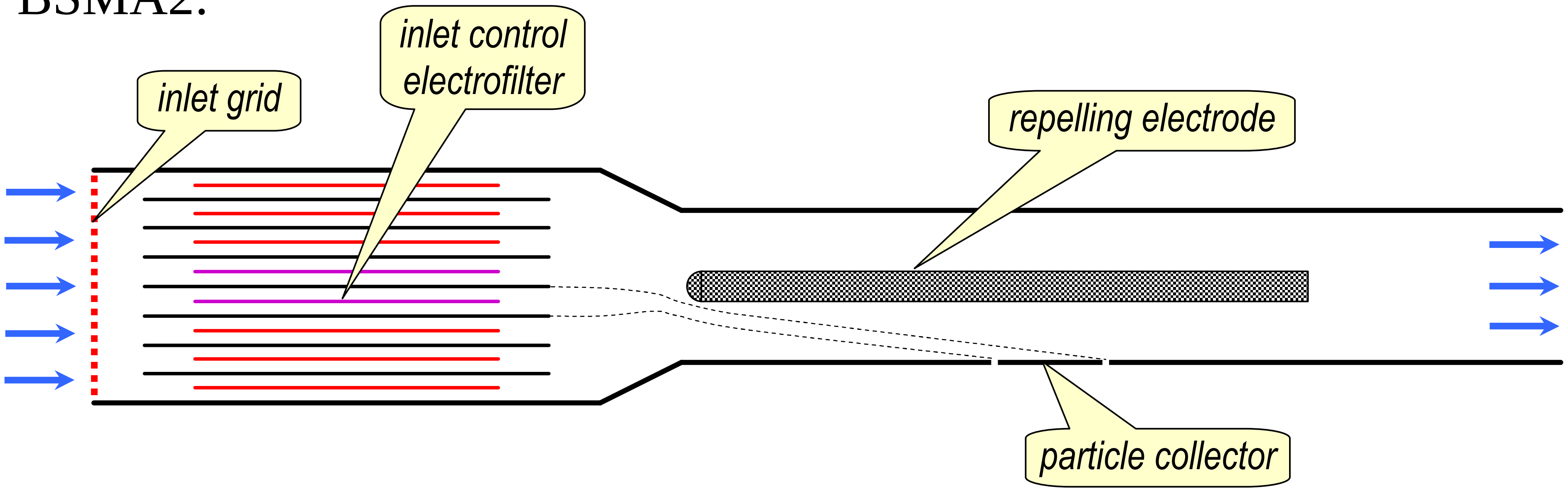
Thus, δ_P depends on the δ_A and A as shown in figure.

$$(1 + \delta_P)^2 = (1 - A / (1 - \delta_A)) / (1 - A \times (1 - \delta_A))$$



Where are the particles lost?

- Inlet tubing - can be considered not as a part of the instrument.
- Inlet grid - an often unavoidable protection against the entering of large particles and other unwelcome subjects (e.g. insects in case of environmental measurements).
- Inlet electrofilter - often used with the aim of controlling the electrometric bias or the background signal.
- Example: outline of the environmental nanometer particle analyzer BSMA2:



Inlet grid: aerosol science model

Cheng, Y.S. (2001) Condensation detection and diffusion size separation techniques. In: *Aerosol Measurement*, Eds. B.A. Baron and K. Willeke. Wiley, New York, pp. 537-602.

thickness of the screen

velocity of entering air

diameter of wire

$$A = 1 - \exp\left(-2.7 \frac{4\alpha h}{\pi(1-\alpha)d} \left(\frac{V_\circ d}{D} \right)^{-2/3} \right)$$

solid volume fraction, for a sparse grid
$\alpha = 0.5\, p\, d / s$

size of the mesh

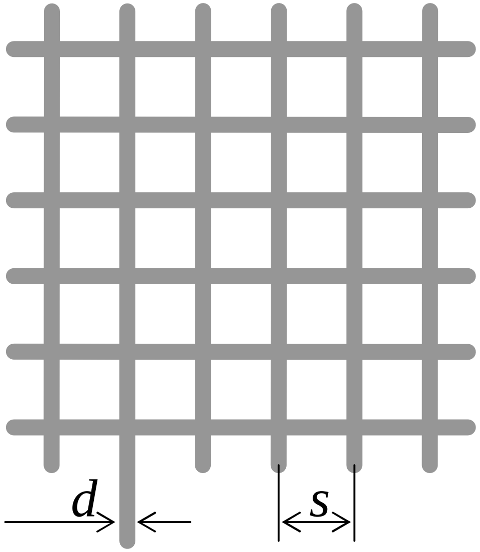
particle diffusion coefficient
$D = kTZ/q$

Boltzmann constant

Kelvin temperature

electric mobility

particle charge



Inlet grid: heat transfer model

Incropera, F.P., Dewitt, D.P. (2002) *Fundamentals of Heat and Mass Transfer*, Fifth Edition, Wiley, New York.

Relative diffusion adsorption on a sparse wire screen is

particle diffusion coefficient

mean Sherwood number related to the wire diameter d

$$A = \frac{2\pi D\, Sh_{md}}{sV_\circ},$$

size of the mesh

velocity of entering air

where Sh_{md} is calculated using the Churchill-Bernstein equation:

$$Sh_{md} = 0.3 + \frac{0.62 Re_d^{1/2} Sc^{1/3}}{\left(1+(0.4/Sc)^{2/3}\right)^{1/4}} \left(1+\left(\frac{Re_d}{282000}\right)^{5/8}\right)^{4/5}.$$

wire diameter

Reynolds number $Re_d = \dfrac{V_\circ d}{\nu}$ and Schmidt number $Sc = \dfrac{\nu}{D}$.

air kinematic viscosity

Comparison of the models

Conditions: temperature 20°C, pressure 1000 mb,
particle density 2 g cm^{-3}, mesh size 2 mm.

$d_{particle}$ nm	d_{wire} mm	V_{air} cm s^{-1}	A_{Cheng}	$A_{Churchill}$	$\frac{A_{Churchill}}{A_{Cheng}}$
1	0.1	10	11.7%	10.0%	85%
1	0.1	100	2.6%	2.6%	98%
1	0.3	100	4.5%	4.3%	95%
3	0.3	100	1.3%	1.2%	93%
10	0.3	100	0.3%	0.3%	92%
10	0.3	10	1.4%	0.9%	65%
10	0.1	10	0.8%	0.6%	67%

Inlet electrofilter: aerosol science model

From *Cheng* (2001): A flat channel is characterized by the parameter μ, which is actually the inverse of the Peclet number:

particle diffusion coefficient

length of the channel

$$\mu = \frac{8DL}{3VH^2} \qquad \left\{ \mu = Pe^{-1} \right\}.$$

average air velocity

separation of the plates

The relative adsorption A in the range of small values of μ up to 0.05 is described by Ingham equation

$$A = 1.526\mu^{2/3} - 0.15\mu - 0.034\mu^{4/3}.$$

This equation is derived expecting the fully developed Poiseuille flow of air between the plates.

Inlet electrofilter: heat transfer model

From *Icropera* and *DeWitt* (2002): The relative adsorption in a flat channel

particle diffusion coefficient

mean Sherwood number related to the channel length

$$A_{flat} = \frac{2D\,Sh_{mL}}{HV}\ .$$

separation of the plates

mean air velocity

The air enters as a plug flow and the boundary layers will develop along the channel. If

air kinematic viscosity

length of the plates

$$\delta_{disp} = 1.72\sqrt{\frac{\nu L}{V}} \ll H\ ,$$

separation of the plates

displacement thickness of the boundary layer

then

$$Sh_{mL} = 0.664 Re_L^{1/2}\,Sc^{1/3}\ .$$

Re_L = VL / n

Sc = n / D

Comparison of the models

Conditions: temperature 20°C, pressure 1000 mb, particle density 2 g cm^{-3}, separation of the plates 5 mm.

$d_{particle}$ nm	L mm	V_{air} cm s^{-1}	A_{Cheng}	$A_{Incropera}$	$\frac{A_{Incropera}}{A_{Cheng}}$
1	25	10	25.6%	16.6%	65%
1	25	100	5.7%	5.2%	93%
1	75	100	11.6%	9.1%	78%
3	75	100	3.3%	2.6%	77%
10	75	100	0.8%	0.6%	76%
10	75	10	3.7%	1.9%	52%
10	25	10	1.8%	1.1%	63%

Engineering tools

Particle size distribution function:

$$f_{corrected}(d) = \frac{f_{uncorrected}(d)}{\left(1 - A_{screen}(d)\right)\left(1 - A_{filter}(d)\right)}\,.$$

particle diameter d is a function of mobility

The relative adsorption:

immediately is measured particle electric mobility Z

$$\left.\begin{aligned} A_{screen}(Z) &= c_{screen}\left(\frac{p}{1000\,\mathrm{mb}}\right)^{1/6}\left(\frac{T}{273\,\mathrm{K}}\right)^{1/3}\left(\frac{Z}{1\,\mathrm{cm}^{2}\mathrm{V}^{-1}\mathrm{s}^{-1}}\right)^{2/3} \\ A_{filter}(Z) &= c_{filter}\left(\frac{p}{1000\,\mathrm{mb}}\right)^{1/6}\left(\frac{T}{273\,\mathrm{K}}\right)^{1/3}\left(\frac{Z}{1\,\mathrm{cm}^{2}\mathrm{V}^{-1}\mathrm{s}^{-1}}\right)^{2/3} \end{aligned}\right\}.$$

The adsorption coefficients c_{screen} and c_{filter} equal to the adsorption of $Z = 1$ particles at 273 K and 1000 mb. The most reliable estimates of the coefficients can be obtained by the measurement of the adsorption.

The size-mobility conversion see:

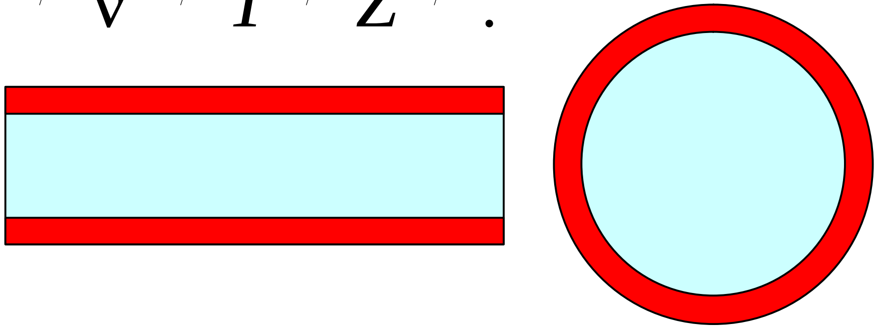
Tammet, H. (1995) Size and mobility of nanometer particles, clusters and ions. *J. Aerosol Sci.*, **26**, 459-475.

Li, Z., Wang, H. (2003) Drag force, diffusion coefficient, and electric mobility of small particles II. Application. *Phys. Rev. E*, 68, 061207.

Estimate of the adsorption coefficients for flat and circular channels

In case of a short inlet channel where the boundary layer displacement thickness is much less than the height or the radius of the channel:

$$A_{flat} = 1.33(k/e)^{2/3} L^{1/2} H^{-1} V^{-1/2} \nu^{-1/6} T^{2/3} Z^{2/3}.$$



For a round tube the height H is to be replaced by the radius R.

$$c_{flat} = 0.0016\sqrt{\frac{L}{V}}H,$$

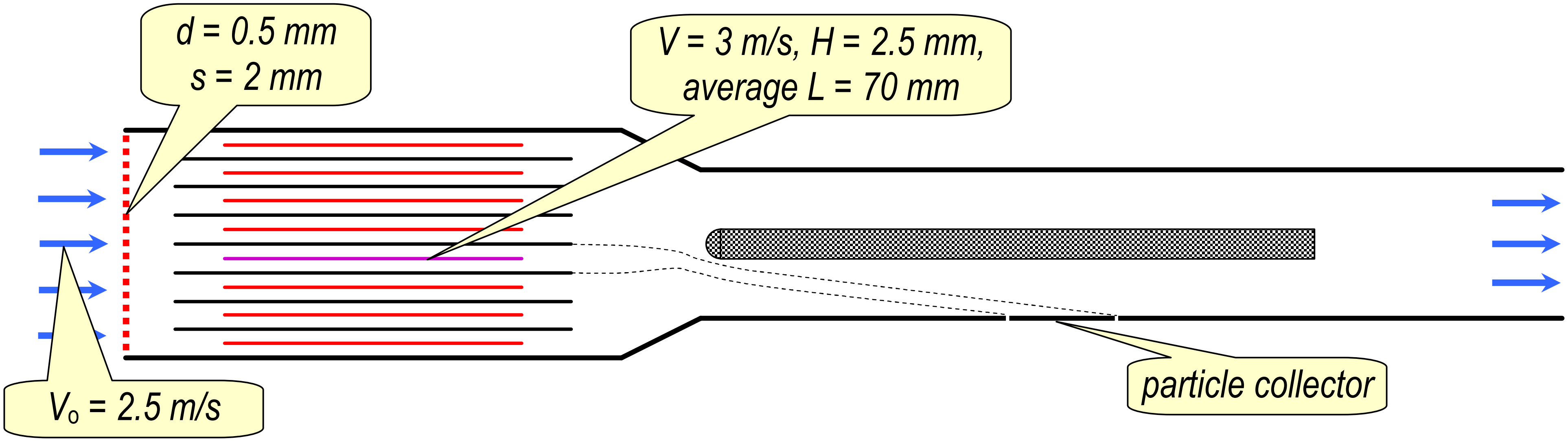
$$c_{circular} = 0.0016\sqrt{\frac{L}{V}}R = 0.0016\sqrt{\frac{\pi L}{Q}}.$$

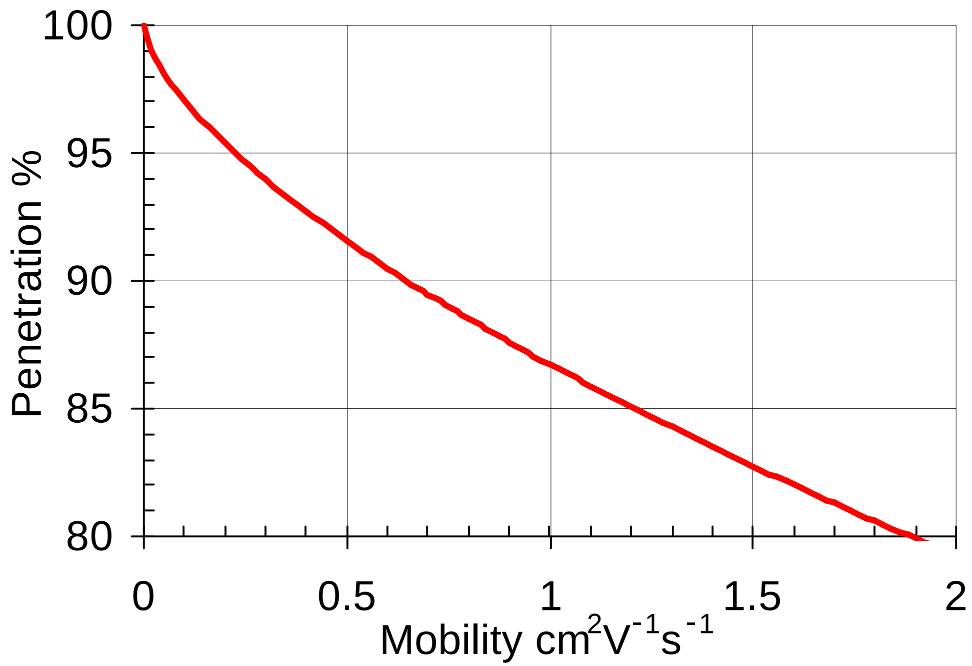
where Q is the flow rate and all arguments must be expressed in SI.

A question: how many times will be reduced the adsorption when we make the inlet tube of the double radius?

Answer: just 1 times because V is proportional to R^{-2}.

Example





$c_{screen} = 3.3\%$

$c_{filter} = 10\%$

Penetration of particles through the inlet at T = 20°C and 1000 mb.

Conclusions

- Inlet loss is a factor of uncertainty in nanoparticle measurement.
- Uncertainties in theoretical and semiempirical estimates of particle adsorption reach several tens of per cent. Adjusted estimates can be attained by means of direct measurement.
- Ratio $\dfrac{\text{relative uncertainty of measurement}}{\text{relative uncertainty of particle loss}}$ is:

  low in case of low adsorption,
  about 1 in case of 50% loss,
  high in case of higher loss.

- The nanometer particle loss on the inlet grid and electrostatic filter can be estimated and corrected quite exactly if the particle adsorption at some particular mobility, temperature, and air pressure is known.