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Detection of the Mass of Airborne Particles in an online Optical Sensor System by Correlation of Geometric and Inertial Filtering

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Abstract

We present a method combining inertial and geometric filtering to approximate the mass of particles for optical particle detection systems. The method consists of three measurement steps and is based on the difference of the filtering behavior of geometric and inertial filters based on particle size and particle density respectively. Our measurements show the feasibility using polystyrene latex particles with sizes 300/500/900 nm and silica particles with diameters 500 nm and 1000 nm.

Keywords: Optical nanoparticle detection; inertial filtering; filter system

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1. Motivation

In optical particle detection systems (OPS) based e.g. on laser light scattering the size of a particle can be determined easily from the detected light signal when the influence by the index of refraction is known or can be compensated. However no information can be obtained on the particle density or mass [1]. This information is especially interesting as environmental safety standards still consider the particle mass, yet the size is expected to have a major influence on the health risk [2,3].

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Nomenclature

d_p	Particle diameter
C_c	Cunningham slip correction factor
Stk_{50}	Stokes number for 50% impaction efficiency (constant)
D_j	Impactor jet diameter
η	Air viscosity
ρ	Particle density
U	Volume flow
λ	Mean free path in air

2. Concept

Our approach uses the correlation of measured particle size distributions (PSD) using geometric and inertial filters in three measurement steps in our OPS.

First the PSD is determined without any filtering. Second a geometric filter, e.g. a membrane filter having a certain pore size and a known filter efficiency curve, is connected before the inlet of the OPS. The changes in the PSD reflect the filtering efficiency curve. The geometric filtering is used to limit the particle size measurement range and to numerically adjust the initially assumed optical index of refraction of the particles using curve fitting and Mie theory. The very first unfiltered measurement is necessary to quantify the effect of the geometric filter.

In a third step an inertial filter, e.g. an impaction filter (IF), is connected before the OPS. The then measured PSD reflects the density-dependant filtering (see Fig. 1a). The filter efficiency curve of the IF does not need to be sharp or highly efficient (see Fig. 1b) and can be determined numerically in a foregoing first calibration step using a polydisperse particle aerosol with constant density and known distribution. The design and the 50% filtering efficiency of a Marple-type impactor filter can be determined by [4,5]

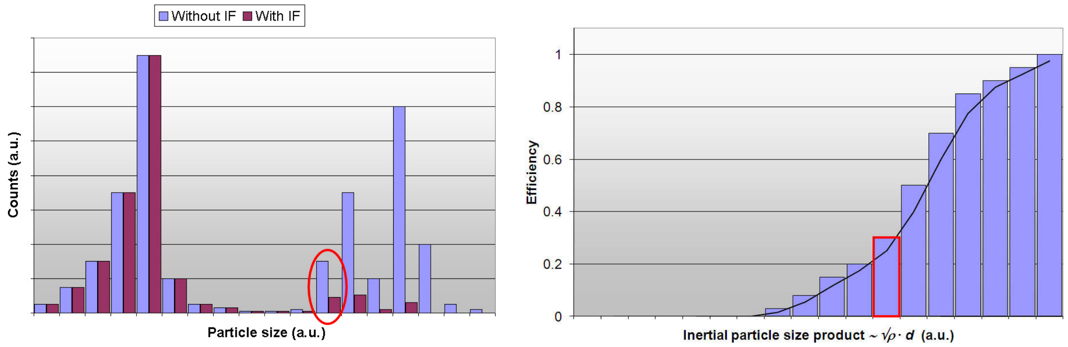
$$\sqrt{\rho}\, d_{p,50} = \sqrt{\frac{9\eta D_j Stk_{50}}{C_c U}} \tag{1}$$

with C_c being the Cunningham slip correction factor as defined by ISO 15900:

$$C_c = 1 + \frac{\lambda}{0.5 \cdot d_p}\left[1.165 + 0.483 \cdot \exp\left(-0.997 \cdot \frac{0.5 \cdot d_p}{\lambda}\right)\right]. \tag{2}$$

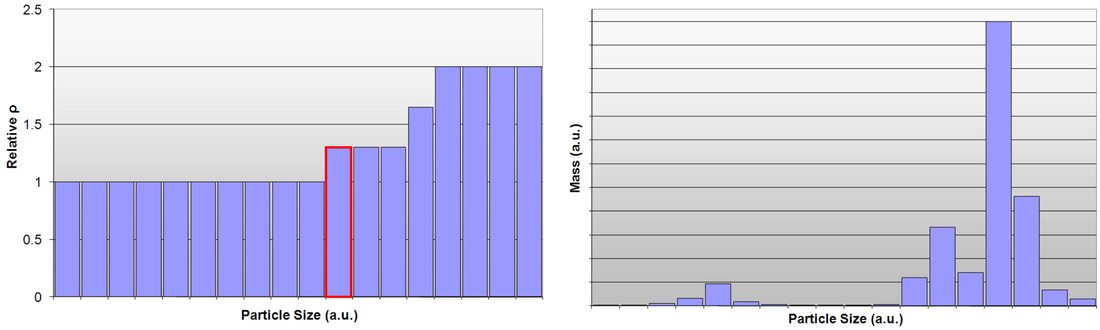
As the filtering efficiency is practically not sharp as some bigger particles get through and some smaller particles are filtered, one has to determine the actual efficiency curve in a first step.

After the measurements the average density of the particles can be calculated from the relative difference of the measured PSDs. Inertial filtering is proportional to the root of the Stokes number of the particles, depending on the density and size of the particles ($\sim\rho^{0.5}\cdot d_p$) (see Fig. 2a). The particle density can be calculated by choosing the size parameter $\sim\rho^{0.5}\cdot d_p$ of the inertial filter associated with a certain relative particle loss (see Fig. 1b) and solving for ρ. The particle mass distribution can then be calculated by multiplication of the distributions of steps two and three (Fig. 2b).



(a) (b)

Fig. 1. (a) Comparison of the particle size distribution with inertial filtering (‘IF’, red) and without IF (blue). The filtering effect increases $\sim\rho^{0.5}\cdot d_p$ and is e.g. 70% for the particle size marked in red (see (b)).
(b) Illustration of a typical filtering efficiency curve of an inertial filter, $\sim\rho^{0.5}\cdot d_p$.



(a) (b)

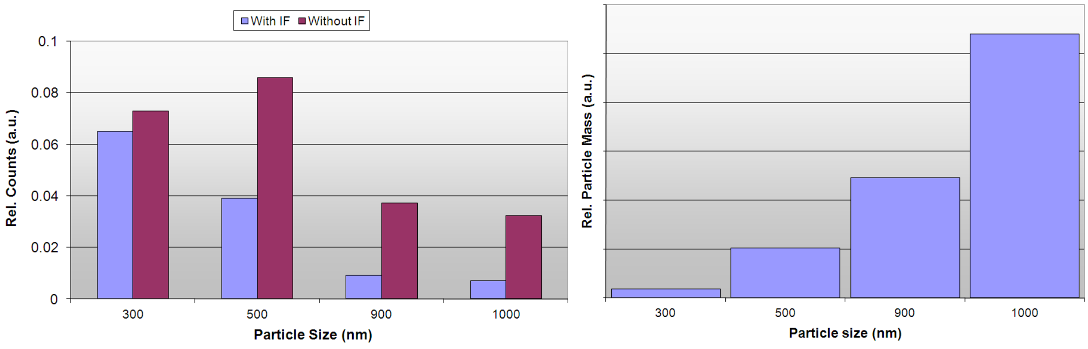
Fig. 2. (a) The calculated relative particle density for the particle size distribution from Fig. 1. The particle density can be calculated by choosing the product $\sim\rho^{0.5}\cdot d_p$ of the inertial filter associated with the specific relative particle loss (see Fig. 1b) and solving for ρ. For the values marked in red in Fig. 1a the result would be ρ=1.3 g/cm³.
(b) Multiplication of the measured PSD and the determined particle density spectrum leads to the particle mass distribution (PMD). Repeating the measurement steps with multiple inertial filters one can derive a well resolved PMD.

3. Measurements

In our measurements we compared the behavior of polystyrene latex particles (PSL; Thermo Scientific with NIST-traceable mean diameter diluted using ultra pure H_2O, used in aerosol generator Grimm Aerosol 7.822 and diffusion dried) with diameters of 300/500/900 nm (ρ=1.05 g/cm³) and 500/1000 nm silica (ρ=2.01 g/cm³) using a Marple-type impactor having a theoretical cut-off diameter at ~550 nm for ρ=1.0 g/cm³. Additionally we used a track-edged polycarbonate membrane filter (Millipore Isopore) and Grimm 5.403 SMPS+C as reference particle measurement system. The results on the feasibility of the above described technique are shown in Fig. 3. Comparing the filtering efficiency of 500 nm PSL and silica directly using high-vacuum grease at the impaction plate, we found values of 0.36 and 0.12

respectively, which illustrate the significant influence of the particle mass on the inertial filtering behavior (see Fig. 4).

In a further development step using multiple inertial filters with different cut-off sizes, the density and composition of a wide particle size range could be well approximated.



(a) (b)

Fig. 3. (a) Measured PSD (relative counts versus particle size) consisting of 300/500/900 nm sized PSL as well as 1000 nm silica particles before (red) and after inertial filtering (blue).
(b) Particle mass distribution determined from measurements shown in (a). Small particles make up a smaller part of the total particulate mass than bigger particles even their concentration is significantly higher.

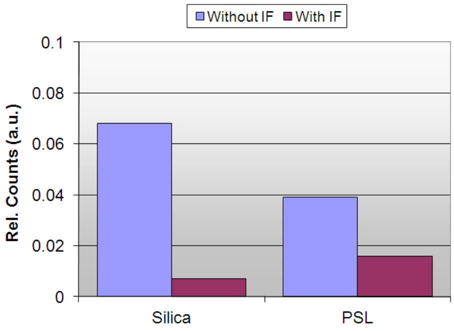


Fig. 4. Measured relative particle counts for 500 nm sized Silica and PSL particles. The inertial filtering efficiency for denser silica particles shows to be significantly higher.

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