



BSI Standards Publication

Workplace exposure — Direct-reading low-cost particulate matter sensors for measuring airborne NOAA — Guidelines for application

National foreword

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A list of organizations represented on this committee can be obtained on request to its committee manager.

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English Version

Workplace exposure - Direct-reading low-cost particulate matter sensors for measuring airborne NOAA - Guidelines for application

Exposition sur les lieux de travail - Capteurs de matière particulaire à lecture directe et à faible coût pour le mesurage des NOAA en suspension dans l'air - Lignes directrices pour l'application

Exposition am Arbeitsplatz - Direkt anzeigende kostengünstige Feinstaubsensoren zur Messung luftgetragener NOAA - Leitlinien für den Einsatz

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European foreword

This document (CEN/TS 18086:2024) has been prepared by Technical Committee CEN/TC 137 “Assessment of workplace exposure to chemical and biological agents”, the secretariat of which is held by DIN.

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Introduction

The production and use of engineered nano-objects and their agglomerates and aggregates (NOAA) has increased over the recent years, as well as the concerns related to their potential adverse health effects. The measurement of nano-objects is particularly difficult because of the small size of the particles and small relative mass in comparison with other contaminants. Human exposure to NOAA is most likely to occur in workplaces, where they are produced, processed and handled in large quantities or over long periods of time. Continuous monitoring of such workplaces would improve exposure assessment, especially in cases where the exposure pattern is very inhomogeneous and large, and fluctuating background concentrations are present.

There has been an increased interest in the use of low-cost particulate matter (PM) sensors in different areas. Up to now, exposure concentrations are measured only during limited time periods and with limited spatial resolution, using expensive bulky static measurement and sampling equipment and/or direct reading personal monitors and personal samplers. In contrast, due to their low-costs and small size, the low-cost PM sensors allow for:

- the setting up of dense measurement networks in workplaces to monitor dust concentrations with high spatio-temporal resolution;
- use as personal monitors;
- use to produce information on the efficiency of process controls of NOAA-production facilities, the background and the far field.

Therefore, due to the lower costs compared with established scientific grade instruments, more devices can be employed for in total lower costs. The main purpose of such sensor networks is to estimate exposure levels in workplaces. At the time of writing this document, low-cost PM sensors should not be considered for any compliance measurements, because they cannot replace reference measurements e.g. with samplers for the respirable fraction. They should rather be considered as complementary to reference measurements. However, this limitation can become obsolete in the future, when new generations of low-cost PM sensors overcome the shortcomings of today's sensors. They can thus be applied as an indicator for exposure, as a warning system or to identify potential particle sources, e.g. as a permanent implementation of a Tier 1 exposure assessment (EN 17058 [1]). Individual threshold values may be defined to implement and/or initiate control measures.

The low-cost PM sensors available are based on measuring the light scattered by airborne particles, which depends on particle size, shape and refractive index. To calibrate the sensors for the determination of particle mass concentrations, average values for these properties, as well as for the effective particle density, must be assumed. The sensors are typically calibrated for use in ambient air monitoring. However, the particle properties assumed in the calibration for ambient use can be very different from those of particles encountered in workplaces. Due to the wide diversity of particle properties in workplace air, a single generalizable calibration for different workplaces is not feasible. In addition, measurement artefacts, e.g. stemming from relative humidity, can be different in workplace and atmospheric measurements.

Low-cost PM sensors exist with different levels of complexity, resulting in different wealth of information, ranging from a voltage output as a measure for the total particle concentration, via different size-integrated fractions of the mass and/or number concentration to number size distributions with high size resolution. The focus of this document is on those sensors that are able to deliver size-integrated number and/or mass concentrations in different size fractions. Most low-cost PM sensors were originally developed for ambient air quality monitoring and are thus calibrated following ambient sampling conventions, e.g. for PM_{2,5} and PM₁₀ (US EPA 40 CFR part 62 [2] and 40

CFR part 53 [3], respectively), which are not identical with the sampling conventions for workplaces, e.g. for the respirable or thoracic fraction according to EN 481 (see Annex A).

The methods and procedures described in this document apply to the sensor modules only and not to complete devices, based on these. Sensor modules are considered to be low-cost, if their prices are at least 10 to 100 times lower than the prices of established instruments of comparable type, e.g. those described in CEN/TR 16013-2 [4] and CEN/TR 16013-3 [5].

1 Scope

This document gives guidelines on the use, calibration and evaluation of low-cost optical particulate matter sensor modules and systems for workplace exposure assessments.

This document is based on extensive laboratory and workplace tests for airborne NOAA.

This document is particularly aimed at engineered NOAA at workplaces and the sensors' applicability for process control of NOAA-producing plants via airborne particle concentration measurements in workplace air.

NOTE This document is also applicable to other airborne particles included in some of the tests during the prenormative research.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 481, *Workplace atmospheres — Size fraction definitions for measurement of airborne particles*

EN 1540, *Workplace exposure — Terminology*

ISO 27891, *Aerosol particle number concentration — Calibration of condensation particle counters*

ISO 21501-1, *Determination of particle size distribution — Single particle light interaction methods — Part 1: Light scattering aerosol spectrometer*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 1540 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

3.1

adjustment of a measuring system

set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured

[SOURCE: ISO/IEC Guide 99:2007, 3.11 [6]]

3.2

advanced aerosol photometer

measurement device that combines a photometric measurement of light scattered by a cloud of particles inside a measurement volume to determine total number and/or mass concentrations with spectrometric features to distinguish between concentrations in different particle size fractions

3.3**aerodynamic aerosol classifier****AAC**

measurement device that size-classifies airborne particles according to the aerodynamic diameter based on classification of the particle relaxation time

3.4**aerosol photometer**

measurement device that determines particle size-integrated number or mass concentrations by measuring the integral intensity of light scattered by a cloud of particles inside a measurement volume

Note 1 to entry: Photometers can only be calibrated for known particle size distributions.

3.5**calibration**

operation that, under specified conditions, in a first step, established a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

[SOURCE: ISO/IEC Guide 99:2007, 2.39]

Note 1 to entry: In practice, a calibration is often done in conjunction with a later adjustment.

3.6**condensation particle counter****CPC**

measurement device that determines in real-time the number concentration of airborne particles ranging from few nm up to several μm in size in a limited range of concentration, but does not discriminate between particles of different sizes or origin

3.7**mobility particle size spectrometer****MPSS**

measurement device that determines number size distributions of airborne submicron particles based on electrical mobility analysis

3.8**optical aerosol spectrometer**

measurement device that determines number size distributions of airborne particles by measuring the intensity of light scattered by individual particles inside a small measurement volume as a measure for the particle size and counting the number of scattered light pulses as a measure for the number concentration

Note 1 to entry: CEN/TR 16013-2 [4] also refers to Optical Aerosol Spectrometers as Optical Particle Counters.

3.9**optical equivalent diameter**

diameter of a spherical particle with known refractive index that causes the same scattering light intensity as the particle under investigation

3.10

PM_x

particulate matter suspended in air which is small enough to pass through a size-selective inlet with a 50 % efficiency cut-off at x µm aerodynamic diameter

[SOURCE: EN 12341:2023, 3.1.16] [7]

Note 1 to entry: Commonly measured PM_x fractions are PM₁, PM_{2,5}, PM₄ and PM₁₀. PM₄ is nearly identical with the respirable fraction.

3.11

reference measurement instrument

instrument that is calibrated against a traceable method and that is designated for the calibration of other measurement devices of a given kind in a given organization

3.12

sensor module

sensor and signal processing algorithms that determine number concentration and/or mass concentration and/or size distribution of airborne particles, based on the measurement of light scattered by particles

Note 1 to entry: Sensor modules are considered to be low-cost if prices are at least 10 to 100 times lower than established instruments of the same type.

3.13

sensor

individual sensor

physical unit that produces a signal related to the concentration of particulate matter in air

Note 1 to entry: The low-cost PM sensors available at the time of writing this document were all based on light scattering. This document might not be applicable to sensors working on a different measurement principle.

3.14

sensor network

set of multiple connected sensors or sensor systems that are spatially distributed to monitor particulate concentrations in a workplace with spatiotemporal resolution

3.15

sensor system

single integrated set of hardware that uses one or more sensor modules to produce a signal related to the concentration of particulate matter in air that can supply real time measurements

Note 1 to entry: Sensor systems contain many common components in addition to the basic sensing or analytical element that is used for detection. Common core components and functions can include:

- sensing detector (the actual sensor);
- sampling capability (generally active sampling for PM);
- power systems, which may include batteries;
- analogue to digital conversion;
- signal processing;

- local data storage;
- data transmission;
- enclosure.

4 Symbols and abbreviations

4.1 Symbols

a	Slope of linear fit curve [-]
b	y-intercept of linear fit curve [$1/\text{m}^3$ or kg/m^3]
C_N	Number concentration [$1/\text{m}^3$]
C_m	Mass concentration [kg/m^3]
C_c	Cunningham slip correction factor [-]
d_{50}	Particle diameter, at which instrument reaches 50 % detection efficiency [m]
d_{ae}	Aerodynamic equivalent diameter [m]
d_{mob}	Mobility equivalent diameter [m]
d_{opt}	Optical equivalent diameter [m]
d_p	Particle diameter [m]
I	Light intensity [cd]
m	Refractive index [-]
R^2	Regression coefficient [-]
α	Scattering parameter [-]
ϕ	Aperture angle [rad]
λ	Wavelength of light [m]
η	Detection efficiency [-]
ρ_0	Unit density [$1000 \text{ kg}/\text{m}^3$]
ρ_{eff}	Effective particle density [kg/m^3]
ρ_p	Particle density [kg/m^3]
θ	Detection angle [rad]

4.2 Abbreviations

AAC	Aerodynamic Aerosol Classifier
APS	Aerodynamic Particle Sizer
CPC	Condensation Particle Counter
DEHS	Di-Ethyl-Hexyl-Sebacate
DEMC	Differential Electrical Mobility Classifier

ELPI	Electrical Low Pressure Impactor
LCS	Low-Cost Sensor
LOQ	Limit of quantification
MPSS	Mobility Particle Size Spectrometer
NOAA	Nano-objects, their agglomerates and aggregates
OAS	Optical Aerosol Spectrometer
PM	Particulate Matter
PSL	Polystyrene Latex
TEOM	Tapered Element Oscillating Microbalance
TiO ₂	Titanium dioxide

5 Measurement principle of low-cost PM sensors

The available low-cost PM sensors are based on the measurement of light, scattered by particles inside a measurement volume, illuminated by a light source, within the sensor. The light-scattering sensors can be categorized in three sub-categories:

- a) Spectrometers;
- b) Photometers;
- c) Advanced photometers.

In a spectrometer, individual particles are transported with a flow through the measurement volume. To ensure that at most a single particle is present inside the measurement volume, its size shall be small. Each individual particle causes a light pulse, whose intensity is determined with a photo-detector as a measure for the particle size. The pulses are furthermore counted and classified based on their height in order to obtain the number size distribution of the particles, based on the optical equivalent diameter (CEN/TR 16013-2 [4]). Mass size distributions are calculated from the number size distributions, by assuming the particles' refractive indices, shapes and densities, which often depend on the particle size. Different number and mass (PM_x) size fractions can be obtained from the corresponding size distributions by weighting them with the required sampling convention (see Annex A) and integration over the particle size.

In a photometer, the light scattered by a cloud of particles inside the measurement volume is measured (CEN/TR 16013-3 [5]). The measurement volume of a photometer is much larger than that of a spectrometer. A photometer cannot distinguish particle sizes and only delivers size-integrated information. Only for stable particle size distributions and compositions, the total light intensity measured by a photometer is proportional to the total particle mass and number concentration. Photometers usually report the mass concentration of one PM_x fraction by assuming the (constant) particle number size distribution, refractive indices, particle shapes and densities.

Advanced photometers use a combination of a photometer and a spectrometer. The size of the measurement volume is usually in-between the sizes in spectrometers and photometers. An advanced photometer measures a photometric signal of a cloud of particles as an offset and a measure for the overall concentration. In addition, individual peaks sticking out of the offset signal are detected. These peaks stem from the typically rather low number of large particles, which, however, have a strong contribution to the mass concentration. These peaks are counted and classified based on their heights in order to differentiate between different size fractions [8]. Advanced photometers are thus able to

deliver mass concentrations in more than one different size fraction. Some advanced photometers also deliver estimates of the number concentration in different size fractions.

Most available low-cost PM sensors apply the advanced photometric or photometric principle due to their lower complexity compared with the spectrometric principle. Whereas the overall measurement principles of the low-cost PM sensors are identical to the ones used in established, scientific grade measurement devices, there are some differences. For example, most low-cost sensors do not use a particle free sheath flow to protect the optics from fouling, which can have an effect on the measurement accuracy, longterm stability and durability.

The sensors typically provide the measurement results in terms of particle mass concentrations in one or more size fractions (PM_x) and in some cases also as particle number concentrations in one or more size fractions. It shall be noted that the intensity of light, scattered by particles depends on multiple particle properties, but not the particle mass and thus a bespoke calibration is needed in order to determine mass concentrations (see Clause 6). A detailed description of the measurement principle of the three sensor categories is provided in Annex E.

Advantages and disadvantages of the three sensor categories are listed in Table 1.

Table 1 — Advantages and disadvantages of low-cost PM sensors

	Advantages	Disadvantages
Photometer	— No fan needed — Lowest cost — Wide concentration range — Fast response to changes inside measurement volume — Easy data handling (single data point per time step)	— Signal not exclusively proportional to mass concentration, specific calibration needed — Dependent on particle size distribution, refractive indices, shapes, but not particle density — Slow dynamic response without forced flow through measurement volume — Single value for total light scattered only, no particle size differentiation
Advanced photometer	— Delivers concentrations in different size fractions — Can deliver both number and mass concentrations — Quick response to dynamic size distribution and concentration changes — Lower costs compared with spectrometers	— Size fractions pre-defined by manufacturer and not freely selectable — Signal not exclusively proportional to number or mass concentration, but dependent on particle size distribution, refractive indices and shapes — Output relies on the typically undisclosed manufacturer calibration and algorithms
Spectrometer	— Delivers particle number size distributions — Size-integrated number and mass concentrations can be calculated for any size fraction within measurement range — Suitable for low concentrations; lower limit depending on measurement volume — Quick response to dynamic size	— Not suitable for particle sizes below approximately $0,3 \mu m$ — Not suitable for high concentrations; upper concentration limit due to coincidence error (depending on measurement volume) — Signal not exclusively proportional to mass concentration — More expensive than photometers and advanced

	distribution and concentration changes	photometers
—	Signal proportional to number concentration	

Figure 1 provides a decision tree for the choice of an appropriate sensor type, depending on the anticipated sensor application.

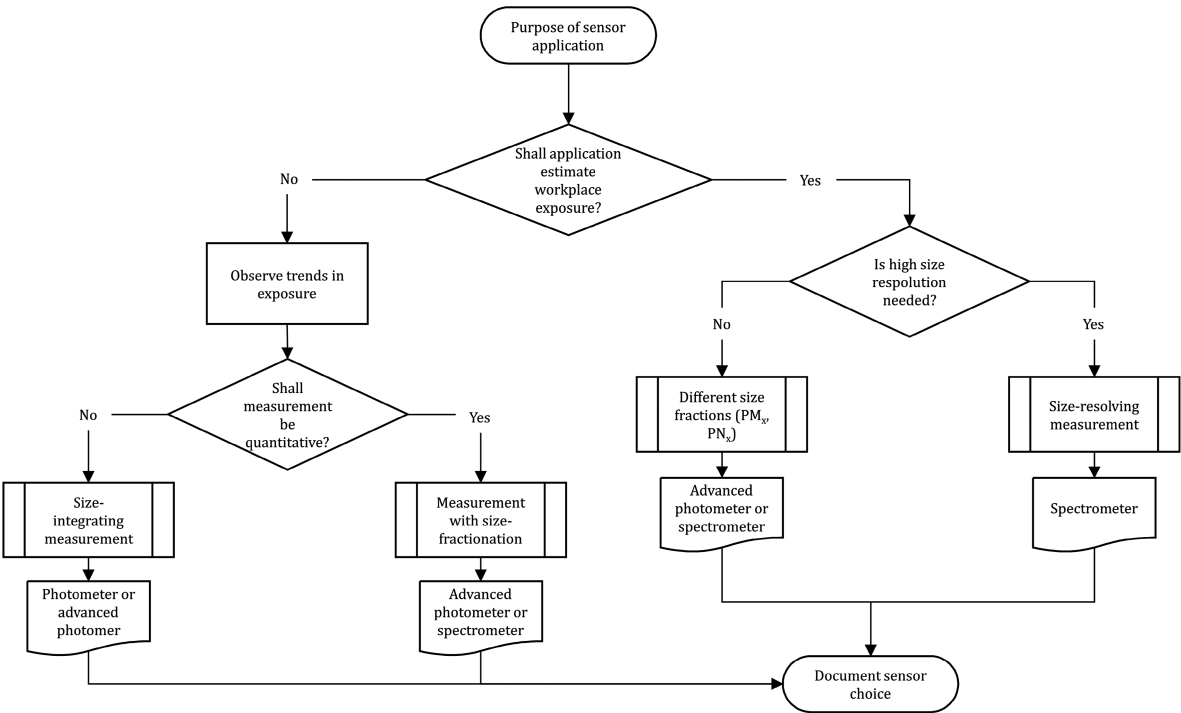


Figure 1— Decision tree for the choice of a sensor type depending on purpose of its application in a workplace

6 Usability of low-cost sensors for monitoring NOAA concentrations in workplaces

Due to their low-costs, PM sensors can allow for establishing measurement networks with high density to permanently monitor the spatio-temporal distribution of different dust fractions in workplaces. With such networks, it is possible to keep track of when and where concentrations increase and can therefore be a valuable indicator for potential particle leaks and areas of increased exposure. It shall, however, be kept in mind that the sensors use a measurement principle, which is based on many assumptions. Further, the possibilities for quality assurance, e.g. an inherent control of the sample flow rate, are reduced and consequently the measurement uncertainty is higher compared to reference instruments.

Therefore, low-cost sensor measurements shall not replace reference measurements for compliance testing according to regulations.

The possibilities to monitor NOAA concentrations is limited due to the detectable particle size range of the sensors. With optical light scattering devices like the PM sensors, particles with optical equivalent

sizes below approximately $0,3\text{ }\mu\text{m}$ cannot or not adequately be detected [9]. Nano-objects have by definition a geometric size which at least in one dimension is smaller than $0,1\text{ }\mu\text{m}$ (ISO 80004-1 [10]). Concentrations of single, unbound nano-objects can therefore normally not or not adequately be measured with optical low-cost PM sensors. In contrast, if the nano-objects are present in agglomerated or aggregated form, their sizes are often $> 0,3\text{ }\mu\text{m}$ and thus detectable. Consequently, the usability of optical low-cost PM sensors in workplaces at least during the production of NOAA is questionable. However, they can be meaningfully applied during downstream use of NOAA, when agglomerated or aggregated particles are to be monitored in air. Quantitative results are only possible if the particle size distribution and chemical composition match the aerosol properties used for calibration.

7 Calibration and adjustment of low-cost PM sensors

7.1 General

The measurement of number or mass concentration with an optical low-cost PM sensor depends on various particle and aerosol properties. The available low-cost PM sensors are typically factory-calibrated for atmospheric aerosols and thus inherently assume mean values for these properties for ambient particles. Depending on the particle and aerosol properties in the workplace to be investigated, the factory calibration of a sensor can yield incorrect concentration values. For understanding the applicability and the proper use of low-cost PM-sensors in workplaces, different types of calibrations shall be applied. Depending on the outcome, either constant adjustment factors or adjustment functions that take into account a potential offset or concentration dependence are determined, if necessary. For the sensor adjustment, the measurement results are multiplied with the adjustment factor or function. Adjustment factors therefore have no physical unit. If the photodetector signal, typically a voltage, is accessible, a calibration factor or function can also be applied that relates the measured light intensity dependent voltage to the corresponding particle concentration. In such cases, the calibration factor

carries the unit $\frac{1}{\text{m}^3 \cdot \text{mV}}$ for number concentrations and e.g. $\frac{\mu\text{g}}{\text{m}^3 \cdot \text{mV}}$ for mass concentrations.

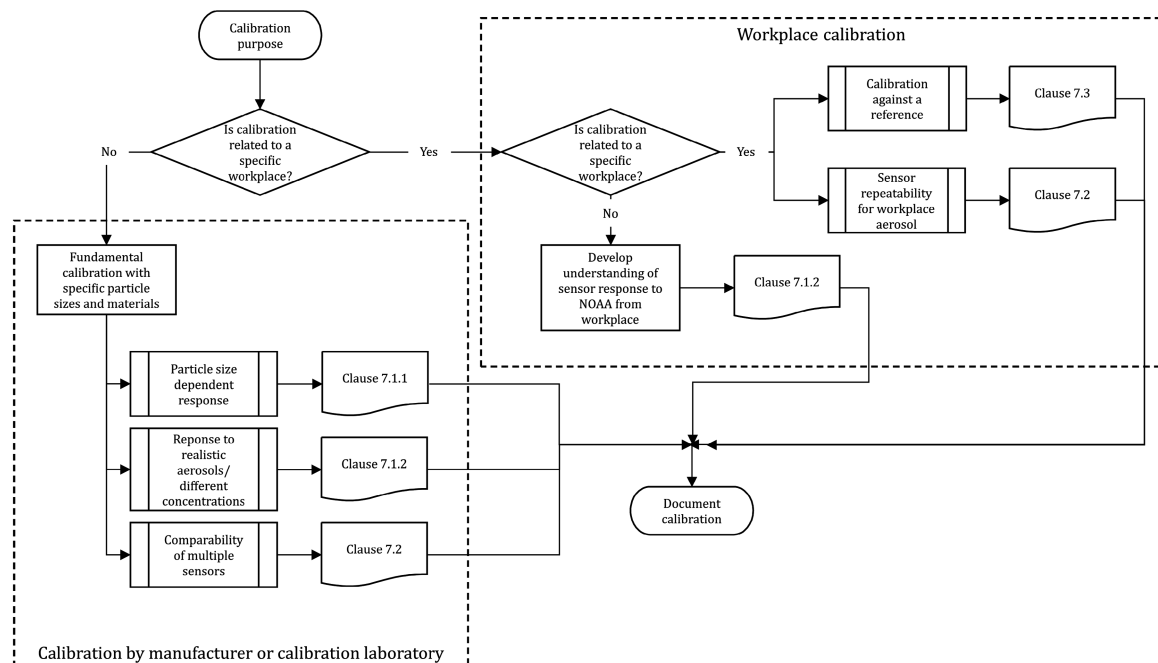


Figure 2 — Decision tree for the choice of an appropriate calibration method

Figure 2 provides a decision tree to select a proper calibration method, depending on the purpose of the calibration. The different calibration and adjustment methods are described in the following. Due to the lower quality assurance of the low-cost PM sensors compared with more expensive established, scientific grade instruments, the inter-specimen variation of sensors of the same type can affect the comparability of measurement data. If multiple sensors are used in the same workplace, the comparability of the results from the sensors shall be checked before the measurements. If necessary, an individual adjustment factor or function shall be determined per sensor specimen.

Any calibration requires the use of reference measurement instruments and/or particle size classifiers. A list of suitable devices for the different metrics is provided in Table 2.

It is additionally recommended to regularly check the flow rate of the sensors. However, most flow meters are not suitable, because they introduce a pressure drop that is too high to be overcome by the fans used by the sensors to establish the sampling flow. Only flow meters with very low pressure drop, e.g. bubble flow meters, shall be used. According to EN 482 bubble flow meters also provide the lowest measurement uncertainty.

Table 2 — Overview of reference measurement instruments and size classifiers to be used for calibration of low-cost PM sensors

Metric	Instrument	Size range	Concentration range	Comments
Number concentration	Condensation Particle Counter (CPC) (EN 16897 [11])	Larger than 2,5 nm to 10 nm (d_{50} , depending on CPC model); upper size limit not well defined, mostly between 1 µm and 10 µm	Up to 3×10^{11} 1/m ³ , depending on CPC model	Water based CPCs are not suitable for highly hydrophobic particles
	Optical Aerosol Spectrometer (OAS) (CEN/TR 16013-2 [4])	Larger than 0,1 µm to 0,3 µm (d_{50} , depending on OAS model)	Up to 10^{12} 1/m ³ , depending on OAS model and coincidence correction	OAS with very different concentration ranges available, high max. concentration means low accuracy at low concentrations and vice versa. Determination of number concentration from the integration of the number size distribution is less accurate than direct number concentration measurements
	Mobility Particle Size Spectro-meter (MPSS) (ISO 15900 [12])	From 2,5 nm to 1,2 µm, depending on employed Differential Electrical Mobility Classifier (DEMC)	Approximately 10^9 1/m ³ to 10^{13} 1/m ³	Only suitable for constant or slowly changing number size distributions Based on mobility equivalent particle diameter Determination of number concentration from the integration of the number size distribution is less accurate than direct number concentration measurements
Mass concentration	Filter sampler for subsequent gravimetric	Any particle size that passes a size selective inlet	Lower concentration limit dependent on	Only suitable for high concentrations, unless sampling times of at least several hours

Metric	Instrument	Size range	Concentration range	Comments
	analysis	upstream, e.g. for the respirable fraction	quantification limit of balance and sampling duration	are feasible Method can only deliver time-integrated average concentrations, no time-resolved data
	Tapered Element Oscillating Microbalance (TEOM)	Any particle size that passes a size selective inlet upstream, e.g. for the respirable fraction	Depending on averaging time, e.g. approximately $> 10 \mu\text{g}/\text{m}^3$ for 15 min averaging	More accurate the higher the concentration and the longer the averaging times; only suitable for constant or slowly changing concentrations
	Optical Aerosol Spectrometer (OAS)	Larger than $0,18 \mu\text{m}$ to $0,3 \mu\text{m}$ (d_{50} , depending on OAS model)	Up to several mg/m^3 , depending on OAS model	Only instrument capable of measuring mass concentrations with high time resolution, but requires individual calibration of mass concentration measurement for each test aerosol
Number size distribution	Mobility Particle Size Spectrometer (MPSS)	From $2,5 \text{ nm}$ to $1,2 \mu\text{m}$, depending on employed Differential Electrical Mobility Classifier (DEMC)	Approximately $10^9 \text{ l}/\text{m}^3$ to $10^{13} \text{ l}/\text{m}^3$	Only suitable for constant or slowly changing number size distributions Based on mobility equivalent particle diameter
	Aerodynamic Aerosol Classifier (AAC) with Condensation Particle Counter (CPC)	25 nm to $5 \mu\text{m}$	Up to $10^{13} \text{ l}/\text{m}^3$	Only suitable for constant or slowly changing number size distributions Based on aerodynamic equivalent particle diameter
	Optical Aerosol Spectrometer (OAS)	Larger than $0,1 \mu\text{m}$ to $0,3 \mu\text{m}$ (d_{50} , depending on OAS model)	Up to $10^{12} \text{ l}/\text{m}^3$, depending on OAS model and coincidence correction	Based on optical equivalent particle diameter
	Aerodynamic Particle Sizer (APS)	$0,5 \mu\text{m}$ to $20 \mu\text{m}$	Usable up to $10^{10} \text{ l}/\text{m}^3$, depending on acceptable coincidence error	Based on aerodynamic equivalent particle diameter
	Electrical Low Pressure Impactor (ELPI)	6 nm to $10 \mu\text{m}$	Different for every size bin; e.g. $0,1 \text{ l}/\text{m}^3$ to $1,7 \times 10^{10} \text{ l}/\text{m}^3$ at $d_{50} = 5,3 \mu\text{m}$; $240 \text{ l}/\text{cm}^3$ to $7,9 \times 10^{13} \text{ l}/\text{cm}^3$ at $d_{50} = 6 \text{ nm}$	Based on aerodynamic equivalent particle diameter; concentrations determined based on current measurement at each impactor stage (unipolar particle charging at device inlet)

Metric	Instrument	Size range	Concentration range	Comments
Particle size	Differential Electrical Mobility Classifier (DEMC)	2,5 nm to 1,2 µm (mobility equivalent diameter), depending on model	n/a	Classifies based on electrical mobility; classified aerosol may contain multiple peaks in the size distribution due to multiply charged particles
	Aerodynamic Aerosol Classifier (AAC)	25 nm to 5 µm (aerodynamic equivalent diameter)	n/a	Classifies based on particle relaxation time

7.2 Laboratory calibration and adjustment

7.2.1 General

Laboratory calibration can be performed at different levels of specificity, i.e. with monodisperse or polydisperse particles of different sizes, shapes, refractive indices and concentrations. This is generally required for a better understanding of a sensor's performance and is recommended prior to making a choice of a sensor type to be used for a specific measurement task. Since the concentration reading of an optical aerosol measurement device will always depend on the prevailing particle and aerosol properties, it can differ from workplace to workplace and thus an individual calibration and if necessary adjustment for each workplace is advisable. Whereas laboratory calibrations can provide detailed information on the overall performance of a low-cost PM sensor and its specific reactions to different particle and aerosol properties, in many practical cases, it is circumvented in favour of carrying out an individual calibration at the workplace for the prevailing specific aerosol instead.

7.2.2 Particle size dependence of sensor reaction

The intensity of light scattered by a particle has a strong dependence on the particle size (see Annex D). For particles smaller than the wavelength of the light, i.e. in the Rayleigh regime, the intensity scales with the sixth power, i.e. its decrease with decreasing particle size is very steep. In an optical aerosol spectrometer this strictly limits the smallest detectable particle size, because scattered light pulses can no longer be distinguished from background noise. In case of a photometer, even very small particles can still be distinguishable from background noise, if they appear in sufficiently high concentrations. The accuracy of the differentiation of different particle sizes further determines an advanced photometer's ability to distinguish different particle size fractions. For large particles, the detection efficiency can be affected by particle losses due to sedimentation or impaction in bends of the aerosol flow path inside the sensor.

The size dependent detection efficiency $\eta(d_p)$ is defined according to Formula (1) as:

$$\eta(d_p) = \frac{C_{\text{sen}}(d_p)}{C_{\text{ref}}(d_p)} \times 100 \% \quad (1)$$

where

$\eta(d_p)$ is the size dependent detection efficiency, in percent;

d_p is the particle diameter;

$c_{\text{sen}}(d_p)$ is the particle concentration measured by the sensor for a given monodisperse particle size;

$c_{\text{ref}}(d_p)$ is the corresponding concentration measured by the reference instrument.

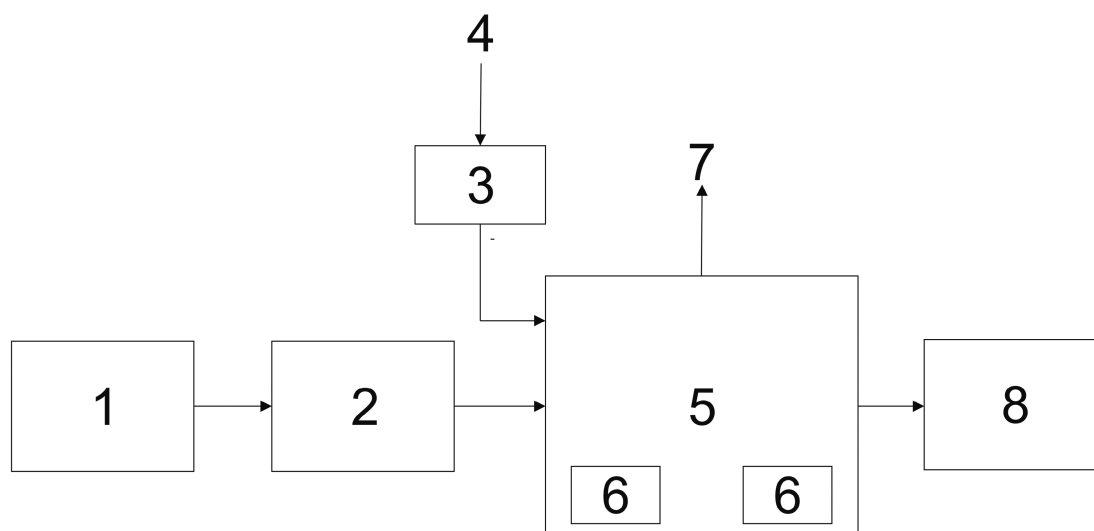
For a well calibrated reference instrument (see Table 2), $c_{\text{ref}}(d_p)$ is considered to be the “true” concentration. Since besides the particle size, the light scattering intensity also depends on the refractive index of the particle material, the detection efficiency is also a function of the particle material. It is therefore commonly determined as a function of the optical equivalent particle diameter, which refers to a particle material with well-known optical properties, usually polystyrene latex (PSL).

The sensors typically use internal algorithms to determine the number and/or mass concentrations in different size fractions from the measured light intensity signals. These algorithms are usually not disclosed by the manufacturer, but can result in different size dependent detection efficiencies for the number and the mass concentration. Consequently, these two detection efficiencies shall be treated separately.

Monodisperse particles of different sizes d_p and concentrations within the measurement range of sensor and reference instrument are used to determine the particle size dependent detection efficiency of a sensor. A suitable monodisperse particle generator shall be applied, e.g. utilizing a vibrating orifice [13] or based on tailored condensation on nuclei [14]. Alternatively, the monodisperse aerosol generator may comprise a generator for polydisperse aerosols, e.g. an atomizer or powder disperser, and a suitable aerosol classifier, e.g. a differential electrical mobility classifier (DEMC) [15] for submicron particles or an aerodynamic aerosol classifier (AAC) [16] for particle sizes up to 5 μm to select monodisperse particles with different sizes. Care needs to be taken to avoid or correct for the effect of larger multiply charged particles, when a DEMC is used. The monodisperse test aerosol shall be conditioned upon classification, i.e. charge neutralized and dried if necessary. Whereas a potential particle charge does not affect the measurement with a low-cost PM sensor, it can cause electrostatic particle transport losses and thus affect the achievable precision that can be achieved with the measurement setup. The monodisperse test aerosol is fed into a container, large enough to host all sensors to be tested simultaneously (see Figure 3). Alternative experimental set ups like calm air chambers are also applicable [17]. If the monodisperse test particles are produced with a classifier, the number of sensors that can be tested is limited due to the low flow rate of the available classifiers.

Prior to any calibration using a DEMC or an AAC, the function of the classifier shall be checked by dispersing monodisperse calibration particles of known size from a polystyrene latex (PSL) suspension. Upon aerosolisation, the test aerosol needs to be dried to remove any particle-borne water. The size of these particles shall be in the range from 100 nm to 300 nm to avoid interferences with residues from the water and surfactants used to stabilize the PSL suspensions. According to CEN/TS 17434 [18], the size detected with the classifier shall not deviate from the certified size of the PSL particles by more than $\pm 3 \%$. If the deviation is in the range from 3 % to 10 %, the sheath flow rate of the classifier shall be adjusted to achieve a more accurate sizing. If the deviation is $> 10 \%$, then the entire classifier system needs to be checked.

The sensors are completely placed inside the container rather than sampling from it to avoid interfering with the sensor flow rate and flow direction. The air flow through the sensors is typically established by means of a simple fan that cannot overcome a pressure difference. A reference instrument samples from the container to determine the reference number or mass concentration and/or size distribution. Depending on the flow rates of the monodisperse aerosol and the reference instrument, additional filtered make up air shall be supplied at a flow rate that ensures the inlet flow to the container to be higher than the flow rate exhausted from the container by the reference instrument. Whenever necessary, the container shall have an opening to exhaust any excess flow. A small fan shall be used inside the container to spatially homogenize the aerosol.

**Key**

- 1 monodisperse aerosol generator
- 2 aerosol conditioner
- 3 filter
- 4 optional make up air
- 5 container
- 6 sensors
- 7 exhaust
- 8 reference instrument

Figure 3 — Experimental set up to test low-cost PM sensors with monodisperse test aerosols

An appropriate reference instrument needs to be chosen, depending on whether the counting efficiency, i.e. the detection in terms of number concentration, or the mass concentration detection efficiency shall be determined. For the counting efficiency, a measurement device shall be chosen that has a well-known and documented counting efficiency of nearly 100 % for the sizes of the monodisperse particles under investigation. This may be a condensation particle counter (CPC) for the total number concentration or an optical aerosol spectrometer (OAS) for the number concentration and particle size distribution of particles larger than 0,1 µm to 0,3 µm, depending on the OAS-model. The reference instrument shall be calibrated according to ISO 27891 for CPCs or ISO 21501-1 for OAS. It shall be noted that the counting efficiency of CPCs for micron sized particles is often unknown and can be biased due to internal particle losses or the inappropriate application of a coincidence error correction algorithm.

To determine a sensor's particle size dependent detection efficiency in terms of the mass concentration, a reference instrument, capable of accurately determining the prevalent mass concentration is needed. Since the mass concentrations of the monodisperse particles will generally be too low to determine the reference mass concentration directly with a gravimetric mass measurement, such as gravimetric analysis of a filter sample or with a tapered element oscillating microbalance [19], it may only be calculated from the measurement of the particle number size distribution. In order to calculate the mass concentration from the number size distribution, the effective density ρ_{eff} of the particles shall be

known. In case of solid, spherical particles, the effective density equals the material density. For non-spherical particles, it can be determined, if the aerodynamic diameter d_{ae} and the mobility diameter d_{mob} of the particles are known [20] according to Formula (2):

$$\rho_{eff} = \rho_0 \cdot \left(\frac{d_{ae} \cdot C_c(d_{ae})}{d_{mob} \cdot C_c(d_{mob})} \right)^2 \quad (2)$$

where

ρ_{eff} is the effective particle density, in kg/m³;

ρ_0 is the unit density, in 1 000 kg/m³;

d_{ae} is the aerodynamic equivalent diameter, in m;

d_{mob} is the mobility equivalent diameter, in m;

C_c is the Cunningham slip correction factor.

C_c is used to describe the particle size dependent effect of the changing molecular momentum transfer onto particles on the drag force [21]. The aerodynamic and mobility diameter can e.g. be determined by classifying the particles first with an aerodynamic aerosol classifier before feeding them into the container and measuring the size distribution with a mobility particle size spectrometer (MPSS) [22] as reference instrument. Alternatively, the particles can be classified with a differential electrical mobility classifier (DEMC) [15] and the size distribution measured with an aerodynamic particle sizer (APS) [23] or a combination of an aerodynamic aerosol classifier with a condensation particle counter. These measurements can only deliver the effective density in the overlapping size ranges of the measurement devices and classifiers, which in some cases might not cover the size range of interest, e.g. to determine the lower detection limit.

Alternatively, an optical aerosol spectrometer may be used as reference instrument, if its mass concentration measurement has been properly calibrated for the specific test aerosol used for these experiments.

The results of these measurements are plotted as the detection efficiency η versus the particle diameter d_p . The lower particle size detection limit of a given aerosol measurement instrument is determined as the particle size d_{50} at which the instrument reaches a detection efficiency of 50 %. Figure 4 exemplarily shows hypothetic detection efficiency curves of three different sensor models as a function of the particle diameter d_p along with an assumed ideal detection efficiency curve of a sensor with a lower detection limit d_{50} at 0,3 μm and that reaches 100 % detection efficiency for all particles $\geq 0,5 \mu\text{m}$. The error bars represent the standard deviations of the results obtained from the tests with multiple sensors of the same type. In this graph, the results of sensor 1 agree very well with the ideal efficiency curve and the inter-specimen variation between the multiple sensors of this type is small. The shape of the results of sensor 2 is in principle similar to that of sensor 1, but the detection efficiency curve is shifted to larger particles with the d_{50} at 0,5 μm . The larger error bars further indicate that the variance among the results from multiple sensors of this type is larger than in case of sensor 1. The results of sensor 3 shows a much stronger particles size dependence and the shape of its detection efficiency curve differs much from the ideal curve. The detection efficiency shows a maximum of 200 % at a particle size of 1 μm , but then decreases and reaches nearly zero for particle sizes $\geq 5 \mu\text{m}$. Such behaviour may be caused by the loss of larger particles inside the sensor due to inertia or sedimentation and has been observed in practice (results from calibrations with monodisperse particles are provided in Annex B).