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Aerosol particle number concentration — Calibration of condensation particle counters

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National foreword

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Aerosol particle number concentration — Calibration of condensation particle counters

*Densité de particules d'aérosol — Étalonnage de compteurs de
particules d'aérosol à condensation*





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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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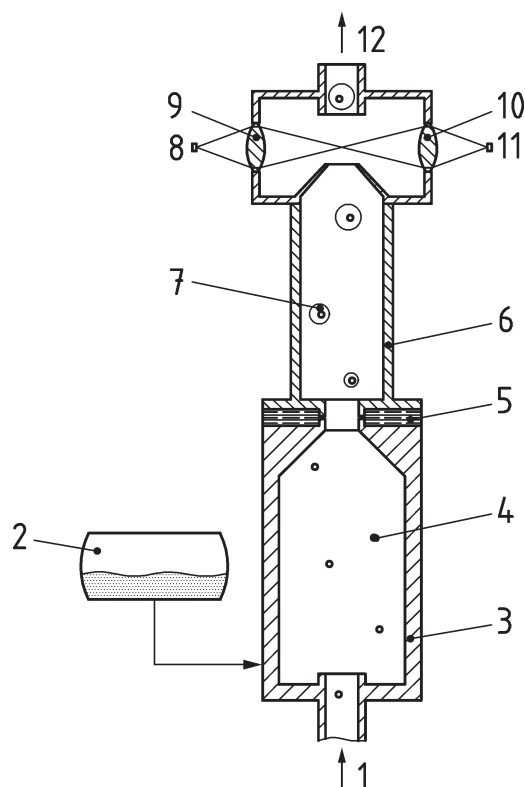
For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT), see the following URL: [Foreword — Supplementary information](#).

The committee responsible for this document is ISO/TC 24, *Particle characterization including sieving*, Subcommittee SC 4, *Particle characterization*.

Introduction

A condensation particle counter (CPC) is a measuring device for the number concentration of small aerosol particles. The common principle of all different CPC types is that condensation of supersaturated vapours is used to grow ultra-fine and nanoparticles to droplets of sizes that can be detected optically. [44] The counting of the droplets is performed via optical light scattering. The droplet passes through a detection area where it is illuminated by a focused light beam and a portion of the scattered light is detected with a photodetector. The frequency of this event leads, with the known volume of sampled air, to the particle number concentration. At low concentrations, the CPC counts individual particles and allows an absolute determination of particle number concentration.

Commercially available CPCs employ different working fluids to generate the vapour, e.g. 1-butanol, 2-propanol, or water. Moreover, different principles are in use to achieve the needed supersaturation in the sample air. The most common CPC uses laminar flow and diffusional heat transfer. The diffusion constant of the working fluid determines the needed heating or cooling steps to initiate condensation and hence, the principle design of a laminar flow CPC. Less common are turbulent mixing CPCs: in these CPCs, the supersaturation is achieved by turbulently mixing the sample air with a particle free gas flow saturated with the working fluid. Figure 1 shows a schematic of the probably most common CPC type with a laminar flow through a heated saturator and a cooled condenser.



Key

- | | |
|---|-----------------------|
| 1 aerosol inlet | 7 droplet |
| 2 working fluid reservoir | 8 light source |
| 3 heated saturator | 9 illumination optics |
| 4 nanoparticle | 10 receiving optics |
| 5 thermoelectric cooling and heating device | 11 photodetector |
| 6 condenser | 12 aerosol outlet |

Figure 1 — Principle of a laminar flow CPC

The accuracy of CPC measurements, however, depends on various influences. For example, if the flow rate had an error, the concentration would have an error. Coincidence error at very high concentration, inefficient activation of particle growth at very small sizes, and losses of particles during transport from the inlet to the detection section are other possible sources of errors. For accurate measurement, the CPC shall be calibrated.

“Calibration” of the CPC is usually done using a Faraday-cup aerosol electrometer (FCAE) as reference instrument.^{[33][36]} In many cases, the purpose of the “calibration” is to determine the limit of particle detection at very small size. The FCAE has been used as the reference since the detection efficiency of the FCAE was considered to be unity at any size. The detection efficiency of a CPC is determined as the ratio of the concentration indicated by the CPC under calibration to that by the FCAE, while aerosols of singly charged, size-classified particles of the same number concentration are supplied simultaneously to both instruments.

This International Standard sets out two distinct methods of CPC calibration: the characterization of a CPC by comparison with an FCAE, which is the same as the traditional approach described above; and by comparison with a reference CPC. An FCAE that has a reputable calibration certificate, covering the relevant particle number concentrations, sizes, and composition, can be used. In the latter case, the reference CPC is one that has a reputable calibration certificate, again covering the relevant particle number concentrations, sizes, and composition. A reputable calibration certificate shall mean either one that has been produced by a laboratory accredited to ISO/IEC 17025 or an equivalent standard, where the type and range of calibration is within the laboratory’s accredited scope, or a European Designated Institute or a National Metrology Institute that offers the relevant calibration service and whose measurements fulfil the requirements of ISO/IEC 17025.

Two major sources of errors are known in CPC calibration: the presence of multiply charged particles and the bias of the particle concentrations between the inlet of the CPC under calibration and that of the reference instrument. Evaluation of these factors and corrections for them shall be included in the calibration procedure, the methods of which are specified in this International Standard.

This International Standard is aimed at

- users of CPCs (e.g. for environmental or vehicle emissions purposes) who have internal calibration programmes,
- CPC manufacturers who certify and recertify the performance of their instruments, and
- technical laboratories who offer the calibration of CPCs as a service, which can include National Metrology Institutes who are setting up national facilities to support number concentration measurements.

Aerosol particle number concentration — Calibration of condensation particle counters

1 Scope

This International Standard describes methods to determine the detection efficiency of condensation particle counters (CPCs) at particle number concentrations ranging between 1 cm^{-3} and 10^5 cm^{-3} , together with the associated measurement uncertainty. In general, the detection efficiency will depend on the particle number concentration, the particle size, and the particle composition. The particle sizes covered by the methods described in this International Standard range from approximately 5 nm to 1 000 nm.

The methods can therefore be used both to determine a CPC calibration factor to be applied across the range of larger particle sizes where the detection efficiency is relatively constant (the plateau efficiency), and to characterize the drop in CPC detection efficiency at small particle sizes, near the lower detection limit. These parameters are described in more detail in [Annex A](#).

The methods are suitable for CPCs whose inlet flows are between approximately 0,1 l/min and 5 l/min.

This International Standard describes a method for estimating the uncertainty of a CPC calibration performed according to this International Standard.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 15900, *Determination of particle size distribution — Differential electrical mobility analysis for aerosol particles*

3 Terms and definitions

For the purpose of this document, the following terms and definitions apply.

3.1

aerosol

system of solid or liquid particles suspended in gas

3.2

bipolar charger

particle charge conditioner to attain the equilibrium, known size-dependent charge distribution by exposing aerosol particles to both positive and negative ions within the device

Note 1 to entry: Exposing aerosol particles to an electrically neutral cloud of positive and negative gas charges with sufficiently high charge concentration and for a sufficiently long period of time leads to an equilibrium with the net charge of the aerosol nearly zero (also known as charge neutralization).

3.3 calibration

operation that, under specified conditions, in a first step, establishes 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

Note 1 to entry: A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.

Note 2 to entry: Calibration should not be confused with adjustment of a measuring system, often mistakenly called "self-calibration", nor with verification of calibration.

Note 3 to entry: Often, the first step alone in the above definition is perceived as being calibration.

[SOURCE: ISO/IEC Guide 99]

3.4 calibration aerosol

charge conditioned and size classified primary aerosol with particle number concentration adjusted for the calibration measurement, as delivered by the flow splitter

3.5 calibration particle material

material of the particles of the calibration aerosol

3.6 charge concentration

concentration of the net electrical charges per unit volume

Note 1 to entry: Charge concentration is the measurand of the FCAE.

Note 2 to entry: FCAE measurement can be displayed as charge concentration, C_Q , (e.g. in fC/cm³), charge number concentration, C_N^* , (e.g. in cm⁻³) or electrical current, I_{FCAE} , (e.g. in fA). Using the elementary charge, e , and the volumetric FCAE inlet flow rate, q_{FCAE} , these displayed values are related as follows:

$$C_N^* = C_Q / e = I_{FCAE} / (q_{FCAE} \times e)$$

EXAMPLE A charge concentration of 1 fC/cm³ corresponds to a charge number concentration of 6241 cm⁻³. When the volumetric FCAE inlet flow rate is 1 l/min, the resulting electrical current is 16,67 fA.

3.7 charge conditioning

process that establishes a steady state charge distribution on the sampled aerosol

3.8 coefficient of variation CV

ratio of the standard deviation to the arithmetic mean value

3.9 coincidence error

probability of the presence of more than one particles inside the sensing zone simultaneously

Note 1 to entry: Coincidence error is related to particle number concentration, flow velocity through the sensing zone and size of sensing zone.

3.10 **condensation particle counter** **CPC**

instrument that measures the particle number concentration of an aerosol

Note 1 to entry: The sizes of particles detected are usually smaller than several hundred nanometres and larger than a few nanometres.

Note 2 to entry: In some cases, a CPC may be called a condensation nucleus counter (CNC).

Note 3 to entry: The CPC used as the reference instrument is called the “reference CPC” throughout this International Standard.

Note 4 to entry: The CPC under calibration is called the “test CPC” throughout this International Standard.

[SOURCE: ISO 15900:2009, modified]

3.11 **detection efficiency**

η

ratio of the concentration reported by an instrument to the actual concentration at the inlet of the instrument

3.12 **differential electrical mobility classifier** **DEMC**

classifier that is able to select aerosol particles according to their electrical mobility and pass them to its exit

Note 1 to entry: A DEMC classifies aerosol particles by balancing the electrical force on each particle with its aerodynamic drag force in an electrical field. Classified particles are in a narrow range of electrical mobility determined by the operating conditions and physical dimensions of the DEMC. Classified particles can have different sizes due to difference in the number of charges that they have.

[SOURCE: ISO 15900:2009, modified]

3.13 **differential mobility analyzing system** **DMAS**

system to measure the size distribution of submicrometre aerosol particles consisting of a pre-conditioner, particle charge conditioner, DEMC, flow meters, a particle detector, interconnecting plumbing, a computer, and software suitable for size-distribution calculation

[SOURCE: ISO 15900:2009, modified]

3.14 **diffusion loss**

reduction of particle number concentration due to thermal (or Brownian) and turbulent diffusion transport (e.g. to the walls of a transport tube)

3.15 **electrometer**

device that measures electrical current of about 1 femtoampere (fA) and higher

[SOURCE: ISO 15900:2009, modified]

3.16 **equivalent particle diameter**

d

equivalent diameter of the sphere with defined characteristics which behaves under defined conditions in exactly the same way as the particle being described

Note 1 to entry: Particle diameter (or simply diameter) used throughout this International Standard always refers to the electrical mobility equivalent diameter, which defines the size of charged particles with the same electrical mobility or the same terminal migration velocity in still air under the influence of a constant electric field.

3.17

Faraday-cup aerosol electrometer

FCAE

electrometer designed for the measurement of electrical charge concentration carried by an aerosol

Note 1 to entry: An FCAE consists of an electrically conducting and electrically grounded cup as a guard to cover the sensing element that includes aerosol filtering media to capture charged aerosol particles, an electrical connection between the sensing element and an electrometer circuit, and a flow meter.

[SOURCE: ISO 15900:2009, modified]

3.18

flow rate

quantity (volume or mass to be specified) of a fluid crossing the transverse plane of a flow path per unit time

Note 1 to entry: For the exact flow rate indication of gases, information on the gaseous condition (temperature and pressure) or the reference to a standard volume indication is necessary.

3.19

GSD

acronym used in this International Standard for geometric standard deviation

3.20

laminar flow

gas flow with no temporally or spatially irregular activity or turbulent eddy flow

3.21

lower limit of the plateau efficiency

$d_{\min, \text{ref}}$

lower size limit for which a reference CPC can be applied for the calibration of a test CPC

Note 1 to entry: This size limit depends on the CPC itself, but also to some extent on experimental conditions and on the particle type.

3.22

monodisperse aerosol

aerosol with a narrow particle size distribution

Note 1 to entry: Monodispersity can be quantified by the geometric standard deviation (GSD) of the size distribution.

Note 2 to entry: In this International Standard, the term “monodisperse” is used for the GSD less than or equal to 1,15.

3.23

particle

piece of matter with defined physical boundary

Note 1 to entry: The phase of a particle can be solid, liquid, or between solid and liquid and a mixture of any of the phases.

3.24

particle charge conditioner

device used for charge conditioning

3.25

particle number concentration

C

number of particles related to the unit volume of the carrier gas

Note 1 to entry: For the exact particle number concentration indication, information on the gaseous condition (temperature and pressure) or the reference to a standard volume indication is necessary.

3.26**particle type**

several particle properties like chemical composition of the particle material (especially chemical surface composition), physical particle shape and morphology (e.g. an agglomerate or aggregate)

Note 1 to entry: The CPC detection efficiency at low particle sizes will depend on the chemical affinity between the particle and the working fluid (see [Annex B](#)).

Note 2 to entry: Much of the underlying theory assumes that the particles are solid spheres. Non-sphericity can affect the size selection by the DEMC, the fraction of multiply charged particles, and the condensation of working fluid on the particle surface.

3.27**plateau efficiency**

mean detection efficiency of a CPC in the size range which is not biased by particle size

3.28**primary aerosol**

aerosol generated and conditioned in the primary aerosol source section of the calibration setup

3.29**single particle counting mode**

measurement mode of a particle number or number concentration measurement device (e.g. a CPC) in which every detected particle is counted to obtain the measurement result

3.30**size distribution**

distribution of particle concentration as a function of particle size

Note 1 to entry: In this International Standard, this term is used in the sense “particle number concentration represented as function of the particle diameter”.

Note 2 to entry: ISO 9276-1 can be applied for the representation of results of particle size distribution analysis.

3.31**turbulent flow**

gas flow with temporally or spatially irregular activity or turbulent eddy flow

3.32**unipolar charger**

particle charge conditioner that expose aerosol particles to either positive or negative ions within the device

4 Symbols

For the purpose of this International Standard, the following symbols and abbreviated terms apply. Units are in accordance with Reference [\[15\]](#).

Symbol	Quantity	Unit	Used in
C_N	total number concentration of particles out of the DEMC	cm ⁻³	6.3.5 e) 7.3.5 c)
$C_N(d_p)$	number concentration of particles out of the DEMC of equivalent particle diameter d and with p charges	cm ⁻³	6.3.3 c) 7.3.3 c)
C_N^*	charge number concentration	cm ⁻³	3.6 NOTE 2
$C_{N,CPC}$	indicated particle number concentration measured by the test CPC	cm ⁻³	5.1
$C_{N,CPC,i}$	i -th indicated number concentration measured by the test CPC when measuring particles	cm ⁻³	6.3.5 b) 7.3.5 a)

Symbol	Quantity	Unit	Used in
$C_{N,CPC,ref,i}$	i -th indicated number concentration measured by the reference CPC when measuring particles	cm ⁻³	7.3.5 a)
$C_{N,FCAE,i}$	i -th calculated number concentration of the calibration aerosol	cm ⁻³	6.3.5 d)
$C_{N,ref}$	indicated particle number concentration measured by the reference instrument	cm ⁻³	5.1
C_Q	indicated charge concentration measured by FCAE when measuring particles	C cm ⁻³	3.6 NOTE 2
$C_{Q,i}$	i -th indicated charge concentration measured by FCAE when measuring particles	C cm ⁻³	6.3.5 a), c)
$C_{Q,0,i}$	i -th indicated charge concentration measured by FCAE when the DEMC voltage set at zero	C cm ⁻³	6.3.5 a), c)
d	equivalent particle diameter	nm	3.16
$d_{min,ref}$	lower size limit for which a reference CPC can be applied for the calibration of a test CPC	nm	3.21 5.4.6 b) 5.5 a)
e	elementary charge = $1,602\,177 \times 10^{-19}$ C	C	3.6 NOTE 2
I_{FCAE}	electrical current	fA	3.6 NOTE 2
k	coverage factor	(dimensionless)	6.4.3 7.4.3
$N_{ambient}$	number of particle counts over 1 min without a HEPA filter	(dimensionless)	6.2.5 a) 2)
N_{FCAE}	number of particle counts over 1 min through the FCAE filter	(dimensionless)	6.2.5 a) 5)
N_{HEPA}	number of particle counts over 1 min with a HEPA filter	(dimensionless)	6.2.5 a) 1)
N_{leak}	= $N_{FCAE} - N_{HEPA}$	(dimensionless)	6.2.5 a) 6)
p	number of net charges on a particle	(dimensionless)	5.1
$q_{CPC,amb}$	inlet flow rate indicated by the test CPC or the nominal inlet flow rate of the test CPC	l min ⁻¹	6.2.6 c) 7.2.6 e)
$q_{CPC,cal,amb}$	inlet flow rate of the test CPC measured with a calibrated flow meter	l min ⁻¹	6.2.6 c) 7.2.6 e)
$q_{CPC,ref}$	inlet flow rate indicated by the reference CPC or the nominal inlet flow rate of the reference CPC	l min ⁻¹	7.2.7 b)
$q_{CPC,ref,cal}$	inlet flow rate of the reference CPC measured with a calibrated flow meter	l min ⁻¹	7.2.7 b)
$q_{CPC,ref,-cal,amb}$	inlet flow rate of the reference CPC measured with a calibrated flow meter	l min ⁻¹	7.2.5 c)
$q_{CPC,ref,amb}$	inlet flow rate indicated by the reference CPC or the nominal inlet flow rate of the reference CPC	l min ⁻¹	7.2.5 c)
$q_{CPC,ref,cert}$	inlet flow rate of the reference CPC in the calibration certificate	l min ⁻¹	7.2.5 b)
q_{FCAE}	inlet flow rate indicated by the FCAE or the nominal inlet flow rate of the FCAE	l min ⁻¹	3.6 NOTE 2 6.2.7 b)
$q_{FCAE,amb}$	inlet flow rate indicated by the FCAE or the nominal inlet flow rate of the FCAE	l min ⁻¹	6.2.5 c)
$q_{FCAE,cal}$	inlet flow rate of the FCAE measured with a calibrated flow meter	l min ⁻¹	6.2.7 b)
$q_{FCAE,cal,amb}$	inlet flow rate of the FCAE measured with a calibrated flow meter	l min ⁻¹	6.2.5 c)
$q_{FCAE,cert}$	inlet flow rate of the FCAE in the calibration certificate	l min ⁻¹	6.2.5 c)

Symbol	Quantity	Unit	Used in
R_{FCAE}	$= N_{\text{leak}}/N_{\text{ambient}}$	(dimensionless)	6.2.5 a) 7)
$r_{q,\text{CPC,ref}}$	accuracy of the inlet flow rate of the reference CPC specified by the manufacturer	l min^{-1}	7.2.5 c)
$r_{q,\text{FCAE}}$	accuracy of the inlet flow rate of the FCAE specified by the manufacturer	l min^{-1}	6.2.5 c)
$U(\eta)$	expanded uncertainty for η	(dimensionless)	6.4.3 7.4.3
$U_r(\eta)$	relative expanded uncertainty for η	(dimensionless)	6.4.3 7.4.3
$u_r(q_{\text{cal,cert}})$	relative standard uncertainty of the flow meter	(dimensionless)	6.2.5 c) 7.2.5 e)
$u_r(q_{\text{CPC,ref}})$	relative standard uncertainty for the inlet flow of the reference CPC	(dimensionless)	7.2.7 b) 7.4.3
$u_r(q_{\text{CPC,ref,cert}})$	relative standard uncertainty for the inlet flow of the reference CPC in the calibration certificate	(dimensionless)	7.2.5 c)
$u_r(q_{\text{FCAE}})$	relative standard uncertainty for the inlet flow of the FCAE	(dimensionless)	6.2.7 b) 6.4.3
$u_r(q_{\text{FCAE,cert}})$	relative standard uncertainty for the inlet flow of the FCAE in the calibration certificate	(dimensionless)	6.2.5 c)
$u(1)$	standard uncertainty for ϕ_1	(dimensionless)	6.4.3
$u(2)$	standard uncertainty for ϕ_2	(dimensionless)	6.4.3
$u(3)$	standard uncertainty for ϕ_3	(dimensionless)	6.4.3
$u_{c,r}(\eta)$	relative combined standard uncertainty for η	(dimensionless)	6.4.3 7.4.3
$u_r(\text{FCAE})$	relative standard uncertainty for the FCAE detection efficiency	(dimensionless)	6.4.3
$u_r(\text{MCC})$	relative standard uncertainty for multiple-charge correction	(dimensionless)	6.4.3
$u_r(\text{RCPC})$	relative standard uncertainty for the reference CPC detection efficiency	(dimensionless)	7.4.3
$u_r(\beta)$	relative standard uncertainty for β	(dimensionless)	6.4.3 7.4.3
$u_r(\eta_{\text{rep}})$	relative standard uncertainty for repeatability	(dimensionless)	6.4.3 7.4.3
β	concentration bias correction factor for flow splitter	(dimensionless)	5.1 6.3.4 7.3.4
η	detection efficiency	(dimensionless)	3.11
η_{CPC}	detection efficiency of the test CPC	(dimensionless)	5.1
η'_{CPC}	estimated plateau efficiency of the test CPC	(dimensionless)	6.3.5 e) 7.3.5 e)
$\eta_{\text{CPC},i}$	i -th detection efficiency of the test CPC	(dimensionless)	6.3.5 e) 7.3.5 e)
$\eta_{\text{CPC,ref}}$	detection efficiency of the reference CPC	(dimensionless)	7.3.5 c)
$\bar{\eta}_{\text{CPC}}$	arithmetic mean detection efficiency of the test CPC	(dimensionless)	6.3.5 f) 7.3.5 d)
η_{FCAE}	detection efficiency of the FCAE	(dimensionless)	6.3.5 e)
η_{ref}	detection efficiency of the reference instrument	(dimensionless)	5.1

Symbol	Quantity	Unit	Used in
$\sigma(\eta_{\text{rep}})$	standard deviation for the repeated measurements of the detection efficiency of the test CPC	(dimensionless)	6.3.5 f) 7.3.5 d)
Φ	fraction of multiply charged particles	(dimensionless)	5.5 b) 6.3.3 c) 7.3.3 c)
ϕ_p	fraction of particles with p charges	(dimensionless)	5.1 6.3.3 c) 7.3.3 c)

5 Calibration using reference instruments — General principles

5.1 General principles

This Clause describes general aspects of CPC calibration using traceable reference instruments, while the subsequent [Clauses 6](#) and [7](#) refer to specific aspects of FCAE and CPC as reference instruments, respectively.

The reference instruments shall have an up-to-date reputable calibration certificate specifying the particle type, the particle sizes, and the particle number concentration range which was used for its calibration. Volumetric inlet flow rate, inlet pressure and inlet temperature at the time of calibration shall also be specified. A reputable calibration certificate shall mean either one that has been produced by a laboratory accredited to ISO/IEC 17025 or an equivalent standard, where the type and range of calibration is within the laboratory's accredited scope, or a European Designated Institute or a National Metrology Institute that offers the relevant calibration service and whose measurements fulfil the requirements of ISO/IEC 17025. Examples of calibration certificates are given in [Annex C](#).

The result of a calibration will be the particle detection efficiency for an individual CPC instrument with specified operating parameters, and for specific cases of

- particle size,
- particle type, and
- particle number concentration.

In CPC single particle counting mode, the detection efficiency is often expressed as a single figure (with uncertainty) over a range of concentrations, i.e. a single factor applies. In other modes, or over wider concentration ranges, more complicated relationships between detection efficiency and particle number concentration may be appropriate ([Annex A](#)). The calculations of the detection efficiency and its uncertainty are described in [Clauses 6](#) and [7](#) and follow the general formula

$$\eta_{\text{CPC}} = \frac{C_{N,\text{CPC}}}{C_{N,\text{ref}}} \cdot \eta_{\text{ref}} \cdot \beta \cdot \sum_p \phi_p \cdot p \quad (1)$$

where

- $C_{N,\text{CPC}}$ is the indicated concentration of the test CPC (i.e. the CPC being calibrated);
- $C_{N,\text{ref}}$ is the concentration of the reference instrument;
- η_{ref} is the efficiency of the reference instrument; and
- β is the concentration bias from the flow splitter.

The summing term in Formula (1) is only used if the reference instrument is an FCAE. ϕ_p is the fraction of particles having p charges [see also Formula (6)].

5.2 Objectives for the calibration aerosol

The role of many of the components described in subsequent clauses is to modify the output of a primary aerosol into a form suitable for the calibration. The calibration aerosol should have the following:

- a narrow size distribution, so that the size of the particles is well defined (typically GSD <1,1 for the primary peak in the size distribution), to minimize uncertainty in size and efficiency;
- stable mode diameter, and stable number concentration in relation to the required time for calibration (typically 10 min), so that the calibration can take place in essentially constant conditions;
- a small fraction of multiply charged particles (typically <5 %), because these become a significant component of the uncertainty for FCAE calibrations, and in both cases they form extra populations of particles at unwanted larger sizes (see [Annex D](#));
- a low vapour content (from water, other dispersion media and/or solvents), to minimize the growth of particles within the system;
- a stable and reproducible gas phase and particle type.

A CPC calibration certificate is only applicable for the calibration aerosol that is described in the calibration certificate, especially at low particle size.

5.3 Setup overview

A primary aerosol source and a DEMC are used to deliver monodisperse calibration aerosols of known size, electrostatic charge and composition. A traceable reference instrument and the test CPC sample this aerosol in parallel downstream of the DEMC. Either an FCAE or a reference CPC is used as traceable reference instrument. [Figure 2](#) shows the schematic setup of the components necessary. A temperature controlled box and heat exchangers for all important air flows may be used in this setup as an option to stabilize all temperatures.

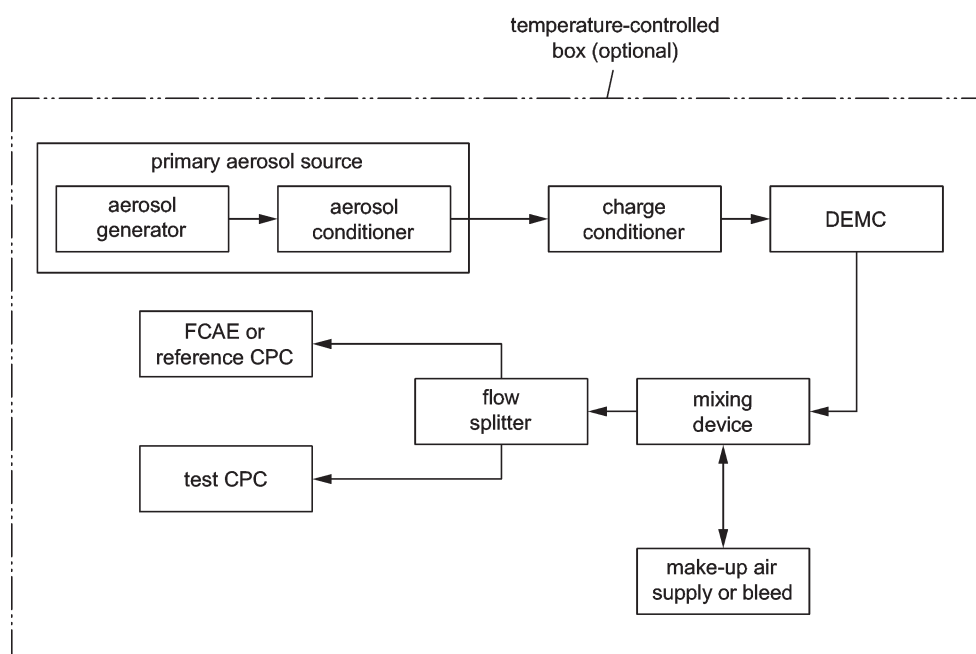


Figure 2 — Schematic calibration setup

In order that results of CPC calibration that is performed according to this International Standard are regarded traceable to national standards, instruments used in the calibration, including the FCAE and reference CPC, shall be calibrated with metrological traceability to international or national standards.

The figures in [Annex E](#) illustrate the metrological traceability chains for quantities that are influential to results of calibration of a CPC.

5.4 Components and their requirements

5.4.1 Primary aerosol source

5.4.1.1 General

The primary aerosol source consists of an aerosol generator and an aerosol conditioner to provide calibration particles in a stable particle type and adequate number concentration.

The stability of flow rate, number concentration and size distribution shall be such that the requirements for the calibration aerosol (see [5.2](#)) are fulfilled.

A narrow primary aerosol source particle size distribution is recommended for particles larger than 20 nm since this minimizes larger, multiply charged particles in the calibration aerosol; it is less important for smaller particles due to their lower probability of multiple charging. This recommendation is valid for both reference instruments, FCAE and CPC.

5.4.1.2 Aerosol generator

The suitability of a generator type depends on the required calibration particle material. Examples for combinations of aerosol generators and calibration particle materials are:

- a) Arc-plasma generator for metal, metal oxide or carbon particles;[\[6\]](#)[\[7\]](#)
- b) Electrospray aerosol generator for oil droplets, poly-alpha-olefin (PAO) droplets, or sucrose particles;[\[16\]](#)
- c) Evaporation condensation aerosol generator[\[5\]](#)[\[10\]](#)[\[51\]](#)[\[53\]](#) for metallic particles like Ag, Au and salt particles like NaCl, KCl, ammonium nitrate, etc.;
- d) Quenched flame aerosol generator for flame soot particles;[\[32\]](#)[\[56\]](#)
- e) Spray atomizer generators for solutions and dispersions;[\[19\]](#)[\[43\]](#)
- f) Glowing wire generator for uniformly sized metal or metal oxide particles.[\[49\]](#)

In addition, the single charged aerosol reference (SCAR) is used for generating singly charged particles over a wide size range.[\[60\]](#)

5.4.1.3 Aerosol conditioner

The aerosol conditioner is used to control the state of the calibration particle material. Which of the following conditioning steps are necessary depends on the chosen aerosol generation method and calibration particle type.

- a) Adapting the primary aerosol number concentration and aerosol flow rate to an appropriate level for reliable charge conditioning ([Annex K](#)). For aerosol dilution setups see [Annex F](#).
- b) Pre-classifying the primary aerosol particles using an additional charge conditioner and DEMC for example if the particle size distribution of the primary aerosol source has too large a fraction of multiply charged particles.[\[57\]](#)
- c) The vapour contents (from water, other dispersion media and/or solvents) in the primary aerosol shall be less than 40 % of the saturated value. High vapour contents in the primary aerosol can lead to condensational growth of the calibration particles, change the equilibrium charge distribution after the bipolar charger, and build-up vapour in the sheath flow loop of the DEMC. This can be achieved by dilution with dry air or vapour adsorption (e.g. with silica gel, zeolites or calcium chloride).

5.4.2 Charge conditioner

In order to achieve a stable, repeatable and reproducible calibration aerosol after the electrostatic size classification in the DEMC, the conditioned primary aerosol entering the DEMC shall have a stable, repeatable and reproducible charge distribution. Unipolar and bipolar chargers produce the ion concentration required to stabilize the charge distribution of the primary aerosol (see e.g. ISO 15900).

Sources with alpha or beta radiation can be used as bipolar chargers. If under appropriate operating conditions the equilibrium charge level is established, the charge distribution according to ISO 15900 shall be applied. Other bipolar chargers may be used if the equivalence to radioactive sources has been proven or the charge distribution has been fully characterized.

For primary aerosol with a mode size larger than 20 nm or with a non-monodisperse size distribution bipolar chargers shall be used. In these cases the equilibrium charge distribution has (compared to a unipolar charger) a significantly lower fraction of multiply charged particles.

If the primary aerosol is already monodisperse or if the primary aerosol does not contain particles larger than 20 nm, all calibration aerosol particles leaving the DEMC are singly charged no matter which type of charge conditioner is used upstream the DEMC. Therefore, in this case, unipolar (e.g. corona discharge device) or bipolar chargers may be used.

NOTE The SCAR^[60] is an exception because it already generates singly charged particles over a wide size range.

5.4.3 DEMC

The DEMC classifies the conditioned primary aerosol particles based on their electrical mobility. It delivers calibration aerosols in a narrow mobility band, either positively or negatively charged. If classified particles carry more than one electrical charge, each charge level corresponds to a different particle size.

The DEMC shall be set up, operated, and calibrated according to ISO 15900.

Ideally, the primary aerosol fed into the DEMC is conditioned in such a way that only singly charged particles leave the DEMC to be used as calibration aerosol. In this case, the calibration aerosol is monodisperse.

If, due to the nature of the conditioned primary aerosol, the calibration aerosol also contains larger, multiply charged particles, corrections shall be applied and the measurement uncertainty may increase. Details about the necessary corrections are given in [Annex D](#).

5.4.4 Make-up or bleed air

Additional make-up air is necessary if the calibration aerosol flow from the DEMC is lower than the sum of the flow rates required by the test CPC and the reference instrument.

The make-up air shall be practically particle free; the particle number concentration should be less than $0,1 \text{ cm}^{-3}$. This can be achieved with a HEPA filter with 99,995 % efficiency (or better).

The relative humidity of the make-up air shall be less than 40 %.

To avoid excessive variations in the number concentration of the calibration aerosol the make-up air flow shall be kept sufficiently stable.

If the calibration aerosol flow from the DEMC is higher than the sum of the flow rates required by the test CPC and the reference instrument, the excess air should be vented off as bleed flow. In this case, the operator should be protected from particle exposure by an exhaust particle filter.

5.4.5 Mixing device, flow splitter and connection tubing

The mixing device, flow splitter, and connecting tubing deliver the calibration aerosol to the test CPC and the reference instrument. The aerosol should have identical size distribution and number concentration when it reaches both instruments.

Concentration bias resulting from poor mixing is a major source of error in CPC calibration. Baffle plates, mixing chambers, and mixing orifices are examples for proven devices to avoid this bias.

The flow splitter divides the calibration aerosol flow coming from the mixing device into two flows, one to the test CPC and one to the reference instrument. Ideally, the flow splitter and the connection tubing are designed in such a way that the particle size dependent transport losses from the inlet of the flow splitter to both instruments are equal.

If the inlet flow rate of both instruments is equal, exchanging the position of the test CPC and the reference instrument can be used to demonstrate the equivalence of both sampling positions (see [Annex G](#)). The differences from each position shall be less than 5 %. The bias correction factor β represents the particle-loss compensated calibration result.

If the inlet flow rate of both instruments cannot be operated at the same flow rate, the length of the connection tubing shall be used to compensate the difference in the transfer losses. The ratio of the different inlet flow rates shall not be larger than 5 or smaller than 0,2. A calibration setup with such different inlet flows does not allow evaluating experimentally transport losses by exchanging the instrument positions. Therefore the uncertainty of measurement is increased by the uncertainty of each flow rate.

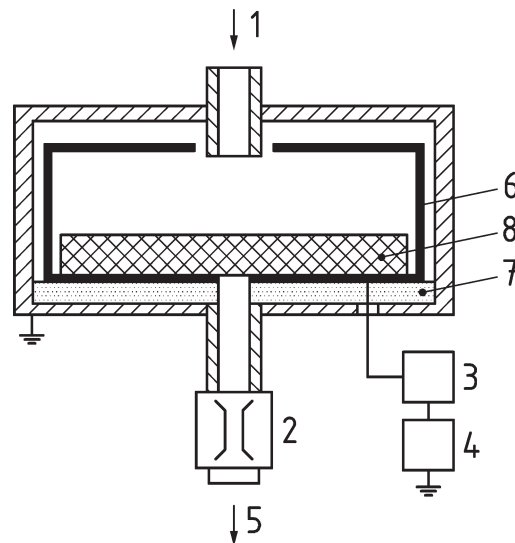
The design of the mixing device, the flow splitter, and the connection tubing shall follow good engineering practices, such as avoiding bends, avoiding sudden change of tubing diameters. Use conductive tubing and provide sufficient electrical grounding for all connections, especially for flexible tubing if it cannot be avoided.

5.4.6 Reference instrument: FCAE or CPC

a) Design and operation of an FCAE

The FCAE consists of an electrically conducting and electrically grounded cup as a guard to cover the sensing element that includes aerosol filtering media to capture aerosol particles, an electrical connection between the sensing element and an electrometer circuit, and a flow meter, as shown in [Figure 3](#).

NOTE The efficiencies for an FCAE are expected to be greater than 95 % for particles covered by this International Standard (>5 nm) and FCAE flow rates greater than 1 l/min.



Key

- 1 charged particles
- 2 flow meter
- 3 preamplifier
- 4 electrometer
- 5 particle-free air
- 6 Faraday cup to collect electrical charge from charged collected particles and to reduce externally-induced electro-magnetic noise
- 7 very-high-resistance electrical insulator to isolate the filter from electrical ground
- 8 high-efficiency particulate air (HEPA) filter to trap airborne charged particles

Figure 3 — Schematic diagram of an FCAE (Adapted from ISO 15900)

b) Design and operation of a reference CPC

The reference CPC shall have a design such that particles in the entire aerosol flow entering the inlet are counted. That is, the aerosol flow sampled through the inlet shall not be diluted or filtered and the total inlet flow shall be led to the optics.

The concentration range for single particle counting mode shall be established from the manufacturer's specifications. The reference CPC shall not be used in photometric mode.

The lower size limit $d_{\min, \text{ref}}$ for the application of the reference CPC for calibration of test CPCs is the smallest value of at least three diameters, the two larger diameters are at least 2 and 3 times $d_{\min, \text{ref}}$. The three respective efficiency values may not differ more than 5 % from the largest of the three efficiency values. The detection efficiency of the reference CPC shall be documented for the relevant particle type in such a way that its $d_{\min, \text{ref}}$ is determined or can be derived from the documented detection efficiencies.

c) Certificates for FCAE and reference CPC

The reference instrument shall have a current, reputable calibration certificate as defined in 5.1. Examples of calibration certificates are given in Annex C.

The calibration certificate for the FCAE shall specify the aerosol flow rate measurement (volumetric flow rate, inlet pressure and inlet temperature) and the electrical charge concentration measurement. The product of charge concentration times aerosol flow rate is typically in the range from 1 fC/s to 10 fC/s.

The calibration certificate for the reference CPC can be the result of either a calibration against a traceable FCAE, or a calibration with another CPC used as a reference instrument. It shall specify the particle type, the particle sizes, the particle number concentrations for which the calibration is valid, and the maximum concentration of the reference CPC in single counting mode. Volumetric inlet flow rate, inlet pressure and inlet temperature at the time of calibration shall also be specified.

The reference instrument detection efficiency can change when internal surfaces become loaded with particles. In addition to the certificate being within its specified time period, the reference instrument shall have had limited accumulated exposure to such particles since calibration. The use of the reference instrument shall therefore be logged, and internal procedures shall be set up to ensure that the accumulated exposure to particles since calibration does not significantly affect the performance of the reference instrument.

The reference instrument shall be recertified

- after maintenance or repair,
- after detection of significant drift in the reference instrument, through QA/QC procedures set up by the user,
- after accumulated exposure to particles reaches a predefined level, to be established by the user, or
- if a period of 3 years has passed since the last certification.

5.4.7 Other tools

The following additional sensors are used for CPC calibration and shall be calibrated using reference instruments that deliver results that are traceable to internationally accepted standards:

- low pressure drop flow meter for checking and setting instrument and calibration flows;
- pressure sensor for measuring the pressure of the calibration aerosol;
- gas temperature sensors for measuring several temperatures;
- humidity sensor is necessary to measure the relative humidity of the primary aerosol.

5.5 Differences between FCAE and CPC as a reference instrument

As a reference instrument FCAE and CPC have different capabilities and demand different requirements. This subclause describes the differences in order to choose the appropriate method for the specific purpose.

a) Lower size detection limits

In general an FCAE can detect charged particles smaller than the particles detected by a CPC. Furthermore, the efficiency curve of the CPC depends to some extent on the details of experimental conditions and particle type. Therefore, a reference CPC shall only be used for the calibration with monodisperse particles with diameters larger than $d_{\min, \text{ref}}$ of the reference CPC. For calibration with particles with broader size distributions, it shall be avoided that significant numbers of the test particles have a size similar to or smaller than $d_{\min, \text{ref}}$ of the reference CPC. Therefore, the median diameter of a polydisperse test aerosol shall be larger than or equal to $d_{\min, \text{ref}}$ times the geometric standard deviation of the size distribution of the test aerosol.

b) Particle charging

For an FCAE comparison, the calibration aerosol needs to consist of singly charged particles, or at least have a known charge distribution with a small fraction of multiply charged particles. This requirement also applies for a reference CPC comparison at the lower size detection limit of a test CPC, since particles with multiple charges have a larger diameter and are counted with a higher efficiency. For a reference CPC comparison at larger particle diameters in the plateau region of the test CPC, this particular

requirement does not apply. Therefore, the use of a reference CPC for calibration with larger particles can result in smaller uncertainties, as their higher probability of multiple charging is less important.

c) Low calibration aerosol particle number concentration

For an FCAE comparison, there is a minimum requirement for the number concentration of charged particles exiting the DEMC (typically about 10^3 cm^{-3}) to provide sufficient charge concentration to the electrometer. This is not needed for a reference CPC comparison if the linearity of the reference CPC is proven.^[44] A method demonstrating validation at lower concentrations than those on the reference instrument certificate is described in [Annex H](#).

d) High calibration aerosol particle number concentration

An FCAE will cover its specified range of particle concentrations using one principle — determining the electrical charge concentration. A CPC can have two or more fundamentally different measurement modes, starting with a simple optical counting mode (single particle counting mode) at low concentrations, with coincidence correction at higher concentrations, and a light intensity-based particle concentration mode at the highest concentrations (sometimes known as photometric mode). The photometric mode is more liable to change in sensitivity due to contamination of the optics, for example. Reference CPCs in this International Standard are therefore constrained to operate in their single particle counting modes (with or without coincidence correction), and the upper number concentration limit will generally be lower than for the FCAE method.

Calibration with a reference CPC therefore has disadvantages compared with an FCAE at low particle size or high particle number concentration. It has the advantages with larger particles, fewer constraints on the calibration aerosol source, and at lower particle concentrations. The differences between the calibration aerosol that can be used with the FCAE and reference CPC are summarized in [Table 1](#).

Table 1 — Calibration aerosol requirements for the FCAE and reference CPC

Reference instrument	Particle diameter range [nm]	Typical particle concentration range [cm^{-3}]	Calibration aerosol particle charge requirements	
			Test CPC calibrated at lower detection limit particle diameters	Test CPC calibrated in plateau range of particle diameters
FCAE	5 – 1 000	10^3 to $> 10^5$	$\phi < 0,1$	$\phi < 0,1$
CPC	$d_{\text{min,ref}}$ – 1 000	~ 1 to $> 10^4$	$\phi < 0,1$	no restriction

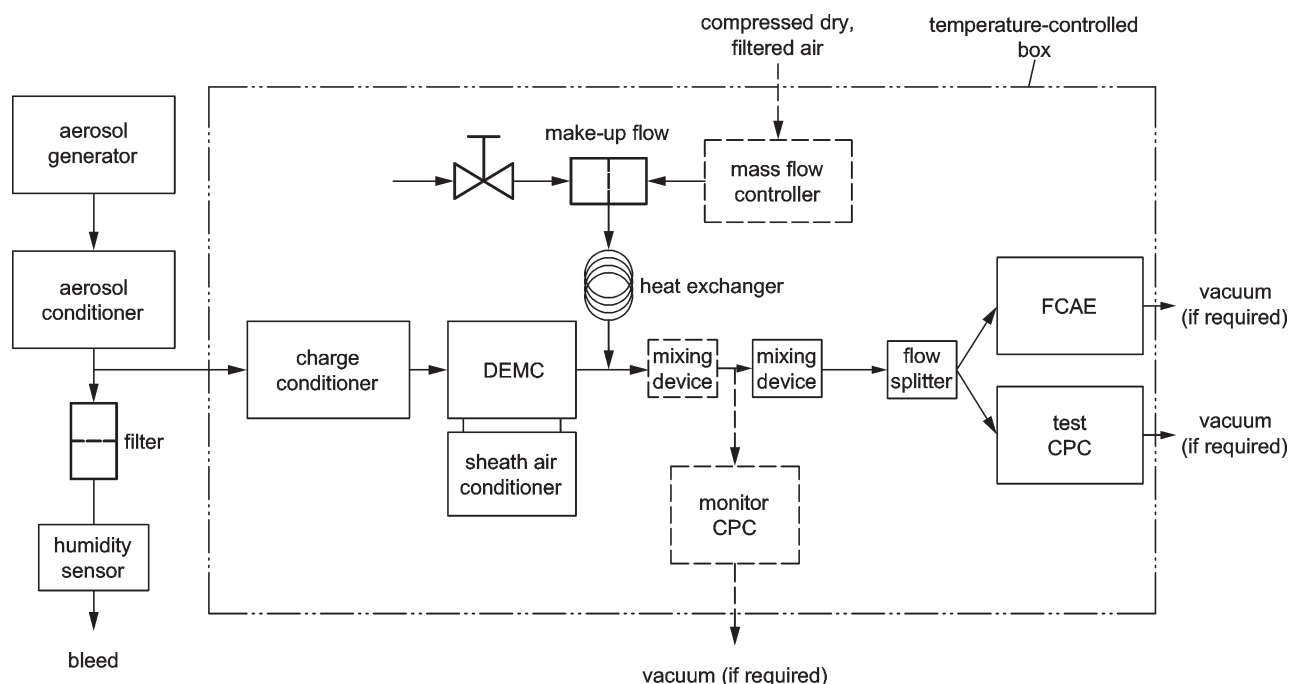
6 Calibration using an FCAE as reference instrument

6.1 Overview of the setup and calibration procedure

A schematic for a typical calibration setup using an FCAE as reference instrument is given in [Figure 4](#). All parts drawn with solid lines are necessary components (see discussion in [Clause 5](#)). These include the aerosol generator, the aerosol conditioner, the humidity sensor to measure the humidity of the aerosol that enters the DEMC, the charge conditioner, the DEMC, the make-up flow, the mixing device, the flow splitter, the FCAE, and the test CPC. Although not shown in the figure a relative humidity sensor shall be used to measure the relative humidity of the make-up air at the beginning and end of the experiments. A pressure sensor might also be necessary for the determination of the volumetric flow rate of the instruments.

In case that the calibration aerosol flow from the DEMC is higher than the sum of the flow rates required by the instruments, the excess air shall be vented off as bleed flow. While it is not shown in the figure, a temperature sensor shall be used to monitor the temperature in the temperature-controlled box or room temperature.

The parts of [Figure 4](#) with dashed lines are recommended but not required. For example the temperature-controlled box and heat exchangers for the DEMC sheath air flow and the make-up air flow can be used to stabilize all temperatures. A monitor CPC can be used to check the stability of the calibration aerosol. The make-up air flow can be controlled with a throttle valve or compressed air with a mass flow controller.



NOTE Dashed lines show equipment that is not required, but highly recommended.

Figure 4 — Typical calibration setup with FCAE as reference instrument

The calibration procedure can be seen in [Table 2](#).

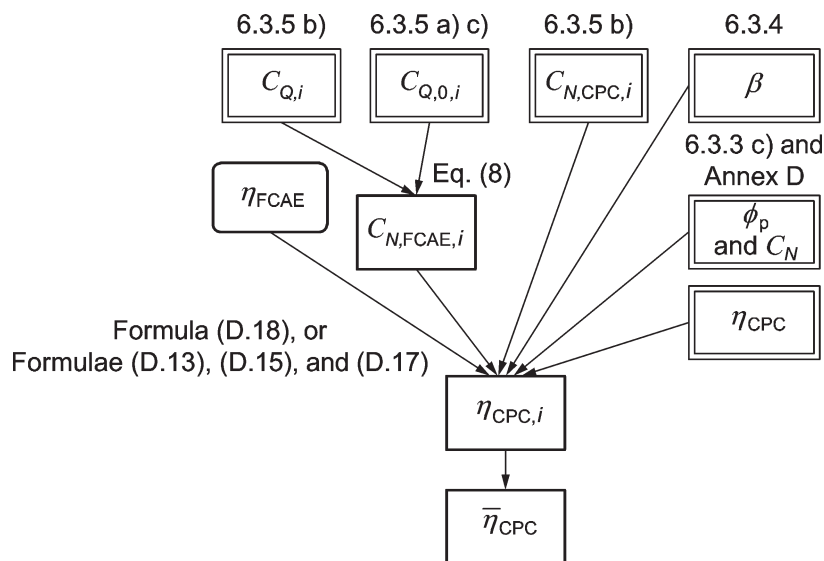
Table 2 — CPC calibration procedure using an FCAE as reference instrument

6.2	Preparation
6.2.2	Aerosol generator and conditioner (size distribution)
6.2.3	Other equipment (e.g. mass flow meters, etc.)
6.2.4	DEMC (according to ISO 15900) and sheath air conditioner
6.2.5	FCAE Absolute zero corrected value for charge concentration times inlet flow rate < 1 fC/s, standard deviation < 2,5 fC/s (from 1-s averages of 15 min) Overall leak test Flow measurement and stability < 2 % (from 5 measurements in 15 min)
6.2.6	Test CPC Zero arithmetic mean < 0,1 cm⁻³ (from 1-s average concentrations of at least 5 min) High response check Flow measurement and stability < 2 % (from 5 measurements in 5 min)
6.2.7	Connect the instruments and the aerosol generator/conditioner to the DEMC DEMC (voltage off), sheath to sample > 7:1 FCAE flow measurement FCAE absolute zero corrected value for charge concentration times inlet flow rate < 1 fC/s, standard deviation < 0,5 fC/s (from 30-s arithmetic means of 2 min) Test CPC zero arithmetic mean < 1 cm⁻³ (from 30-s arithmetic means of 2 min) Determine minimum level of FCAE charge concentration times inlet flow rate with Formula (5)

Table 2 (continued)

6.3	Detection efficiencies
6.3.2	DEMC diameter adjustment
6.3.3	Primary aerosol adjustment The concentration to be within the capability of the charge conditioner Multiply charged particles fraction < 10 % Concentration within the range of the FCAE
6.3.4	Splitter bias β measurement
6.3.5	Test CPC efficiency measurement Set DEMC voltage 0 (or off) for initial zero measurement — Record 1 min FCAE, test CPC, use the last 30 s for the calculations — FCAE absolute zero corrected arithmetic mean <1 fC/s — FCAE standard deviation <0,5 fC/s — CPC arithmetic mean <1 cm ⁻³ At the specific diameter and concentration: — Record 1 min FCAE, test CPC, use the last 30 s for the calculations — FCAE (CPC) CV < 3 %, or standard deviation <0,5 fC/s (0,5 cm ⁻³) Set DEMC voltage 0 (or off) — Record 1 min FCAE, test CPC, use the last 30 s for the calculations — FCAE absolute zero corrected arithmetic mean <1 fC/s — FCAE standard deviation <0,5 fC/s — CPC arithmetic mean <1 cm ⁻³ Calculate detection efficiency $\eta_{CPC,i}$ Repeat another 4 times Calculate the arithmetic mean detection efficiency $\bar{\eta}_{CPC}$. All $\eta_{CPC,i}$ shall be within $\bar{\eta}_{CPC} \pm 0,02$
6.3.6	Measurement of a different concentration (optionally) Go to 6.3.3 and then 6.3.5
6.3.7	Measurement of a different size (optionally) Go to 6.3.2
6.3.8	Repetition of first measurement If > 5 points have been tested (difference has to be within 0,025)
6.3.9	Fill in the calibration certificate

[Figure 5](#) provides a graphical summary of the derivation of the detection efficiency.



NOTE Plain rectangles represent calculated values while double-lined and round-cornered rectangles are for measured values and values taken from certificates, respectively.

Figure 5 — A map of parameters and formulae needed to derive the detection efficiency in calibration with an FCAE

[Annex I](#) gives an example of a protocol for the calibration of a CPC using an FCAE as the reference instrument.

6.2 Preparation

6.2.1 General preparation

Check that all instruments operate properly according to the manufacturers' specifications (see [6.2.2](#) to [6.2.6](#)), then prepare (according to [Figure 4](#)) and check the complete setup ([6.2.7](#)). Do not proceed to the calibration procedure of detection efficiency ([6.3](#)) unless all tests have been passed.

6.2.2 Primary aerosol

Start the operation of the primary aerosol source according to the manufacturer's recommendations. It is highly recommended to measure the generated size distribution after the aerosol conditioner with a DMAS (e.g. combine DEMC with FCAE) if it is not known. Ensure that the relative vapour contents (from water and/or solvents) in the primary aerosol is less than 40 %.

6.2.3 Other equipment

Switch on and allow all auxiliary necessary equipment to stabilize. Turn on the charge conditioner if it is off. Prepare the calibrated pressure sensor(s), the calibrated temperature sensor(s), and the calibrated flow meter for the measurement of the FCAE and test CPC flow rates and the humidity sensors.

Any other recommended instruments in the setup should be also turned on and prepared according to the manufacturers' manuals (e.g. a monitor CPC, mass flow meters, mass flow controllers, pressure and temperature sensors, etc.). If the whole setup (i.e. DEMC and instruments) is in a temperature-controlled box, set the desired temperature and leave the system time to stabilize.

6.2.4 DEMC

Turn on the instrument, check the DEMC according to ISO 15900, and set the desired flows. Prepare the conditioner of the sheath flow.

6.2.5 FCAE

Turn on the FCAE. Leave it running for at least 30 min. If switched on after transport or a longer period without use, it may require several hours of operation until it reaches the necessary stability.

NOTE Ideally the FCAE's electrometer electronics should remain turned on all time.

Check the zero level and flow rates of the FCAE at ambient conditions. All indicators (e.g. for temperatures, flows and pressures) shall show error-free operation of the instrument. The following checks ensure that the instrument is working properly before connecting it to the calibration setup.

a) Zero check

Zero the FCAE, following the advice in the FCAE's user manual or following an appropriate external zeroing method. Report the chosen method in the Calibration Certificate.

Attach a HEPA filter (>99,99 % efficiency) to the inlet of the FCAE. Record the FCAE's zero-corrected value for charge concentration times inlet flow rate ($C_Q \times q_{\text{FCAE}}$) for at least 15 min with 1-s reading interval and 1-s averaging time. There should be no obvious decreasing or increasing tendency of the value. If there is such a tendency, allow more time for the FCAE to stabilize, repeat FCAE zeroing, and repeat this test. Do not proceed unless the FCAE reaches stable operation.

Calculate the arithmetic mean and standard deviation for the recorded values. As a result of a successful zero-correction the FCAE's zero-corrected absolute arithmetic mean value for $C_Q \times q_{\text{FCAE}}$ shall be < 1 fC/s. The standard deviation shall be less than 2,5 fC/s.

The FCAE requires attention from the manufacturer if the FCAE fails twice this zero test.

b) FCAE overall leak test

For this test, the ambient concentration should be at least 500 cm⁻³. This test is not applicable for FCAEs with internal bypass flow, e.g. to allow operation conditions for a flow control valve.

- 1) Connect a HEPA filter to inlet of the test CPC. Let the test CPC zero for 1 min, then measure the number of counts over 1 min as N_{HEPA} .
- 2) Disconnect the HEPA filter from the test CPC, then sample the room air and measure the number of counts over 1 min as N_{ambient} .
- 3) Disconnect the vacuum from the test CPC and connect the inlet of the test CPC to the outlet of the FCAE. Connect the HEPA filter to the inlet of the FCAE so that it will sample filtered room air. Connect a vacuum to the test CPC to pull filtered room air through the FCAE.
- 4) Wait 3 min to zero the system.
- 5) Measure and record the number of counts over 1 min as the test CPC pulls filtered ambient air through the FCAE. Record the number counted by the CPC as N_{FCAE} .
- 6) Calculate the value $N_{\text{leak}} = N_{\text{FCAE}} - N_{\text{HEPA}}$. If this value is negative, then use $N_{\text{leak}} = 0$.
- 7) Calculate the ratio $R_{\text{FCAE}} = N_{\text{leak}}/N_{\text{ambient}}$. The value of R_{FCAE} shall be less than 0,000 1 to perform the calibration. If $R_{\text{FCAE}} > 0,000 1$, check the FCAE plumbing for leaks, verify that the filter is adequate, and perform steps 1 to 7 again.

c) Flow rate measurement

If the inlet flow rate of the FCAE is adjustable, set it to the nominal value specified in the calibration certificate for which the FCAE calibration is valid before the flow rate measurement.

Measure the nominal (see calibration certificate) volumetric inlet flow rate of the FCAE at ambient conditions with an appropriate low pressure drop, calibrated flow meter ([Annex J](#)). The flow shall be stable over time, i.e. the CV of at least 5 measurements uniformly spaced over 15 min shall be < 2 %. There should be no obvious decreasing or increasing tendency of the flow. If not fulfilled, leave the

FCAE more time to stabilize, check the pump (or vacuum connection) of the FCAE and repeat. The FCAE requires attention from the manufacturer if the flow check fails twice.

Compare the (calculated) arithmetic mean of the measured inlet flow rates of the FCAE ($q_{\text{FCAE,cal,amb}}$) with the arithmetic mean value indicated by the FCAE for the same time intervals or with the nominal value of the FCAE ($q_{\text{FCAE,amb}}$). The latter case applies if no flow rate is reported or when the nominal value is used by the FCAE for the charge concentration calculation. The difference should be within the FCAE manufacturer's specifications, indicated as an accuracy $r_{q,\text{FCAE}}$ in %. If not, the manufacturer should be contacted.

The flow rate $q_{\text{FCAE,cal,amb}}$ should also be compared with the flow rate of the FCAE in its calibration certificates ($q_{\text{FCAE,cert}}$) and the deviation shall be within:

$$\frac{|q_{\text{FCAE,cal,amb}} - q_{\text{FCAE,cert}}|}{q_{\text{FCAE,cert}}} < 2\sqrt{u_r^2(q_{\text{FCAE,cert}}) + u_r^2(q_{\text{cal,cert}}) + \frac{1}{3}r_{q,\text{FCAE}}^2} \quad (2)$$

where

$u_r(q_{\text{FCAE,cert}})$ is the relative standard uncertainty for the inlet flow of the FCAE in its calibration certificate;

$u_r(q_{\text{cal,cert}})$ is the relative standard uncertainty of the flow meter used to measure $q_{\text{FCAE,cal,amb}}$.

Higher deviations might indicate issues with the flow control of the FCAE.

All flow rates shall refer to the same temperature and pressure. Depending on the flow control used in the FCAE, different corrections should apply (see [Annex J](#)).

6.2.6 Test CPC

When a CPC has been transported for calibration, it will generally have been drained of working fluid. In that case, switch the test CPC on, fill with the required working fluid to the specified level (observing manufacturer's precautions regarding moving the unit when full) and allow the saturator, condenser and optics to reach their specified temperatures. Leave it running for at least 1 h.

When a CPC is to be calibrated without being drained of the working fluid, manufacturer's precautions regarding moving the unit when full shall be observed. Switch on the test CPC, leave it running for at least 30 min, and allow the saturator, condenser and optics to reach their specified temperatures.

All indicators (e.g. for temperatures, flows and pressures) shall show error-free operation of the instrument.

a) Zero count check

For zero count check, attach at least one HEPA filter (>99,99 % efficiency) to the test CPC inlet (an additional HEPA filter in series with the first one may be necessary to achieve extremely low concentrations). Run the CPC for a minimum of 5 min and record the concentration values with 1-s reading interval and 1-s averaging time. After any leaks are eliminated, the arithmetic mean concentration shall be $<0,1 \text{ cm}^{-3}$. Contact the customer if this requirement is not met.

b) High response check

Perform a simple check to demonstrate that the test CPC can detect particles. This can, for example, be done by sampling room air if the number concentration of the room air is expected to be higher than 500 cm^{-3} . The number concentration measured by the test CPC should be higher than 500 cm^{-3} . Aerosols from other sources with sufficiently high number concentrations may also be used for this test. Or, follow the manufacturer's recommendations. Contact the customer if this requirement is not met.

c) Flow rate measurement

Measure the volumetric inlet flow rate of the test CPC at ambient conditions with an appropriate low pressure drop, calibrated flow meter ([Annex I](#)). The flow shall be stable over time, i.e. the CV of at least 5 measurements uniformly spaced over 5 min shall be <2 %. There should be no obvious decreasing or increasing tendency of the flow. If not fulfilled, leave the test CPC more time to stabilize, check the pump (or vacuum connection) of the test CPC and repeat. The test CPC requires maintenance if the flow check fails twice.

Compare the (calculated) arithmetic mean of the measured inlet flow rates of the test CPC ($q_{\text{CPC,cal,amb}}$) with the arithmetic mean value indicated by the test CPC for the same time intervals or the nominal value for the test CPC ($q_{\text{CPC,amb}}$). The latter case applies if no flow rate is reported or when the nominal value is used by the test CPC for the particle number concentration calculation. The difference should be within the test CPC manufacturer's specifications. If not, the customer should be contacted. Higher differences might indicate issues with the flow control of the test CPC.

All flow rates shall refer to the same temperature and pressure. Depending on the flow control used in the test CPC, different corrections should apply (see [Annex J](#)).

6.2.7 Check of the complete setup

Initially the make-up flow path is connected downstream of the DEMC (typically a HEPA filter, or a mass flow controller with a HEPA filter). Then connect the mixing device and pressure sensor. The test CPC and FCAE are connected to the flow splitter which is positioned after the mixing device. Make sure that there is at least one opening free (e.g. the inlet of the DEMC or the make-up flow path) in order to avoid overpressure or underpressure at the inlet of the test CPC and FCAE. If there is a monitor CPC, this should be connected before the mixing device with another mixing device.

Connect the aerosol generator and conditioner to the inlet of the DEMC, making sure that the excess flow is vented, or that filtered air is added if the DEMC flow rate is higher.

Check if the pressure at the inlet of the FCAE and test CPC has remained in the desired range (i.e. no extreme underpressure or overpressure, outside the manufacturers' specifications). If not, adjust accordingly the make-up air flow rate or the throttling valve.

a) DEMC flow rate

Set the desired DEMC sheath flow rate. If required, set the desired DEMC inlet flow rate by adjusting the make-up flow (or bleed air). The ratio of sheath to sample flow rates shall be $\geq 7:1$ to ensure narrow monodisperse distribution after the DEMC.

After setting these flow rates, it is recommended to not adjust them during the calibration procedure. If adjusted the volumetric flow rates of the FCAE and the test CPC have to be measured again (see steps b) and c) below).

b) FCAE flow measurement

Measure the volumetric flow rate of the FCAE by inserting the calibrated flow meter between the splitter and the inlet of the FCAE. Compare this measured value ($q_{\text{FCAE,cal}}$) with the value reported by the FCAE or its nominal value (q_{FCAE}). The latter case applies if no flow rate is reported or when the nominal value is used by the FCAE for the charge concentration calculation. The difference should be within the FCAE manufacturer's specifications, indicated as an accuracy $r_{q,\text{FCAE}}$ in %. If not the manufacturer should be contacted.

The flow rate $q_{\text{FCAE,cal}}$ should also be compared with the flow rate of the FCAE in its calibration certificate ($q_{\text{FCAE,cert}}$) and the deviation shall be within:

$$\frac{|q_{\text{FCAE,cal}} - q_{\text{FCAE,cert}}|}{q_{\text{FCAE,cert}}} < 2\sqrt{u_r^2(q_{\text{FCAE,cert}}) + u_r^2(q_{\text{cal,cert}}) + \frac{1}{3}r_{q,\text{FCAE}}^2} \quad (3)$$

where

$u_r(q_{\text{FCAE,cert}})$ is the relative standard uncertainty for the inlet flow of the FCAE in its calibration certificate;

$u_r(q_{\text{cal,cert}})$ is the relative standard uncertainty of the flow meter used to measure $q_{\text{FCAE,cal}}$.

Higher deviations might indicate issues with the flow control of the FCAE.

The relative standard uncertainty of q_{FCAE} is calculated as Formula (4):

$$u_r(q_{\text{FCAE}}) = \frac{|q_{\text{FCAE,cal}} - q_{\text{FCAE,cert}}|}{\sqrt{3} q_{\text{FCAE,cert}}} \quad (4)$$

All flow rates shall refer to the same temperature and pressure. Depending on the flow control used in the FCAE, different corrections should apply (see [Annex J](#)).

NOTE 1 The flow rate is affected by the composition of the gas. For more details, see [Annex J](#).

NOTE 2 The flow measurement is repeated here to account for flow rate changes due to changed FCAE inlet pressure.

c) Test CPC flow rate measurement

Measure the volumetric flow rate of the test CPC by inserting the calibrated flow meter between the splitter and the inlet of the test CPC. Compare this measured value with the value reported by the test CPC or its nominal value. The latter case applies if no flow rate is reported or when the nominal value is used by the test CPC for the particle number concentration calculation. The difference should be within the test CPC manufacturer's specifications. If not the customer should be contacted. Higher differences might indicate issues with the orifice or the pump of the test CPC. This value shall be reported in the calibration certificate, along with the test CPC reported or nominal value.

All flow rates shall refer to the same temperature and pressure. Depending on the flow control used in the test CPC, different corrections should apply (see [Annex J](#)).

NOTE 1 The flow rate is affected by the composition of the gas. For more details, see [Annex J](#).

NOTE 2 The flow measurement is repeated here to account for flow rate changes due to changed test CPC inlet pressure.

d) Zero levels

Set the DEMC voltage to 0 V (or off). The FCAE and test CPC readings shall remain comparable to the zero levels measured before [6.2.5 a) and 6.2.6 a)]: measure for a minimum of 2 min, the absolute, zero corrected 30-s arithmetic mean value (with 1-s reading interval) of the FCAE shall be lower than $C_Q \times q_{\text{FCAE}} = 1 \text{ fC/s}$ and the standard deviation shall be lower than 0,5 fC/s. The arithmetic mean value (with 1-s reading interval) of the CPC shall be lower than $C_{N,\text{CPC}} = 1 \text{ cm}^{-3}$. If not, check for leaks in the calibration setup. Other reasons for increased zero levels can be — for example — an excessively high concentration at the inlet of the DEMC, overloading or failure of the filters inside the DEMC.

e) Determine the FCAE minimum level

Determine the arithmetic mean and standard deviation of $C_Q \times q_{\text{FCAE}}$ reported by the FCAE in 30 s (at 1-s reading interval). Multiply the standard deviation by 3 and add the value:

$$(C_Q \times q_{\text{FCAE}})_{\min} = (C_Q \times q_{\text{FCAE}})_{\text{mean}} + 3\sigma_{C_Q \times q_{\text{FCAE}}} \quad (5)$$

Compare this value with the lowest value of $C_Q \times q_{\text{FCAE}}$ in its calibration certificate. The greater one is the minimum $C_Q \times q_{\text{FCAE}}$ at the inlet of the FCAE that may be used in the calibration (defined here as the “minimum $C_Q \times q_{\text{FCAE}}$ level”).

Write down all parameters: Readings of the FCAE and test CPC, flow rates, pressures, temperatures, make-up flow (if available), sheath, sample flow rates, humidity, etc. All this information will be reported in the calibration certificate (see [Clause 8](#) and [Annex C](#)).

6.3 Calibration procedure of detection efficiency

6.3.1 General

The following procedure describes the measurement of the detection efficiency of a test CPC at one given calibration particle size and particle number concentration.

6.3.2 DEMC diameter adjustment

Adjust the DEMC such that the particle size of singly charged calibration particles leaving the DEMC equals the desired calibration particle size.

NOTE It is highly recommended to begin with a big size (such that the detection efficiency of the test CPC is at the maximum, i.e. at least 3 times the size where the detection efficiency is expected to be 50 %) and check the linearity of the test CPC (i.e. different concentrations at the same size). Then the detection efficiency at the steep part of the detection efficiency curve may follow. This is because the tests at the steep part of the detection efficiency curve usually need adjustment of the size distribution produced by the generator and are more time consuming.

6.3.3 Primary aerosol adjustment

Adjust the aerosol conditioner in such a way that the concentration of the calibration aerosol equals the desired concentration for the measurement of the detection efficiency. However the following requirements shall be fulfilled.

a) Minimum level

The concentration shall be higher than the value $(C_Q \times q_{\text{FCAE}})_{\min}$ of the FCAE, as defined in Formula (5) in [6.2.7 e](#)).

b) Maximum level

The concentration shall be lower than the maximum determined by the maximum charge concentration the FCAE may measure, as specified in its calibration certificate.

The total number concentration of the conditioned primary aerosol shall be low enough to reach charge equilibrium after passing through the charge conditioner and to avoid particle charge caused bias in the DEMC. A method to check this is described in [Annex K](#).

c) Fraction of multiply charged particles Φ

The value of multiply charged particles Φ shall be $<0,1$. Determine the fractions of particles of p charges $[(\phi_p, \text{Formula (6)})]$ according to one of the methods described in [Annex D](#), and calculate the fraction of multiply charged particles (Φ) with Formula (7). The criterion $\Phi < 0,1$ is a pass/fail criterion; the calibration procedure shall not be continued until it is fulfilled. The Φ can be decreased by, e.g. adjusting the mode diameter or the geometric standard deviation of the size distribution of the primary aerosol.

The fraction of particles with p charges, ϕ_p , within the aerosol leaving the DEMC is calculated as

$$\phi_p = C_N(d_p) / \sum_{p \geq 1} C_N(d_p) \quad (6)$$

where

$C_N(d_p)$ is the concentration of particles with p charges.

The fraction of multiply charged particles, Φ , is calculated as

$$\Phi = \sum_{p \geq 2} \phi_p \quad (7)$$

NOTE 1 Depending on the polarity of the voltage in the DEMC, the charges of the particles can be either positive or negative. In this International Standard, we define p as the absolute number of charges.

NOTE 2 It is highly recommended that the geometric mean size of the primary distribution is smaller than the size at which the detection efficiency of the test CPC will be measured.

NOTE 3 If a tandem DEMC setup is employed (i.e. two DEMCs in series with a charge conditioner in between), the fraction of multiply charged particles, Φ , is reduced significantly.

NOTE 4 The fraction of multiply charged particles can be reduced by the method described in Reference [60].

6.3.4 Splitter bias β measurement

Perform the splitter bias measurement according to [Annex G](#). If the obtained bias (β) is greater than 1,05 or less than 0,95, check for any inhomogeneity of the calibration aerosol.

6.3.5 Test CPC efficiency measurement

Determine the detection efficiency of the test CPC according to the following steps.

a) Initial reading at DEMC voltage 0 (or off)

Set the DEMC voltage to 0 V (or off) and record the FCAE charge concentration and the number concentration reported by the test CPC every second for 1 min. Calculate the arithmetic mean ($C_{Q,0,0}$) and standard deviation of the charge concentrations reported by the FCAE and the arithmetic mean of the number concentrations reported by the test CPC for the last 30 s of the 1-min measurement interval.

The absolute, zero corrected arithmetic mean value and the standard deviation of the FCAE charge concentration times its inlet flow rate shall be less than 1 fC/s and 0,5 fC/s, respectively. The arithmetic mean of the number concentration of the test CPC shall be $<1 \text{ cm}^{-3}$. If not, the measurement is not valid. Check the generator or other sources of instability and repeat.

b) Recordings at specific size and concentration

Record the FCAE charge concentration and the number concentration reported by the test CPC every second for 1 min. Calculate the arithmetic mean ($C_{Q,1}$) and standard deviation of the charge concentrations reported by the FCAE and the arithmetic mean ($C_{N,CPC,1}$) and standard deviation of the number concentrations reported by the test CPC for the last 30 s of the 1-min measurement interval ([Annex L](#)).

The CV of the FCAE charge concentration times its inlet flow rate shall be $<3 \%$ or the standard deviation $<0,5 \text{ fC/s}$. The CV of the number concentration of the test CPC shall be $<3 \%$ or the standard deviation $<0,5 \text{ cm}^{-3}$. Either the CVs or the standard deviations shall respectively fulfil the criterion easiest to comply with. If not, the measurement is not valid. Check the generator or other sources of instability and repeat.

c) Recordings at DEMC voltage 0 (or off)

Set the DEMC voltage to 0 V (or off) and record the FCAE charge concentration and the number concentration reported by the test CPC every second for 1 min. Calculate the arithmetic mean ($C_{Q,0,1}$) and standard deviation of the charge concentrations reported by the FCAE and the arithmetic mean of the number concentrations reported by the test CPC for the last 30 s of the 1-min measurement interval.

The absolute, zero corrected arithmetic mean value and the standard deviation of the FCAE charge concentration times its inlet flow rate shall be less than 1 fC/s and 0,5 fC/s, respectively. The arithmetic mean of the number concentration of the test CPC shall be $<1 \text{ cm}^{-3}$. If not, the measurement is not valid. Check the generator or other sources of instability and repeat.

d) Calculation of FCAE number concentration assuming singly charged particles

Calculate the number concentration by FCAE ($C_{N,\text{FCAE},1}$) according to Formula (8). From the measured charge concentration (corrected for zero) and assuming that particles each carry a single electrical charge, the number concentration for measurement i is given by:

$$C_{N,\text{FCAE},i} = \frac{C_{Q,i} - (C_{Q,0,i-1} + C_{Q,0,i})/2}{e} \quad (8)$$

where

$C_{N,\text{FCAE},i}$ is the calculated number concentration of the calibration aerosol;

$C_{Q,i}$ is the indicated charge concentration measured by the FCAE when measuring particles;

$C_{Q,0,i}$ is the indicated charge concentration measured by the FCAE with the DEMC voltage set at zero;

e is the elementary charge.

e) Calculation of the detection efficiency of the test CPC

If the primary aerosol cannot be conditioned in such a way that the calibration aerosol contains one elementary charge, corrections shall be applied ([Annex D](#)).

[Annex D](#) also quantifies the effect of multiple charges on the determination of particle size.

Information from the FCAE certificate regarding any correction factor required by the FCAE shall be incorporated ([Annex D](#)).

Calculate the detection efficiency $\eta_{\text{CPC},1}$ of the test CPC using formulae in [Annex D](#).

- If the particle size is in the range where the detection efficiency of the test CPC is known to be constant against size, substitute $C_{N,\text{FCAE},1}$ [[6.3.5 d](#)], $C_{N,\text{CPC},1}$ [[6.3.5 b](#)], ϕ_p [[6.3.3 c](#)], β [[6.3.4](#)] and η_{FCAE} (from the calibration certificate of the FCAE) into Formula (D.18).
- If the particle size is in the range where the detection efficiency of the test CPC is known to vary with size, substitute $C_{N,\text{FCAE},1}$ [[6.3.5 d](#)], $C_{N,\text{CPC},1}$ [[6.3.5 b](#)], ϕ_p (and C_N obtained in [Annex D](#)) [[6.3.3 c](#)], β [[6.3.4](#)], η_{FCAE} (from the calibration certificate of the FCAE), and an estimated plateau efficiency η'_{CPC} of the test CPC into Formulae (D.13), (D.15) and (D.17).

Record in the calibration certificate which method of calculation was used.

f) Measurement repetition

Repeat steps b) to d) four more times (i.e. five in total). Calculate the arithmetic mean detection efficiency $\bar{\eta}_{\text{CPC}}$ and its standard deviation $\sigma(\eta_{\text{rep}})$ for the specific concentration and size using the five detection efficiencies $\eta_{\text{CPC},i}$ ($i = 1 - 5$). The calibration is valid only if all five $\eta_{\text{CPC},i}$ values are within $\pm 0,02$ of the arithmetic mean detection efficiency $\bar{\eta}_{\text{CPC}}$

6.3.6 Measurement of different particle concentrations

If a different concentration (at the same size) has to be measured, adjust the concentration of the primary aerosol (go to [6.3.3](#) and then [6.3.5](#)). The measurement of the fraction of multiply charged particles [[6.3.3 c](#))] is not necessary to repeat. Note that the splitter bias ([6.3.4](#)) and the FCAE flow rate [[6.2.7 b](#))] do not have to be tested. For concentrations lower than the maximum level, there is no need to re-check the charge conditioner [[6.3.3 b](#))]. If the CPC is to be calibrated at concentrations below the lowest charge concentration at the nominal inlet flow rate for which the FCAE has been certified, the method described in [Annex H](#) can be followed.

If the DEMC flow rates have to be adjusted or if any change in the setup is made that can lead to a different pressure at the inlet of the FCAE and test CPC, measure the inlet flow rates of the FCAE and the test CPC (see [6.2.7](#)).

6.3.7 Measurement of different sizes

If a different particle size has to be tested, then go to [6.3.2](#). In this case, all following steps ([6.3.3](#) to [6.3.6](#)) have to be performed.

If the DEMC flow rates have to be adjusted or if any change in the setup are made that can lead to a different pressure at the inlet of the FCAE and test CPC, measure the inlet flow rates of the FCAE and the test CPC (see [6.2.7](#)).

NOTE 1 It is also highly recommended to conduct all detection efficiency tests on the same test CPC at various particle sizes at approximately the same particle number concentration. This would avoid any influence from a nonlinear CPC response.

NOTE 2 When planning the concentrations to be used, attention shall be paid to the concentrations at which the measurement mode of the test CPC changes (as stated in the manufacturer's manual), so that discontinuities can be anticipated.

6.3.8 Repetition of first measurement point

When several points are tested, or when a measurement instrument was switched off, or when a malfunction occurred, the detection efficiency measurement with the first set of aerosol parameters has to be repeated (i.e. concentration and size). This includes the determination of the fraction of multiply charged particles. The difference of the two detection efficiencies should be within $\pm 0,025$. In addition the flow rates of the FCAE and test CPC have to be within 5 % of their original measurements in [6.2.7](#). If not, all tests conducted are not valid.

NOTE The repetition of the first point can be done e.g. after three tests, but also after more tests. However when more than five tests are conducted the risk of losing all measurements is higher (due to a higher than 0,025 difference between the first and last points).

6.3.9 Preparation of the calibration certificate

Fill in the calibration certificate (see [Clause 8](#) and [Annex C](#)). This completes the measurements for the determination of the detection efficiency of the test CPC.

6.4 Measurement uncertainty

6.4.1 General

The result of the CPC calibration takes the form of a detection efficiency, η , at a certain particle size, a certain particle number concentration, for a certain type of generated particles. The principal quantities requiring well-defined measurement uncertainties are the particle size and the detection efficiency, covered in [6.4.2](#) and [6.4.3](#). The particle number concentration is less critical, and its uncertainty is largely covered by that of the detection efficiency. It is covered in [6.4.4](#).

6.4.2 Particle size

The particle size associated with the calibration is determined by the DEMC supplying the calibration aerosol to both instruments. The particle size and its measurement uncertainty shall be determined according to ISO 15900.

When there is a significant fraction of multiply charged particles in the calibration aerosol, significant numbers of particles will have much larger sizes than the selected size. The fractions ϕ_p , which have been determined according to [Annex D](#), shall be noted on the calibration certificate. When the fraction has not been determined a note shall be made on the certificate describing the scale of any relevant effects expected from the system used.

6.4.3 Detection efficiency

The uncertainty in the result for detection efficiency is principally determined by components from:

- the FCAE (as described on its certificate);
- the multiple-charge correction;
- differences in particle concentrations sampled by the FCAE and the test CPC (the splitter bias correction factor);
- the accuracy and variations of the FCAE input flow measurements;
- the repeatability of the detection efficiency calibration;
- the effect of uncertainty in the particle size determination (when the particle size is such that the CPC detection efficiency is significantly affected by the particle size).

As stated in [6.1](#), the FCAE shall have an unexpired calibration certificate specifying the charge concentration or current and flow rate range for which the calibration is valid. The certificate will give an uncertainty for the charge concentration, or alternatively for the current and the flow rate that can be combined to form an uncertainty for the particle charge concentration. Note that this will often be expressed as expanded uncertainties ($k = 2$; approximately 95 % confidence) values, while uncertainties must be combined as standard uncertainties ($k = 1$) values.

Correction for multiply charged particles is made according to formulae in [Annex D](#). As a first approximation, the uncertainty in the correction factor is best determined semi-empirically by repeated determination of the multiply charged fractions ϕ_p , and expressing the variation as a standard deviation associated with the multiple-charge correction. If the uncertainties for the fractions ϕ_1 , ϕ_2 , ϕ_3 are termed $u(1)$, $u(2)$, and $u(3)$ respectively, the required relative uncertainty component $u_r(\text{MCC})$ is given by Formula (9):

$$u_r(\text{MCC}) = \frac{100}{\sum_{p \geq 1} \phi_p \cdot p} \cdot \sqrt{u^2(1) + 4u^2(2) + 9u^2(3)} \quad (9)$$

This uncertainty component applies in the detection efficiency plateau region (see [D.1](#)). The more complicated case away from the plateau region is not covered by this International Standard.

The procedure for calculating the bias correction factor β and its uncertainty are given in [Annex G](#).

If the input flow to the FCAE is different at the time of the test CPC calibration to when the FCAE was calibrated, there will be a proportionate effect on the detection efficiency determination. The flows shall be measured with calibrated flow meters on each occasion, as described in [6.2.7 b\)](#), and shall agree within the specified tolerance. The uncertainty associated with the FCAE flow is set by this tolerance. A correction could be made to allow for different flows, with a consequent reduction in uncertainty, but this is not covered by this International Standard.

The five repeated measurements specified in [6.3.5 e\)](#) give an estimate of short-term repeatability of the detection efficiency measurement. The standard deviation of the repeated measurements is included in

the uncertainty calculation. The uncertainty calculation therefore applies only to individual batches of these five repeated measurements.

Guidance on cases where the uncertainty associated with the particle size is expected to have a significant effect on the uncertainty of the detection efficiency is given in [Annex M](#).

The calculation of uncertainty in the detection efficiency is summarized in [Table 3](#).

Table 3 — Relative uncertainty components for calibration with an FCAE

Component	Symbol	Reference	Comment
FCAE detection efficiency	$u_r(\text{FCAE})$	Taken from FCAE certificate	Expressed as % of FCAE reading
Multiple charge correction	$u_r(\text{MCC})$	Formula (9)	Expressed as %
Splitter bias correction factor	$u_r(\beta)$	Annex G , Formulae (G.10) (Refer to Annex G for the case of unequal flows.)	Expressed as %, i.e. $u_r(\beta) = 100 u(\beta)/\beta$
FCAE flow rate deviation	$u_r(q_{\text{FCAE}})$	6.2.7 b)	Expressed as %
Repeatability	$u_r(\eta_{\text{rep}})$	6.3.5 f)	Expressed as %, i.e. $u_r(\eta_{\text{rep}}) = 100 \sigma(\eta_{\text{rep}}) / \bar{\eta}_{\text{CPC}}$

All components are to be in the form of relative standard uncertainties, corresponding to standard deviations.

The combined relative standard uncertainty is given by Formula (10):

$$u_{c,r}(\eta) = \sqrt{u_r^2(\text{FCAE}) + u_r^2(\text{MCC}) + u_r^2(\beta) + u_r^2(q_{\text{FCAE}}) + u_r^2(\eta_{\text{rep}})} \quad (10)$$

The relative expanded uncertainty $U_r(\eta)$ is obtained by multiplying the combined relative standard uncertainty by a coverage factor k : $U_r(\eta) = k u_{c,r}(\eta)$. Typically a value of $k = 2$ is used.

A worked example is given in [Annex I](#).

6.4.4 Particle number concentration

The particle number concentration to be reported on the CPC calibration certificate provides information relevant when nonlinearity is expected in the response of the CPC, for example when changing between instrument measurement modes. The concentration to be reported on the certificate is the arithmetic mean concentration recorded by the FCAE, after corrections have been applied for multiple charge correction and FCAE flow. It is not necessary to estimate an uncertainty for this figure. The uncertainty would be expected to be slightly less than the uncertainty of the detection efficiency, as all of the components except the splitter bias correction factor would apply.

The uncertainty that can be assigned to measurements made with the test CPC after calibration is a more complicated topic, which is addressed in [Annex N](#).

7 Calibration using a CPC as reference instrument

7.1 Overview of the setup and calibration procedure

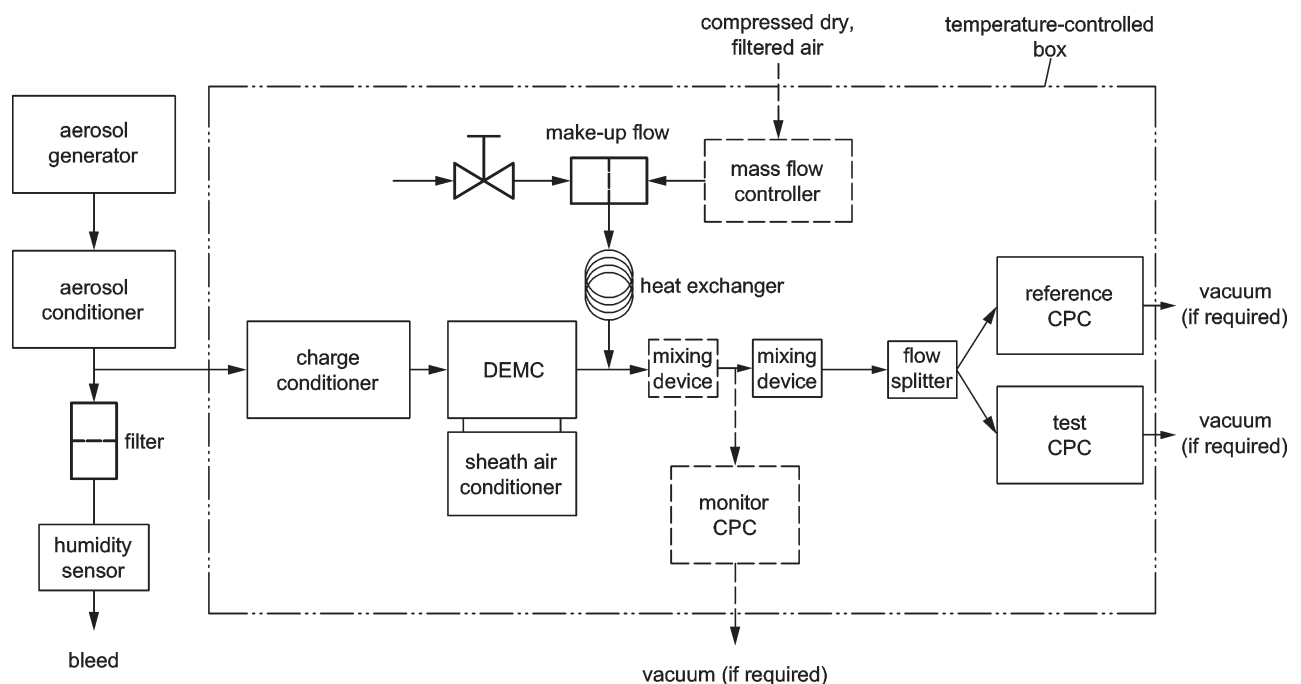
A schematic for a typical calibration setup with a reference CPC is given in [Figure 6](#). All parts drawn with solid lines are necessary components (see discussion in [Clause 5](#)). These include the aerosol generator, the aerosol conditioner, the humidity sensor to measure the humidity of the aerosol that enters the DEMC, the charge conditioner, the DEMC, the make-up flow, the mixing device, the flow splitter, the reference and test CPCs. Although not shown in the figure, a relative humidity sensor shall be used to measure

the relative humidity of the make-up air at the beginning and end of the experiments. A pressure sensor might also be necessary for the determination of the volumetric flow rate of the instruments.

In case that the calibration aerosol flow from the DEMC is higher than the sum of the flow rates required by the instruments, the excess air shall be vented off as bleed flow. While it is not shown in the figure, a temperature sensor shall be used to monitor the temperature in the temperature-controlled box or room temperature.

The parts of [Figure 6](#) with dashed lines are recommended but not required. For example, the temperature-controlled box and heat exchangers for the DEMC sheath air flow and the make-up air flow can be used to stabilize all temperatures. A monitor CPC can be used to check the stability of the calibration aerosol. The make-up air flow can be controlled with a throttle valve or compressed air with a mass flow controller.

NOTE Apart from the reference CPC, the components and the respective requirements are the same as those for the FCAE comparison ([Clause 6](#)).



NOTE Dashed lines show equipment that is not required, but highly recommended.

Figure 6 — Typical calibration setup with CPC as reference instrument

The calibration procedure can be seen in [Table 4](#).

Table 4 — CPC calibration procedure using a CPC as reference instrument

7.2	Preparation
7.2.2	Aerosol generator and conditioner (size distribution)
7.2.3	Other equipment (e.g. mass flow meters, etc.)
7.2.4	DEMC (according to ISO 15900) and sheath air conditioner
7.2.5	Reference CPC Zero arithmetic mean $<0,1 \text{ cm}^{-3}$ (from 1-s average concentrations of at least 5 min) High response check Flow measurement and stability $<2 \%$ (from 5 measurements in 15 min)

Table 4 (continued)

7.2.6	Test CPC Zero arithmetic mean $<0,1 \text{ cm}^{-3}$ (from 1-s average concentrations of at least 5 min) High response check Flow measurement and stability $<2 \%$ (from 5 measurements in 5 min)
7.2.7	Connect the instruments and the aerosol generator/conditioner to the DEMC DEMC (voltage off), sheath to sample $>7:1$ Reference CPC flow measurement Ref. CPC zero arithmetic mean $<1 \text{ cm}^{-3}$ (from 30-s arithmetic means of 2 min); Ref. CPC zero arithmetic mean $<0,1 \text{ cm}^{-3}$ if calibration is extended to lower concentration (Annex H) Test CPC zero arithmetic mean $<1 \text{ cm}^{-3}$ (from 30-s arithmetic means of 2 min) ; test CPC zero arithmetic mean $<0,1 \text{ cm}^{-3}$ if calibration is extended to lower concentration (Annex H) Determine minimum level of Ref. CPC with Formula (14)
7.3	Detection efficiencies
7.3.2	DEMC diameter adjustment
7.3.3	Primary aerosol adjustment The concentration to be within the capability of the charge conditioner Multiply charged particles fraction $<10 \%$ Concentration within the range of the Ref. CPC
7.3.4	Splitter bias β measurement
7.3.5	Test CPC efficiency measurement At the specific diameter and concentration: Set DEMC voltage off (or 0) — Record 60 s CPC concentrations, use the last 30 s for the calculations. — Check each CPC's arithmetic mean $<1 \text{ cm}^{-3}$. Set DEMC voltage for the specific diameter — Record 180 s CPC concentrations, use the last $5 \times 30 \text{ s}$ for the calculations. — Check each CPC's CV for each of the five 30 s intervals $<3 \%$, or standard deviation $<0,5 \text{ cm}^{-3}$. Calculate detection efficiency $\eta_{\text{CPC},i}$ for each of the five 30 s intervals. Calculate the arithmetic mean detection efficiency $\bar{\eta}_{\text{CPC}}$. All $\eta_{\text{CPC},i}$ shall be within $\bar{\eta}_{\text{CPC}} \pm 0,02$.
7.3.6	Measurement of a different concentration (optionally) Go to 7.3.3 and then 7.3.5
7.3.7	Measurement of a different size (optionally) Go to 7.3.2
7.3.8	Repetition of first measurement If >5 points have been tested (difference of $\bar{\eta}_{\text{CPC}}$ has to be within 0,025)
7.3.9	Fill in the calibration certificate

[Figure 7](#) provides a graphical summary of the derivation of the detection efficiency.