INTERNATIONAL STANDARD

ISO 29463-2

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High-efficiency filters and filter media for removing particles in air —

Part 2:
Aerosol production, measuring equipment and particle-counting statistics

Filtres à haut rendement et filtres pour l'élimination des particules dans l'air —

Partie 2: Production d'aérosol, équipement de mesure et statistique de comptage de particules

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 29463-2 was prepared by Technical Committee ISO/TC 142, *Cleaning equipment for air and other gases*.

ISO 29463 consists of the following parts, under the general title *High-efficiency filters and filter media for removing particles in air*:

- *Part 1: Classification, performance, testing and marking*
- *Part 2: Aerosol production, measuring equipment, particle-counting statistics*
- *Part 3: Testing flat sheet filter media*
- *Part 4: Test method for determining leakage of filter element — Scan method*
- *Part 5: Test method for filter elements*

Introduction

ISO 29463 (all parts) is derived from EN 1822 (all parts) with extensive changes to meet the requests from non-EU p-members. It contains requirements, fundamental principles of testing and the marking for high-efficiency particulate air filters with efficiencies from 95 % to 99,999 995 % that can be used for classifying filters in general or for specific use by agreement between users and suppliers.

ISO 29463 (all parts) establishes a procedure for the determination of the efficiency of all filters on the basis of a particle counting method using a liquid (or alternatively a solid) test aerosol, and allows a standardized classification of these filters in terms of their efficiency, both local and overall efficiency, which actually covers most requirements of different applications. The difference between ISO 29463 (all parts) and other national standards lies in the technique used for the determination of the overall efficiency. Instead of mass relationships or total concentrations, this technique is based on particle counting at the most penetrating particle size (MPPS), which, for micro-glass filter mediums, is usually in the range of 0,12 µm to 0,25 µm. This method also allows testing ultra-low penetration air filters, which was not possible with the previous test methods because of their inadequate sensitivity. For membrane filter media, separate rules apply, and are described in ISO 29463-5:2011, Annex B. Although no equivalent test procedures for testing filters with charged media is prescribed, a method for dealing with these types of filters is described in ISO 29463-5:2011, Annex C. Specific requirements for test method, frequency, and reporting requirements can be modified by agreement between supplier and customer. For lower efficiency filters (group H, as described below), alternate leak test methods noted in ISO 29463-4:2011, Annex A, can be used by specific agreement between users and suppliers, but only if the use of these other methods is clearly designated in the filter markings as described in ISO 29463-4:2011, Annex A.

There are differences between ISO 29463 (all parts) and other normative practices common in several countries. For example, many of these rely on total aerosol concentrations rather than individual particles. For information, a brief summary of these methods and their reference standards are provided in ISO 29463-5:2011, Annex A.

High-efficiency filters and filter media for removing particles in air —

Part 2:
Aerosol production, measuring equipment and particle-counting statistics

1 Scope

This part of ISO 29463 specifies the aerosol production and measuring equipment used for testing high-efficiency filters and filter media in accordance with ISO 29463-3, ISO 29463-4 and ISO 29463-5, as well as the statistical basis for particle counting with a small number of counted events. It is intended to be used in conjunction with ISO 29463-1, ISO 29463-3, ISO 29463-4 and ISO 29463-5.

2 Normative references

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

ISO 29463-1, *High-efficiency filters and filter media for removing particles in air — Part 1: Classification, performance, testing and marking*

ISO 29463-3, *High-efficiency filters and filter media for removing particles in air — Part 3: Testing flat sheet filter media*

ISO 29463-4:2011, *High-efficiency filters and filter media for removing particles in air — Part 4: Test method for determining the leakage of filter element — Scan method*

ISO 29463-5:2011, *High-efficiency filters and filter media for removing particles in air — Part 5: Test method for filter elements*

ISO 29464[1], *Cleaning equipment for air and other gases — Terminology*

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[1] To be published.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 29463-1, ISO 29464, and the following apply.

3.1
counting efficiency
expression of that proportion of the particles of detectable size suspended in the volume flow under analysis that make their way through the measured volume and are counted by the particle counter

EXAMPLE The ratio of the concentration measured to actual aerosol concentration.

NOTE The counting efficiency depends on the particle size, and decreases progressively in the proximity of the lower detection limit of the particle counter.

4 Aerosol production

When testing a filter, a test aerosol with liquid particles shall be used as reference test method in accordance with ISO 29463-1. Alternatively, a solid PSL aerosol may be used for local efficiency (leak) testing (see ISO 29463-4:2011, Annex E).

The testing of high-performance filters (ISO 65 U and higher) requires methods of aerosol production with high production rates (10^{10} s^{-1} to 10^{11} s^{-1}), in order to provide statistically significant measurements downstream of the filter.

By adjusting the operating parameters of the aerosol generator, it shall be possible to adjust the mean particle diameter of the aerosol so that it is equal to the MPPS. The concentration and the size distribution of the aerosol produced shall remain constant throughout the test.

4.1 Aerosol substances

A suitable aerosol substance for the reference test method is a liquid with a vapour pressure that is so low at the ambient temperature that the size of the droplets produced does not change significantly due to evaporation over the time scale relevant for the test procedure (in the order of a few seconds).

4.1.1 Possible substances include, but are not limited to,

- DEHS,
- PAO,
- paraffin oil (low viscosity).

4.1.2 The most critical properties of a possible aerosol substance are the following, which should not differ significantly from the values given for the three substances suggested in Table 1:

- index of refraction;
- vapour pressure;
- density.

Standard laboratory safety regulations shall be observed when handling these substances. It shall be ensured by means of suitable exhaust systems and air-tight aerosol ducting systems that the test aerosols are not inhaled. In case of doubt, the safety data sheets for the appropriate substances shall be consulted.

Table 1 — Important data for aerosol substances at 20 °C

Trivial name	DEHS	PAO[a]	Paraffin oil (low visc.)
Chemical designation	Sebacic acid-bis(2-ethylhexyl) ester (e.g. CAS No. 122-62-3)	Poly-alpha-olefin (e.g. CAS[b] No. 68649-12-7)	Mixture (e.g. CAS # 64742-46-7)
Trivial name	Diethylhexylsebacate	Polyalphaolefin	Paraffin oil
Density, kg/m^3	912	800 to 820 (820[c])	843
Melting point, K	225	~280	259
Boiling point, K	529	650 to 780 (674[c])	526
Flash point, K	>473	445 to 500	453
Vapour pressure at 293 K, kPa	1,9 < 0,1 kPa at 423 K	0,1 to 0,13	<0,1
Dynamic viscosity, kg/m·s	0,022 to 0,024	0,003 1 to 0,003 4 at 373 K 0,014 at 313 K[c]	0,026 0,002 5 to 0,003 8 at 313 K
Kinematic viscosity, mm^2/s	—	3,8 to 4,2 at 373 K	3,0 to 4,5 at 313 K
Index of refraction/wavelength, nm	1,450/650 1,452/600 1,4535/550 1,4545/500 1,4585/450 1,475/400	(1,455 6[c])	(1,466[c])

[a] US Patents 5,059,349, 5,059,352, and 5,076,965 describe and restrict the use of PAO for filter testing.

Material properties of PAO are as given in Japan JACA Standard No. 37-2001 and ISO 14644-3.

[b] CAS #, Chemical Abstract Service Registry Number, substances have been registered in Chemical Abstract, issued by American Chemical Society.

[c] Data for “Emery 3004” as a specific example of a PAO.

Source: Crosby, David W., *Concentration produced by a Laskin nozzle generator, a comparison of substitute materials and DOP*, 21st DOE/NRC Nuclear Air Cleaning Conference.

4.2 Producing mono-disperse aerosols

4.2.1 Condensation methods

Condensation methods are preferred for the creation of mono-disperse aerosols, i.e. the particles are formed by condensation from the vapour phase. It is necessary to distinguish between heterogeneous and homogeneous condensation.

4.2.1.1 Heterogeneous condensation

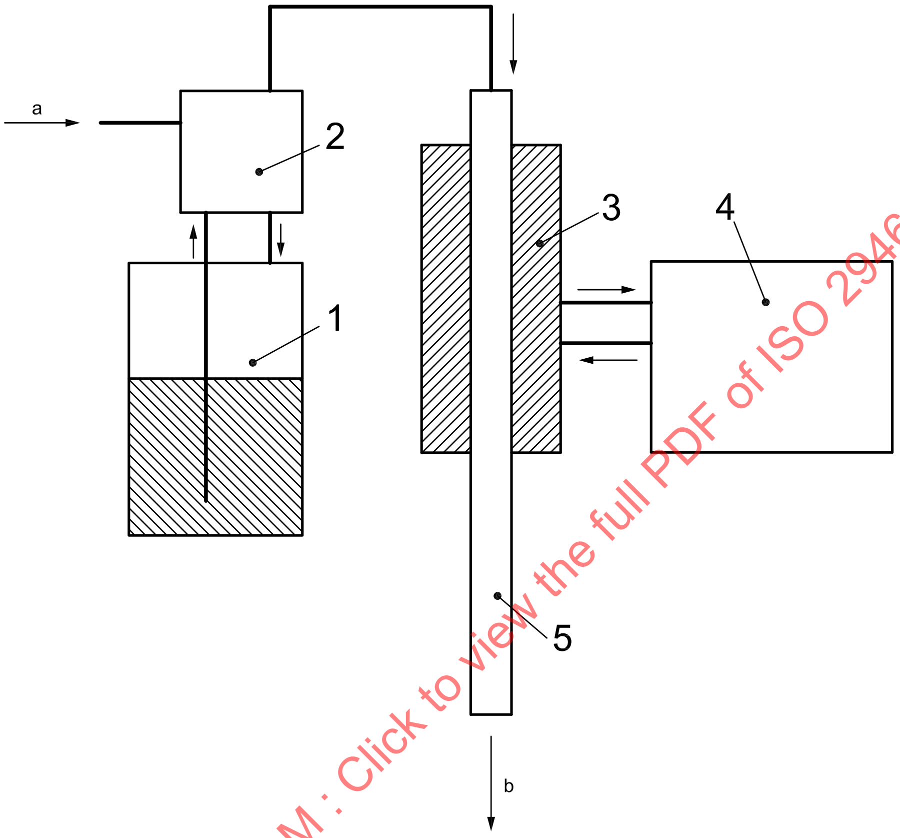
In the case of heterogeneous condensation, the vapour condenses at a relatively low level of super-saturation onto very small particles that are already present, the so-called condensation nuclei. The size distribution of the resultant aerosol has a geometrical standard deviation between $\sigma_g = 1{,}05$ and $\sigma_g = 1{,}15$.

One type of aerosol generator that operates using the principle of heterogeneous condensation and that is suitable for testing filters in accordance with this part of ISO 29463 is the Rapaport-Weinstock generator (see Figure 1).

4.2.1.1.1 Rapaport-Weinstock generator

NOTE See Figure 1.

An aerosol substance is nebulized through a nozzle, either as a pure substance or in solution, and the resultant poly-disperse aerosol is then vaporized along the heated section of a glass tube. Residual nuclei of the impurities in the material remain.



Key

1 liquid reservoir
2 nebulizer
3 vaporization section
4 thermostat
5 condensation section

[a] Compressed air.
[b] Aerosol.

Figure 1 — Structure of the Rapaport and Weinstock aerosol generator

In the subsequent condensation section, the aerosol substance then condenses on these nuclei to form a mono-disperse aerosol (see also Reference [1]).

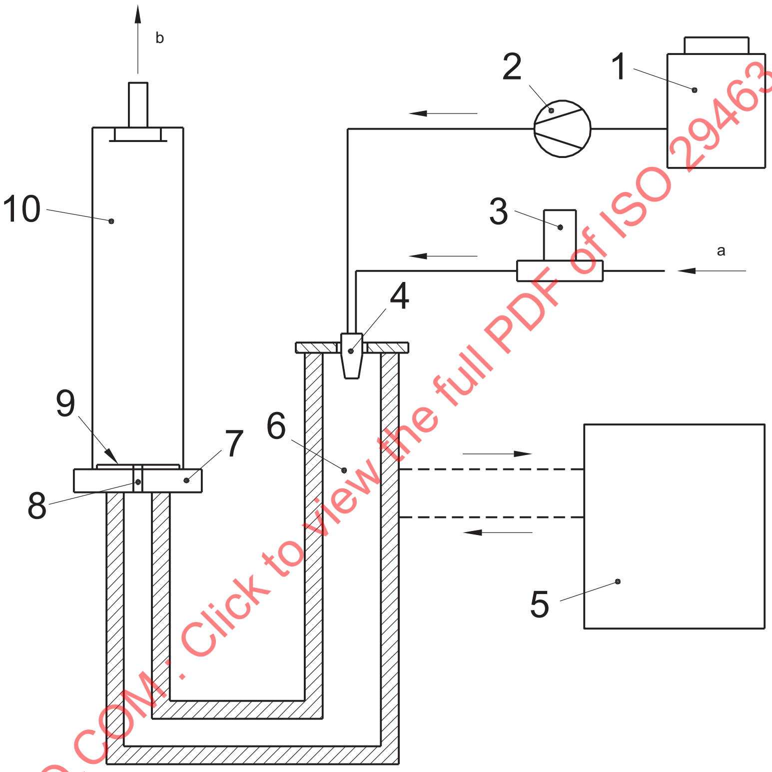
The particle diameter of this aerosol is determined by the mixing ratio of aerosol substance and solvent. The final aerosol contains the solvent used (e.g. propanol) as a vapour.

Generators of this type achieve particle production rates of 10^9 s^{-1}; the particle diameter can be adjusted between approximately 0,1 µm and 1,5 µm.

4.2.1.2 Homogeneous condensation

At higher levels of super-saturation, clusters of vapour molecules form spontaneously without the presence of condensation nuclei, and these then grow to particles that are some nanometres in diameter (homogeneous condensation). Larger particles then form as a result of coagulation of these particles with one another. The resultant size distribution has a standard deviation of $\sigma_g \sim 1{,}5$ independent of the median particle size, and can thus only be referred to as quasi-mono-disperse. On the other hand, rates of production of particles achieved can be as much as two orders of magnitude larger than those possible using heterogeneous condensation (more than 10^{11} s^{-1}).

Figure 2 shows the structure of a free-jet condensation aerosol generator that makes use of this principle.



Key

1	DEHS tank
2	pump
3	flow controller
4	ultra-sonic nebulizer
5	thermostat
6	vaporization pipe with heater and insulation
7	sheath air
8	nozzle
9	sintered metal plate
10	coagulation section

[a] Nitrogen.

[b] Aerosol.

Figure 2 — Set-up of a free-jet condensation aerosol generator

A pump delivers aerosol substance to an ultrasonic nebulizer at a defined rate. The relatively large (> 20 µm) droplets that are produced are then vaporized in a heated pipe. The concentration of residual nuclei is so low that they do not influence the subsequent homogeneous condensation process. The hot stream of nitrogen carrying the vapour then passes through a nozzle into a cold, laminar flow of sheath air. The turbulent mixing of the free jet with the cold air produces the super-saturation necessary for the homogeneous condensation.

The particle size and particle concentration can be adjusted by varying the volume flow rates of the aerosol substance (DEHS), nitrogen and envelope air.

4.2.2 Particle size classification

Using a differential mobility analyser as described in 5.3, it is possible to separate a fraction with almost the same electrical mobility from a poly-disperse aerosol (see also Reference [2]). Provided all these particles carry only a single electrical charge, then this mono-mobile fraction is also mono-disperse. If necessary, larger particles that carry a multiple charge, and that thus have the same electrical mobility as the single-charged particles, shall be removed from the poly-disperse input aerosol by suitable means.

Since the proportion of singly charged particles in the relevant size range is less than 10 %, from which only a narrow size band is selected, then the number concentration of the mono-disperse output aerosol is lower than the input concentration by a factor of at least 100. As a consequence, this method of producing mono-disperse aerosols is suitable only for the measurement of the particle size efficiency of the filter medium (see ISO 29463-3).

The degree of mono-dispersity achieved by this method can be described by a geometrical standard deviation of $\sigma_g < 1{,}1$. In practise, however, the operating parameters are often amended to increase the particle concentration at the expense of a greater standard deviation.

4.3 Generating poly-disperse aerosols

Poly-disperse liquid aerosols are usually produced by nebulizing the aerosol substance through a binary nozzle using compressed air.

A subsequent inertial separator, in the form of baffle plates or a cyclone separator, serves to precipitate larger particles and to reduce the range of the size distribution. The geometrical standard deviation of the distribution generated lies between 1,6 and 2,5. The particle diameter can be influenced to a small degree by changing the operating pressure of the nozzle. Greater influence on the particle size is usually achieved by dissolving the aerosol in a volatile solvent (e.g. propanol) before nebulization. When the solvent evaporates, it leaves behind particles whose size is governed by the ratio of aerosol substance to solvent that was used.

It is comparatively simple to increase the particle production rate by using a number of jets in parallel.

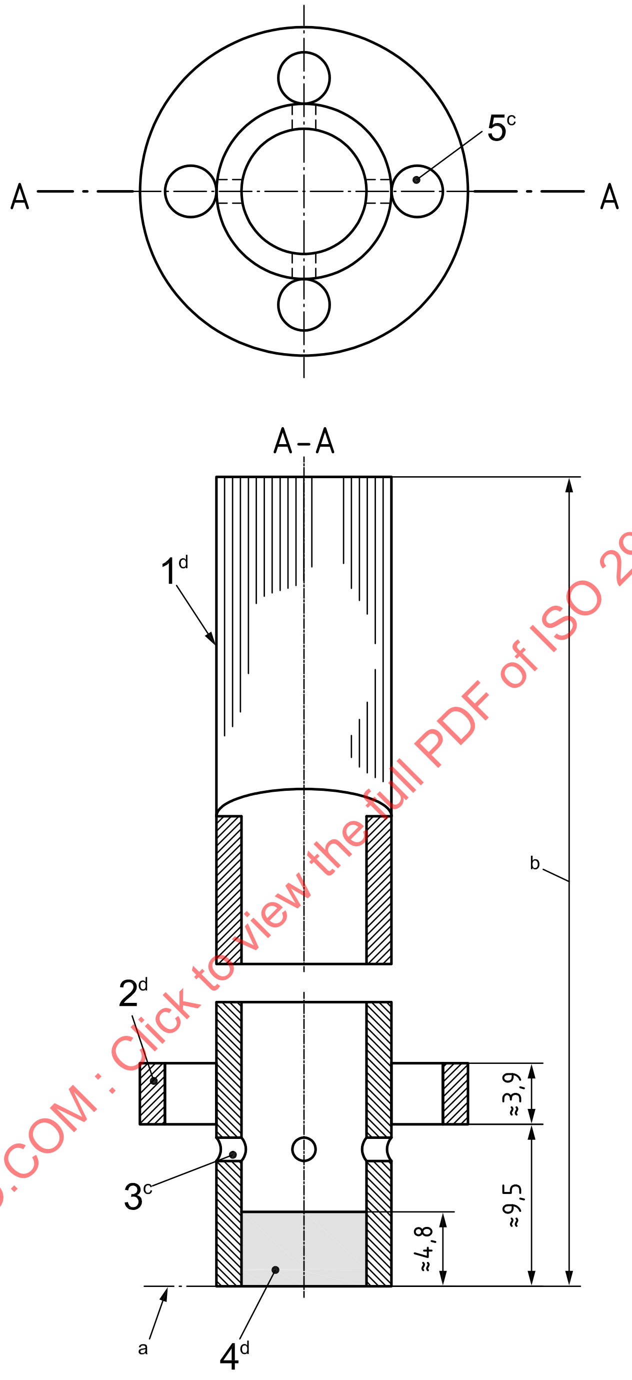
The maximum rate of particle production that can be achieved using one nozzle is $5 \times 10^{10}\ \text{s}^{-1}$.

NOTE A typical jet nebulizer is described, for example, in Reference [3].

Where higher aerosol outputs are desired (ISO 29463-5), a Laskin Nozzle aerosol generator is recommended.

4.3.1 Laskin Nozzle poly-disperse aerosol generator

The Laskin Nozzle aerosol generator system uses a nozzle to generate a poly-disperse aerosol from a liquid, such as DOP, DEHS or PAO and employs a source of compressed gas (see also Reference [4]). The generator creates an aerosol having a mass mean diameter of approximately 0,45 µm, a light-scattering geometric diameter of approximately 0,72 µm, and a light-scattering mean droplet-size distribution as shown in Figure 3 (see also Reference [4]).



Key

1 brass tubing, 9,5 mm (3/8 in) OD × 1,7 mm (0,065 in) wall
2 brass collar, 15,9 mm (5/8 in) OD, silver brazed to tubing 1
3 radial holes, 1 mm (0,04 in) diameter, 1,6 rad (90°) apart; top edge of holes just touching bottom of collar (4 required)
4 brass plug – Silver braze in place (full penetration)
5 2 mm (0,08 in) diameter longitudinal holes next to tube in line with radial holes (4 required)

[a] Approximately 12,7 mm (1/2 in) above bottom of can.
[b] Length variable to suit installation.
[c] Tolerances are ±0,05 mm for the dimensions on the holes.
[d] Tolerances are ±0,51 mm for all other dimensions.

Figure 3 — Details of a Laskin Nozzle[4]

4.3.2 Laskin Generator — Verification of pressure-flow characteristics

Detailed procedures are found in IEST RP CC013. An additional gravimetric sampling method is also included to determine the actual challenge in micrograms per litre generated by each Laskin nozzle.

4.4 Neutralization of aerosols

Since electrically charged particles are removed more effectively by filters than are uncharged particles, electrically neutral particles should be used for testing filters. A neutral state of charge is generally understood to be the stationary equilibrium achieved when charged aerosol particles are brought together with a sufficient number of positive and negative gas ions. This is usually carried out by ionizing the carrier gas of the aerosol using a radioactive source or by a corona discharge. The low level of residual charge in the aerosol after this neutralization can be neglected for the filtration process.

Aerosol particles become electrically charged when there is a division of charges in the course of production (e.g. nebulization). This occurs, above all, in the case when polar liquids such as water (or, to a lesser extent, propanol) are nebulized. In the case of pure DEHS or DOP, relatively few charges occur. Condensation processes without prior nebulization generate virtually charge-free aerosols, which do not have to be neutralized.

In order to ensure neutralization of the highly concentrated aerosols required for testing filters, it is necessary for the neutralizers to have a sufficiently high concentration of ions. The aerosol shall also be kept in the ionizing atmosphere for a sufficiently long period (see also Reference [5]).

4.5 Minimum performance parameters for aerosol generators

The following apply:

a) generators for testing media:

   1) particle production rate: 10^6 s^{-1} to 10^8 s^{-1},

   2) particle diameter adjustable over the range: 0,04 µm to 1,0 µm;

a) generators for testing filter elements:

   1) particle production rate: 10^8 s^{-1} to 10^{11} s^{-1},

   2) particle diameter adjustable over the range: 0,08 µm to 1,0 µm.

4.6 Sources of error

Care shall be taken that the pressure of the gas supply for the aerosol generators (compressed air, nitrogen) remains constant. The supplied gas shall be free of particles and of a sufficiently low humidity.

Nebulizer nozzles can gradually become blocked, leading to unnoticed changes in the nebulization characteristics.

Condensation generators are sensitive to variations in temperature along the condensation path arising, for example, due to draughts. Further aerosol substances that are subjected to higher temperatures for long periods can undergo changes in their physical and chemical properties and, hence, should be replaced at regular intervals.

4.7 Maintenance and inspection

Aerosol generators shall be maintained regularly in accordance with the manufacturer's instructions.

Suitable measuring systems in accordance with Clause 5 shall be used to check the size distribution and the constancy of the production rate at the intervals specified in Clause 6.

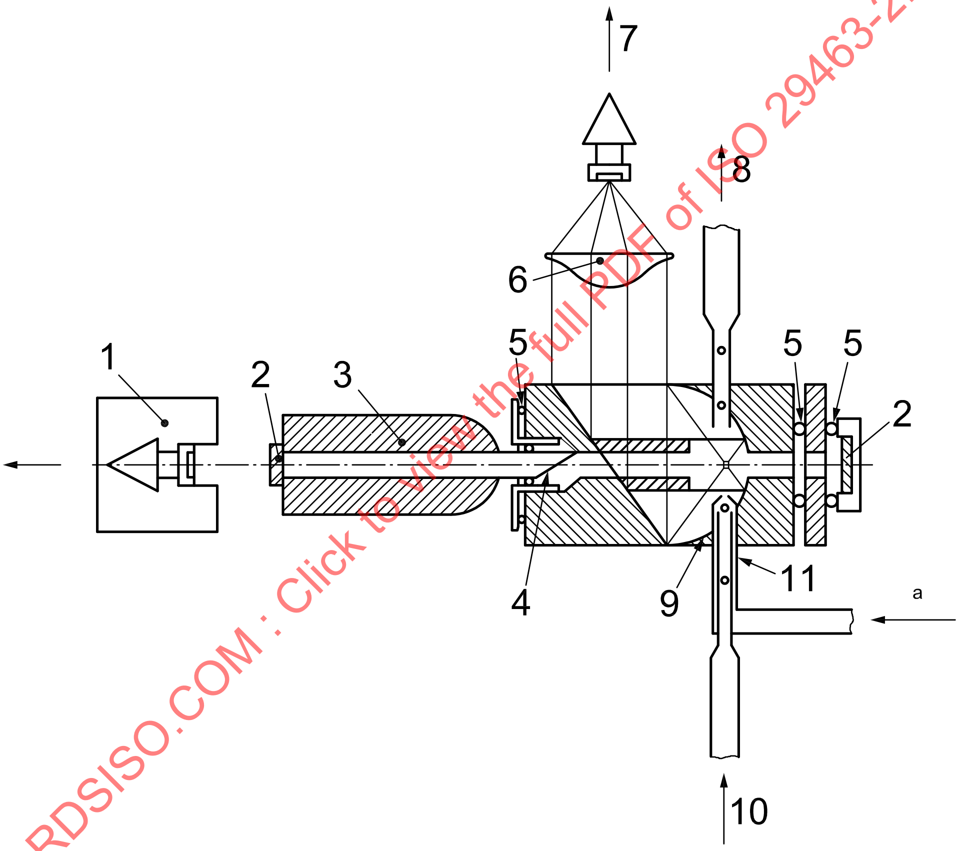
5 Measuring devices

5.1 Optical particle counters

5.1.1 Operation

In an optical particle counter, the particles are led individually through an intensively illuminated measuring volume. When passing through the measuring volume, the particle scatters light, which is detected at a defined spatial angle by a photo detector and transformed into an electrical pulse. The level of this pulse corresponds to the size of the particle, and the number of pulses per unit time with the particle concentration in the air volume analysed.

Figure 4 shows an example of the general structure of an optical particle counter with a laser light source.



Key

1 reference detector
2 laser mirror
3 He-Ne laser
4 Brewster-window
5 gasket ring
6 aspherical lens
7 photo detector
8 aerosol outlet
9 parabolic mirror
10 aerosol inlet
11 aerosol nozzle

[a] Sheath air.

Figure 4 — Structure of an optical particle counter — Example

5.1.2 Minimum performance parameters

The following apply.

a) Optical particle counters should comply with requirements in ISO 21501-1 and/or ISO 21501-4.

b) Measuring range for the particle size: 0,1 µm to 2,0 µm (for 50 % counting efficiency) with at least one channel with a mean size smaller than the MPPS of the filter under test; preferably half the size of MPPS.

c) Minimum number of particle size classes between 0,1 µm and 0,3 µm:

   1) for testing the filter medium, five size classes;

   2) for testing the filter element, two size classes. From a practical point of view, the 0,1 to 0,2 and 0,2 to 0,3 channel size ranges common to many commercial counters can meet this requirement.

d) Zero count rate: $<1\ \text{min}^{-1}$.

5.1.3 Sources of error and limit errors

The particle size determined by an optical particle counter is a scattered-light equivalent diameter (see also Reference [7]), which is dependent not only on the geometrical particle size but also on the shape of the particle and the optical properties of the particle material. The nature of this dependency varies according to the constructional type of the particle counter. Measurement results can be compared between two different particle counters only if these have been calibrated for the particle material in question.

If the particle concentration is too high, so-called coincidence errors occur. This means that several particles enter the measuring volume at the same time, and are interpreted as one larger particle. Suitable dilution measures shall be adopted (see 5.5) to ensure that the maximum concentration is not exceeded. The maximum concentration for a specific particle counter can be determined by generating an aerosol at a constant rate into a known volume of air. The concentration should provide approximately 20 000 counts per minute to 30 000 counts per minute in a precise measured volume of air. Once the concentration is determined, continue the same particle generation but reduce the airflow volume. Using Equation (1), compare the new higher measured concentration to calculated concentration.

$$C_c \times V_c = C_m \times V_m \tag{1}$$

where

C_c is the calculated concentration;

V_c is the calculated volume;

C_2 is the measured concentration;

V_2 is the measured volume.

If the measured and calculated values correspond, repeat the procedure at a new, lower airflow rate. Continue the process until the measured concentration is 95 % of the calculated concentration. This is the maximum aerosol concentration that can be measured with that counter with a ≤5 % coincidence loss.

The volume flowmeter on the counter shall be calibrated against a traceable standard.

5.1.4 Maintenance and inspection

Optical particle counters shall be regularly maintained and inspected by qualified personnel. This also includes a calibration using PSL (polystyrene latex) aerosols.

The inspection of the correct operation by the user shall include a check of the flow rate, as well as a regular check of the zero count rate by inserting a suitable upstream filter of class ISO 35 H or higher.

If several counters are available, a further operational check is possible by comparative measurements of a test aerosol.

5.1.5 Calibration

Optical particle counters are normally calibrated using PSL particles (see also References [8] and [9]). A calibration with other, usually liquid aerosol materials (e.g. DEHS) is possible using a vibrating orifice aerosol generator (see also Reference [10]) or independent aerosol sizing equipment.

The determination of the counting efficiency requires the production of mono-disperse aerosols of known concentration (e.g. with the aid of a differential mobility analyser and an aerosol electrometer or condensation particle counter (see also Reference [2]), so that this is usually possible only in well-equipped aerosol laboratories. As an alternative, the counting efficiency can also be tested using PSL aerosols by means of comparative measurements with another optical particle counter. In this case, the lower measuring limit of the comparison counter shall be lower than that of the counter being calibrated.

5.2 Condensation particle counter

5.2.1 Operation

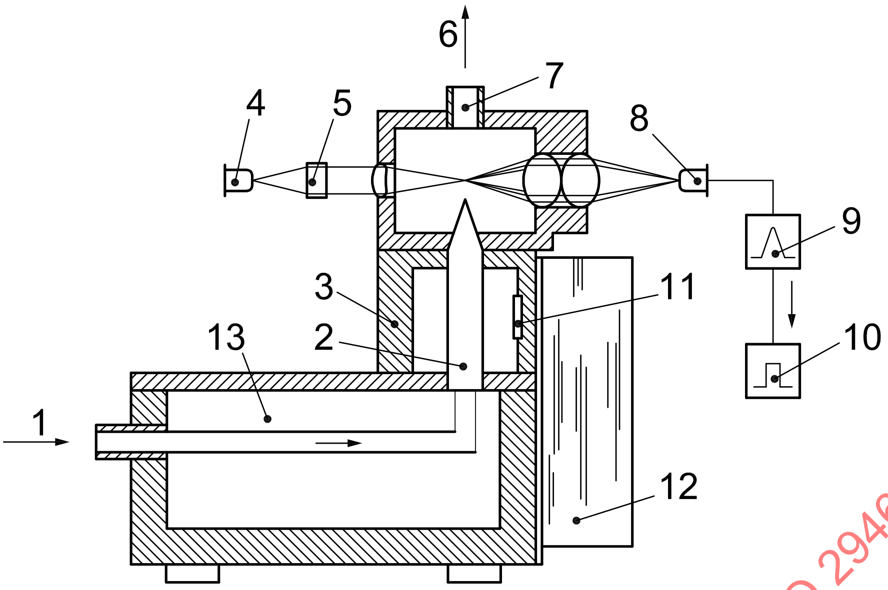
In a condensation particle counter (CPC), particles that are too small for direct optical measurement are enlarged by condensation of a vapour before being subjected to light scattering or light extinction measurements. The concentration of the resultant droplets is determined by counting or by photometry. However, using this method, the information about the original size of the particles is lost.

The super-saturation required for the vapour condensation can be produced for CPCs with continuous flow in two ways.

The first is that the aerosol is first saturated with the vapour at a temperature above the ambient temperature, and then cooled by contact with a cold pipe wall (external cooling) (see also Reference [11]). Figure 5 shows the structure of such a device. The aerosol flows through a pipe in which it is saturated with butanol vapour, and then through a condensation pipe in which it is cooled from outside. The resultant drops are then registered by a scattered light sensor.

In the second case, the aerosol at ambient temperature is mixed with a warmer, particle-free, vapour saturated air flow. The mixing leads to super-saturation and condensation (see also Reference [12]). This principle is shown in Figure 6.

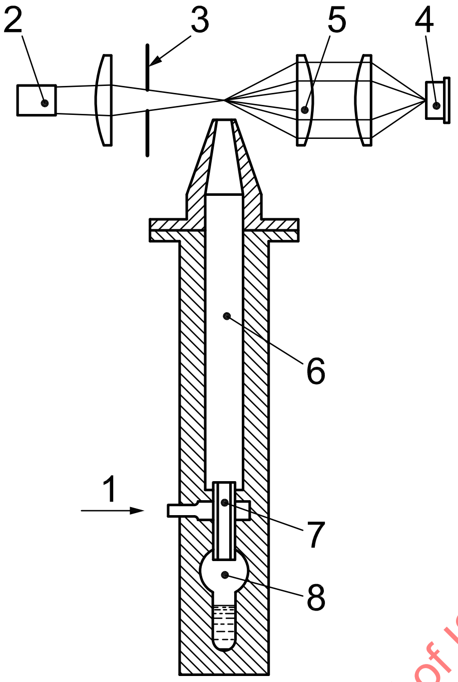
Here the aerosol is led directly to a mixing nozzle by the shortest route. The drops of propylene glycol that form along the condensation section are again registered by a scattered light sensor.



Key

1	aerosol inlet
2	condensation pipe
3	thermal insulation
4	laser diode
5	lens system
6	aerosol outlet
7	nozzle
8	photo detector
9	analogue signal
10	digital signal
11	peltier element
12	heat sink (free convection)
13	saturation tube and alcohol reservoir

Figure 5 — Structure of a condensation particle counter using the principle of external cooling



Key

1 aerosol inlet
2 laser diode
3 aperture
4 photo detector
5 light trap
6 condensation section
7 mixing nozzle
8 vapour inlet

Figure 6 — Structure of a condensation particle counter using the mixing principle

5.2.2 Minimum performance parameters

The following apply:

— measuring range for the particle size: 50 nm to 0,8 µm (for 100 % counting efficiency);

— zero count rate: $<1 \text{ min}^{-1}$.

5.2.3 Sources of error and limit errors

If a CPC is used in the counting mode, then the determination of the particle concentration depends primarily on the accuracy of the sampling volume flow rate. Depending on the measuring or control method used, this lies between 2 % and 5 %.

In the photometric mode of operation, the relationship between the number concentration and the output signal also depends on the size of the droplets produced. Operation in the photometric mode should be avoided because, in extreme cases, the measuring inaccuracies can be as large as 100 % (see also References [13] and [14]).

5.2.4 Maintenance and inspection

The level of the vapour substance in the reservoir shall be checked at regular intervals. The vapour substance shall be exchanged at intervals, since water accumulates in it and changes its thermodynamic properties.

The inspection of correct operation shall include a check of the flow, as well as a regular check of the zero count rate by inserting a suitable upstream filter of class ISO 35 H or higher.

If several counters are available, a further operational check is possible by comparative measurements of a test aerosol.

5.2.5 Calibration

A condensation particle counter operating in the counting mode can be regarded as an independent measuring method that requires nearly no calibration. It is necessary to check only the sampling volume flow from time to time by comparison, for example, with a floating element flowmeter.

The calibration of a CPC in its photometric mode and the determination of its counting efficiency require the production of mono-disperse aerosols of known concentration (using a differential mobility analyser and an aerosol electrometer; see also Reference [2]) and is usually possible only in well-equipped aerosol laboratories.

5.3 Differential mobility analyser

5.3.1 Operation

In a differential mobility analyser (DMA), particles can be classified according to their electrical mobility. The electrical mobility of a particle is a function of the particle size and the number of electrical charges on the particle. Figure 7 shows the structure of a DMA.

The mobility analyser itself consists of two concentric cylindrical electrodes. The poly-disperse aerosol being classified is first brought to a defined state of electrical charge by the attachment of gas ions, and finally introduced through a narrow circular gap along the outer electrode into the DMA. Isokinetic, particle-free air is introduced along the inner electrode. Under the influence of an electric field between the electrodes, particles with a single charge migrate at right angles to the flow direction towards the central electrode, whereas the particles with the opposite charge polarity are attracted to the outer electrode. At the lower end of the inner electrodes is a narrow slit through which a partial flow of particles with a defined electrical mobility is extracted.

An appropriate choice of size distribution of the poly-disperse primary aerosol ensures that these particles all have only a single electrical charge and are thus of the same size.

5.3.2 Minimum performance parameters

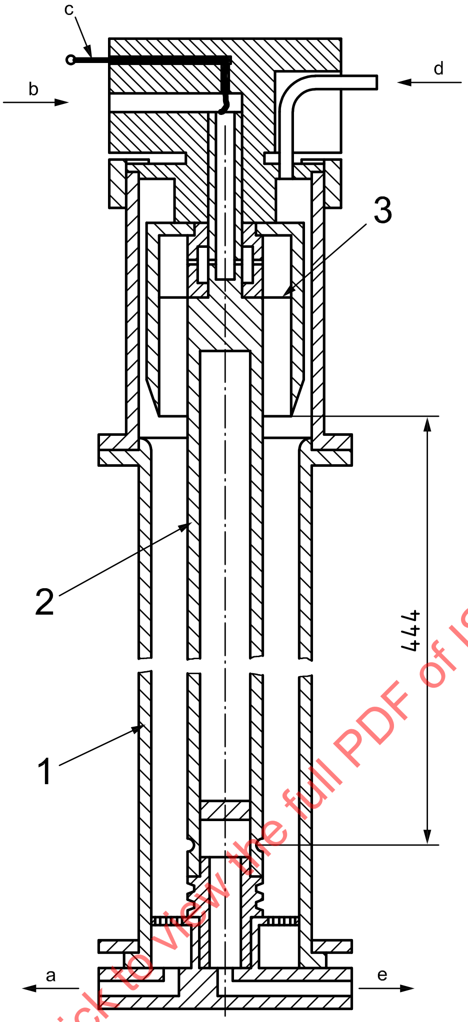
The following apply:

- operational particle size range: 10 nm to 0,8 µm;
- geometrical standard deviation of the (quasi) mono-disperse aerosol: <1,3.

5.3.3 Sources of error and limit errors

If the size distribution of the primary aerosol is not precisely adapted to the size of the mono-disperse output aerosol, then in the particle size range above 0,1 µm there can be a considerable proportion of larger particles with multiple charges in the output aerosol.

Leaks and maladjusted volume flow rates can lead to a drift from the selected particle size and inadequate mono-dispersity.



Key

1	outer electrode
2	central electrode
3	flow laminator

[a] Excess air.

[b] Sheath air.

[c] High voltage.

[d] Poly-disperse aerosol.

[e] Mono-disperse aerosol.

Figure 7 — Structure of a differential mobility analyser

5.3.4 Maintenance and inspection

Since particles are deposited on the electrodes in the course of operation these shall be cleaned at regular intervals.

After every cleaning, the apparatus shall be tested for leaks in accordance with the manufacturer's instructions. From time to time, the calibration of the internal gas flowmeters shall be checked. The correct adjustment of volume flow rates in the apparatus is of the greatest importance for its proper operation. If particles are observed at the outlet of the apparatus when there is no potential difference between the electrodes, then it is necessary to check the volume flow rates.

5.3.5 Calibration

It is possible to calculate the diameter of the mono-disperse output aerosol from the known geometry of the apparatus, the volume flow rate and the applied potential difference. For this reason, the apparatus is often used as a calibration standard. The proper function of the apparatus should be checked at regular time intervals by using reference filters with known efficiency at specific particle sizes. If it seems that the apparatus is not working properly, a comparison with another device of the same type, or the use of PSL aerosols (see also References [8] and [15]) can be necessary to calibrate the apparatus.

5.4 Particle size analysis system on the basis of differential mobility analysis

5.4.1 Operation

The differential mobility particle sizer (DMPS) described in this subclause involves a combination of a DMA and a CPC. If the number concentration of the mono-disperse aerosol is measured at the output of the DMA with a number of suitable central electrode voltages, then the size distribution of the initial poly-disperse aerosol can be calculated if the distribution of the electrical charges on the aerosol particles is known. The measurement process of the DMPS is controlled by the same computer that evaluates the measurement data.

5.4.2 Minimum performance parameters

The following apply:

a) sampling volume flow rate: >0,3 l/min;

b) measuring range:

   1) for the particle size: 10 nm to 0,8 µm,

   2) for the particle concentration: 10^3 cm^{-3} to 10^6 cm^{-3}.

5.4.3 Sources of errors and error limits

In order to use this measuring method, it is necessary to know the charge distribution for the aerosol. The charging mechanism of the particles can be disturbed by the composition of the carrier gas (e.g. alcohol molecules), but also by concentrations of particles that are too high.

5.4.4 Maintenance and inspection

See 5.2.4 (CPC) and 5.3.4 (DMA).

5.4.5 Calibration

See 5.2.5 (CPC) and 5.3.5 (DMA).

5.5 Dilution systems

5.5.1 Operation

Dilution systems reduce the concentration of an aerosol to a defined extent by the addition of a particle-free gas (usually air). Typically, dilution systems sample a precise small volume of raw aerosol. The remaining sample volume of the counter being used comes from HEPA-filtered air. The dilution behaviour for the relevant particle size range shall be independent of the particle size and shall be constant over time.

The clean air can be obtained by filtering a partial flow of the aerosol. The unfiltered part is usually fed along a capillary and the drop of pressure over this capillary is used to check the volume flow rate (see also Reference [15]).

Another possibility is the introduction of external particle-free air, for example, from a compressed air line.

Some systems operate on the ejector principle. The pure air flow creates a pressure drop at a constriction, which draws in the aerosol being diluted (see also Reference [17]). The dilution ratio of these systems is defined solely by the geometry of the set-up and, as a rule, cannot be altered by the operator.

A further option is the controlled mixing of an aerosol flow with a pure-air flow without using the ejector effect. The volume flow of the aerosol in this case shall be determined by taking a balance of the other volume flows. The dilution ratio can be freely adjusted within certain limits.

By means of a cascade system using several dilution systems, high (up to 10 000) dilution factors can be achieved with a high level of accuracy (see also References [16] and [18]).

5.5.2 Minimum performance parameters

The following apply:

a) volume flow adjustable to the relevant measuring device;

b) dilution ratio between 10 and 10 000 depending on the initial gas concentration and the measuring device used;

c) accuracy: 10 % of the dilution ratio;

d) zero count rate: $<10\ \text{min}^{-1}$ (measured with an absolute filter at the intake of the dilution system).

5.5.3 Sources of error and limit errors

Clogging of the capillaries and the nozzles can alter the dilution ratio.

5.5.4 Maintenance and inspection

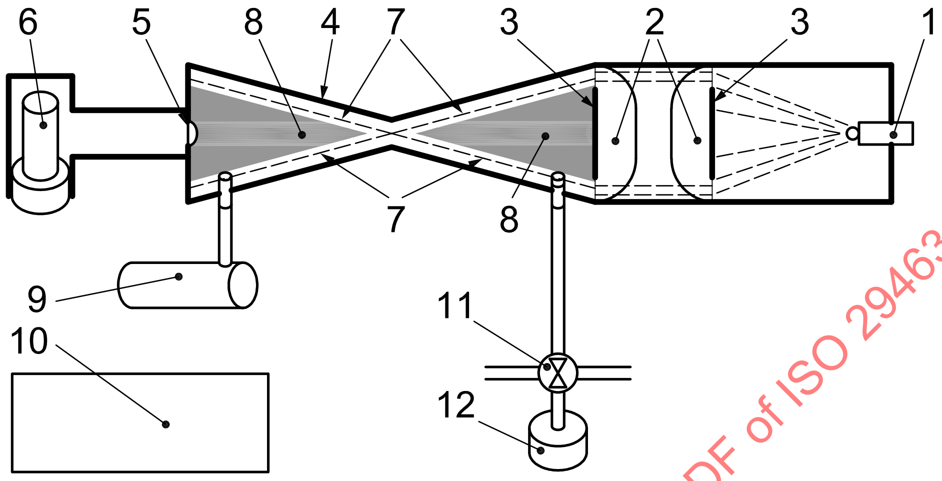
Installed filters shall be replaced at the intervals specified by the manufacturers. If, on testing the system with particle-free air, it is found to “produce” particles, then the dilution system shall be cleaned. The dilution ratio shall be checked from time to time, for example by measuring the particle concentration at the intake and the outlet of a dilution stage.

5.6 Aerosol photometer

An aerosol photometer is an aerosol measurement device that is also based on light scattering. The photometer is the accepted device for the alternate method for leak testing of group H filters as prescribed in ISO 29463-4:2011, Annex B. Unlike a single particle counter, a photometer measures the total aerosol concentration from the light scattering intensity of the entire aerosol instead of individual particles. Since the intensity of light scattered by the aerosol varies approximately with the cube of the particle diameter (within a definable size range), this device is often mistakenly assumed to measure aerosol mass or volume. However, due to this relationship with particle volume, these devices are usually calibrated against gravimetric measurement of aerosols of known size. Hence it is customary to use aerosol mass instead of particle size for filter performance testing using this device. As noted in Annex A, using the mass and the count-weighted particle size distribution interchangeably leads to erroneous results.

5.6.1 Operation

The aerosol photometer samples the upstream and downstream mass concentrations of a filter under test and converts the reading into a direct percentage of penetration. Particulate-free air is passed through the forward light-scattering chamber as the instrument is electrically balanced with respect to any incidental stray light. A response baseline is set as a basis of comparison, either from the sampled upstream concentration or using an internal reference circuit. The upstream concentration is set for a desired range between 10 µg/l to 100 µg/l of a known type of oil-based poly-disperse aerosol particles. Once the base line has been set, any subsequent downstream penetration reading is expressed as a percentage relative to that baseline. The range of concentration measurement is from 100 % to 0,000 1 %. The aerosol photometer may use several oil-based aerosols, providing that the aerosol photometer has been calibrated against that aerosol or that the manufacturer has published known correction factors for alternative aerosols. Since the instrument measures mass concentrations of particulates, the size, shape or colour of the aerosol is not critical, providing there is a sufficient number of them to be detected. Figure 8 shows the structure of an aerosol photometer.



Key

1	light source	7	cones of light
2	objective lenses	8	cones of darkness
3	light stops	9	vacuum pump
4	optics chamber	10	electronic processor and metering circuits
5	focusing lens	11	airflow selector valve, upstream, downstream, clear
6	photomultiplier detector	12	internal HEPA filter

Figure 8 — Structure of the aerosol photometer

5.6.2 Minimum performance parameters

The following apply:

a) sampling volume flow rate: 28,3 l/min ± 10 %;

b) measuring range: 0,000 1ug of PAO per litre of air, with upstream concentrations between 10 µg/l and 100 µg/l;

c) accuracy: 1 % of full scale for the decade or scale in use;

d) sensitivity/resolution: 0,001 µg/l;

e) detectable particle sizes: approximately 0,1 µm and larger.

5.6.3 Sources of errors and error limits

Since aerosol photometers are mass measurement devices, they are dependent upon receiving a sufficient concentration of upstream aerosol. Aerosol concentrations below 10 µg/l can create extraneous signal noise issues towards the lower end of the operating range of 0,000 1 %. The optics chamber is prone to collecting large-size particulate matter that falls out of the air stream. Particulate matter entrapped within the chamber can reflect light to the detection circuit, resulting in intermittent false penetration readings. Sampling system leaks can lead to erroneous penetration readings.

5.6.4 Maintenance and inspection

The handheld probe and sampling should be inspected daily for leaks. The sampling system capture screen should be inspected and cleaned daily or as necessary. The aerosol photometer should be able to maintain a stable 0,000 % reading at the highest sensitivity setting at the 10 µg/l internal reference setting when monitoring either three decimal places (0,000) or on the 0,1 % scale setting. The detection circuit linearity and stability may be tested by sampling untreated room air after setting the internal reference setting for 10 µg/l and 100 µg/l challenges, respectively. The two room air sample readings should be one log or one decade apart ±10 %.

5.6.5 Calibration

Aerosol photometers are normally calibrated using 100 µg/l aerosol source, sample rate, amplifier linearity and accuracy, and detection circuit linearity and stability tests.

Depending on the nature of the aerosol photometer used, the optics chamber and airflow sampling system typically require extensive teardown and cleaning during the calibration process to remove oil build-up and particulates on the optics, the chamber and all components upstream of the optics chamber. Calibration interval should be determined based upon the amount of use and levels of aerosol sampled through the aerosol photometer. Detailed aerosol photometer calibration procedures are found in IEST RP CC013.

5.7 Differential pressure measuring equipment

In order to determine the pressure drop across a filter, a pressure-measuring device can be used which either measures this directly (such as a liquid manometer or a membrane manometer) or measures it indirectly (such as an electrical or pneumatic measuring transducer). Electrical transducers require regular calibration.

Minimum performance parameters:

- accuracy: <3 % of the measured value;
- minimum resolution: 2,5 Pa.

5.8 Absolute pressure measuring equipment

The absolute pressure at the intake of the restrictor may be measured using a mercury barometer, aneroid barometer or a barometer with electrical sensor/transducer.

Minimum performance parameters:

- measuring range: 90 kPa to 120 kPa;
- accuracy: ±0,6 kPa;
- minimum resolution: 5 Pa.

5.9 Thermometers

The temperature may be determined using either a liquid thermometer or a thermometer with electrical sensor/transducer (see also Reference [19]).

Minimum performance parameters:

- measuring range: 273 K to 313 K;
- accuracy: 2 K.

5.10 Hygrometer

The relative humidity may be determined, in the simplest case, using a hair hygrometer. The use of more complicated equipment is also possible (electrolysis, LiCl dew-point hygrometer, dew-point mirror hygrometer, psychrometer, etc.; see also Reference [19].

Minimum performance parameters:

- measuring range: 25 % to 95 % relative humidity;
- accuracy: 5 % relative humidity.

6 Maintenance and inspection intervals

For the individual devices, the maintenance and inspection procedures specified in Table 2 shall be carried out at least once within the given time periods. The successful accomplishment of the annual instrument calibration shall be documented with individual calibration protocols.

Table 2 — Summary of the maintenance and inspection intervals

Item	Per filter	Daily	Weekly	Monthly	Annually	After changes[a]
Pressure difference	—	—	—	—	—	—
Zero adjustment	—	—	—	—	—	x
Absolute pressure	—	—	—	—	x	x
Temperature	—	—	—	—	x	x
Relative humidity	—	—	—	—	x	x
Laser particle counter	—	—	—	—	—	—
Zero count rate	x	—	—	—	—	—
Size determination	—	—	—	—	x	x
Counting efficiency	—	—	—	—	x	x
Coincidence error	—	—	—	—	x	x
Volume flow rate	—	—	—	—	x	x
DMA	—	—	—	—	—	—
Zero voltage check	—	x	—	—	—	x
Volume flow rates	—	—	—	—	x	x
Cleaning	—	—	—	x		x
CPC	—	—	—	—	—	—
Zero count rate	x	—	—	—	—	x
Counting efficiency	—	—	—	—	x	x
Coincidence error	—	—	—	—	x	x
Volume flow rate	—	—	—	—	x	x
Filling level	—	x		—	—	x
Aerosol generator	—	—	—	—	—	—
Size distribution	—	—	—	—	—	x
Stability	—	—	—	—	x	x
Neutrality	—	—	—	—	x	x
Dilution system	—	—	—	—	—	—
Zero count rate	—	x	—	—	—	x
Dilution factor	—	—	—	—	x	x

[a] Alteration to the test set-up or the relevant device.

7 Particle counting statistics

Counting particles is subject to statistical variation. The smaller the number of events that are counted, the lower is the level of confidence. The level of confidence can be estimated by the use of the Poisson distribution.

The following table gives limits for the 95 % two-sided confidence interval for a given number of events using the Poisson distribution.

Table 3 — Upper and lower limit of the 95 % confidence interval of a Poisson distribution for particle numbers

No. of particles	Lower limit	Upper limit	No. of particles	Lower limit	Upper limit
0	0,0	3,7	35	24,4	48,7
1	0,1	5,6	40	28,6	54,5
2	0,2	7,2	45	32,8	60,2
3	0,6	8,8	50	37,1	65,9
4	1,0	10,2	55	41,4	71,6
5	1,6	11,7	60	45,8	77,2
6	2,2	13,1	65	50,2	82,9
8	3,4	15,8	70	54,6	88,4
10	4,7	18,4	75	59,0	94,0
12	6,2	21,0	80	63,4	99,6
14	7,7	23,5	85	67,9	105,1
16	9,4	26,0	90	72,4	110,6
18	10,7	28,4	95	76,9	116,1
20	12,2	30,8	100	81,4	121,6
25	16,2	36,8	—	—	—
30	20,2	42,8	—	—	—

For example, if five particles are being counted, then Table 3 shows that 95 % of repeated measurements of the same object would produce measuring rates between 1,6 and 11,7.

For small counts, the limit values of the confidence interval are very asymmetrically distributed in terms of the number counted. For larger numbers, the Poisson distribution transforms into a symmetrical normal distribution. In these cases the 95 % confidence range may be calculated from Equation (2):

$$N_{95\,\%} = \pm 1{,}96 \times N^{1/2} \tag{2}$$

When calculating the filter efficiency and the penetration on the basis of the numbers of particles counted, the least favourable limit value of the confidence interval shall be determined and used as a basis for the calculation. This normally means that instead of the measured value, the lower limit value shall be used for the upstream measurement, and the upper limit value for the downstream measurement.

Care shall be taken that the limit value is determined on the basis of the primary counts, rather than derived quantities, such as particle concentrations or numbers in which dilution factors have already been included.

The Poisson statistics can be used to account only for errors arising from small numbers of counted particles. Where they can be determined, other random and systematic errors shall be reduced by additional corrections.