INTERNATIONAL STANDARD

ISO 23210

First edition
2009-08-01

Stationary source emissions — Determination of $PM_{10}/PM_{2,5}$ mass concentration in flue gas — Measurement at low concentrations by use of impactors

Émissions de sources fixes — Détermination de la concentration en masse de $PM_{10}/PM_{2,5}$ dans les effluents gazeux — Mesurage à des faibles concentrations au moyen d'impacteurs

Reference number
ISO 23210:2009(E)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

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 23210 was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 1, *Stationary source emissions*.

Introduction

In order to quantify the amount of PM_{10} and $PM_{2,5}$ particles in stationary source emissions or to identify the contribution sources of PM_{10} and $PM_{2,5}$ in ambient air, it is necessary to measure fine particulate matter in the flue gas of industrial sources.

This International Standard describes a measurement method for the determination of mass concentrations of PM_{10} and $PM_{2,5}$ emissions, which realizes the same separation curves as those specified in ISO 7708:1995 for PM_{10} and $PM_{2,5}$ in ambient air. The method is based on the principle of impaction. During sampling, the particle fraction is divided into three groups with aerodynamic diameters greater than 10 µm, between 10 µm and 2,5 µm and smaller than 2,5 µm.

The measurement method allows the simultaneous determination of concentrations of PM_{10} and $PM_{2,5}$ emissions. The method is designed for stack measurements at stationary emission sources.

The contribution of stationary source emissions to PM_{10} and $PM_{2,5}$ concentrations in ambient air can be classified as primary and secondary. Those emissions that exist as particulate matter within the stack gas and that are emitted directly to air can be considered “primary”. Secondary particulate consists of those emissions that form in ambient air due to atmospheric chemical reactions. The measurement technique in this International Standard does not measure the contribution of stack emissions to the formation of secondary particulate matter in ambient air.

This International Standard includes normative references to ISO 12141:2002. The corresponding requirements in ISO 12141:2002 are identical to those in European Standards EN 13284-1:2001 and EN 15259:2007.

Stationary source emissions — Determination of $PM_{10}/PM_{2,5}$ mass concentration in flue gas — Measurement at low concentrations by use of impactors

1 Scope

This International Standard specifies a standard reference method for the determination of PM_{10} and $PM_{2,5}$ mass concentrations at stationary emission sources by use of two-stage impactors. The measurement method is especially suitable for measurements of mass concentrations below 40 mg/m^3 as half-hourly averages in standard conditions (273 K, 1 013 hPa, dry gas). It is an acceptable method for the measurement in the flue gas of different installations, such as cement and steel production plants, as well as combustion processes.

This International Standard is not applicable to the sampling of flue gases that are saturated with water vapour.

This International Standard is not applicable where the majority of the particles are likely to exceed PM_{10}, for example, in the case of raw gases or plant operating failures.

NOTE 1 Measurements of particulate concentrations higher than 40 mg/m^3, as a half-hourly average in standard conditions (273 K, 1 013 hPa, dry gas), can lead to overloading of the collecting plates and backup filters and also could result in shorter sampling times.

NOTE 2 The collecting plates and backup filters can be used for further chemical analysis.

This International Standard cannot be used for the determination of the total mass concentration of dust.

NOTE 3 For data assessment purposes, it can be useful to perform measurements of total particulate matter in parallel to the PM_{10} and $PM_{2,5}$ measurements.

This International Standard describes the design, use and theory of round-nozzle impactors. It does not exclude other types of impactors, provided these systems meet the performance criteria specified in this International Standard in a validation of the impactor performed by an independent testing laboratory.

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 7708:1995, *Air quality — Particle size fraction definitions for health-related sampling*

ISO 12141:2002, *Stationary source emissions — Determination of mass concentration of particulate matter (dust) at low concentrations — Manual gravimetric method*

ISO 20988:2007, *Air quality — Guidelines for estimating measurement uncertainty*

3 Terms and definitions

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

3.1 Flow-related terms

3.1.1
aerodynamic diameter
diameter of a sphere of density 1 g/cm^3 with the same terminal velocity due to gravitational force in calm air as the particle, under prevailing conditions of temperature, pressure and relative humidity

NOTE Adapted from ISO 7708:1995, 2.2.

3.1.2
cut-off diameter
aerodynamic diameter where the separation efficiency of the impactor stage is 50 %

3.1.3
PM_{10}
particles which pass through a size-selective inlet with a 50 % efficiency cut-off at 10 µm aerodynamic diameter

NOTE PM_{10} corresponds to the "thoracic convention" as defined in ISO 7708:1995, Clause 6.

3.1.4
$PM_{2,5}$
particles which pass through a size-selective inlet with a 50 % efficiency cut-off at 2,5 µm aerodynamic diameter

NOTE $PM_{2,5}$ corresponds to the "high-risk respirable convention" as defined in ISO 7708:1995, 7.1.

3.1.5
Reynolds number
dimensionless parameter describing a flow

3.1.6
Stokes's number
dimensionless instrument-specific quantity

NOTE See B.2.

3.1.7
Cunningham factor
correction factor taking into account the change in the interaction between particles and the gas phase

NOTE Stokes's law is based on the assumption that the relative gas velocity at the particle edge equals zero. This assumption is not valid for particle sizes close to the mean free path length. Such particles cannot move continuously due to collisions with particles and gas atoms. In this case, Stokes's law has to be amended by a correction factor, i.e. the Cunningham factor. This factor only depends on the mean free path length and the particle diameter.

3.1.8
Sutherland constant
constant characteristic of a gas used for calculating the dependence of the viscosity of a gas on its temperature

3.1.9
aerosol
suspension in a gaseous medium of solid particles, liquid particles or solid and liquid particles having a negligible falling velocity

[ISO 4225:1994, 3.2]

3.2 Instrument-related terms

3.2.1
filter set
separator consisting of two collecting plates and a backup filter

3.2.2
collecting plate
plane filter used for particle collection by impaction

3.2.3
backup filter
plane filter used for collection of the $PM_{2,5}$ particle fraction

3.2.4
collecting plate holder
support of the collecting plate

3.2.5
backup filter holder
punched plate as support of the backup filter

3.2.6
diffuser
conical part in front of the nozzle plates to avoid stall

3.3 Sampling-related terms

3.3.1
measurement site
sampling site
place on the waste gas duct in the area of the measurement plane(s) consisting of structures and technical equipment

NOTE The measurement site consists, for example, of working platforms, measurement ports and energy supply.

3.3.2
measurement section
region of the waste gas duct which includes the measurement plane(s) and the inlet and outlet sections

3.3.3
measurement plane
sampling plane
plane normal to the centreline of the duct at the sampling position

4 Symbols and abbreviated terms

A	separation efficiency
BF	backup filter
$c_{1,i}$	ith concentration value of the first measuring system
$c_{2,i}$	ith concentration value of the second measuring system
C	Cunningham factor

CP2	collecting plate of the second impactor stage
d_{ae}	aerodynamic diameter
d_e	equivalent volumetric diameter
d_{in}	impactor nozzle diameter
d_{nozzle}	entry nozzle diameter
d_{50}	cut-off diameter
E	collection efficiency
f_n	mass concentration of water vapour in standard conditions and with dry gas
g	acceleration due to gravity
i	series element number, i = 1, 2, 3, … m
j	series element number, j = 1, 2, 3, … n
l_{in}	impactor nozzle length
m	sampled mass
m(BF)	particle mass on the backup filter
m(CP2)	particle mass on the collecting plate of the second impactor stage
M	molar mass
n	number of measurement pairs
N	number of impactor nozzles
p	absolute gas pressure
p_{atm}	atmospheric pressure at the measurement site (barometric pressure)
p_n	standard pressure
p_{st}	difference between the static pressure in the measurement cross-section and the atmospheric pressure at the measurement site
r	volume fraction
R	gas constant
Re	Reynolds number
s	distance between the end of the nozzle and the impactor plate
s_D	standard deviation of paired measurements
S	Sutherland constant
St	Stokes's number

T	gas temperature
T_n	standard temperature
T_{crit}	critical temperature
v_{fg}	flue gas velocity
v_{in}	gas velocity in the impactor nozzle
v_{nozzle}	gas velocity in the entry nozzle
v_P	particle drift rate
V	sample volume
V_n	sample volume in standard conditions and for dry gas
$\dot{V}$	volumetric flow rate
WV	water vapour
λ	mean free path length
χ	dynamic shape factor for non-spherical particles
η	dynamic viscosity of the gas
ρ_n	density of the dry gas in standard conditions
$\rho_{n,WV}$	density of water vapour in standard conditions
$\rho_{p,t,h}$	density of the gas in operating conditions
ρ_P	particle mass density
$\rho_{0,P}$	particle unit mass density

5 Principle of the method

5.1 General

In particle measurements, the following three relevant physical characteristics can be distinguished:

— mass concentration (e.g. total dust, PM_{10}, $PM_{2,5}$) and distribution of mass fractions;

— particle number concentration and particle size distribution by number concentration;

— morphology of particles (e.g. shape, colour, optical properties).

The PM_{10} and $PM_{2,5}$ mass concentrations are determined by size-selective separation of gas-borne particles by use of the different inertia of particles. In general, two methods of separation based on the inertia principle can be distinguished:

— impactors (sub-types: e.g. slot-type nozzle impactor, round-nozzle impactor, virtual impactor);

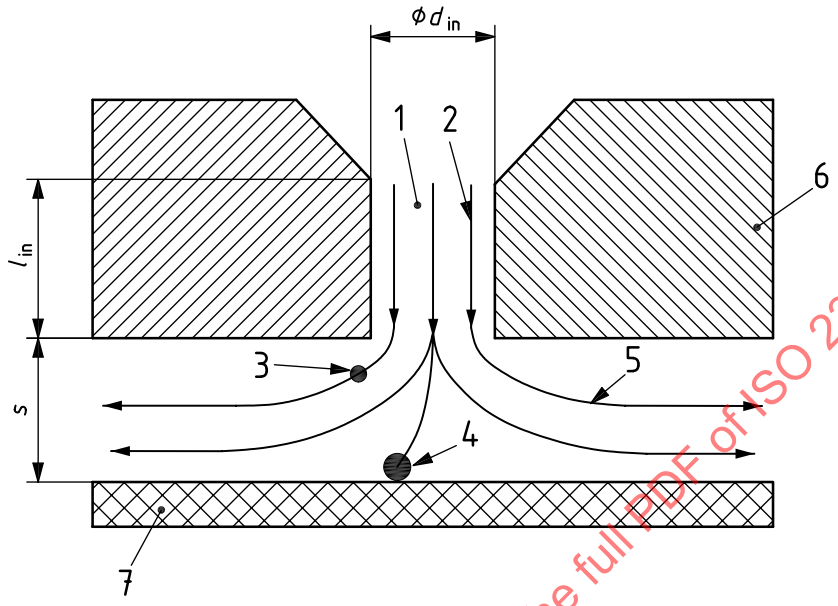
— cyclones (sub-types: e.g. cascade cyclone, sharp-cut cyclone).

Impactors are used at low mass concentrations, whereas cyclones are applied at high mass concentrations.

This International Standard specifies a measurement method for the determination of PM_{10} and $PM_{2,5}$ mass concentrations based on impaction with a round-nozzle impactor.

5.2 Theory of impaction

An impactor separates particles according to their specific aerodynamic diameter. The aerosol is accelerated through a nozzle and then deflected by 90°. Particles with greater aerodynamic diameters are not able to follow the gas flow due to their mass inertia. They are impacted on the collecting plate (see Figure 1).



Key

1	impactor nozzle	l_{in}	impactor nozzle length
2	flow line	s	distance between nozzle outlet and collecting plate
3	particle remaining in the flow	d_{in}	impactor nozzle diameter
4	impacted particle		
5	particle trajectory		
6	nozzle plate		
7	collecting plate		

Figure 1 — Principle of impaction

An impactor stage is defined by the so-called cut-off diameter d_{50}. For particles with this aerodynamic diameter, the separation efficiency of the impactor is 50 %. Equation (1) is used to calculate the cut-off diameter d_{50} of a single-stage round-nozzle impactor (see Reference [11] in the Bibliography):

$$d_{50} = \sqrt{\frac{9\pi\, St_{50}\, \eta N d_{in}^3}{4 \rho_{0,P}\, C \dot{V}}} \tag{1}$$

where

St_{50} is the Stokes's number in relation to the cut-off diameter d_{50};

η is the dynamic viscosity of the gas;

N is the number of impactor nozzles;

d_{in} is the impactor nozzle diameter;

$\rho_{0,P}$ is the particle unit mass density (1 g/cm^3);

C is the Cunningham factor;

$\dot{V}$ is the volumetric flow rate through the impactor in operating conditions.

The following conditions apply to the design and to the application of Equation (1):

a) Distance between nozzle and collecting plate

The ratio of the distance s between the nozzle outlet and the collecting plate to the nozzle diameter d_{in} shall be between

$$0{,}5 \leqslant s / d_{in} \leqslant 5{,}0 \quad (2)$$

b) Ratio of nozzle length to nozzle diameter

The ratio of the impactor nozzle length l_{in} to the nozzle diameter d_{in} shall be between

$$0{,}25 \leqslant l_{in} / d_{in} \leqslant 2{,}0 \quad (3)$$

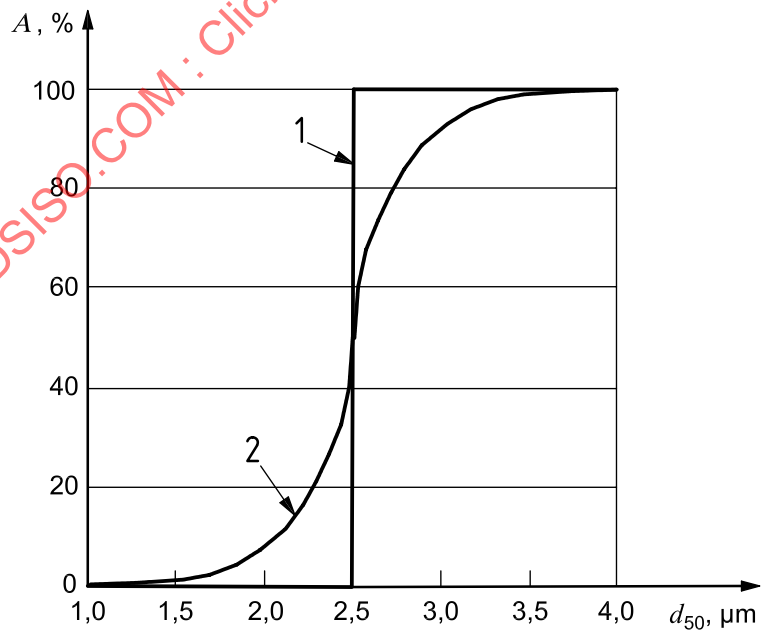
This leads to a uniform flow profile at the nozzle outlet, i.e. the flow has a uniform velocity at the nozzle outlet. If the ratio is too small ($l_{in}/d_{in} < 0{,}25$), the flow is still non-uniform. If the ratio is too large ($l_{in}/d_{in} > 2{,}0$), the velocity at the nozzle edge is smaller than the velocity at the centre of the nozzle due to friction.

c) Reynolds number

The Reynolds number Re of the gas flow in the nozzle shall be in the region of laminar flow ($100 < Re < 3\,000$).

5.3 Cut-off diameter

In reality, the particle separation is not ideal. In practice, impactors exhibit separation curves similar to the example shown in Figure 2.



Key
1 ideal
2 real

Figure 2 — Separation efficiency A of an impactor as a function of the cut-off diameter d_{50}

5.4 Cascade impactor

This International Standard specifies a two-stage cascade impactor for the determination of PM_{10} and $PM_{2,5}$ mass concentrations (see Reference [9] in the Bibliography).

NOTE A cascade impactor consists of several impactor stages. The first impactor stage separates the greatest particles on a collecting plate; smaller particles reach the following stages.

The separation curves of PM_{10} and $PM_{2,5}$ emission measurements shall correspond to the separation curves specified for PM_{10} and $PM_{2,5}$ ambient air quality measurements. During sampling, the particles are divided into three fractions, with aerodynamic diameters greater than 10 µm, between 10 µm and 2,5 µm, and smaller than 2,5 µm. Therefore, the measurement method allows the simultaneous determination of emission concentrations of PM_{10} and $PM_{2,5}$.

6 Specification of the two-stage impactor

6.1 General

The two-stage impactor for the determination of PM_{10} and $PM_{2,5}$ concentrations in flue gas described in this International Standard divides the particles into the following three fractions:

a) particles with aerodynamic diameters greater than 10 µm (first impactor stage);

b) particles with aerodynamic diameters between 10 µm and 2,5 µm (second impactor stage);

c) particles with aerodynamic diameters smaller than 2,5 µm (backup filter).

The $PM_{2,5}$ mass corresponds to fraction c), and the PM_{10} mass corresponds to the sum of fractions b) and c). The fraction with aerodynamic diameters greater than 10 µm is not used for the PM_{10} and $PM_{2,5}$ data evaluation.

6.2 Separation curves

The impactor stages for PM_{10} and $PM_{2,5}$ shall be designed such that the separation curves of PM_{10} and $PM_{2,5}$ meet the requirements of the separation efficiencies specified in Tables 1 and 2. The permissible deviations specified in Tables 1 and 2 are absolute percentages concerning the separation efficiencies specified in ISO 7708:1995 (see Figure 3) for the corresponding particle diameters. Furthermore, the requirements of 5.2 shall be fulfilled.

NOTE The shape of the separation curves can differ from the curves shown in Figure 3 due to experimental influences (e.g. detailed design of the impactor and gas flow conditions).

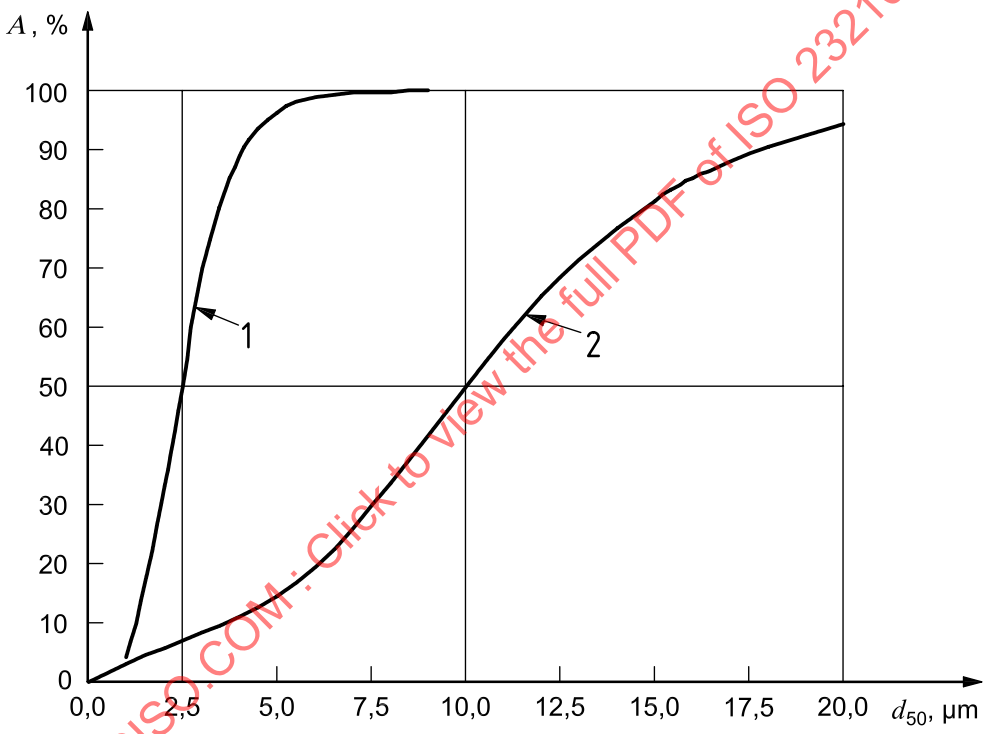
Table 1 — Separation efficiency for the $PM_{2,5}$ impactor stage

Particle diameter	Separation efficiency for mono-disperse latex aerosol and greased collecting plates	Separation efficiency for mono-disperse latex aerosol and quartz-fibre filters
1,0 µm to 2,5 µm [a]	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a permissible deviation of ±10 %	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a permissible deviation of ±10 %
> 2,5 µm to 10,0 µm [a]	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a permissible deviation of ±15 %	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a permissible deviation of ±30 %

[a] Approximate diameters.

Table 2 — Separation efficiency for the PM_{10} impactor stage

Particle diameter	Separation efficiency for mono-disperse latex aerosol and greased collecting plates	Separation efficiency for mono-disperse latex aerosol and quartz-fibre filters
2,0 µm, to 10,0 µm [a]	Separation efficiency of ISO 7708:1955 at the corresponding particle diameter with a permissible deviation of ±10 %	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a permissible deviation of ±10 %
>10,0 µm to 20,0 µm [a]	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a permissible deviation of ±15 %	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a permissible deviation of ±30 %
[a] Approximate diameters.		



Key

1 high-risk respirable convention ($PM_{2,5}$)
2 thoracic convention (PM_{10})
A separation efficiency, in percent (%)
d_{50} cut-off diameter, in micrometres (µm)

Figure 3 — Separation curves of PM_{10} and $PM_{2,5}$ specified in ISO 7708:1995

6.3 Verification of the separation curves

The impactor shall be validated in order to prove that the performance criteria specified in 6.2 are met. The validation shall be carried out by a testing laboratory operating an internationally recognized quality-management system.

NOTE Requirements for testing laboratories are specified, for example, in ISO/IEC 17025.

The separation efficiency shall be determined in accordance with the following procedure for each stage and the particle diameter ranges specified in Tables 1 and 2.

The separation efficiency of the impactor stages shall be determined by performing two experiments for each stage with mono-disperse latex aerosols of different particle diameters.

First, greased collecting plates are used to increase the adhesion and to reduce possible rebound of particles to evaluate the optimum separation efficiency under laboratory conditions. Second, quartz-fibre filters (with the smooth surface towards the top) are used as collecting plates, as in the intended operation of the impactor. For the $PM_{2,5}$ stage, tests with at least six different particle diameters between 1 µm and 10 µm shall be performed. For the PM_{10} stage, tests with at least six different particle diameters between 2 µm and 20 µm shall be performed. In both cases, the particle diameters shall be distributed over the full range about the cut-off diameter. One of these particle diameters shall be as close as possible to the cut-off diameter.

The resulting experimental separation efficiencies shall be compared with the reference curves specified in ISO 7708:1995 (see Figure 3). The deviations of the experimental separation efficiencies shall be within the permissible deviations specified in Tables 1 and 2.

The values of Stokes's number St_{50} for the 2,5 µm and 10 µm stages of the impactor under examination in relation to the cut-off diameter shall be calculated on the basis of the experimental data (see Annex B).

The separation efficiencies and the values of Stokes's number determined shall be reported.

6.4 Operating conditions

To meet the given cut-off limits of 10 µm and 2,5 µm particle diameters, the impactor shall be operated with a constant sample volumetric flow rate, to be previously determined. For a given impactor design, the volumetric flow rate depends only on the flue gas conditions and is calculated in accordance with Annex A. Isokinetic sampling should be established by selection of an appropriate sampling nozzle (see 8.3.4). If this is impossible, over-isokinetic sampling is preferred.

Over-isokinetic sampling is preferred since the error in the collection efficiency is smaller than for sampling below isokinetic conditions (see 10.4).

The measurement method specified in this International Standard is applicable for the operating conditions given in Table 3. Typical gas compositions range from air to flue gases with up to 30 % carbon dioxide.

Table 3 — Typical operating conditions of the measurement method

Parameter	Mean value	Minimum value	Maximum value
Dust concentration in mg/m^3	10	1	50
Temperature in °C	135	20	250
Pressure in hPa	1 000	850	1 100
Humidity in g/m^3 [a]	30	0	100
[a] The dew-point shall be below the flue gas temperature.			

If these operating conditions are not met, especially at a higher water-vapour content or higher flue gas temperatures, measures shall be taken so that the Reynolds number of each impactor stage is between 100 and 3 000. In this case, the similarity condition according to the theory of Marple (see Reference [11] in the Bibliography) is still fulfilled. The Reynolds number of the flow in each stage can be determined according to A.2.6.

6.5 Components

The two-stage impactor shall have the following components:

— inlet cone in accordance with the requirements of ISO 12141, if needed;

NOTE The corresponding requirements are identical to those in EN 13284-1.

— PM_{10} nozzle plate;

— collecting plate for the particle fraction greater than 10 µm;

— first diffuser, if needed;

— $PM_{2,5}$ nozzle plate;

— collecting plate for the particle fraction between 10 µm and 2,5 µm;

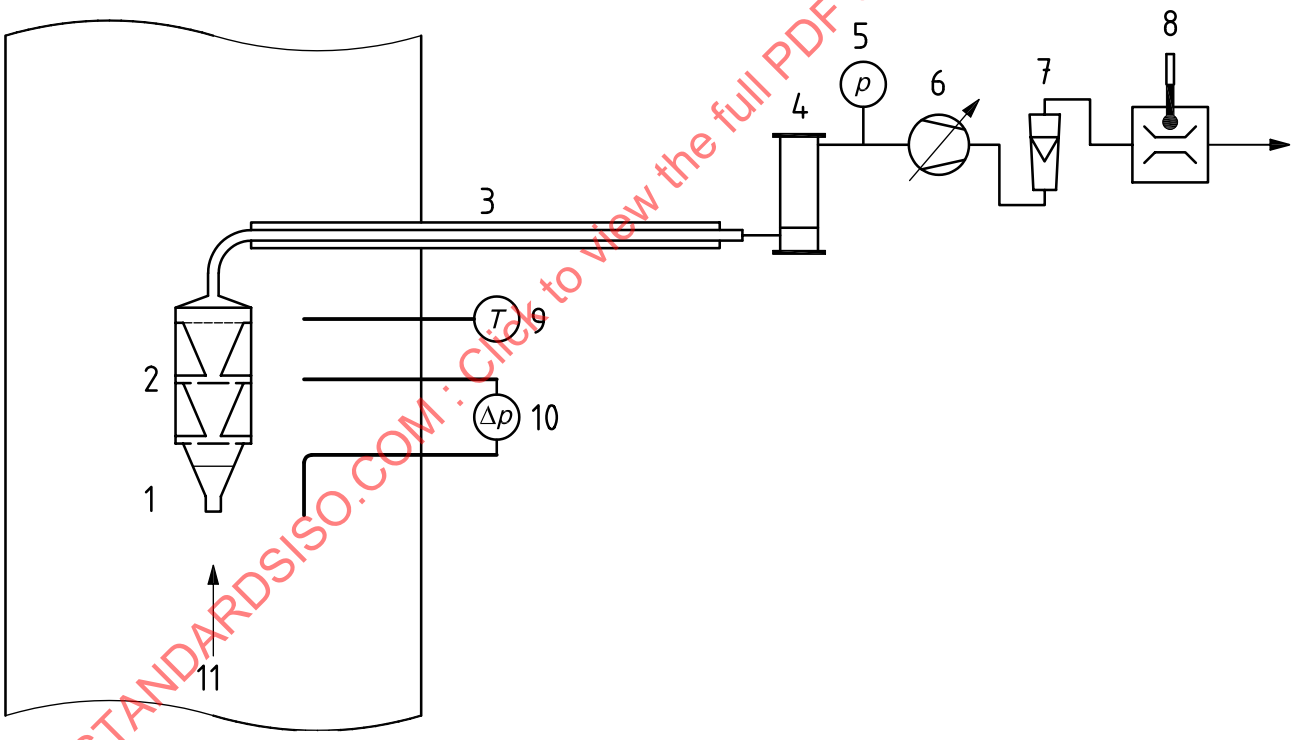
— second diffuser, if needed;

— backup filter for the particle fraction smaller than 2,5 µm.

7 Sampling train

7.1 Measuring setup

Figure 4 shows an example of the general measurement setup.



Key

1	entry nozzle	7	flowmeter
2	two-stage impactor	8	gas-volume measuring device with thermometer
3	suction tube	9	temperature measuring device
4	drying column	10	Pitot tube with differential pressure meter
5	manometer	11	gas flow in the flue gas duct
6	suction device		

Figure 4 — Example of the design of the sampling system

Measurements with an in-stack sampling system with a straight entry nozzle are recommended.

In-stack measurements with a goose-neck nozzle in front of the impactor can cause higher particle losses in the probe. Furthermore, out-stack measurements require an exact external thermal control of the impactor to meet the exact cut-off diameter. If in-stack measurements with a goose-neck nozzle in front of the impactor are performed, extensive validation experiments shall be performed, including the quantification of losses related to coarse and fine particles. These measurement setups shall only be used if losses of particles in the sampling train are below 10 % of the total mass of fine particles collected on the collecting plate and backup filter.

The requirements for components downstream of the impactor shall be in accordance with ISO 12141.

NOTE The corresponding requirements are identical to those in EN 13284-1.

7.2 Equipment and working materials

7.2.1 Sampling equipment

The impactor shall be of corrosion-proof material, e.g. titanium or stainless steel.

The entry nozzle shall be of the same material as the impactor. A set of nozzles with effective diameters between at least 6 mm and 18 mm shall be available (see Annex F).

7.2.2 Equipment for extraction and adjustment of the sample volumetric flow rate

The following equipment for extraction and adjustment of the sample volumetric flow rate shall be provided:

— bend downstream of the impactor of corrosion-proof material, if needed;

— suction tube downstream of the bend of corrosion-proof material with an appropriate internal diameter; for lengths over 2 m, a sufficiently stable supporting tube can be needed;

— gas-carrying flexible tubes of sufficient length for connecting the parts of the sampling train downstream of the suction tube;

— special heater for heating up the complete impactor, if needed;

— drying tower with a desiccant for drying the sample gas;

— suction device (e.g. a corrosion-proof gastight pump with a protective filter and minimum delivery output of 4 m^3/h at 400 hPa at the extraction side, preferably with automatic flow-control);

— gas volume meter of nominal capacity of 6 m^3/h;

— gas flowmeter;

— temperature measuring device for the sample gas flow;

— pressure measuring device for static pressure in the duct or static differential pressure between the duct and the atmosphere at the measurement site;

— time measuring device;

— barometer for measuring the atmospheric pressure at the measurement site;

— shut-off and control valves or other device for adjustment of the sample gas flow.

Depending on the gas properties, a condensate trap can be necessary to avoid back-flow of condensate to the measuring filter. If necessary, heating or cooling of the condensate trap shall be provided.

NOTE Requirements concerning the equipment for extraction and adjustment of the sample volumetric flow rate are specified, for example, in ISO 12141 and EN 13284-1.

7.2.3 Equipment for measuring the gas velocity, gas composition and reference quantities

The following equipment for measuring the gas velocity and the gas composition shall be provided:

— gas-velocity measuring device, e.g. Pitot tube with a micromanometer;

— gas analysers for determining CO_2 and O_2 in the flue gas;

— temperature measuring device;

— humidity measuring device.

NOTE Requirements concerning the equipment for measuring the gas velocity and the gas composition are specified, for example, in ISO 12141 and EN 13284-1.

7.2.4 Equipment for pre-treatment and post-treatment in the laboratory

The following equipment for the pre-treatment and post-treatment of the filter samples in the laboratory shall be provided:

— microbalance, e.g. measuring range: 60 g; resolution: 0,01 mg;

— drying chamber;

— transport container for the sampling plates and filters;

— punch for punching the plane filters, if needed.

7.2.5 Working materials

The following working materials shall be provided:

— plane filter of quartz-fibre material;

— drying agent, e.g. silica gel with colour indicator.

The collecting plates and the backup filter shall consist of quartz-fibre plane filters, which shall comply with the following minimum requirements.

a) The filter efficiency shall be better than 99,5 % on a test aerosol with a mean particle diameter of 0,3 µm at the maximum flow rate anticipated or 99,9 % on a test aerosol of 0,6 µm mean diameter. This efficiency shall be certified by the filter supplier.

b) The filter material shall not react with, or adsorb, gaseous compounds contained in the gas to be sampled and shall be thermally stable, taking into account the maximum temperature anticipated (conditioning, sampling, etc.).

8 Preparation, measurement procedure and post-treatment

8.1 General

Measurement ports should be consistent with the requirements of International or National Standards with respect to the location, number and design.

The dimensions of the measurement ports should allow straight insertion of the impactor into the flue gas duct without any contact with the inner duct walls.

The measurement section shall be in accordance with the requirements of the applicable standard.

NOTE Requirements concerning the measurement section are specified, for example, in ISO 12141 or EN 15259.

The flue gas conditions should be constant during sampling, to ensure that the isokinetic rate is kept between 90 % and 130 % of the calculated value (see 8.3.4).

The impactor shall be used in the flue gas duct with the entry nozzle in the upstream direction (see Figure 4).

Sampling shall be performed at a sampling point representative of the flue gas velocity. This representative sampling point shall be determined in accordance with Annex G.

It shall be guaranteed that the cut-off diameter does not change during sampling. Under constant flue gas conditions, this can be realized by a constant sample gas flow.

An overall blank sample shall be taken as a quality control measure after each measurement series, or at least once a day without starting the suction device. This leads to an estimation of the dispersion of results related to the whole procedure, with a dust concentration close to zero, i.e. taking into account the contamination of filters during handling on site, and during transport, storage, handling in the laboratory and weighing. All overall blank values shall be reported individually.

8.2 Pre-treatment

8.2.1 Impactor

The impactor shall be cleaned in accordance with the manufacturer's instructions and at a frequency specified in the measurement plan.

NOTE Requirements concerning the measurement plan are specified, for example, in EN 15259.

All internal surfaces of the impactor shall be cleaned between measurements on site, e.g. with a microfibre cloth.

8.2.2 Collecting plates and backup filters

Preparation of filter sets shall be carried out in the laboratory.

If needed, collecting plates (first and second impactor stage) shall be punched with a concentric hole of an appropriate diameter suitable for the construction of the given impactor stage. After punching, check the punch edges visually and carefully remove loose fibres with a pair of tweezers.

Collecting plates shall be used with the smooth surface towards the top.

This International Standard recommends the use of non-greased quartz-fibre filters. However, the separation efficiency can be improved by the use of greased collecting plates. This requires additional validation in the field to take into account, for example, the influence of high temperatures.

Collecting plates and backup filters shall be placed in uniquely marked holders. Then the collecting plates and the backup filter with the holders shall be dried, equilibrated and weighed in accordance with ISO 12141.

NOTE The corresponding requirements are identical to those in EN 13284-1.

The collecting plates and the backup filters shall be stored and transported in closed and clearly labelled boxes.

8.3 Measurement procedure

8.3.1 Measurement planning

Measurement planning should generally include

a) operating conditions of the plant, including fuel or feedstock, flue gas components and reference quantities (e.g. temperature, pressure, water-vapour content) to be measured,

b) sampling date and time and location of measurements,

c) measurement methods to be applied,

d) measurement sections and measurement sites,

e) technical supervisor and necessary personnel for carrying out of the measurements, and

f) reporting procedures.

NOTE Recommendations for testing laboratories are specified, for example, in ISO/IEC 17025.

The sampling duration depends on the dust concentration and the grain size distribution in the flue gas. If these parameters are unknown, they should be determined by pre-measurements. The sampling duration shall be specified such that overloading of collecting plates and backup filters is avoided and a weighable dust mass is sampled.

8.3.2 Flue gas data

The following flue gas data shall be determined before a measurement is carried out:

a) flue gas velocity;

b) flue gas composition: O_2, CO_2, N_2, humidity;

c) temperature;

d) static pressure.

8.3.3 Determination of the sample gas volumetric flow rate

The sample gas volumetric flow rate in operating conditions shall be determined in accordance with Annex A. This volumetric flow rate shall be converted to the conditions at the volume measuring device. The input quantities for the calculation are the measured values determined in accordance with 8.3.2.

NOTE The determination can be made using a spreadsheet program. An example of a spreadsheet program is attached to this International Standard.

The sample gas volumetric flow rate shall be monitored and kept constant during sampling within ±5 % of the nominal value, to ensure that the cut-off characteristics of both impactor stages do not change.

8.3.4 Selection of the entry nozzle

The effective diameter of the entry nozzle shall be calculated in accordance with A.2.4.

NOTE The effective diameter of the entry nozzle can be calculated by means of a spreadsheet program. An example of a spreadsheet program is attached to this International Standard.

Sampling shall be carried out with an isokinetic rate between 90 % and 130 % of the calculated value. The entry nozzle shall be selected accordingly.

8.3.5 Leak check

The sampling system shall be assembled and checked for possible leaks by sealing the entry nozzle and starting the suction device. The leak flow shall be below 2 % of the normal flow rate. This can be measured, for example, by pressure variations after evacuation of the sampling train at the maximum vacuum reached during sampling. During sampling, a leak check can be monitored by continuously measuring the concentration of a relevant gas component (CO_2, O_2, etc.) directly in the duct and downstream of the sampling train. Any detectable difference between those concentrations indicates a leak in the sampling equipment parts located outside the flue gas duct. This leak shall then be investigated and rectified.

8.3.6 Measurement

The impactor shall be at the flue gas temperature before a measurement is started. If the flue gas temperature is close to the water-vapour dew-point, the complete impactor shall be heated up to the flue gas temperature outside the duct.

NOTE The large impactor mass can lead to long heating periods.

During installation, the sampling train shall be inserted into flue gas duct, such that any contact between the entry nozzle and the flue gas duct is avoided. The measurement ports shall be sealed to minimize oxygen entering the duct or flue gas escaping the duct.

The angle between the centreline of the entry nozzle and the flow direction shall be smaller than 10°. The shut-off valve shall be opened, the suction device shall be switched on and the volumetric flow shall be set to the value calculated in Annex A.

The volumetric flow rate shall be checked at least every 5 min during sampling and shall be adjusted in the case of deviations from the calculated value.

The dynamic pressure shall be continuously checked with a Pitot tube or with another suitable measuring device installed at a fixed location or at the sampling train or it shall be recorded at least every 5 min.

The sampling train shall be removed from the flue gas duct after sampling.

The sample volume of the measurement shall be determined and recorded.

8.3.7 Filter change

The backup filter holder with the backup filter, and the collecting plate holders with the collecting plates, shall be removed from the impactor and transferred into the transport containers. Any contamination of the filters shall be avoided.

8.4 Post-treatment

For data evaluation, the backup filter and the collecting plate of the second impactor stage are used.

In the case of visible dust deposits on the walls in the internal part of the impactor in front of the first nozzle plate, examine the backup filter in a scanning electron microscope. If coarse particles have bounced onto the backup filter, the measurement method is not suitable for the process under investigation and the measurement results shall be rejected. In the other case (no coarse particles on the backup filter), the dust deposits are not taken into account for the determination of the particle fractions $PM_{2,5}$ and PM_{10} by convention, since these deposits consist mainly of coarse particles (see 10.5).

The collecting plate of the second impactor stage and the backup filter with the holders shall be dried, equilibrated and weighed in accordance with ISO 12141.

NOTE The corresponding requirements are identical to those in EN 13284-1.

Drying and reweighing of the measuring filter and control filter sets shall be carried out under the same conditions as were present during pre-treatment.

8.5 Weighing

The backup filter and the collecting plate of the second impactor stage shall be weighed.

NOTE As a plausibility check, the first impactor stage can be weighed too.

9 Calculation of the results

The concentration $c(PM_{2,5})$ of $PM_{2,5}$ in the flue gas shall be calculated by Equation (4):

$$c(PM_{2,5}) = \frac{m(BF)}{V_n} \quad (4)$$

where

$m(BF)$ is the particle mass on the backup filter;

V_n is the sample volume in standard conditions and for dry gas.

The concentration $c(PM_{10})$ of PM_{10} in the flue gas shall be calculated by Equation (5):

$$c(PM_{10}) = \frac{m(BF) + m(CP2)}{V_n} \quad (5)$$

where

$m(BF)$ is the particle mass on the backup filter;

$m(CP2)$ is the particle mass on the collecting plate of the second impactor stage;

V_n is the sample volume in standard conditions and for dry gas.

The sample volume V_n in standard conditions and for dry gas shall be calculated from the sample volume in the conditions at the gas-volume measuring device.

The collecting plate of the first impactor stage may not be used for the determination of the total dust concentration.

NOTE Impactors always exhibit particle losses. These particle losses are attributed to coarse particles by convention. If the $PM_{2,5}$ and PM_{10} fraction in the total dust is to be determined, an additional parallel total dust measurement is needed.

10 Performance characteristics

10.1 Impactor load

The load of the backup filter and of the collecting plates of the impactor stages should not exceed the maximum load specified by the manufacturer.

The sampling period depends on the dust concentration and the grain size distribution in the flue gas. Both can be determined in pre-measurements to select a sampling period, which avoids overloading of the collecting plates and the backup filter.

10.2 Detection limit

The detection limit of the impactor shall be estimated on the basis of the absolute detectable mass on the filter and the nominal sample volume.

The detection limit of PM_{10} is influenced by two independent weighings (backup filter and collecting plate of second stage). Therefore, the detection limit is greater than the value of $PM_{2,5}$.

10.3 Measurement uncertainty

The measurement uncertainty of the impactor shall be determined in the field by paired measurements with two identical measuring systems under repeatability or reproducibility conditions. The samples shall be taken

at the same measurement point in the measurement cross-section. The measurement uncertainty shall be estimated, in accordance with ISO 20988, by the standard deviation s_D from paired measurements by means of Equation (6):

$$s_D = \sqrt{\sum_{i=1}^{n} \frac{\left(c_{1,i} - c_{2,i}\right)^2}{2n}} \tag{6}$$

where

$c_{1,i}$ is the ith concentration value of the first measuring system;

$c_{2,i}$ is the ith concentration value of the second measuring system;

n is the number of paired measured values.

Determine the measurement uncertainty at least during the validation of the impactor under plant operating and waste gas conditions, which are representative of the future application of the impactor. The tests shall be carried out by a testing laboratory operating an internationally recognized quality management system.

NOTE Requirements for testing laboratories are specified, for example, in ISO/IEC 17025.

10.4 Additional uncertainty contributions

In addition to the measurement uncertainty determined by multiple determinations in repeatability or reproducibility conditions, further uncertainty contributions are caused by sampling at only one measurement point in the cross-section or by deviations from isokinetic sampling.

It is assumed that all measurements are carried out at a representative sampling point which represents the conditions in the measurement cross-section. Therefore, this uncertainty contribution can be neglected.

The diameter of the entry nozzle for isokinetic sampling can only be estimated, since the volumetric flow through the impactor is calculated before the measurement and shall be kept constant during sampling. The corresponding contributions to measurement uncertainty can be estimated theoretically for different particle sizes.

Table 4 gives examples of the influence of the entry nozzle selection on the isokinetic rate for different flue gas conditions.

Table 4 — Influence of the entry-nozzle selection on the isokinetic rate

Sample volumetric flow m^3/h	Flue gas velocity m/s	Calculated entry nozzle diameter mm	Applied entry nozzle diameter mm	Gas velocity in the entry nozzle m/s	Isokinetic rate [a]
2,5	3	17,2	17	3,1	1,0
	5	13,3	13	5,2	1,0
	8	10,5	10	8,8	1,1
	10	9,4	9	10,9	1,1
	12	8,6	8	13,8	1,2
	14	7,9	7	18,0	1,3
	16	7,4	7	18,0	1,1
	20	6,6	6	24,6	1,2
	24	6,1	6	24,6	1,0

[a] Ratio of the gas velocity in the entry nozzle to the flue gas velocity.

The collection efficiency of a sampling system for particles with different aerodynamic diameters can be calculated from the isokinetic rate (see Reference [7]). Figure 5 shows examples of collection efficiencies of different particle fractions as a function of the ratio of the gas velocity in the entry nozzle to the flue gas velocity in the duct. The calculations were based on a flue gas velocity of 10 m/s and an entry nozzle diameter of 10 mm.

NOTE The collection efficiency is the ratio of the sampled concentration sampled at a specific isokinetic rate to the concentration at isokinetic sampling with an isokinetic rate of 1,0.

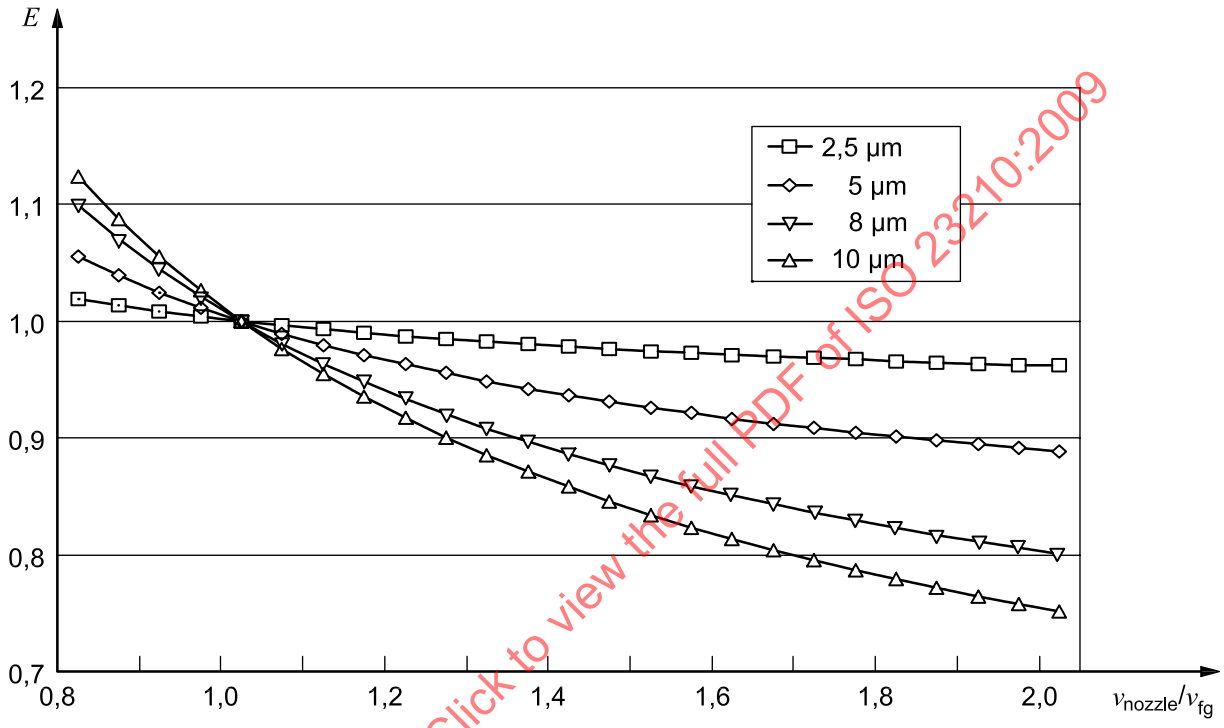


Figure 5 — Theoretical dependence of the collection efficiency E on the ratio of the gas velocity in the entry nozzle v_{nozzle} to the flue gas velocity v_{fg}

For particles with an aerodynamic diameter d_{ae} = 10 µm (not to be confused with PM_{10}) and an over-isokinetic sampling with a factor of 1,5, the findings are reduced by approximately 15 %. This error decreases with decreasing particle size and can be nearly neglected at d_{ae} = 2,5 µm. If the ratio of sampling velocity to flue gas velocity is between 0,9 and 1,3, the maximum error as reduced or increased findings of particle mass is approximately 10 %.

The error caused by deviations from the isokinetic sampling is significantly smaller then the maximum values given above, which were calculated for a particle size of 10 µm, since the particles usually have a size distribution when emission measurements are carried out in purified flue gas.

10.5 Particle losses

Particle losses generally occur during particulate sampling when impactors are used. A portion of particles is not separated according to the theory (see Reference [12]) on the collecting plates and the backup filter, but diffusively on the walls and the nozzle plates. These particles are not taken into account in the mass determination of the fractions considered by convention. As a consequence, the sum of the mass on the collecting plates and on the backup filter is usually not identical to the total mass concentration of dust in the flue gas.

Comprehensive investigations (see References [8] and [10]) have shown that the loss of particles increases with increased particle size.

NOTE 1 If the individual fractions (PM_{10} and $PM_{2,5}$) are related to the impacted mass, the calculated distribution is shifted to smaller particle sizes, since equally distributed particle losses are assumed.

NOTE 2 If the individual fractions (PM_{10} and $PM_{2,5}$) are related to the total dust mass measured at the same time, the calculated distribution is shifted to larger particle sizes, since it is assumed that particle losses are related to coarse particles only. This assumption is close to reality, since it is well known that particle losses are related to the coarse-particle fraction.

11 Reporting

The results of the emission measurements, including the measurement uncertainty, shall be presented in the measurement report, which shall include detailed information on the plant and on all elements relevant for measurement planning (8.3.1) and all measured and calculated values and results.

Annex A
(normative)

Calculation of the sample volumetric flow rate of the impactor

A.1 Spreadsheet program to calculate the sample volumetric flow rate of the impactor

For the convenience of users of this International Standard, a spreadsheet program (developed in Microsoft Excel®) to calculate the sample volumetric flow rate of the impactor in accordance with A.2 is provided as an electronic insert. This spreadsheet is given for information only as an aid to calculation; it has not been optimized for printing. The presentation of the symbols and equations is not identical with that used in the text. The spreadsheet program requires the input of the following variables:

a) gas composition;

b) gas conditions;

c) gas velocity.

A.2 Calculation parameters

A.2.1 Sample volumetric flow rate

The sample required volumetric flow rate $\dot{V}_i$ in operating conditions, is calculated by Equation (A.1):

$$\dot{V}_i = \frac{9\,\pi\,d_{\mathrm{in},i}^3\;St_{50}\;\eta(T)\;N_i}{4\,d_{50,i}^2\;C_i\;\rho_{0,\mathrm{P}}} \qquad \text{(A.1)}$$

where

i is the index to identify the particle fraction (i = 2,5 µm, 10 µm);

$d_{\mathrm{in},i}$ is the impactor nozzle diameter (constant);

St_{50} is Stokes's number (constant);

$\eta(T)$ is the temperature-dependent viscosity of the gas;

N_i is the number of impactor nozzles (constant);

$d_{50,i}$ is the cut-off particle diameter (50 % value of separation at the nozzle plate; constant);

C_i is the Cunningham factor of particle fraction i;

$\rho_{0,\mathrm{P}}$ is the particle unit-mass density (1 g/cm^3).

The volumetric flow rates of both nozzle plates are calculated separately. Then the arithmetic mean of both values is calculated according to Equation (A.2):

$$\bar{\dot{V}} = \frac{\dot{V}_{2,5\,\mu m} + \dot{V}_{10\,\mu m}}{2} \tag{A.2}$$

The sample volumetric flow rate of the sample $\dot{V}_n$ in standard conditions and for dry gas shall be calculated using the averaged volumetric flow rate $\bar{\dot{V}}$ by Equation (A.3):

$$\dot{V}_n = \bar{\dot{V}} \frac{T_n (p_{atm} + p_{st})}{p_n T \left(1 + \frac{f_n}{\rho_{n,WV}}\right)} \tag{A.3}$$

where

T is the gas temperature in operating conditions;

T_n is the standard temperature; T_n = 273,15 K;

p_{atm} is the atmospheric pressure at the measurement site (barometric pressure);

p_n is the standard pressure; p_n = 1 013,25 hPa;

p_{st} is the difference between the static pressure in the measurement cross-section and the atmospheric pressure at the measurement site (barometric pressure);

f_n is the mass concentration of water vapour in standard conditions and with dry gas;

$\rho_{n,WV}$ is the density of water vapour in standard conditions; $\rho_{n,WV}$ = 0,803 8 kg/m^3.

For the calculation of the volumetric flow rates according to Equation (A.1), the following parameters shall be calculated:

— the dynamic viscosity $\eta(T)$ of the gas mixture in operating conditions;

— the Cunningham factor C_i of particle fraction i.

A.2.2 Temperature-dependent dynamic viscosity of the gas

For the calculation of the dynamic viscosity in operating conditions, the volume fractions of the different gas constituents shall be determined. Then the dynamic viscosity of the constituents in operating conditions is calculated. The viscosity of the gas mixture is calculated from the viscosities of the constituents.

The dynamic viscosity of the individual gas constituent of the sample gas in operating conditions is calculated by Equation (A.4):

$$\eta_j(T) = \eta_{n,j} \sqrt{\frac{T}{T_n}} \frac{1 + \frac{S_j}{T_n}}{1 + \frac{S_j}{T}} \tag{A.4}$$

where

j is the index to identify the individual constituent of the sample gas (j = CO_2, O_2, N_2, air, water vapour);

$\eta_j(T)$ is the dynamic viscosity of constituent j in operating conditions;

$\eta_{n,j}$ is the dynamic viscosity of constituent j at the standard temperature T_n (constant);

T is the gas temperature;

T_n is the standard temperature; T_n = 273,15 K;

S_j is the Sutherland constant of constituent j.

The corresponding volume fractions r_j in wet flue gas shall be calculated by Equation (A.5) and Equation (A.6), respectively:

— for j = CO_2, O_2, N_2 and air:

$$r_j = r_{n,j} \frac{1}{1 + \frac{f_n}{\rho_{n,WV}}} \tag{A.5}$$

— for j = water vapour:

$$r_{WV} = \frac{f_n}{\rho_{n,WV}} \times \frac{1}{1 + \frac{f_n}{\rho_{n,WV}}} \tag{A.6}$$

where

$r_{n,j}$ is the volume fraction of constituent j in dry gas;

f_n is the mass concentration of water vapour in standard conditions and with dry gas;

$\rho_{n,WV}$ is the density of water vapour in standard conditions (constant);

The temperature-dependent dynamic viscosity of the gas $\eta(T)$ in operating conditions shall be calculated by Equation (A.7):

$$\eta(T) = \frac{\sum_j r_j \, \eta_j(T) \sqrt{M_j \, T_{crit,j}}}{\sum_j r_j \, \sqrt{M_j \, T_{crit,j}}} \tag{A.7}$$

where

j is the index to identify the individual constituent of the sample gas (j = CO_2, O_2, N_2, air, water vapour);

r_j is the volume fraction of constituent j of the gas mixture;

$\eta_j(T)$ is the dynamic viscosity of constituent j in operating conditions;

$T_{crit,j}$ is the critical temperature of constituent j (constant);

M_j is the molar mass of constituent j (constant).

A.2.3 Cunningham factor

The calculation of the Cunningham factor requires the determination of the mean free path length and the mean molar mass of the gas. The mean free path length λ is calculated by Equation (A.8):

$$\lambda = 2\frac{\eta(T)}{p}\sqrt{\frac{\pi RT}{8\bar{M}}} \tag{A.8}$$

where

$\eta(T)$ is the temperature-dependent viscosity of the gas;

p is the absolute gas pressure;

T is the gas temperature;

$\bar{M}$ is the mean molar mass of the gas mixture;

R is the gas constant.

The mean molar mass $\bar{M}$ of the sample gas shall be calculated by Equation (A.9):

$$\bar{M} = \sum_j r_j M_j \tag{A.9}$$

where

j is the index to identify the individual constituent of the sample gas (j = CO_2, O_2, N_2, air, water vapour);

M_j is the molar mass of constituent j;

r_j is the volume fraction of constituent j.

The Cunningham factor C_i of particle fraction i shall be calculated by Equation (A.10):

$$C_i = 1 + \frac{2\lambda}{d_{50,i}}\left[1{,}23 + 0{,}41\exp\left(-0{,}88\frac{d_{50,i}}{2\lambda}\right)\right] \tag{A.10}$$

where

i is the index to identify the particle fraction (i = 2,5 µm, 10 µm);

λ is the mean free path length;

$d_{50,i}$ is the cut-off diameter of particle fraction i.

A.2.4 Entry nozzle diameter

The diameter d_{nozzle} of the entry nozzle is calculated from the required sample volumetric flow and the flue gas velocity at the sampling point by Equation (A.11):

$$d_{\text{nozzle}} = \sqrt{\frac{4\dot{V}}{\pi\, v_{\text{fg}}}} \tag{A.11}$$

where

$\dot{V}$ is the sample volumetric flow rate in operating conditions;

v_{fg} is the flue gas velocity at the sampling point.

A.2.5 Gas velocity in the impactor nozzles

The gas velocity in the nozzles of the nozzle plates is calculated by Equation (A.12):

$$v_{in,i} = \frac{4\dot{V}}{N_i \pi d_{in,i}^2} \tag{A.12}$$

where

$\dot{V}$ is the sample volumetric flow rate in operating conditions;

i is the index to identify the particle fraction (i = 2,5 µm, 10 µm);

$v_{in,i}$ is the gas velocity in the impactor nozzles of nozzle plate i;

N_i is the number of impactor nozzles in nozzle plate i (constant);

$d_{in,i}$ is the diameter of the impactor nozzles in nozzle plate i (constant).

A.2.6 Reynolds numbers

The Reynolds numbers Re are calculated by Equation (A.13):

$$Re_i = \frac{v_{in,i} \quad d_{in,i} \quad \rho_{p,t,h}}{\eta(T)} \tag{A.13}$$

where

i is the index to identify the particle fraction (i = 2,5 µm, 10 µm);

$v_{in,i}$ is the gas velocity in the nozzles of nozzle plate i;

Re_i is the Reynolds number of nozzle plate i;

$\rho_{p,t,h}$ is the gas density in operating conditions;

$d_{in,i}$ is the diameter of the impactor nozzles in nozzle plate i (constant);

$\eta(T)$ is the dynamic viscosity of the gas in operating conditions.

A.2.7 Gas density

The density $\rho_{p,t,h}$ of the wet gas in operating conditions is calculated by Equation (A.14):

$$\rho_{p,t,h} = \frac{(p_{atm} + p_{st})\, T_n\, (\rho_n + f_n)}{p_n T \left(1 + \dfrac{f_n}{\rho_{n,WV}}\right)} \tag{A.14}$$

The density ρ_n of the dry gas mixture is calculated by Equation (A.15):

$$\rho_n = \sum_j r_j \, \rho_{n,j} \tag{A.15}$$

where

j is the index to identify the individual constituent of the sample gas (j = CO_2, O_2, N_2, air);

r_j is the volume fraction of constituent j of the gas mixture;

T is the temperature in operating conditions;

T_n is the standard temperature; T_n = 273,15 K;

p_{atm} is the atmospheric pressure at the measurement site (barometric pressure);

p_{st} is the difference between the static pressure in the measurement cross-section and the atmospheric pressure at the measurement site (barometric pressure);

p_n is the standard pressure; p_n = 1 013,25 hPa;

f_n is the mass concentration of water vapour in standard conditions and with dry gas;

$\rho_{n,WV}$ is the density of water vapour in standard conditions; $\rho_{n,WV}$ = 0,803 8 kg/m^3.

A.2.8 Cut-off diameter

The cut-off diameter $d_{50,i}$ is calculated by Equation (A.16):

$$d_{50,i} = \sqrt{\frac{9\pi St_{50,i}\eta(T)N_i d_{in,i}^3}{4\rho_{0,P}C_i\dot{V}}} \tag{A.16}$$

where

i is the index to identify the particle fraction (i = 2,5 µm, 10 µm);

$St_{50,i}$ is the Stokes's number related to the particle fraction i;

$\eta(T)$ is the dynamic viscosity of the gas;

N_i is the number of impactor nozzles in nozzle plate i;

$d_{in,i}$ is the diameter of the impactor nozzles in nozzle plate i;

$\rho_{0,P}$ is the particle unit mass density (1 g/cm^3);

C_i is the Cunningham factor of particle fraction i;

$\dot{V}$ is the volumetric flow rate through the impactor in operating conditions.

A.2.9 Constants

Table A.1 — Constants required for the calculations

Constant	Symbol	Value	Unit
Gas constant	R	8,314 51	J/(mol K)
Standard temperature	T_n	273,15	K
Standard pressure	p_n	1 013,25	hPa
Density of CO_2 in standard conditions	ρ_{n,CO_2}	1,977	kg/m^3
Density of O_2 in standard conditions	ρ_{n,O_2}	1,429	kg/m^3
Density of N_2 in standard conditions	ρ_{n,N_2}	1,251	kg/m^3
Density of dry air in standard conditions	$\rho_{n,air}$	1,293	kg/m^3
Density of water vapour in standard conditions	$\rho_{n,WV}$	0,804	kg/m^3
Particle unit mass density	$\rho_{n,P}$	1 000	kg/m^3
Dynamic viscosity of CO_2	η_{n,CO_2}	$1{,}370\times10^{-5}$	kg/ms
Dynamic viscosity of O_2	η_{n,O_2}	$1{,}928\times10^{-5}$	kg/ms
Dynamic viscosity of N_2	η_{n,N_2}	$1{,}652\times10^{-5}$	kg/ms
Dynamic viscosity of air	$\eta_{n,air}$	$1{,}717\times10^{-5}$	kg/ms
Dynamic viscosity of water vapour	$\eta_{n,WV}$	$8{,}660\times10^{-6}$	kg/ms
Molar mass of CO_2	M_{CO_2}	44,01	g/mol
Molar mass of O_2	M_{O_2}	32,00	g/mol
Molar mass of N_2	M_{N_2}	28,02	g/mol
Mean molar mass of dry air	$\bar{M}_{air}$	28,97	g/mol
Molar mass of water vapour	M_{WV}	18,02	g/mol
Sutherland constant of CO_2	S_{CO_2}	273	K
Sutherland constant of O_2	S_{O_2}	125	K
Sutherland constant of N_2	S_{N_2}	104	K
Sutherland constant of air	S_{air}	113	K
Sutherland constant of water vapour	S_{WV}	650	K
—	$\sqrt{MT_{crit}}$ (CO_2)	115,7	$\sqrt{\text{g mol}^{-1}\,\text{K}}$
—	$\sqrt{MT_{crit}}$ (O_2)	70,4	$\sqrt{\text{g mol}^{-1}\,\text{K}}$
—	$\sqrt{MT_{crit}}$ (N_2)	59,5	$\sqrt{\text{g mol}^{-1}\,\text{K}}$
—	$\sqrt{MT_{crit}}$ (air)	61,9	$\sqrt{\text{g mol}^{-1}\,\text{K}}$
—	$\sqrt{MT_{crit}}$ (water vapour)	107,9	$\sqrt{\text{g mol}^{-1}\,\text{K}}$

Annex B
(informative)

General equations concerning impaction theory

B.1 Aerodynamic diameter

The aerodynamic diameter equals the diameter of a sphere with a particle unit-mass density of 1 g/cm^3, which exhibits, under the influence of external mechanical forces in equilibrium conditions, the same drift rate in the gas as the particles investigated. As long as the external forces are limited to gravity, the gas is motionless and the aerodynamic drag occurs in the Stokes's law range, the drift rate of a particle becomes constant. This final particle velocity can be calculated approximately (with no buoyancy force being taken into account) by Equation (B.1):

$$v_P = \frac{\rho_P \, d_e^2 \, g}{18 \, \eta \, \chi} = \frac{\rho_{0,P} \, d_{ae}^2 \, g}{18 \, \eta} \qquad \text{(B.1)}$$

where:

v_P is the final particle velocity;

ρ_P is the particle mass density;

$\rho_{0,P}$ is the particle unit mass density;

d_e is the equivalent volumetric diameter;

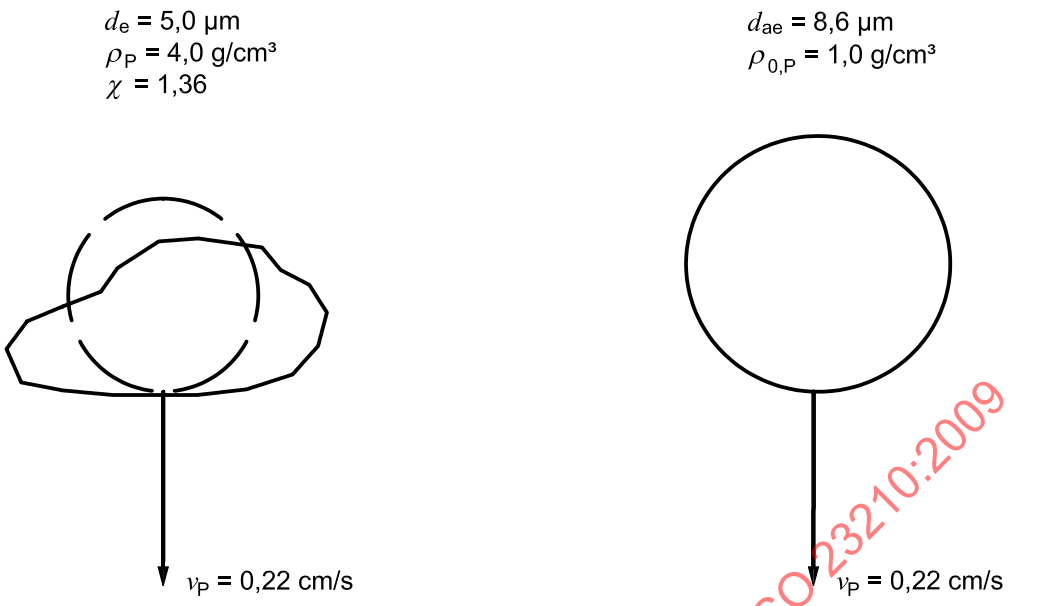
d_{ae} is the aerodynamic diameter;

χ is the dynamic shape factor;

g is the acceleration due to gravity;

η is the dynamic viscosity of the gas.

An example of the values of the quantities interrelated by Equation (B.1) is shown in Figure B.1.



a) Irregular particle **b) Aerodynamically equivalent sphere**

Figure B.1 — Comparison of irregular particle and the aerodynamically equivalent sphere

NOTE For more information on the behaviour of particles in fluids, see Reference [13].

B.2 Stokes's number

The Stokes's number is a measure of the inertial impaction of a particle moving in the gas stream near an obstacle. It is a dimensionless quantity, which is constant for a given design of the impactor stage. The Stokes's number in relation to the cut-off diameter d_{50} is described by the quantity St_{50}.

For the design of round-nozzle impactors, the value of the Stokes's number St_{50} is assumed to be 0,24.

The exact value of the Stokes's number St is determined during calibration and calculated by Equation (B.2):

$$St = \frac{\rho_{0,P} d_{ae}^2 C(d_{ae}) v_{in}}{9\eta d_{in}} \quad \text{(B.2)}$$

where:

St is the Stokes's number;

$\rho_{0,P}$ is the particle unit mass density;

d_{ae} is the aerodynamic diameter;

$C(d_{ae})$ is the Cunningham factor;

v_{in} is the gas velocity in the impactor nozzle;

η is the dynamic viscosity of the gas;

d_{in} is the impactor nozzle diameter.

Annex C
(informative)

Results of method validation

C.1 General

The method of measurement specified in this International Standard was validated in validation experiments with two different two-stage round-nozzle impactors. The results of these studies and the performance characteristics obtained are shown in Clauses C.2 and C.3.

C.2 Results of first validation study

C.2.1 Characteristic data of the impactor

The characteristic data of the impactor used in the first validation study are given in Table C.1 (see Reference [6]). An example of the influence of the gas conditions on the velocity in the impactor nozzles and the Reynolds number is given in Table C.2.

Table C.1 — Characteristic data of the impactor

	Impactor	PM_{10} stage	$PM_{2,5}$ stage
Total length	approx. 350 mm	—	—
Diameter	approx. 70 mm	—	—
Number of nozzles	—	6	12
Nozzle diameter	—	7,80 mm	2,38 mm
Aerodynamic cut-off diameter	—	9,95 µm	2,53 µm
Stokes's number	—	0,201	0,235
Cone angle of the diffuser	—	30°	30°
Filter and collecting plate diameter	50 mm	—	—
Diameter of the flow continuance	16 mm	—	—

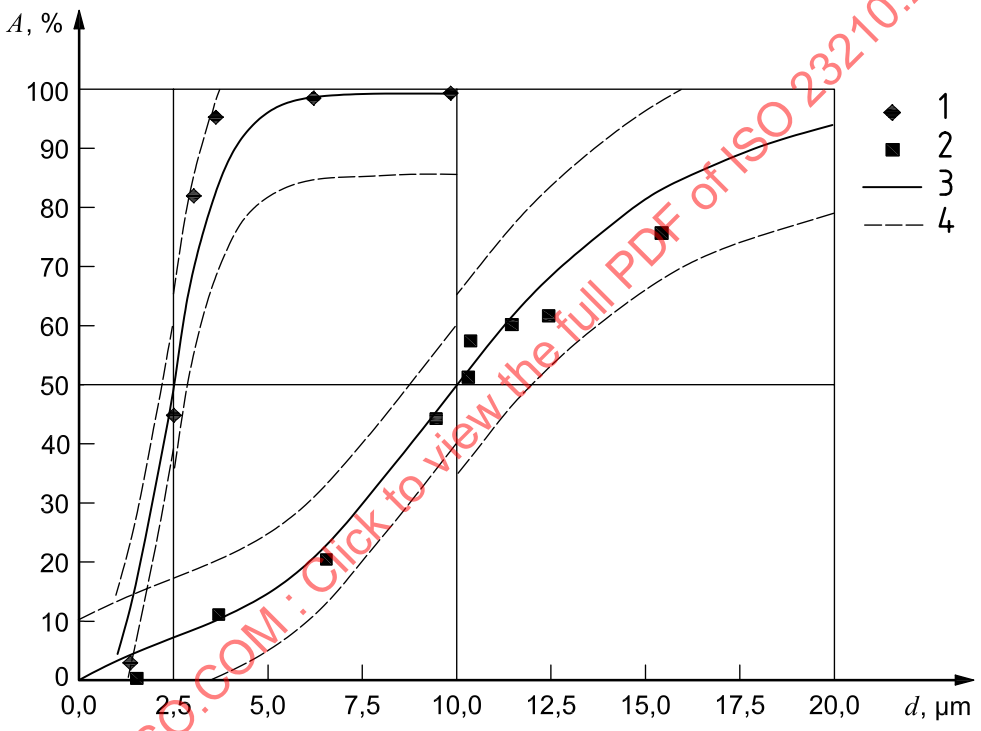
Table C.2 — Example of the velocity in the impactor nozzles and the Reynolds number for a given set of gas parameters

	Parameters	PM_{10} stage	$PM_{2,5}$ stage
Gas composition	air	—	—
Volumetric flow rate in operating conditions	3,20 m^3/h	—	—
Temperature	135 °C	—	—
Pressure	1 000 hPa	—	—
Humidity	30 g/m^3	—	—
Velocity in the nozzles	—	3,10 m/s	16,65 m/s
Reynolds number	—	899	1 473

C.2.2 Verification of separation curves

To check that the separation of the impactor stages corresponds to the calculated separation efficiencies, two experiments with mono-disperse latex aerosols were performed. First, each separate stage was used with greased collecting plates to increase the adhesion and reduce possible rebound of particles. Second, quartz-fibre filters (type Munktell 360 [1)] with the smooth surface towards the top) were used as collecting plates, as in the intended operation of the impactor.

Figure C.1 shows the experimentally determined separation efficiencies of the $PM_{2,5}$ and PM_{10} stages for the greased collecting plates and a comparison with the reference curves in accordance with ISO 7708:1995. Figure C.2 shows the experimentally determined separation efficiency of the $PM_{2,5}$ and PM_{10} stages for the quartz-fibre filters and a comparison with the reference curves in accordance with ISO 7708:1995. The limits of the permissible deviations specified in Tables 1 and 2 are indicated in both figures.

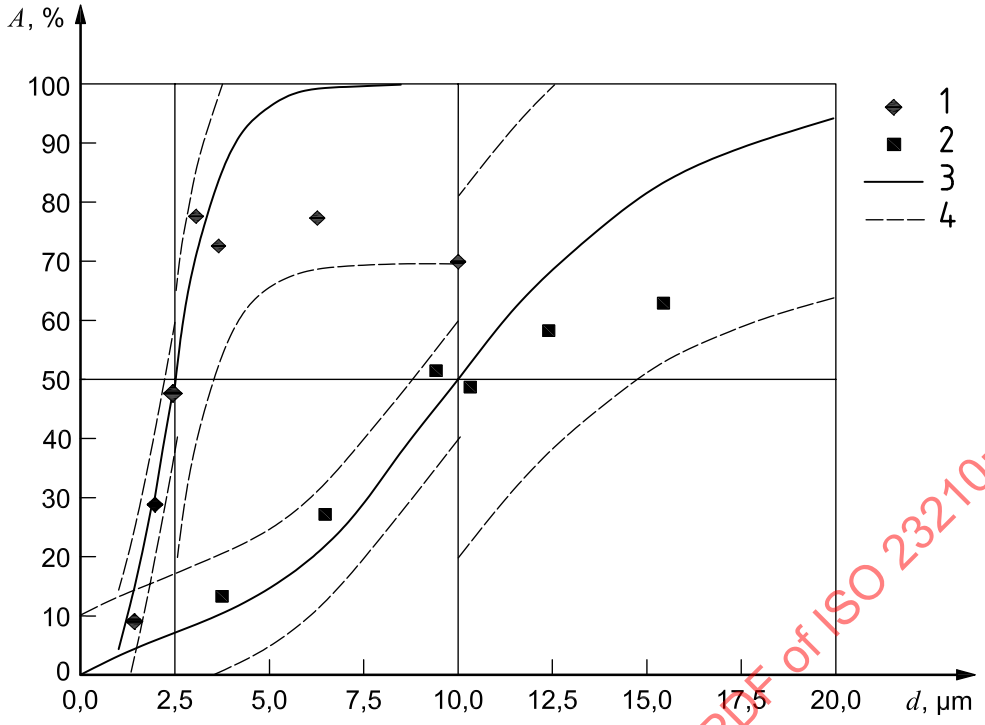


Key

1 separation efficiency of the $PM_{2,5}$ stage
2 separation efficiency of the PM_{10} stage
3 ISO 7708:1995 reference curves
4 limits of the permissible deviations according to Tables 1 and 2

Figure C.1 — Separation efficiency A as a function of the particle diameter d for greased collecting plates in comparison with the ISO 7708:1995 reference curves and limits of the permissible deviations according to Tables 1 and 2

1) Munktell 360 is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.



Key

1 separation efficiency of the $PM_{2,5}$ stage

2 separation efficiency of the PM_{10} stage

3 ISO 7708:1995 reference curves

4 limits of the permissible deviations according to Tables 1 and 2

Figure C.2 — Separation efficiency A as a function of the particle diameter d for quartz-fibre filter collecting plates in comparison with the ISO 7708:1995 reference curves and limits of the permissible deviations according to Tables 1 and 2

C.2.3 Detection limit

The detection limit of weighing the separate filters (backup filter and collecting plate of the second impactor stage) is 0,3 mg. The detection limit of weighing $PM_{2,5}$ is, correspondingly, 0,3 mg. The detection limit of the concentration for a sample volume of 1 m^3 (sampling duration approximately 0,5 h) is 0,3 mg/m^3.

Since the detection limit of PM_{10} is influenced by two independent weighings (backup filter and collecting plate of the second stage), the detection limit of 0,4 mg is greater than the value of $PM_{2,5}$. Due to uncertainty propagation, the corresponding detection limit of the concentration for a sample volume of 1 m^3 (sampling duration approximately 0,5 h) is 0,4 mg/m^3.

C.2.4 Measurement uncertainty

Tables C.3 and C.4 give standard deviations obtained by paired measurements and calculated by Equation (6) for different plant types. These standard deviations take into account influences such as sampling and differential weighing of collecting plates and backup filters.

Table C.3 — Standard deviation from paired measurements (one operator of the method)

Plant type	Number of paired measurements n	Average PM_{10} content mg/m^3	Standard deviation of PM_{10} content mg/m^3	Average $PM_{2,5}$ content mg/m^3	Standard deviation of $PM_{2,5}$ content mg/m^3
Gas flow channel	5	5,6	0,3	2,5	0,2
Sinter plant	5	35,4	2,4	29,1	2,3
Steel factory	5	9,4	0,4	5,1	0,2

Table C.4 — Standard deviation from paired measurements (two operators of the method)

Plant type	Number of paired measurements n	Average PM_{10} content mg/m^3	Standard deviation of PM_{10} content mg/m^3	Average $PM_{2,5}$ content mg/m^3	Standard deviation of $PM_{2,5}$ content mg/m^3
Gas flow channel	6	10,9	0,7	4,2	0,6

C.3 Results of second validation study

C.3.1 Characteristic data of the impactor

The characteristic data of the impactor used in the second validation study are given in Table C.5. An example of the influence of the gas conditions on the velocity in the impactor nozzles and the Reynolds number is given in Table C.6.

Table C.5 — Characteristic data of the impactor

	Impactor	PM_{10} stage	$PM_{2,5}$ stage
Total length	190 mm	—	—
Diameter	75 mm	—	—
Number of nozzles	—	1	14
Nozzle diameter	—	8,3 mm	1,4 mm
Aerodynamic cut-off diameter (individually pressure calibrated for each impactor)	—	~10 µm	~2,5 µm
Stokes's number	—	0,23	0,21
Collecting substrate diameter	25 mm	—	—
Filter diameter	47 mm	—	—

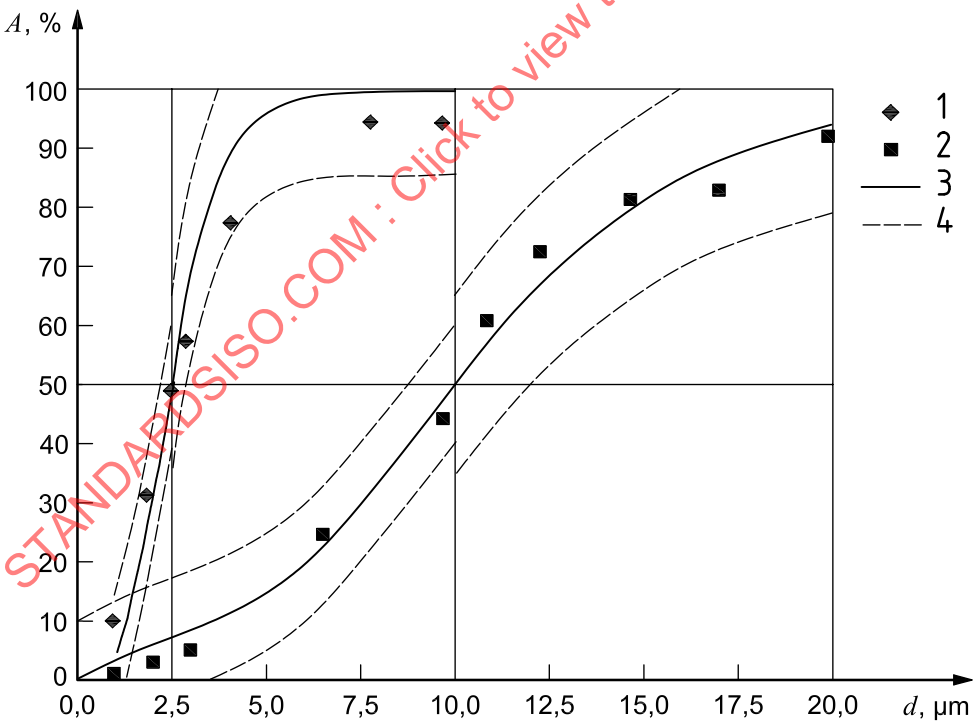
Table C.6 — Example of the velocity in the nozzles and the Reynolds number for a given set of gas parameters

	Parameters	PM_{10} stage	$PM_{2,5}$ stage
Gas composition	air	—	—
Volumetric flow rate	1,8 m^3/h	—	—
Temperature	135 °C	—	—
Pressure	1 000 hPa	—	—
Humidity	30 g/m^3	—	—
Velocity in the nozzles	—	3,6 m/s	9,1 m/s
Reynolds number	—	1 109	473

C.3.2 Verification of separation curves

The impactor was tested by using both solid latex particles with sizes from 1 µm to 15 µm and solid spherical salbutamol particles, which are known to be very bouncy during impactor measurements. The impactor separation efficiency was obtained from measurements with greased aluminium foils and with quartz foils.

Figure C.3 shows the experimentally determined separation efficiency of the $PM_{2,5}$ and PM_{10} stages for the greased aluminium foils used as collecting plates and a comparison with the reference curves in accordance with ISO 7708:1995. Figure C.4 shows the experimentally determined separation efficiency of the $PM_{2,5}$ and PM_{10} stages for the quartz foils and a comparison with the reference curves in accordance with ISO 7708:1995. The limits of the permissible deviations specified in Tables 1 and 2 are indicated in both figures.



Key

1 separation efficiency of the $PM_{2,5}$ stage
2 separation efficiency of the PM_{10} stage
3 ISO 7708:1995 reference curves
4 limits of the permissible deviations according to Tables 1 and 2

Figure C.3 — Separation efficiency A as a function of the particle diameter d for greased collecting plates in comparison with the ISO 7708:1995 reference curves and limits of the permissible deviations according to Tables 1 and 2