Simultaneous PM10 And PM2.5 Measurement From Stacks According to New ISO 23210 Standard

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ABSTRACT

A new ISO standard 23210 for simultaneous measurement of PM10 and PM2.5 was finalized in July 2009. The method is based on the principle of impaction and is designed for stack measurements at stationary emission sources. Due to the principle of the method, it is especially suitable for mass concentrations below 40mg/m^3 and the collected PM can be used for further chemical analysis.
A cascade impactor is used to enable the simultaneous measurement of PM10 and PM2.5. The PM10 and PM2.5 collection efficiency curves for the impactor stages are as specified in the ISO 7708:1995[1]. The particulate matter is collected on quartz filters which are weighed before and after the PM collection to find the amount of collected PM in each size fraction.
In the standard, it is recommended that the impactor is placed in the stack directly against the flue gas flow. Goose-neck and out-stack sampling is allowed only if extensive loss analysis is done and the deposited material is carefully retrieved from the probe.
The requirements for the impactor are set so that the measurement results with any two systems are comparable. The collection efficiency curves of the impactor stages must agree as specified with the ISO 7708:1995 standard[1]. In addition, paired field measurement must be conducted to ensure the repeatability of the measurements.
The development of this international standard is an important step in the field of standard measurement to provide a method for accurate measurement of PM2.5 and perhaps even more significantly to define the impactor principle. This principle will be an efficient tool for future standardization as the interest and demand for PM1.0 and PM0.1 measurements grow.
In this paper, the scope, requirements and the limitations of the standard will be presented in detail along with PM measurement results from stationary sources.

INTRODUCTION

Measurement of stationary source PM emissions in low concentration according to ISO standards is described in ISO 12141:20022, which presents a method for TSP measurement in low concentrations. There is however a need for more detailed information on the PM emissions, because ambient air pollution standards define limits for the concentration of PM2.5 in the atmosphere and the TSP measurements at the stationary sources might not correlate with the actual PM2.5 emissions from the source. Therefore a new ISO standard 23210 has been developed that allows simultaneous PM10 and PM2.5 concentration measurements from stationary source flue gas. This is an important development as the cumulative data from these measurements will provide much needed detail to the stationary source PM emission information for the evaluation of environmental impacts and health effects.
The standard has been developed especially for low concentrations below 40 mg/m3 and the sizing of the PM to the size classes is based on the use of a cascade impactor.

There are several benefits from using a cascade impactor for the size classification. First of all, with the impaction method, the PM is classified according to the aerodynamic size of the particles, which is the same size definition what is used in ambient standards. Particulate mass deposition in lungs is also governed mainly by impaction and the selected PM10 and PM2.5 size classes in the standard represent the thoracic and high risk respirable conventions, respectively. Typical impactor design allows the sample collection to be done on a lightweight substrate or filter, which increases the mass sensitivity of the method.

In addition, the collected samples can be also used in chemical analysis for more information on the PM characteristics. Cascade impactors can also be quite compact in size, which is a benefit in flue gas PM sampling.

The drawback from using cascade impactors is that the method is not suitable for high concentration measurements. Overloading of the collection plates can cause bounce and blow-off phenomena, which will distort the mass concentrations in the segregated size classes. Also, the use of a PM10, PM2.5 cascade impactor increases the work with sample handling, because the collected PM is divided into three samples according to the aerodynamic size of the particles; above 10µm, between 10µm and 2.5µm and below 2.5µm.

The particle emissions from a stationary source can be divided into primary and secondary emissions. The primary particle emissions is the PM that exists is the stack gas, while the secondary emission is the PM that forms during mixing of the stack gas with ambient air or later due to chemical reactions. The measurement technique presented here can only be used to estimate the primary particle emissions.

In terms of future standard development, this standard is an important step towards more detailed sampling from combustion sources, as the cascade impactor measurement size range can be extended as low as few tens of nanometers. The next development of the standard in a few years may be the addition of PM1.0 measurement to the setup.

In this work we present the scope of the standard along with requirements for instrument calibration and limitations for applying this standard. In addition we present calibration data from an impactor that fulfills the requirements of the standard.

OVERVIEW

The ISO standard 23210 defines a standard reference method for simultaneous measurement of PM10 and PM2.5 from stationary emission sources with a two-stage impactor. The method is aimed especially for low-concentration measurements below 40 mg/m3 defined as 30 minute averages in standard conditions of 273K, 1013hPa and dry gas. The measurement method can be used in the stack gas measurements of any industry such as combustion, cement or steel production as long as the requirements for the stack gas conditions and PM are fulfilled.

The standard may not be used in conditions where the stack gas is saturated with water vapor or when there is a significant fraction of particles above 10µm. A further limitation of the standard is that it may not be used for the determination of total mass concentration of the dust.

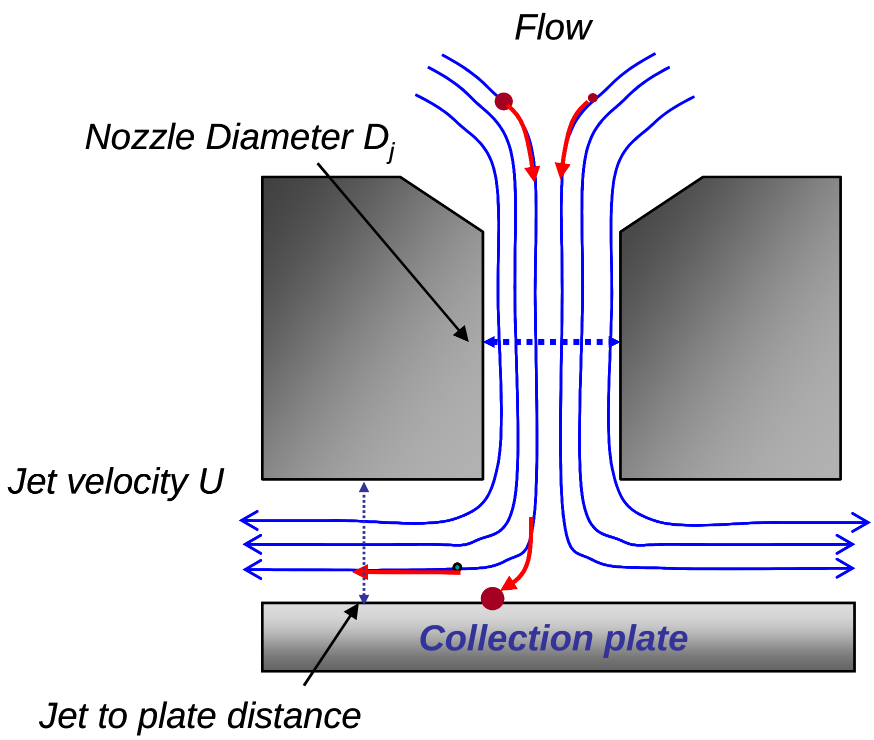
ISO standard 23210

The key parts of the ISO 23210 standard are reviewed in this section with comments and additional information where appropriate.

Impaction theory

An impactor is a simple device having two co-linear plates of which the other has a small nozzle in it. Aerosol passes through this nozzle with high speed and makes a sharp turn with the flow between the plates. Particles with sufficient inertia cannot follow the flow and impact on the second plate but particles with inertia small enough remain in the flow. The cut diameter for an impactor is defined as the size of particles collected with 50% efficiency. The plate with nozzles in it is called the jet plate and the second one the collection plate. Operational diagram of a single impactor stage is presented in Figure 1.

Figure 1. Operational diagram of a single impactor stage



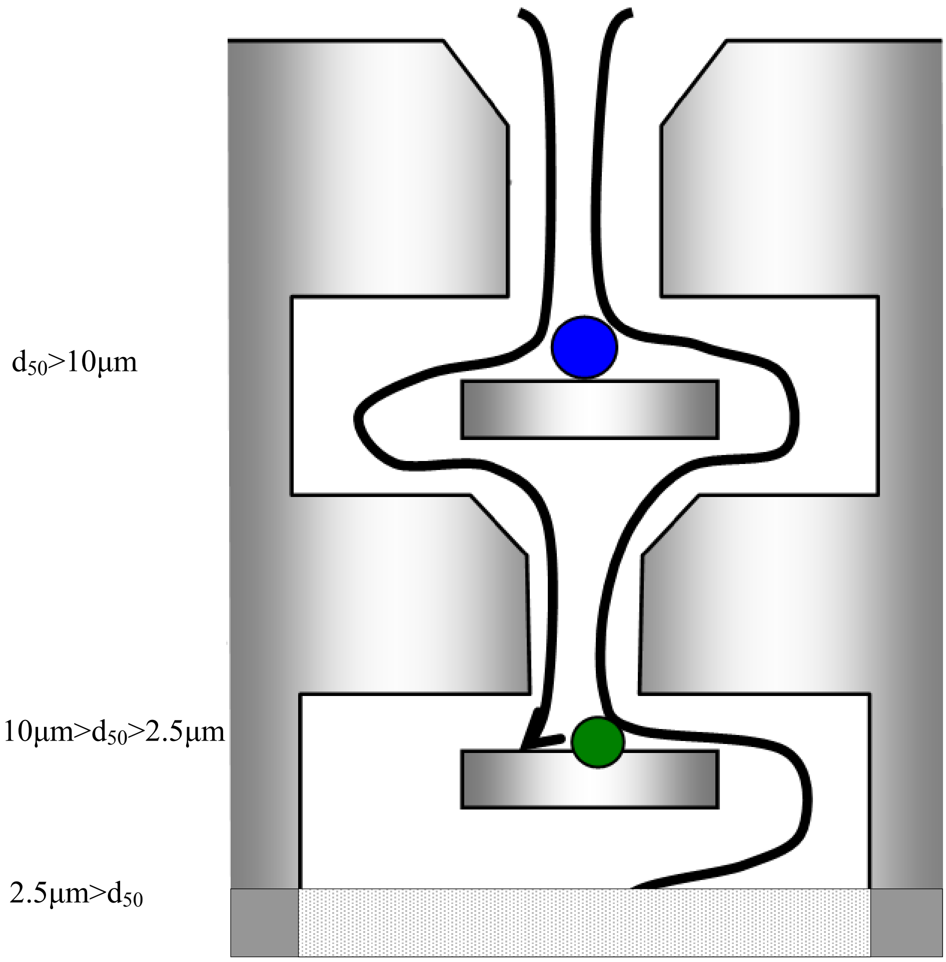
Impactor stage characteristic is usually defined with a cut-off diameter d50. 50% of the particles with this aerodynamic diameter cannot follow the flow and will impact onto the collection plate. The d50 value is calculated with the following equation3:

$$d_{50} = \sqrt{\frac{9\pi St_{50}\eta N D_j^3}{4\rho_{0p} C \dot{V}}}$$

where,
d50=impactor cut-off diameter
St50=Stokes number related to the cut-off diameter
η=Dynamic viscosity of the gas
N=Number of impactor nozzles
Dj=Nozzle diameter
ρ 0p=Particle unit mass density
C=Cunningham slip correction factor
V=Volumetric flow rate through the impactor at standard conditions

Cascade impactors consist of several successive impactor stages with decreasing cut diameters. The impactor defined in this standard collects particles above 10µm on the first collection plate, particles between 10µm and 2.5µm on the second collection plate and particles below 2.5µm on the backup filter. The basic operation principle of the cascade impactor can be seen in Figure 2.

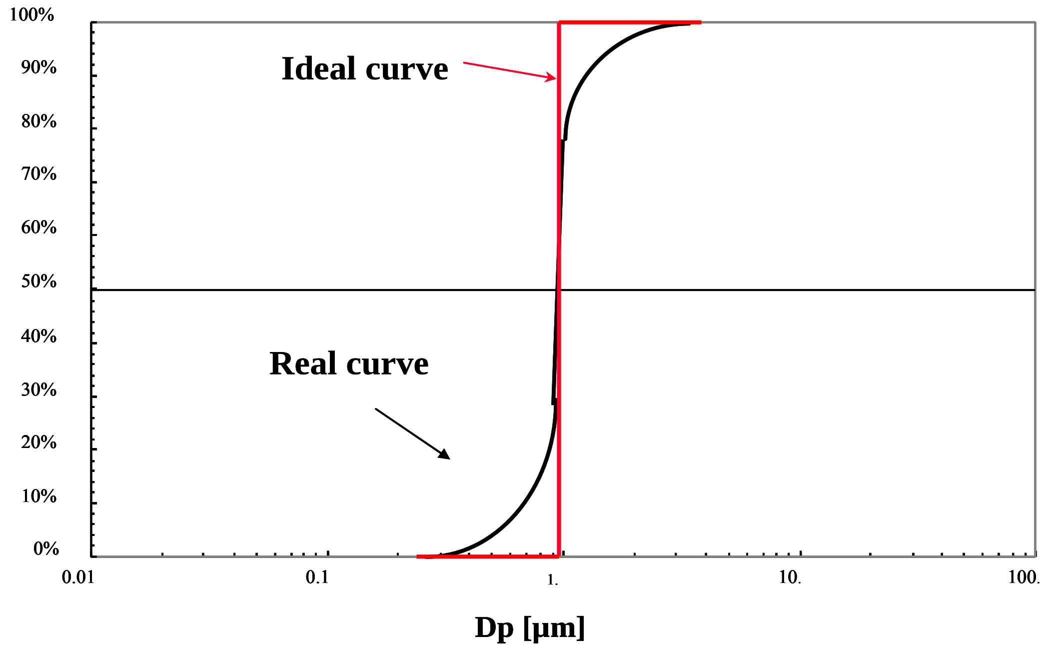
Figure 2. Basic operation principle of a cascade impactor



Cut-off curve

The impactor cut-off curve would ideally be a straight line from 0% to 100% at the cut-off size, However in reality the cut-off curve is always S-shaped. Figure 3 shows the difference between an ideal and real cut-off curve.

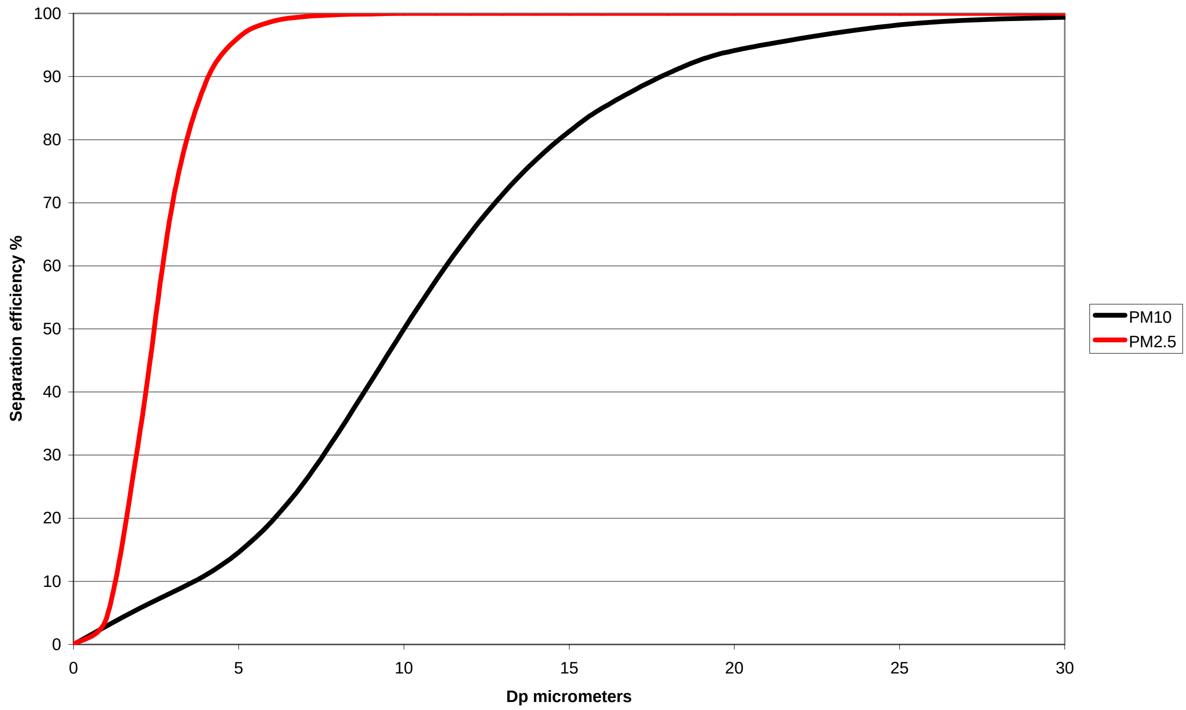
Figure 3. Ideal and real cut-off curve of a single impactor stage



Separation (collection) efficiency curves

The non-ideal shape of the cut-off curve causes that the separation curves for the impactor cannot be defined with single cut-off values. Therefore the curve for both PM10 and PM2.5 must be defined with enough individual points to characterize the real curve. These cut-off curves are the PM10 and PM2.5 curves defined in the ISO standard 7708:19951 as the thoracic and high risk respirable conventions, respectively. The PM10 and PM2.5 separation curves can be seen in Figure 4.

Figure 4. PM10 and PM2.5 separation curves as specified in ISO7708:1995[1]



Operating conditions

The impactor must always operated at the volumetric flow as specified by the manufacturer to achieve the required separation curves. In contrast to filter measurements, with the impactor method the volumetric flow must always be same and constant. Due to this, isokinetic sampling must be achieved by using different size isokinetic nozzles and not by changing the sampling flow rate. If isokinetic sampling cannot be achieved, overisokinetic sampling is preferred. Typical operating conditions for the method are presented in Table 1.

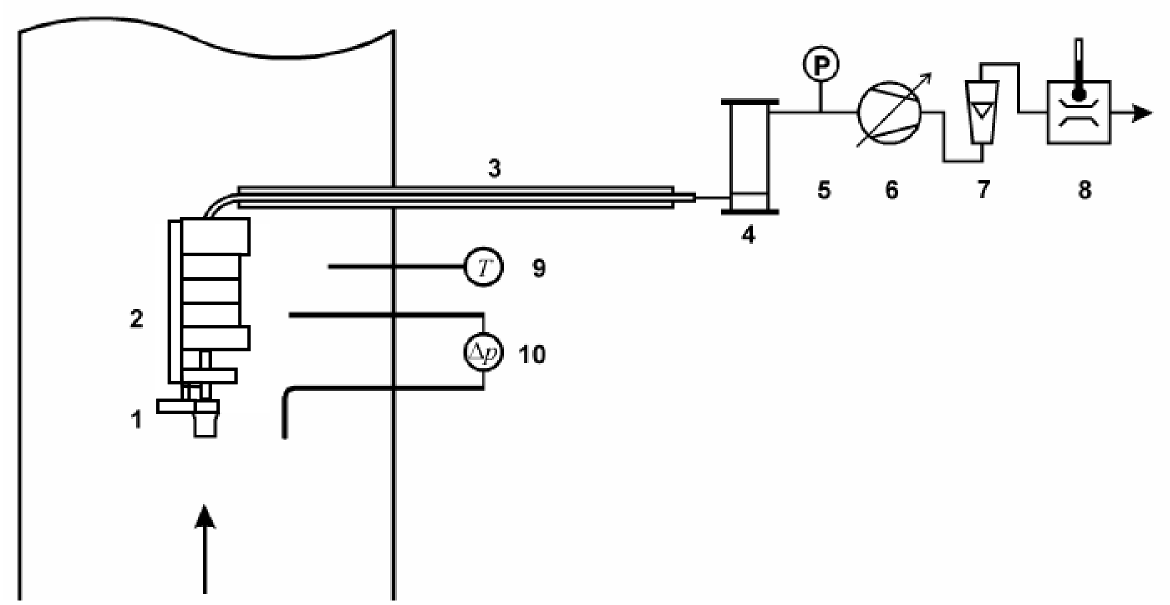
Table 1. Typical operation conditions

	Mean value	Minimum value	Maximum value
Dust concentration in mg/m^3	10	1	50
Temperature in Celcius	135	20	250
Pressure in hPa	1000	850	1100
Humidity in g/m^{3*}	30	0	100
*dew-point must be below flue gas temperature			

General measurement setup

It is always highly recommended that the impactor is placed inside the stack directly against the flue gas flow. Out-stack sampling with a gooseneck probe is accepted only if detailed loss analysis from the extraction probe is carried out. The maximum accepted amount of losses in the extraction probe is 5% of the total mass collected with the impactor. Impactor must also be heated to the flue gas temperature if out-stack sampling is used. General measurement setup is presented in Figure 5.

Figure 5. General measurement setup



Components of the setup are given below:

1. Isokinetic nozzle
2. Two-stage impactor
3. Suction tube
4. Drying column
5. Manometer
6. Pump
7. Flow meter
8. Gas volume measurement device with thermometer
9. Temperature measurement device
10. Pitot tube with differential pressure meter

General measurement procedure

Preliminary flue gas measurements
The following characteristics of the flue gas must be measured before the start of sampling:

1. Flue gas velocity
2. Flue gas composition O_2, CO_2, N_2 and humidity
3. Flue gas temperature
4. Static pressure

Also if there is no information about the PM level in the flue gas, pre-measurements are recommended to determine a suitable sampling time so that the instrument is not overloaded but a weighable mass is collected.

Determination of impactor volumetric flow
The correct volumetric flow through the impactor is then calculated based on the flue gas characteristics. The used volumetric flow during sampling must be within +/- 5% of the determined value. The equations used to determine the volumetric flow are given in the ISO standard 23210.

Determination of the isokinetic nozzle
The correct isokinetic nozzle size is then calculated based on the information of flue gas characteristics and on the impactor volumetric flow. The selected nozzle must achieve an isokinetic sampling rate between 90 and 130% of the exact isokinetic velocity. The equations used to determine the nozzle size are given in the ISO standard 23210.

Leak check
The complete sampling system shall be checked for leaks prior to starting the measurement. The leak flow must not exceed 2% of the used sampling flow. If the setup does not pass the leak check, the leak must be found and rectified.

Measurement
The impactor must be at flue gas temperature before the measurement is started. If the water vapor in the flue gas is close to the dew-point, the impactor must be heated to the flue gas temperature before it is inserted into the stack.
The angle between the isokinetic nozzle and the flue gas flow must not be greater than 10 degrees to avoid losses due to misalignment of the nozzle. After the nozzle is aligned properly, the pump is started and the sampling flow is adjusted to the correct calculated value. Both the sampling flow and the stack dynamic pressure shall be checked repeatedly during the measurement. The sampling flow however must not be adjusted if the stack dynamic pressure changes, the dynamic pressure changes are documented and reported with rest of the data.
The sampling train is removed from the stack and the total volume of sampled gas is determined after the sampling period is over.

Post treatment of samples
The samples are dried, equilibrated and weighed according to ISO 121412. The impactor parts are checked for signs of bouncing of blow-off of particles. If there is clear evidence of bounce or blow-off, the measurement must be rejected.

Verification of an impactor according to ISO 23210

The requirements for an impactor to comply to ISO 23210 are presented in this chapter. The key points are the verification of the impactor separation curves and the uncertainty analysis from paired field measurements.

Verification of the impactor separation curves

The impactor separation curves must be verified with a measurement of mono-disperse solid particles using greased aluminum foils and quartz filters. The separation efficiency must be measured with at least six particle sizes for both PM10 and PM2.5 stages. Particle sizes must span the range of 2-20μm and 1-10μm for the PM10 and PM2.5 stages, respectively. One particle size must be as close as possible to the d50% cut size of the stage. The determined separation efficiencies must follow the ISO 7708:1995 standard1. The accepted deviations for PM2.5 and PM10 stages are given in the Tables 2 and 3, respectively.

Table 2. Requirements on the separation efficiency for the PM2,5 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**
1.0μm to 2.5μm	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a tolerance of ±10 %	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a tolerance of ±10 %
>2.5μm to 10.0μm	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a tolerance of ±15 %	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a tolerance of ±30 %

Table 3. Requirements on the separation efficiency for the PM10 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**
2.0μm to 10μm	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a tolerance of ±10 %	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a tolerance of ±10 %
>10μm to 20μm	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a tolerance of ±15 %	Separation efficiency of ISO 7708:1995 at the corresponding particle diameter with a tolerance of ±30 %

Paired field measurements

Paired field measurements must be carried out with two identical setups at the same measurement cross-section. The measurement uncertainty of the impactor is then determined from the results based on ISO standard 20988.

Results and Discussion

The verification measurement results from one type of impactor are presented in this chapter. The separation curves are presented first, followed by measurement results from paired measurements. An example impactor construction and characteristics are also presented.

Separation curves

The PM10 and PM2.5 separation curves measured with greased aluminum foils and with quartz filters are presented in Figures 6 and 7, respectively

Figure 6. Separation efficiency A as a function of particle size d for PM10and PM2.5 stages, measured with greased aluminum substrates. Reproduced from the draft standard 23210

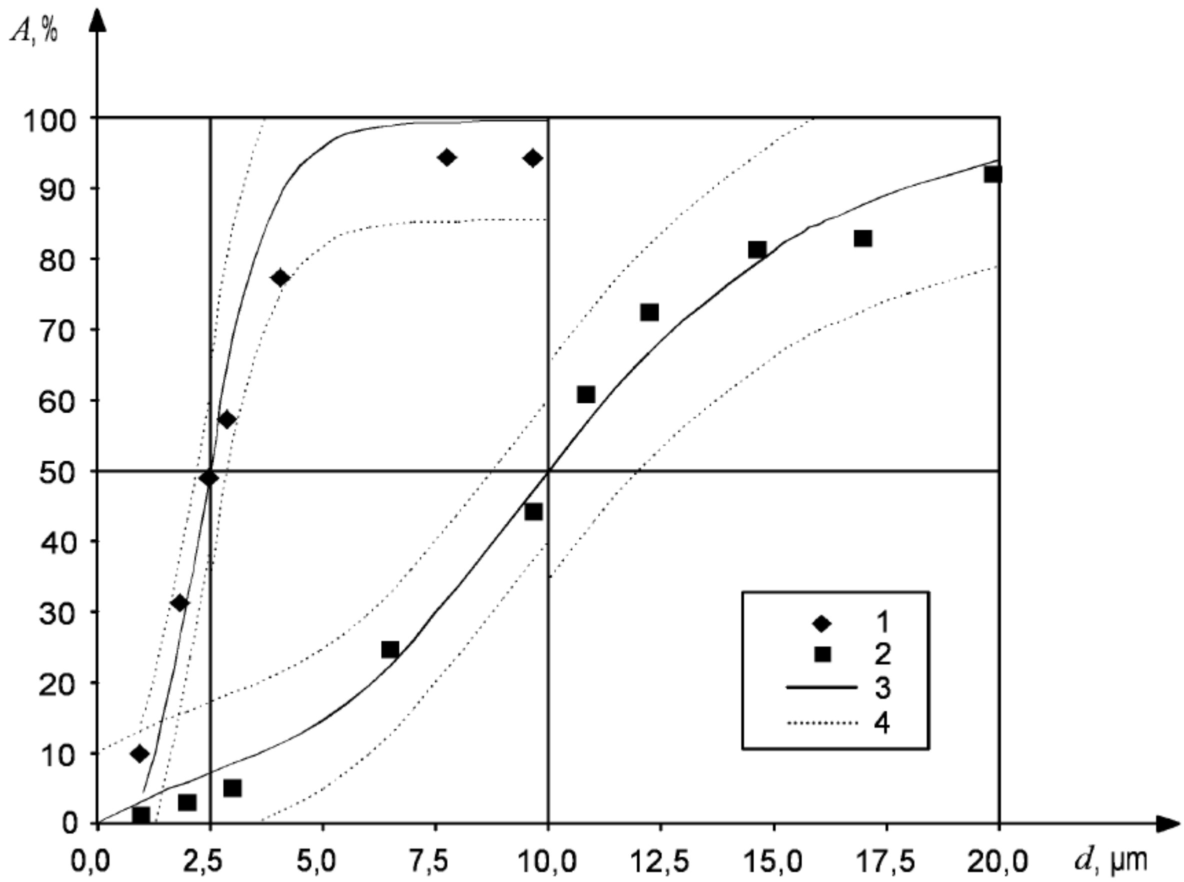
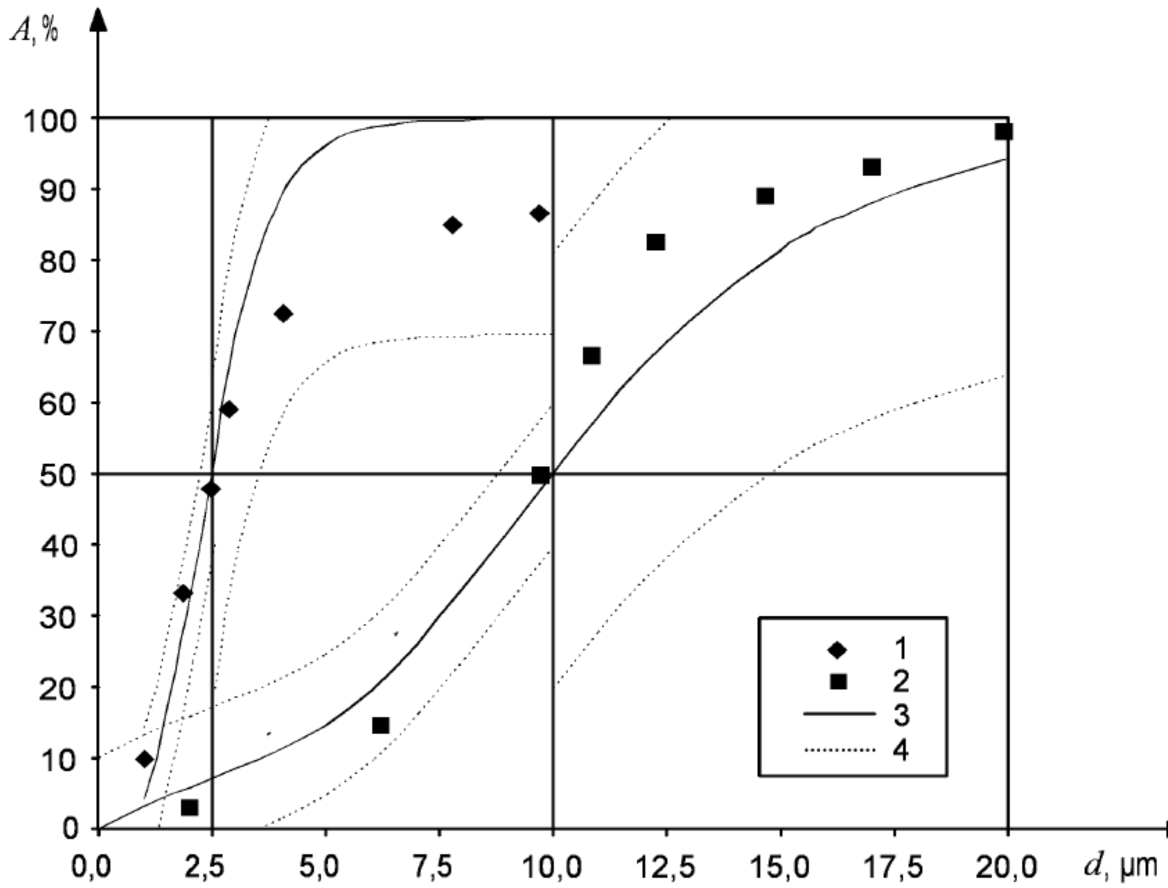


Figure 7. Separation efficiency A as a function of particle size d for PM10and PM2.5 stages, measured with quartz filter substrates. Reproduced from the draft standard 23210



The legend key for Figure 6 and 7 is below:

1. Separation efficiency of the PM2.5 stage
2. Separation efficiency of the PM10 stage
3. ISO 7708:1995 reference curves
4. The accepted deviation limits from Tables 2 and 3

The separation efficiency is better with greased aluminum foils, because the grease on the collection substrate reduces the possibility of bounce. Because the measurement is done using solid spherical particles which have a known tendency to bounce from the impaction plate, the measured separation efficiency curves reflect a worst case real-life situation with an especially difficult aerosol to measure. Therefore in actual measurements from stack gas, the separation efficiency curves are likely to be similar or steeper than what is presented here.

Paired measurements

Results from paired measurements at three different installations are presented in Table 4.

Table 4. PM10 and PM2.5 measurement data from three different installations

	Number of measured pairs	Average PM mg/m^3	Standard deviation of PM content	Average PM10 mg/m^3	Standard deviation of PM10 content	Average PM2.5 mg/m^3	Standard deviation of PM2.5 content
Stack							
Bark boiler	5	4.43	0.31	3.25	0.27	1.44	0.08
Waste incinerator	5	2.03	0.09	1.19	0.08	0.42	0.08
Lime kiln	5	18.81	0.72	13.62	1.00	8.01	0.45

The data in Table 4 shows that the method can be used effectively in a range of concentrations and in different installations with a low standard deviation.

The characteristics of an example impactor are presented in Table 5.

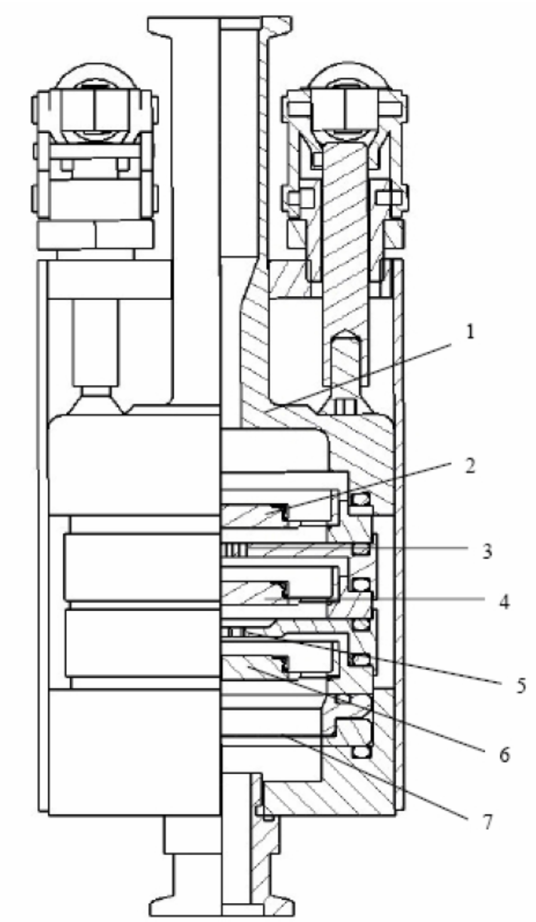
Table 5. Characteristics of an example impactor

	Impactor	PM10 stage	PM2.5 stage
Total length	190mm		
Diameter	75mm		
Number of nozzles		1	14
Nozzle diameter		8.3mm	1.4mm
Aerodynamic cut-off diameter		10µm	2.5µm
Stokes number		0.23	0.21
Collection substrate diameter	25mm		
Filter diameter	47 mm		
Gas composition	Air		
Volumetric flow rate	1.8 m^3/h		
Temperature	135 degrees Celcius		
Pressure	1000 hPa		
Humidity	30 g/m^3		
Velocity in the nozzles		3.6m/s	9.1m/s
Reynolds number		1109	473

Example impactor construction

An example of an impactor construction can be seen in Figure 8.

Figure 8. Example of an impactor construction



1. Inlet of impactor / PM10 jet plate
2. Collection plate for particles bigger than 10µm
3. PM2.5 jet plate
4. Collection plate for particles bigger than 2.5µm
5. PM1 jet plate (removed if PM1 is not measured)
6. Collection plate for particles bigger than 1µm (removed if PM1 is not measured)
7. Backup filter holder

SUMMARY

ISO standard 23210 defines an impactor method for simultaneous measurement of PM10 and PM2.5 from flue gases. The method is especially suitable for low concentration measurements and it can be used also for collection of material for chemical analysis. The operation conditions, measurement procedure and equations for data analysis and evaluation are given in detail in the standard. In addition the standard defines the verification procedure to check the compliance of an impactor to the standard. An example of an impactor that fulfills the requirements of the standard was also presented with separation efficiency curves and data from paired field measurements.

This standard method gives a very useful tool for more detailed measurement of flue gas PM especially for low concentrations. The presented impactor method also makes future standardization for lower particle size mass measurement more straightforward.

ACKNOWLEDGMENTS

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