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Stationary source emissions — Guidance on the application of EN ISO 16911-1

National foreword

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Émissions de sources fixes - Préconisations concernant l'application de l'EN ISO 16911-1

Emissionen aus stationären Quellen - Leitlinien zur Anwendung von EN ISO 16911-1

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CEN-CENELEC Management Centre: Avenue Marnix 17, B-1000 Brussels

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European foreword

This document (CEN/TR 17078:2017) has been prepared by Technical Committee CEN/TC 264 “Air quality”, the secretariat of which is held by DIN.

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Introduction

This CEN Technical Report provides supporting guidance on the application of EN ISO 16911-1:2013. It has been produced in response to the request from Member State mirror committees for clarification on elements of EN ISO 16911-1:2013 and on how certain requirements specified within it should be interpreted. EN ISO 16911-1:2013 has been written to apply to a range of applications with different uncertainty requirements. This CEN Technical Report makes recommendations in regards to which requirements and performance characteristics apply to specified measurement objective(s) and application area(s) in order to achieve a consistent application of EN ISO 16911-1:2013.

1 Scope

This CEN Technical Report provides guidance only on the application of the European Standard EN ISO 16911-1:2013.

This CEN Technical Report does not provide guidance on the application of EN ISO 16911-2:2013.

2 Normative references

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

EN 14181, *Stationary source emissions - Quality assurance of automated measuring systems*

EN 15259:2007, *Air quality - Measurement of stationary source emissions - Requirements for measurement sections and sites and for the measurement objective, plan and report*

EN ISO 16911-1:2013, *Stationary source emissions - Manual and automatic determination of velocity and volume flow rate in ducts - Part 1: Manual reference method (ISO 16911-1:2013)*

EN ISO 16911-2:2013, *Stationary source emissions - Manual and automatic determination of velocity and volume flow rate in ducts - Part 2: Automated measuring systems (ISO 16911-2:2013)*

ISO 10780, *Stationary source emissions — Measurement of velocity and volume flowrate of gas streams in ducts*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN ISO 16911-1:2013 and the following apply.

3.1
emission source
separately identifiable part of an installation or a process within an installation, from which relevant greenhouse gases are emitted and are regulated under the EU Emissions Trading System

[SOURCE: Commission Regulation (EU) No. 601/2012, Article 3, Definition (5)]

3.2
tier
set requirement under the EU Emissions Trading System used for determining activity data, calculation factors, annual emission and annual average hourly emission, as well as for payload

[SOURCE: Commission Regulation (EU) No. 601/2012, Article 3, Definition (8)]

4 Symbols and abbreviations

For the purposes of this document, the symbols and abbreviations given in EN ISO 16911-1:2013 and the following apply.

4.1 Symbols:

dl	change in length (m, inches)
L_0	initial length of measuring rod (m, inches)
α	linear temperature expansion coefficient (m/m°C)
t_0	initial temperature (°C)
t_1	final temperature (°C)
CF_i	correction factor at position i
V_{fav}	average velocity of fixed device measurements
V_{fi}	velocity of fixed measurement device at position i
V_{ticorr}	corrected velocity at position i
V_{meas}	velocity measured
hs	corrected height of the indicating fluid to standard temperature
ht	height of the indicating fluid at the temperature when read
ps	density of the indicating fluid at standard temperature
pt	density of the indicating fluid at the temperature when read
gs	gravitational acceleration assumed at calibration, ms^{-2}
gt	gravitational acceleration at test location, ms^{-2}
θ	latitude (North/South position with the Equator being zero), °
H	height above sea level, m

4.2 Abbreviations:

EU ETS	Emissions Trading System
CO_2(e)	Carbon Dioxide equivalent

5 General guidance on manual determination of velocity and flow rate in ducts

5.1 General

5.1.1 Role of this CEN Technical Report

The role of this CEN Technical Report is to provide guidance on the application of the European Standard EN ISO 16911-1:2013 on the manual determination of velocity and flow rate in ducts. This Technical Report offers clarification on matters of interpretation of EN ISO 16911-1:2013 and provides recommendations on its application depending on the uncertainty requirements of the measurement objective. The adoption of the full Technical Report or parts of it may be decided by individual Member States' regulatory authorities.

Throughout this Technical Report, reference to the Standard refers to EN ISO 16911-1:2013.

5.1.2 How to use this Technical Report

This Technical Report does not follow the numbering of EN ISO 16911-1:2013; however for easier handling it uses the same headings and sub-headings as EN ISO 16911-1:2013. It does not repeat text, tables or diagrams from EN ISO 16911-1:2013, instead it refers to the relevant sections of the Standard. It is therefore essential that the reader has a copy of the Standard to refer to. For sections of the Standard where this Technical Report does not provide any text or guidance it is deemed that the relevant section does not require any additional clarification.

An error has been identified in Formula (F.10) of the uncertainty example in EN ISO 16911-1:2013, Annex F. It is recommended that the uncertainty example provided in this CEN Technical Report (see Clause 8) replaces the existing one in the Standard.

5.2 Scope and structure of EN ISO 16911-1

5.2.1 Scope of EN ISO 16911-1

EN ISO 16911-1:2013 is applicable to industrial plants falling under the European Industrial Emission Directive (2010/75/EU). It is also applicable to industrial plants falling under the EU Emissions Trading System Directive (EU ETS) (2003/87/EC) that are required or have opted to use the measurement-based methodology as specified in Commission Regulation (EU) No 601/2012 of 21 June 2012 on the monitoring and reporting of greenhouse gas emissions (MRR).

5.2.2 Concept of EN ISO 16911-1

EN ISO 16911-1 has been written to apply to different measurement objectives with different uncertainty requirements ranging from very stringent (EU ETS Tier 4 - ± 2,5 %) to less demanding (support of isokinetic sampling). The performance characteristics and requirements within the Standard have been specified as a means of achieving the most stringent uncertainty requirements. Although not explicitly specified within the Standard, it is implied that the level of quality control should be determined by the uncertainty requirements of the measurement objective. Therefore for measurement objectives with lesser uncertainty requirements the level of quality assurance and control can be reduced. It is the role of this Technical Report to make these distinctions and provide guidance as to the level of quality control that may be applied.

5.2.3 Relationship to other international standards

EN ISO 16911-1 does not replace existing standards. This Technical Report does not reproduce any detailed procedures; therefore users will have access to the documents referenced in Clause 2 and in the final Bibliography.

5.3 Summary of different requirements for determination of velocity and flow rate

5.3.1 Velocity and flow rate monitoring requirements under the Industrial Emissions Directive

The measurement of velocity and flow rate is required under the Industrial Emissions Directive as part of periodic monitoring for compliance purposes or pollution inventory reporting which involves the determination of mass emissions. It is also required for the control of isokinetic conditions during the manual sampling of atmospheric pollutants.

5.3.2 Velocity and flow rate monitoring requirements under the EU ETS Directive

The MRR specify that all flow automated measuring systems (AMS) used for the monitoring and reporting of GHG under the EU ETS, shall follow the quality assurance procedures specified within EN 14181 and other corresponding EN standards and therefore by deduction require the flow AMS to adhere to EN ISO 16911-2:2013 and its calibration (procedure specified in EN ISO 16911-2) to be carried out using one of the techniques specified within EN ISO 16911-1:2013.

The MRR prescribe Tiers and corresponding maximum permissible uncertainties (Table 1) for emission sources regulated under the EU ETS. An emission source is considered tier 4 if it emits more than 5,000 tonnes of CO_2(e) per year or contributes more than 10 % of the total annual emissions of the installation (Commission Decision [EU] No. 601/2012 – 2012). The maximum permissible uncertainty specified for each tier is the combined uncertainty of the concentration AMS and flow AMS expanded to a 95 % confidence interval. Under tier 4 – assuming an equal value on both uncertainty components (concentration and flow) – the target value for each uncertainty component is approximately ± 1,8 %. The requirement to achieve such a low uncertainty value has dictated the selection and associated values of certain performance characteristics and requirements specified within EN ISO 16911-1.

Table 1 — Maximum permissible uncertainty for measurement-based methods

	Tier 1	**Tier 2**	**Tier 3**	**Tier 4**
CO_2 emission sources	±10 %	±7,5 %	±5 %	±2,5 %
N_2O emission sources	±10 %	±7,5 %	±5 %	N/A
Source: Commission Regulation (EU) No. 601/2012 of 21 June 2012 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council.				

5.3.3 Other requirements for monitoring velocity and flow rate in ducts and stacks

A flow profile characterization at the measurement plane may be required. This may be part of the pre-installation work carried out before a new flow AMS is commissioned and installed or for any other measurement objective that may require information on the uniformity of flow at the measurement plane.

The majority of times the calibration of a flow AMS is carried out for reasons of compliance with the EU ETS Directive. However the calibration of a flow AMS for any other regulatory reasons is not excluded from the scope of EN ISO 16911-1. The user should adopt those elements required to achieve the specified uncertainty requirement for their application.

6 Specific guidance on the application of EN ISO 16911-1

6.1 Scope

No guidance required.

6.2 Normative references

No guidance required.

6.3 Terms, definitions

No guidance required.

6.4 Symbols and abbreviated terms

6.4.1 Symbols

No guidance required.

6.4.2 Abbreviated terms

No guidance required.

6.5 Principle

6.5.1 General

No guidance required.

6.5.2 Principle of flow velocity determination at a point the duct

EN ISO 16911-1 specifies the use of 2D Pitot tubes as one of the techniques for the determination of flow velocity at a measurement point within a duct or stack. In regard with quality assurance and control of 2D Pitot tubes it refers users to US EPA Method 2G. Table 2 of this Technical Report reproduces the main performance characteristics and requirements for 2D Pitot tubes as specified in US EPA Method 2G. For test laboratories wishing to use 2D Pitot tubes the full set of specifications and requirements of US EPA Method 2G should be adhered to. These requirements only apply to 2D Pitot tubes that are not covered in detail in EN ISO 16911-1. For example they do not apply for manual S-type Pitot tubes as the performance characteristics for these are specified within the main text of the Standard.

Table 2 —Performance characteristics and requirements for 2D Pitot tubes as specified in US EPA Method 2G

Performance characteristic	Criterion	Frequency
Calibration acceptance criterion for 2D-Probe (yaw and pitch angles)	±3° at 0°	Prior to use
Width of reference scribe line (to determine yaw angles of flow)	≤ 1,6 mm	Prior to use
Diameter of tubing used to connect the probe and pressure readout device	≥ 3,2 mm	Prior to use
Uncertainty of yaw angle-measuring device	≤ ± 1°	Prior to use
Horizontal straightness check	< 5°	Before field measurement
Rotational positional check of angle measuring device	±1°	Before field measurement
Rotational positional check of angle measuring device	±2°	Post field measurement check
Calibration acceptance criterion for yaw-angle measuring device	±2° of a known angle θ of the triangular block used for calibration	Prior to use

6.6 Principle of measurement of flow rate

6.6.1 General

No guidance required

6.6.2 Principle of volume flow rate determination from point velocity measurements

EN ISO 16911-1 specifies the use of S-type, 3D or 2D Pitot tubes for the determination of swirl at a measurement plane. This Technical Report recommends the use of L-type Pitot tubes as another viable technique for this type of measurement. For more information on the procedure for measuring the degree of swirl at the measurement plane see 6.12.5.

6.6.3 Determination of volume flow rate using tracer dilution measurements

No guidance required.

6.6.4 Determination of volume flow rate using transit time tracer measurements

No guidance required.

6.6.5 Determination of volume flow rate from plant thermal input

No guidance required.

6.7 Selection of a monitoring approach

6.7.1 Measurement objective

This Technical Report adopts a slightly different grouping for measurement objectives than EN ISO 16911-1. This is in order that objectives are grouped based on the proposed quality control that will be recommended throughout this Technical Report. The grouping of measurement objectives is as follows:

a) periodic monitoring for compliance purposes according to EN 15259 or pollution inventory reporting which involves the determination of mass emissions and for the control of isokinetic conditions during manual sampling;

b) calibration of flow AMS under EN 14181 and EN ISO 16911-2 and/or flow profile characterization either to meet the requirements of the EU ETS Directive or any other regulatory requirements;

c) any other periodic measurements under the requirements of the EU ETS Directive.

For simplicity any reference throughout this Technical Report to measurement objective 1, 2 or 3 refers to the above list.

On the selection of techniques for different measurement objectives as aforementioned in 6.2.2 of this document the inclusion of L-Type Pitot tubes as another technique for the determination of swirl at the measurement plane is recommended by this Technical Report.

6.7.2 Choice of technique to determine point flow velocity

No guidance required.

6.7.3 Choice of technique for volume flow rate and average flow determination

No guidance required.

6.8 Measuring equipment

6.8.1 General

No guidance required.

6.8.2 Measurement of duct area

EN ISO 16911-1 prescribes the use of direct dimensional measurements for the determination of the internal duct area and excludes the use of engineering drawings or specifications without verification. The use of design information is allowed as a verifying tool of the direct dimensional measurement approach (see EN ISO 16911-1, 9.3.1). It is recommended that these may be used when accurate direct measurement of the internal duct area is challenging due to access restrictions, irregular dimensions, non-constant wall thickness and/or other complications. In such cases engineering drawings may be used for additional information in order to verify and increase confidence of the direct dimensional measurement approach. In extreme cases where any sort of direct dimensional measurement is impossible due to one or more of the above reasons the use of engineering drawings may be the only viable option to determine stack dimensions. In this case great care should be taken that this approach does not introduce large errors and that the uncertainty criterion on stack dimension can still be met. For example, in the case of a circular stack, the external circumference can be measured and the cladding thickness and wall thickness then subtracted from the external diameter, in order to cross-check the internal diameter given on the drawing. It is recommended that this is reported as a deviation and that the site operator is notified and advised that improvements to allow a direct dimensional measurement should be considered and if implemented would improve the uncertainty of the measurement. However, it should also be noted that the dilution tracer method, also described in EN ISO 16911-1, determines stack flow rate directly and does not require stack dimensions.

EN ISO 16911-1 requires the measurement of the length of all sampling ports and wall thickness at each one and the use of the mean value (as sampling port length and/or wall thickness) unless one or more is “significantly different” than the mean. The Standard purposely does not quantify this statement as it is intended to depend on the measurement objective and corresponding uncertainty requirement. As general guidance a difference between individual port depth measurement and the mean value of < 10 % can be considered as not “significantly different”. However, for measurement objectives with strict uncertainty specifications, such as EU ETS tier 4, a lower value may be selected as a means to achieve the overall required uncertainty.

NOTE If the port protrudes beyond the inside wall, the extent of the protrusion needs to be estimated e.g. with a U-shaped wire inserted through the port and then retracted until the inside wall is found.

The requirement of the Standard to consider temperature effects on measuring rods can be accounted for by using the following formula:

$$dl = L_0 \cdot \alpha \cdot (t_1 - t_0) \quad (1)$$

where

dl	is the change in length (m, inches)
L_0	is the initial length (m, inches)
α	is the linear expansion coefficient (m/m°C)
t_0	is the initial temperature (°C)
t_1	is the final temperature (°C)

Where the duct area value is corrected for temperature effects using Formula (1) they do not need to be accounted for within the uncertainty assessment.

6.9 Performance characteristics and requirements

EN ISO 16911-1 prescribes performance characteristics and performance criteria, for the manual determination of the point velocity across a measurement plane. These characteristics have all been demonstrated for the techniques specified within the Standard during the validation laboratory and field studies. Any technique used which is not specified within the Standard will have to demonstrate that it meets the same performance requirements.

As part of ongoing quality control it is recommended that test laboratories carry out checks at periodic intervals to demonstrate that their measuring systems continue to meet the requirements of the Standard. It is recommended that test laboratories follow Table 3 of this Technical Report which lists the checks and minimum required frequency of these depending on the measurement objective.

The acceptance criteria specified apply to the whole measurement system (with the exception of standard deviation of repeatability in the laboratory). Therefore, it is preferable that they are carried out on the whole measurement system. However, as the majority of test laboratories use interchangeable parts (e.g. different differential pressure readout devices with different Pitot tubes and vice versa) it is recognized that this is not always possible in which case this Technical Report recommends that one of the two following procedures is adhered to in order for compliance with the acceptance criteria is demonstrated:

Method 1 – Table 3 checks are carried on the whole measurement system and the requirements of Table 3 are demonstrated on the whole system. The checks can be carried out either by the test laboratory and/or a calibration laboratory.

Method 2 – Table 3 checks are carried out separately on individual parts of a measurement system, in which case the test laboratory will have to ensure that results for each check are combined in order to demonstrate compliance with each acceptance criterion. If the worst Pitot tube result for a specific performance characteristic is combined with the worst differential pressure readout device result of the same performance characteristic and the combined result meets the acceptance criterion it can be safely assumed that all different combinations meet the required value. For components that may have only been checked once (e.g. Pitot tubes for lack-of-fit) this value can be carried over annually to use in combination with a value from a differential pressure readout device check in order to demonstrate compliance with an acceptance criterion. The checks can be carried out either by the test laboratory and/or a calibration laboratory.

This Technical Report recommends that the check of the standard deviation of repeatability in the laboratory is only carried out on the differential pressure readout device. For measurement objectives 2 and 3 the demonstration of this criterion on the whole measurement system in the Standards' laboratory validation studies and the repeatability check of the whole system in the field prior to measurement (see 6.12.4) are deemed acceptable for the uncertainty requirements of these application areas. For measurement objective 1 the demonstration of this criterion in the Standards' laboratory validation studies on the whole measurement system is deemed acceptable for these application areas.

Table 3 — Ongoing quality control checks

Checks	Component	Frequency	Measurement objective	Acceptance Criteria
Standard deviation of repeatability of measurement in the laboratory	Differential pressure readout device	At least every year	1	< 1 % of calibration range
			2 and 3	< 1 % of calibration range for differential pressure ≤ 60 Pa < 1 % of value for differential pressure ≥ 60 Pa
Lack-of-fit (linearity)	Pitot tubes	At least once and every time they fail a visual inspection (see EN ISO 16911-1:2013, 9.3.1 for visual inspection checklist)	1	< 2 % of range (including differential pressure readout)
			2 and 3	< 2 % of value (including differential pressure readout)
	Differential pressure readout device	At least every year	1	< 2 % of range (including Pitot tube)
			2 and 3	< 2 % of value (including Pitot tube)
Uncertainty due to calibration	Pitot tubes	At least every year	1,2 and 3	< 2 % of range of differential pressure readout device (including Pitot tube)
	Differential pressure readout device			
Lowest measureable flow	Pitot tubes	After calibration	1,2 and 3	Lowest measurable flow is intended to be the lowest point at which the system has been calibrated at. Any use below this point will have to have been validated by the user before a measurement is made.
	Differential pressure readout device			

6.10 Measurement Procedure — Site survey before testing

EN ISO 16911-1 requires the measurement plan to be designed to average out flow variations when these are unstable and are expected to change over the duration of the measurement period (peak-to-peak variation > 10 % of the average flow conditions). In these circumstances – or indeed for all circumstances that variations of flow with time need to be accounted for – test laboratories can either use two measurement devices (one at a fixed point and one that traverses the measurement plane) or increase the time measuring each measurement point in order for flow variations to be accounted for.

The above requirement is important for measurement objectives 2 and 3 especially when characterizing a flow profile. If flow variations are not considered there is a risk that a flow profile may seem to be asymmetric due to time varying flow when it is actually not; and so this may mean incorrectly assuming that a measurement plane is not suitable for the installation of a flow AMS or more effort is needed than is actually required for the calibration of an existing cross duct flow AMS.

The correction factor to account for flow variations over time when using two devices can be determined by the following formula:

$$CF_i = V_{fav} / V_{fi} \quad (2)$$

$$V_{ticorr} = CFi \times V_{ti} \quad (3)$$

where:

CFi is the correction factor at position i

V_{fav} is the average velocity of fixed device measurements

V_{fi} is the velocity of fixed measurement device at position i

V_{ticorr} is the corrected velocity at position i

V_{ti} is the velocity of traverse measurement device at position i

For measurement objective 1, especially when measuring flow to maintain isokinetic conditions, accounting for flow variations with time is not as significant and it is recommended by this Technical Report that only one traverse measurement device is required. Test laboratories may consider extending the time spent measuring flow at each measurement point when carrying out a flow traverse for the determination of mass emissions if flow variations are to be expected.

EN ISO 16911-1 prescribes that the area of the measurement assembly shall not obstruct more than 5 % of the measurement plane area. For flow measurement assemblies that have integrated sampling devices (nozzle arm and nozzle, in-stack filter, etc.), mainly for the support of isokinetic sampling, this Technical Report recommends the adoption of the provisions of the UK Method Implementation Document (MID) for EN ISO 16911-1. These provisions allow for an obstruction of the measurement plane area of up to 10 % for stack or duct areas of less or equal to 1,5 m^2 to account for the larger measurement assembly area resulting from the integrated sampling device. For stacks with a very small sample plane area it may not be possible to carry out isokinetic sampling and measure flow at the same time because the area of the sampling equipment may obstruct more than 10 % of the stack or duct sampling area. Under these circumstances the MID for EN ISO 16911-1 allows for the flow measurement to be carried out prior to the isokinetic sampling and the values derived from the flow traverse to be used to control isokinetic conditions.

6.11 Determination of sampling plane and number of measurement points

No guidance required.

6.12 Checks before sampling

6.12.1 General

Experience with low cost electronic pressure readout devices has shown that on occasion their calibration can be invalidated in the field leading to an increased level of uncertainty. This can be simply through wear and tear, e.g. accidental drops or bumps during transport to site and/or transfer to the sampling location, that may lead to internal problems within the devices and which may not be detectable through a visual inspection. It is with this in mind that EN ISO 16911-1 specifies that a calibration check of electronic pressure readout devices is carried out prior to measurement. More costly manometers tend to be more robust and less susceptible to damage. This Technical Report recommends that the calibration check of electronic pressure readout devices should be carried out only for measurement objectives 2 and 3 that have stricter uncertainty requirements. It recommends that the check may be made against a device with a better or **equal** uncertainty to the electronic pressure readout device under test. The Technical Report recognizes that some test laboratories may only possess one type and model of differential pressure readout devices from the same manufacturer with very similar uncertainties. For measurement objective 1 test laboratories should consider carrying out a set of functional checks prior to use. These may include, but are not limited to checking the zero value of the device, checking that the instrument responds to gas flow and ensuring if required that the correct input values are stored within the manometer when conversions from differential pressure to velocity are carried out internally.

Inclined manometers do not have any parts that can wear or age. However, they too can suffer damage from accidental drops or bumps and the associated damage can affect the manometer’s accuracy, although this is usually easily detected by a simple visual inspection.

EN ISO 16911-1 also prescribes the use of electronic pressure readout devices with a resolution of at least 2 decimal places per Pa. These electronic pressure readout devices are not commonly used by test laboratories mainly due to their high cost and possibly larger size compared to smaller more compact units that are easier transported to the sampling location. More commonly used devices have resolutions of either 1 decimal place per Pa or 1 Pa. The resolution of 2 decimal places per Pa can be used as a means of meeting stricter uncertainty requirements such as for EU ETS Tier 4 measurements. This Technical Report therefore recommends the adoption of the provisions of the UK Method Implementation Document (MID) for EN ISO 16911-1 that allows the use of electronic pressure readout devices with a resolution of at least 1 Pa for measurement objective 1. For measurement objectives 2 and 3 this Technical Report recommends the use of devices with resolution of at least 1 decimal place per Pa however at very low differential pressures or very strict uncertainty requirements (EU ETS tier 4) the use of 2 decimal places is more appropriate. In each case, and for all measurement objectives, test laboratories need to observe the uncertainty requirement for differential pressure readout devices specified within the Standard and ensure that this is satisfied. Table 4 of this Technical Report provides a list of differential pressure values and the lowest uncertainty achievable based on the resolution of the device.

Table 4 — Lowest uncertainty achievable by electronic pressure readout devices based on resolution

Differential Pressure (Pa)	Resolution (Pa)	Lowest uncertainty achievable based on resolution (%)
5	0,01	0,2
	0,1	2
	1	20
10	0,01	0,1
	0,1	1
	1	10
20	0,01	0,05
	0,1	0,5
	1	5

This Technical Report recommends the uncertainty criterion for differential pressure readout devices for measurement objective 1 to be set at less than 0,5 % of the range see 6.13 of this document.

NOTE Resolution can exceed uncertainty but uncertainty cannot exceed resolution.

The measurement of stack dimensions and the use of fixed point flow measurement devices have already been covered by this document in 6.8.2 and 6.10.

EN ISO 16911-1 prescribes an internal leakage pre-measurement check between pressure taps. A suitable pre-test leak check of the whole measurement system can also satisfy the requirement of the internal leakage check. As an internal leakage check is also specified post-measurement, this Technical Report recommends a post-measurement leak check of the whole measurement system to be carried out at the same time which is considered good practice and can be achieved with no additional effort. For provisions on how to carry out leak check of the measurement system see the next Subclause (6.12.2) of this document.

6.12.2 Pre-test leak check

EN ISO 16911-1 refers to a leak check procedure; however the procedure is only provided as an example and is not a mandatory requirement. Test laboratories can specify their own leak check procedure. An example procedure is specified in US EPA Method 2G (see Annex B of this Technical Report). This Technical Report recommends that a leak check is also carried out each time the system is disconnected.

Pressurizing the system to the static pressure in the stack may not be enough when carrying out a leak check since the static pressure may be much lower than the differential pressure encountered during measurement. It is recommended that the leak check is carried out to at least as high a pressure as the differential pressure expected during the measurement or to 50 % of the range of the differential pressure readout device whichever is higher. The pressure should remain stable to within ± 2,5 mm H_2O (for at least 15 s).

NOTE A zero pressure drop across a 5 min period is difficult to achieve due to ambient temperature effects on the differential pressure readout device.

6.12.3 Check on stagnation and reference pressure taps (S-type Pitot tube)

The stagnation test is useful as it can indicate local swirl, blockage of pitot, etc., however the specified tolerance value of 10Pa between the two taps static pressure readings may be within the uncertainty of some instruments. This Technical Report therefore recommends that the difference in the measured static pressure should be less than 0,5 % of the range of the differential pressure readout device with a minimum tolerance value of 10 Pa. If the difference in readings exceeds this tolerance this may indicate local swirl, blockage of pitot, etc. In this case the reason should be investigated.

6.12.4 Test of repeatability at a single point

This Technical Report recommends that the test of repeatability at a single point is only carried out for measurement objectives 2 and 3. For measurement objective 1, meeting the performance characteristic criterion on repeatability in the laboratory is deemed adequate for the uncertainty requirements of these measurements.

6.12.5 Swirl or cyclonic flow

EN ISO 16911-1 prescribes the use of the procedure for the determination of the degree of swirl in a stack or duct specified in ISO 10780. As an alternative to this procedure, this Technical Report recommends the use of the procedure specified in the UK MID for EN 13284-1 (only applicable to S-type Pitot tubes) as it provides more detail and is more practical (see Annex A of this Technical Report). For L-type Pitot tubes, which have already been recommended in this document as another technique for the determination of swirl, the procedure in ISO 10780 can be followed. Note that an L-type Pitot tube cannot be nulled. However, the degree of swirl can be determined by using the maximum flow point instead of the null point.

NOTE EN ISO 16911-1 precedes ISO 10780 but does not replace it.

EN ISO 16911-1 provides a formula for the calculation of velocity in instances where swirl is more than 15° at one or more measurement points. In order to calculate the velocity in such a way the velocity vector parallel to the stack or duct axis is measured at each point where swirl is above 15° and that velocity value is corrected through the formula:

$$V_{corr} = \left(cos_{\theta meas}\right) \times V_{meas}$$

where

$Vcorr$ is the corrected velocity

V_{meas} is the velocity measured

$cos_{\theta meas}$ is the cosine of angle measured

using the cosines of the measured angles above 15° in order to account for the angle of swirl (EN ISO 16911-1:2013, 9.3.5).

When carrying out isokinetic testing and swirl is identified above 15° this Technical Report recommends the approach of the UK Method Implementation Document for EN 13284-1 which requires doubling the number of sampling points (up to a maximum of 20 sampling points) and the removal of the non-complaint points from sampling (i.e. the points that the angle of swirl has been identified to be above 15°). This sampling deviation shall be documented and reported.

In instances where swirl above 15° is identified the operator should be informed and the first option should always be to seek an alternative sampling location. If another sampling location cannot be found then depending on the measurement objective one of the above procedures may be followed.

6.13 Quality control

EN ISO 16911-1 specifies performance requirements during the field measurement of flow. This Technical Report recommends that, for the uncertainty requirements of measurement objective 1, the following performance requirements may be disregarded: field repeatability (see 6.12.4 of this document); positional accuracy of the flow sensor in the stack and determining the angle of the probe to the measurement plane.

In addition a calibration value of less than 0,5 % of the full range of a differential pressure readout device is deemed to be acceptable by this Technical Report for the uncertainty requirements of measurement objective 1. Care should be taken that a differential pressure device with an appropriate range is selected such that the differential pressure measurements are within the stated calibration range. The uncertainty in flow measurement device (including both Pitot tube and differential pressure reading device) is deemed acceptable to be equal to the performance requirements of the ongoing quality control values in Table 3 of this Technical Report.

Table 5 — Performance requirements during field measurements

Parameter	**Criterion**	**Recommended applicable measurement objective**
Field repeatability	≤ 5 % velocity	2 and 3
Angle of flow sensor to gas flow	< 15 °	All
Stack internal area	≤ 2 % of value	2 and 3
Positional accuracy of flow sensor in stack	≤ 10 % of measurement plane	2 and 3
Angle of the probe to measurement plane (pitch or probe)	≤ 10 ° from measurement plane	2 and 3
Uncertainty in flow measurement device calibration – Pitot tube and differential pressure device	< 2 % of range of differential pressure readout device (including Pitot tube)	All
Uncertainty in differential pressure reading device calibration	≤ 1 % of value (measurement objectives 2 and 3) ≤ 0,5 % of range (measurement objective 1)	All
Uncertainty temperature measurement device which includes the temperature sensor and indicator	≤ 1 % of value ≤ 1 % of range	2 and 3 1
Uncertainty in stack gas density	≤ 0,05 kg/m^3	All

6.14 Measurement of flow at locations within the measurement plane

No guidance required.

6.15 Post-measurement quality control

This Technical Report recommends that a post-measurement leak check of the whole measurement system is carried out at this stage as described in Subclauses 6.12.1 and 6.12.2 of this document.

6.16 Calculation of results

6.16.1 General

No guidance required.

6.16.2 Measurement of velocity

No guidance required.

6.16.3 Determination of the mean velocity

No guidance required.

6.16.4 Correction of average velocity for wall effects

This Technical Report recommends the application of wall adjustment factors in all cases where mass emissions are determined. Their use in measurements in support to isokinetic sampling is not meaningful and is not recommended.

The Standard provides some default wall adjustment factors values for smooth and rough walled circular stacks and ducts. This Technical Report recommends the use of the smooth wall default factor in cases where there is not enough information on the texture of the duct wall.

In regards to rectangular ducts this Technical Reports recommends either calculating factors from US EPA CTM-041 or using the default values for circular ducts. Following the method in US EPA CTM-041 will provide a more accurate factor but may need additional measurements in the duct and lengthy calculations.

6.16.5 Calculation of the volume flow rate from the average velocity

No guidance required.

6.16.6 Conversion of results to standard conditions

No guidance required.

6.17 Establishment of uncertainty results

No guidance required.

6.18 Evaluation of the method

No guidance required.

7 Annex A: Measurement of velocity using differential pressure based techniques

7.1 A.1: Principle of differential pressure based technique

No guidance required.

7.2 A.2: Measuring Equipment

7.2.1 A.2.1: Pitot tubes

No guidance required.

7.2.2 A.2.2: Differential pressure flow measurement equipment

7.2.2.1 A.2.2.1: General

EN ISO 16911-1 prescribes the use of two sets of equipment (Pitot tube, probe, temperature sensor, atmospheric pressure sensor, etc.) for simultaneous measurements of the traverse and fixed point velocities. This Technical Report deems as acceptable the use of only one atmospheric pressure sensor as the sensor can be a standalone one and the same atmospheric pressure readings may be used for both measurement systems. It also deems as acceptable the use of weather station values for measurement objective 1 measurements. However, corrections for altitude should be applied where possible.

7.2.2.2 A.2.2.2: Pitot tube

EN ISO 16911-1 specifies that integrated sampling (in-stack filter assemblies, etc.) and Pitot probes are calibrated together. This is certainly preferable since attaching a sampling device to a separately calibrated Pitot tube may result in invalidation of the calibration. However, this is not always possible or practical as test laboratories may have several differential pressure measurement and readout devices, which are interchangeable between different systems. They may also use different lengths of probes and lines to connect systems together. This Technical Report recommends that, wherever possible, integrated systems are calibrated as a system whilst recognizing that this will not always be possible.

Although the Standard does not require a repeated calibration of Pitot tubes that have not been mechanically damaged this document recommends that Pitot tubes are calibrated at least annually to ensure that mechanical damage can be detected during calibration.

This Technical Report recommends that the tubing or lines used to connect the Pitot tube to the differential pressure device are as short in length and as thick as possible.

7.2.2.3 A.2.2.3: Differential pressure measurement system

EN ISO 16911-1 requires an ambient temperature correction to differential pressure readings of inclined liquid manometers to account for liquid density changes with temperature. The following formula can be used to apply this correction:

$$hs = \left(\frac{pt}{ps}\right) \times \left(\frac{gt}{gs}\right) ht$$

where

hs	is the corrected height of the indicating fluid to standard temperature
ht	is the height of the indicating fluid at the temperature when read
ps	is the density of the indicating fluid at standard temperature
pt	is the density of the indicating fluid at the temperature when read
gs	is the gravitational acceleration assumed at calibration, ms^{-2}

(Assume a default of 9,81 ms^{-2} if unknown, noting that gs is 9,8067 ms^{-2} at sea level and a latitude of 45,54°N)

gt	is the gravitational acceleration at test location, ms^{-2}

and:

$$gt = 9.7803184\ (1 + 0.0053024*\sin^2\theta - 0.0000059*\sin^2 2\theta) - 3.086*10^{-6}\ H$$

where

θ is the latitude (North/South position with the Equator being zero), °

H is the height above sea level, m

NOTE The temperature correction is of the order of +0,3 % for water at 30 °C if the water manometer is calibrated at 15 °C and the gravitational variation is of the order of ± 0,3 % across the full range of test locations.

Table A.1 of the Standard specifies a required calibration uncertainty for differential pressure readout devices of less or equal to 1 % or 20 Pa whichever is greater. The value of 20 Pa is a typographical error and should read 0,2 Pa as at differential pressures of anything below 20 Pa the uncertainty allowed would be more than 100 %. As aforementioned (see 6.13) this Technical Report recommends that for the uncertainty requirements of measurement objective 1 a calibration value of less than 0,5 % of the full range is acceptable.

8 Annex F: Example of uncertainty budget established for velocity and volume flow rate measurements by Pitot tube

8.1 F.1: Process of uncertainty estimation

8.1.1 F.1.1: General

The procedure for calculating measurement uncertainty is based on the law of propagation of uncertainty laid down in EN ISO 14956 or ISO/IEC Guide 98-3. The calculation procedure presents different steps (F.1.2 to F.1.5).

8.1.2 F.1.2: Determination of model function

The measurand and all the parameters that influence the result of the measurement, called “input quantities”, shall be clearly defined.

All sources of uncertainty contributing to any of the input quantities or to the measurand directly shall be identified.

Then the model function, i.e. the relationship between the measurand and the influence quantities, shall be established, if possible in the form of a mathematical formula.

8.1.3 F.1.3: Quantification of uncertainty components

Each uncertainty source is estimated to obtain its contribution to the overall uncertainty by using available performance characteristics of the measurement system, data from the dispersion of repeated measurements, data provided in calibration certificates.

All uncertainty components (e.g. performance characteristics) are converted to standard uncertainties of input and influence quantities.

8.1.4 F.1.4: Calculation of the combined uncertainty

Then the combined uncertainty, uc, is calculated by combining standard uncertainties, by applying the law of propagation of uncertainty.

In general, the uncertainty associated with a measurand is expressed in expanded uncertainty form. The expanded combined uncertainty Uc corresponds to the combined standard uncertainty, obtained by multiplying by a coverage factor, k: Uc = kuc. The value of the coverage factor k is chosen on the basis of the level of confidence required. In most cases, k is taken to be equal to 2, for a level of confidence of approximately 95 %.

8.1.5 F.1.5: Other sources of errors

The mathematical modelling of the measured local velocities then determinations of mean velocity and volume flow rate, are carried out starting from the basic formulae used to calculate these parameters.

In these formulae, all the parameters have an uncertainty associated with their value which contributes to the total uncertainty of the result of measuring.

However, a thorough analysis of the implementation of measurement could result in counting other sources of uncertainties that do not appear explicitly in the expression used to calculate velocity and the volume flow rate. These sources are in particular related to the operational limits of the method, and to the disturbances of the velocity to characterize by the realization of measuring itself:

— nature of the gas stream: the gas stream should be continuous in single phase or should behave as such;

— inhomogeneity of the physicochemical characteristics of gas across the measurement section;

— nature of the flow: the calculation formulae are rigorous only if the flow is stable and presents neither transverse gradient, nor turbulence — however, in practice, both coexist in the closed ducts;

— dimension of the Pitot tube: the ratio of the diameter of the antenna of the Pitot tube to the diameter of the duct should be limited in order to minimize the error on the flow resulting from the gradient of velocity and the obstruction caused by the Pitot tube;

— influence of the turbulence: turbulence has an influence on the determination of the velocity and the measurement of the static pressure — the upward bias induced by turbulence on the determination of velocity is a function of the degree of turbulence;

— slow fluctuations of velocity: the error due to an insufficiently long time of measurement to allow a correct integration of the slow fluctuations of velocity decreases when the number and the duration of measurements in a given point increase;

— inclination of the tube of Pitot compared to the direction of the stream: the error increase with the angle of incline;

— pressure loss between total pressure port and static pressure ports: the static pressure ports being located at the downstream of the total pressure port, the dynamic pressure measured with an error equal to the pressure loss by friction in the duct at this distance — this error increases with the distance of the pressures ports and with the roughness of the duct;

— the position of the Pitot tube in the measurement section;

— the number of measurement points: if the curve distribution of velocity shows a distribution not sufficiently homogeneous, the number of measurement points usually prescribed in the standards may not be sufficient.

8.2 F.2: Example uncertainty calculation

Estimate of uncertainty velocity and uncertainty volume flow rate of a gas stream in a duct whose characteristics are as follows:

a) duct of a power plant with a diameter of 4,5 m, explored in 20 points by means of an L-type Pitot: uncertainty in the measurement of the diameter of the duct is calculated starting from the maximum permissible error equal to 2 % of the diameter;

b) temperature of gases on the measurement section: 110 °C = 383 K — accurate to within 1 % of the absolute temperature, in K (as mentioned in ISO 10780);

c) atmospheric pressure: 100 300 Pa — uncertainty in the atmospheric pressure is calculated starting from the maximum permissible error which is 300 Pa and the error due to the reading estimated at 25 Pa;

d) composition of gases:

 1) oxygen content measured in the conduit: 6,9 % volume fraction on dry gas ± 5 % relative (k = 2);

 2) carbon dioxide content measured in the conduit: 12,5 % volume fraction on dry gas ± 5 % relative (k = 2);

 3) water vapour content: 10,9 % volume fraction on wet gas ± 11,6 % relative (k = 2);

e) mean local dynamic pressures, in Pa, at each measurement point:

subarea	position	meas. 1	meas. 2	meas. 3	meas. 4	meas. 5	$\overline{\Delta p_i}$
axis.point	mm	Pa	Pa	Pa	Pa	Pa	Pa
1.1	115	440	420	470	420	470	444
1.2	368	430	430	460	430	460	442
1.3	659	360	345	365	345	365	356
1.4	1 018	375	375	387	375	387	380
1.5	1 538	520	515	515	515	515	516
1.6	2 962	540	550	550	550	550	548
1.7	3 482	612	600	619	600	619	610
1.8	3 841	612	610	620	610	620	614
1.9	4 132	607	595	618	595	618	607
1.10	4 385	534	525	568	525	568	544
2.1	115	495	500	510	500	560	513
2.2	368	493	483	520	483	520	500
2.3	659	470	484	510	484	510	492
2.4	1 018	435	420	500	420	490	453
2.5	1 538	570	560	520	540	550	548

subarea	position	meas. 1	meas. 2	meas. 3	meas. 4	meas. 5	$\overline{\Delta p_i}$
axis.point	mm	Pa	Pa	Pa	Pa	Pa	Pa
2.6	2 962	390	380	400	380	400	390
2.7	3 482	300	270	312	270	312	293
2.8	3 841	285	265	260	265	260	267
2.9	4 132	280	260	262	260	262	265
2.10	4 385	240	240	260	240	260	248

f) static pressures, in Pa, on each explored measurement line: it is carried out five measurements on each diameter:

subarea	position	static pressure			
axis.point	mm	Pa			
1.1	115	−230			
1.2	368	−233			
1.3	659	−225			
1.4	1 018	−230			
1.5	1 538	−250			
1.6	2 962	−230			
1.7	3 482	−225			
1.8	3 841	−240			
1.9	4 132	−250			
1.10	4 385	−220	$\left(\overline{P_{stat,1}}\right)$	−233	Pa
2.1	115	−230			
2.2	368	−230			
2.3	659	−240			
2.4	1 018	−220			
2.5	1 538	−210			
2.6	2 962	−230			
2.7	3 482	−230			
2.8	3 841	−230			
2.9	4 132	−230			
2.10	4 385	−230	$\left(\overline{P_{stat,2}}\right)$	−228	Pa

The mean pressure on the measurement section is taken equal to the arithmetic mean of the mean static pressures on each diameter.

$$\overline{P_{\text{stat}}} = \frac{1}{2}\left(\overline{P_{\text{stat,1}}} + \overline{P_{\text{stat,2}}}\right) = -231 \text{ Pa}$$

$$u^2\left(\overline{P_{\text{stat}}}\right) = \frac{1}{4} \times \left(u^2\left(\overline{P_{\text{stat,1}}}\right) + u^2\left(\overline{P_{\text{stat,2}}}\right)\right)$$

8.2.1 F.2.1: Calculation of the physicochemical characteristics of the gas effluent

a) Molar mass gases: M = 28,9 × 10^{-3} kg/mol;

b) density of gases: ρ = 0,909 kg/m^3 in actual conditions of temperature and pressure, on wet gas;

c) absolute pressure: p_C = 100 069 Pa;

d) local velocities:

subarea	position	velocity
axis.point	mm	m/s
1.1	115	31,2
1.2	368	31,2
1.3	659	28,0
1.4	1 018	28,9
1.5	1 538	33,7
1.6	2 962	34,7
1.7	3 482	36,6
1.8	3 841	36,8
1.9	4 132	36,5
1.10	4 385	34,6
2.1	115	33,6
2.2	368	33,2
2.3	659	32,9
2.4	1 018	31,6
2.5	1 538	34,7
2.6	2 962	29,3
2.7	3 482	25,4
2.8	3 841	24,2
2.9	4 132	24,1
2.10	4 385	23,4
mean velocity		$\overline{v}$ = 31,22

e) volume flow rate:

1) $q_{v,w}$ = 1 787 785 m^3/h in actual conditions of temperature and pressure and on wet gas,

2) $q_{v,0d}$ = 1 121 635 m^3/h in standard conditions and on dry gas,

3) $q_{v,0d,O2ref}$ = 1 054 336 m^3/h in standard conditions, on dry gas and to a reference oxygen concentration of 6 vol. %.

8.2.2 F.2.2: Calculation of uncertainty associated with the determination of local velocities

$$\frac{u^2(v_i)}{v_i^2} = \frac{u^2(K)}{K^2} + \frac{u^2(\overline{\Delta P_i})}{4 \times \overline{\Delta P_i}^2} + \frac{u^2(\rho)}{4\rho^2} \quad (F.1)$$

8.2.2.1 F.2.2.1: Standard uncertainty on the coefficient of the Pitot tube

Characteristics of the Pitot tube: K = 1,01 ± 0,02 (coverage factor k = 2)

$$u(K) = \frac{0,02}{2} = 0,01$$

8.2.2.2 F.2.2.2: Standard uncertainty associated with the mean local dynamic pressures

$$u^2(\overline{\Delta p_i}) = \frac{\sigma^2_{\Delta p_i}}{m} + \sum_{f=1}^{r} u^2\left(C_f\right) \quad (F.2)$$

where

$\sigma_{\Delta p_i}$ is the standard deviation of the *m* dynamic pressure measurements at the point *i*;

$\sigma_{\Delta p_i} / \sqrt{m}$ is the standard deviation of the mean of the *m* dynamic pressure measurements at point *i*;

C_f, f = 1 ... *r* are the corrections to the dynamic pressure measurements.

The standard deviation is calculated as follows:

— If the number of measurements is lower or equal to 10:

$$\sigma_{\Delta p_i} = d_n \left(\Delta p_{i,\max} - \Delta p_{i,\min}\right)$$

where

$\Delta p_{i,\max}$, $\Delta p_{i,\min}$ are the maximum and minimum values of dynamic pressure measured;

d_n is the factor loading, function of the number of measurements.

Number of measurements/values *n*	d_n	Number of measurements/values *n*	d_n
2	0,885	12	0,307
3	0,591	15	0,288
4	0,486	20	0,268
5	0,430	25	0,254
6	0,395	30	0,245
7	0,370	40	0,227
8	0,351	50	0,222
9	0,337	60	0,216
10	0,325	80	0,206
11	0,315	100	0,199

— If the number of measurements is greater than 10:

$$\sigma_{\Delta p_i} = s_{\Delta p_i} \quad \text{or} \quad \sigma_{\Delta p_i} = d_n \left(\Delta p_{j,\max} - \Delta p_{j,\min} \right)$$

where

$s_{\Delta p_i}$ is the experimental standard deviation of the series of the dynamic pressure measurements.

The corrections to dynamic pressure measurements are related to:

— the resolution of the sensor used;

— its uncertainty of calibration;

— its drift;

— its linearity;

— hysteresis.

Characteristics of the pressure sensor used (in the example):

— range: 0 Pa to 1 000 Pa;

— resolution: 1 Pa;

— calibration uncertainty: ± 2 Pa (with coverage factor k = 2);

— drift: 0,1 % of the range between two calibrations;

— Lack-of-fit: 0,1 % of the range.

$$u^2(\overline{\Delta p_i}) = \frac{\sigma^2_{\Delta p_i}}{m} + \left(\frac{1}{2\sqrt{3}}\right)^2 + \left(\frac{2}{2}\right)^2 + \left[\frac{(0,1/100)\times 1\ 000}{\sqrt{3}}\right]^2 + \left[\frac{(0,1/100)\times 1\ 000}{\sqrt{3}}\right]^2$$

NOTE sqrt(3) corresponds to a 95 % confidence interval of a rectangular distribution.

subarea	$\overline{\Delta p_i}$	$\sigma_{\Delta p_i} = d_n\left(\Delta p_{i,\max} - \Delta p_{i,\min}\right)$	$\sigma_{\Delta p_i} / \sqrt{m}$	$u\left(\overline{\Delta p_i}\right)$
axis.point				
1.1	444	21,50	9,62	9,7
1.2	442	12,90	5,77	5,9
1.3	356	8,60	3,85	4,1
1.4	380	5,16	2,31	2,7
1.5	516	2,15	0,96	1,6
1.6	548	4,30	1,92	2,3
1.7	610	8,17	3,65	3,9
1.8	614	4,30	1,92	2,3
1.9	607	9,89	4,42	4,6
1.10	544	18,49	8,27	8,4
2.1	528	27,95	12,50	12,6
2.2	524	15,91	7,12	7,2
2.3	520	17,20	7,69	7,8
2.4	483	34,40	15,38	15,4
2.5	577	21,50	9,62	9,7
2.6	390	8,60	3,85	4,1
2.7	293	18,06	8,08	8,2
2.8	267	10,75	4,81	5,0
2.9	265	8,60	3,85	4,1
2.10	248	8,60	3,85	4,1

8.2.2.3 F2.2.3: Standard uncertainty associated with the density of the gas effluent

$$\frac{u^2(\rho)}{\rho^2} = \frac{u^2(P_c)}{P_c^{\ 2}} + \frac{u^2(T_c)}{T_c^{\ 2}} + \frac{u^2(M)}{M^2} \tag{F.3}$$

where

- ρ is the density of the gas effluent under the conditions of temperature and pressure of gas, in kg/m³;
- M is the molar mass of wet gas effluent, in kg/mol;
- p_c is the absolute pressure in the duct in the measurement section, in Pa;
- T_c is the gas temperature in the duct, in K.

8.2.2.3.1 F.2.2.3.1: Standard uncertainty associated with the molar mass of gas

$$M = 10^{-5} \times \left[32 \times \phi_{O_2,w} + 44 \times \phi_{CO_2,w} + 18 \times \phi_{H_2O,w} + 28 \times \left(100 - \phi_{O_2,w} - \phi_{CO_2,w} - \phi_{H_2O,w} \right) \right]$$

$$u^2(M) = \left(\frac{\partial M}{\partial \phi_{O_2,w}} \right)^2 \times u^2\left(\phi_{O_2,w}\right) + \left(\frac{\partial M}{\partial \phi_{CO_2,w}} \right)^2 \times u^2\left(\phi_{CO_2,w}\right) + \left(\frac{\partial M}{\partial \phi_{H_2O,w}} \right)^2 \times u^2\left(\phi_{H_2O,w}\right) \tag{F.4}$$

Sensivity coefficients:

NOTE Derivation after $\delta\phi_{O2,w}$, derivation after $\delta\phi_{CO2,w}$, derivation after $\delta\phi_{H2O,w}$

$$\frac{\partial M}{\partial \phi_{O_2,w}} = 4 \times 10^{-5} \qquad \frac{\partial M}{\partial \phi_{CO_2,w}} = 16 \times 10^{-5} \qquad \frac{\partial M}{\partial \phi_{H_2O,w}} = -10^{-4}$$

Standard uncertainty:

$$u^2(M) = \left(4 \times 10^{-5}\right)^2 \times u^2\left(\phi_{O_2,w}\right) + \left(16 \times 10^{-5}\right)^2 \times u^2\left(\phi_{CO_2,w}\right) + \left(10^{-4}\right)^2 \times u^2\left(\phi_{H_2O,w}\right)$$

where $\phi_{O_2,w}$, $\phi_{CO_2,w}$, and $\phi_{H_2O,w}$ are percentage volume fractions on wet gas.

The contents on wet gas of oxygen and carbon dioxide are given by the following formulae:

$$\phi_{O_2,w} = \phi_{O_2,d} \times \frac{100 - \phi_{H_2O,w}}{100} = 6,9 \times \frac{100 - 10,9}{100} = 6,15\ \%\ \text{(volume fraction)}$$

$$\phi_{CO_2,w} = \phi_{CO_2,d} \times \frac{100 - \phi_{H_2O,w}}{100} = 12,5 \times \frac{100 - 10,9}{100} = 11,14\ \%\ \text{(volume fraction)}$$

The uncertainty-types associated with the oxygen contents, carbon dioxide and water vapour on wet gas are calculated according to the following formulae:

$$u(\phi_{H_2O,w}) = \frac{11,6}{2 \times 100} \times 10,9 = 0,63\ \%\ \text{(volume fraction) on wet gas}$$

$$u\left(\phi_{O_2,w}\right) = \phi_{O_2,w} \times \sqrt{\left[\frac{u\left(\phi_{O_2,d}\right)}{\phi_{O_2,d}}\right]^2 + \left[\frac{u\left(\phi_{H_2O,w}\right)}{100\text{-}\phi_{H_2O,w}}\right]^2}$$

$$u\left(\phi_{O_2,w}\right) = 6,15 \times \sqrt{\left(\frac{\frac{5}{2\times 100}\times 6,9}{6,9}\right)^2 + \left(\frac{\frac{11,6}{2\times 100}\times 10,9}{100-10,9}\right)^2} = 0,16 \text{ \% (volume fraction)}$$

$$u\left(\phi_{CO_2,w}\right) = \phi_{CO_2,w} \times \sqrt{\left(\frac{\phi_{CO_2,d}}{\phi_{CO_2,d}}\right)^2 + \left(\frac{u(\phi_{H_2O,w})}{100-\phi_{H_2O,w}}\right)^2}$$

$$u\left(\phi_{CO_2,w}\right) = 11,14 \times \sqrt{\left(\frac{\frac{5}{2\times 100}\times 12,5}{12,5}\right)^2 + \left(\frac{\frac{11,6}{2\times 100}\times 10,9}{100-10,9}\right)^2} = 0,29 \text{ \% (volume fraction)}$$

$u(M) = 7,9 \times 10^{-5}$ kg/mol

8.2.2.3.2 F.2.2.3.2: Standard uncertainty associated with the temperature T_C

Uncertainty associated with the temperature measurement is dependent:

— with the resolution of the temperature sensor used;

— with the uncertainty of calibration of the measuring equipment: sensor and the measurement instrument;

— with the drifts of the measuring equipment;

— with the linearity-measuring equipment;

— with the hysteresis-measuring equipment.

The expanded uncertainty associated with the temperature measurement is ± 2,5 K.

The standard uncertainty u(Tc) is thus equal to:

$$u(T_C) = \frac{2,5}{2} = 1,25 \text{ K}$$

8.2.2.3.3 F.2.2.3.3: Standard uncertainty associated with the absolute pressure in the duct, p_c

Uncertainty of the absolute pressure is given by:

$$u^2(p_C) = u^2(p_{atm}) + u^2\left(\overline{p_{stat}}\right) \quad \text{(F.5)}$$

Uncertainty associated with the atmospheric pressure measurement depends on:

— the resolution of the sensor used;

— the uncertainty of calibration of the sensor;

— the drift of the sensor;

— the linearity of the sensor;

— the hysteresis of the sensor.

In this example, we know the maximum permissible error which includes drift, lack of fit, and hysteresis, as well as the uncertainty due to the reading. Standard uncertainty is given by:

$$u^2(p_{\text{atm}}) = \left(\frac{300}{\sqrt{3}}\right)^2 + \left(\frac{25}{2\sqrt{3}}\right)^2 = 30\ 067{,}6\ \text{Pa}$$

$$u(p_{\text{atm}}) = \sqrt{30\ 067{,}6} = 173{,}4$$

NOTE sqrt(3) corresponds to a 95 % confidence interval of a rectangular distribution.

If, at each measurement point k, p measurements are carried out, the standard uncertainty associated with the mean static pressure in this point is given by Formula (F.6):

$$u^2(\overline{p_{\text{stat,k}}}) = \frac{\sigma_{p_{\text{stat, k}}}^{\ 2}}{p} + \sum_{f=1}^{q} u^2(C_{\text{f}}) \quad \text{(F.6)}$$

where

$\sigma_{p_{\text{stat},k}}$	is the standard deviation of *p* static pressure measurements at point *k*;
$\sigma_{p_{\text{stat},k}} / \sqrt{p}$	is the standard deviation of the mean of the static pressure measurements at point *k*;
$C_f, f = 1 \ldots q$	are the corrections to the static pressure measurements.

The standard deviation of static pressure measurements is calculated in the following way:

— If the number of measurements is lower or equal to 10:

$$\sigma_{P\text{stat,k}} = d_{\text{n}} \times\cdot (p_{\text{stat,k,max}} - p_{\text{stat,k,min}})$$

where

$p_{\text{stat},k,\max}$, $p_{\text{stat},k,\min}$	are the maximum and minimum values of static pressure in point *k*;
d_n	is the factor loading, function of the number of measurements.

— If the number of measurements is greater than 10:

$\sigma_{\mathrm{Pstat,k}} = s_{\mathrm{Pstat,k}}$ or $\sigma_{\mathrm{Pstat,k}} = d_{\mathrm{n}} \times (p_{\mathrm{stat,k,max}} - p_{\mathrm{stat,k,min}})$

where

$s_{p_{\mathrm{stat},k}}$ is the experimental standard deviation of the series of the measurements.

The corrections to static pressure measurements are due to:

— the resolution of the sensor used;

— its uncertainty of calibration;

— its drift;

— its linearity;

— hysteresis.

Standard uncertainty associated with the mean static pressure $\overline{p_{\mathrm{stat}}}$ is equal to:

$$u^2(\overline{p_{\mathrm{stat}}}) = \frac{1}{r^2}\sum_{k=1}^{r} u^2(\overline{p_{\mathrm{stat,k}}}) = \frac{1}{r^2}\sum_{k=1}^{r}\left(\frac{\sigma_{\mathrm{pstat,k}}{}^2}{p} + \sum_{f=1}^{q} u^2(C_{\mathrm{f}})\right) \quad (F.7)$$

Standard uncertainty associated with absolute pressure is equal to:

$$u^2(p_{\mathrm{c}}) = u^2(p_{\mathrm{atm}}) + u^2\left(\overline{p_{\mathrm{stat}}}\right) = u^2(p_{\mathrm{atm}}) + \frac{1}{r^2} \times \sum_{k=1}^{r}\left(\frac{\sigma^2_{\mathrm{Pstat,k}}}{p} + \sum_{f=1}^{q} u^2\left(C_{\mathrm{f}}\right)\right) \quad (F.8)$$

$$u^2(p_{\mathrm{c}}) = u^2(p_{\mathrm{atm}}) + \frac{1}{4} \times \left(u^2(\overline{p_{\mathrm{stat,1}}}) + u^2(\overline{p_{\mathrm{stat,2}}})\right)$$

In the example, the static pressure is measured with the same pressure sensor as that used to measure the dynamic pressures. Uncertainties of corrections are thus the same.

Value Pa	**Diameter**	
	1	**2**
$\overline{p_{\mathrm{stat},k}}$	−233	−228
$\sigma_{p_{\mathrm{stat},k}} = d_n\left(p_{\mathrm{stat},k,\max} - p_{\mathrm{stat},k,\min}\right)$	9,75	9,75
$\sigma_{p_{\mathrm{stat},k}} / \sqrt{p}$	3,08	3,08

NOTE Diameter 1 and 2 each 10 points/axis:

$$u\left(p_{\text{stat},1}\right)=\sqrt{3,08^2+\left(\frac{1}{2\sqrt{3}}\right)^2+\left(\frac{2}{2}\right)^2+\left[\frac{\left(0,1/100\right)\times 1000}{\sqrt{3}}\right]^2+\left[\frac{\left(0,1/100\right)\times 1000}{\sqrt{3}}\right]^2}=3,35\text{ Pa}$$

$$u\left(p_{\text{stat},2}\right)=\sqrt{3,08^2+\left(\frac{1}{2\sqrt{3}}\right)^2+\left(\frac{2}{2}\right)^2+\left[\frac{\left(0,1/100\right)\times 1000}{\sqrt{3}}\right]^2+\left[\frac{\left(0,1/100\right)\times 1000}{\sqrt{3}}\right]^2}=3,35\text{ Pa}$$

$$u\left(\overline{p_{\text{stat}}}\right)=\frac{1}{2}\times\sqrt{u^2\left(\overline{p_{\text{stat},1}}\right)+u^2\left(\overline{p_{\text{stat},2}}\right)}=2,37\text{ Pa}$$

Uncertainty associated with the absolute pressure:

$$u^2(p_c)=u^2(p_{atm})+u^2\left(\overline{p_{stat}}\right)=(173,4)^2+(2,37)^2$$

results

$$u(p_c)=173,4\text{ Pa}$$

8.2.2.3.4 F.2.2.3.4: Standard uncertainty associated with the density

$$\frac{u^2(\rho)}{\rho^2}=\frac{u^2(M)}{M^2}+\frac{u^2(P_c)}{P_c^{\,2}}+\frac{u^2(T_c)}{T_c^{\,2}}=\frac{\left(7,9\times 10^{-5}\right)^2}{\left(28,9\times 10^{-3}\right)^2}+\frac{173,4^2}{100\ 069^2}+\frac{1,25^2}{383^2}=2,113\times 10^{-5}$$

$$u(\rho)=4,18\times 10^{-3}\text{ kg/m}^3$$

8.2.2.4 F.2.2.4: Standard uncertainty associated with the local velocities

The standard uncertainty associated with the local velocities is given by:

$$\frac{u^2(v_i)}{v_i^2}=\frac{u^2(K)}{K^2}+\frac{u^2\left(\overline{\Delta P_i}\right)}{4\overline{\Delta P_i}^2}+\frac{u^2(\rho)}{4\rho^2} \quad \text{(F.9)}$$

The results are recapitulated in the table which follows:

subarea	velocity	$u^2(K)/K^2$	$\frac{u^2\left(\overline{\Delta P_i}\right)}{4\overline{\Delta P_i}^2}$	$\frac{u^2(\rho)}{4\rho^2}$	$u^2(vi)$	$u(vi)$
axis.point	m/s				m^2/s^2	m/s
1.1	31,2	9,98E-05	1,19E-04	5,28E-06	0,22	0,47
1.2	31,2	9,98E-05	4,48E-05	5,28E-06	0,15	0,38
1.3	28,0	9,98E-05	3,26E-05	5,28E-06	0,11	0,33
1.4	28,9	9,98E-05	1,23E-05	5,28E-06	0,10	0,31
1.5	33,7	9,98E-05	2,51E-06	5,28E-06	0,12	0,35
1.6	34,7	9,98E-05	4,54E-06	5,28E-06	0,13	0,36
1.7	36,6	9,98E-05	1,01E-05	5,28E-06	0,15	0,39
1.8	36,8	9,98E-05	3,61E-06	5,28E-06	0,15	0,38
1.9	36,5	9,98E-05	1,45E-05	5,28E-06	0,16	0,40
1.10	34,6	9,98E-05	5,92E-05	5,28E-06	0,20	0,44
2.1	33,6	9,98E-05	1,42E-04	5,28E-06	0,28	0,53
2.2	33,2	9,98E-05	4,77E-05	5,28E-06	0,17	0,41
2.3	32,9	9,98E-05	5,64E-05	5,28E-06	0,17	0,42
2.4	31,6	9,98E-05	2,56E-04	5,28E-06	0,36	0,60
2.5	34,7	9,98E-05	7,08E-05	5,28E-06	0,21	0,46
2.6	29,3	9,98E-05	2,72E-05	5,28E-06	0,11	0,34
2.7	25,4	9,98E-05	1,95E-04	5,28E-06	0,19	0,44
2.8	24,2	9,98E-05	8,72E-05	5,28E-06	0,11	0,34
2.9	24,1	9,98E-05	5,90E-05	5,28E-06	0,10	0,31
2.10	23,4	9,98E-05	6,72E-05	5,28E-06	0,09	0,31

8.2.3 F.2.3: Calculation of uncertainty associated with the mean velocity

Uncertainty associated with the mean velocity is calculated as follows:

$$\frac{u^2(\overline{v})}{\overline{v}^2} = \frac{u^2(K)}{K^2} + \frac{u^2(\rho)}{4\rho^2} + \frac{u^2\sum_{i=1}^{n}\left[u^2\left(\overline{\Delta p_i}\right)/4\overline{\Delta p_i}\right]}{\left(\sum_{i=1}^{n}\sqrt{\overline{\Delta p_i}}\right)^2} \quad \text{(F.10)}$$

where

$$u^2\left(\sum_{i=1}^{n}\sqrt{\overline{\Delta P_\mathrm{i}}}\right)=\sum_{i=1}^{n}\left(\left(\frac{1}{2\sqrt{\overline{\Delta P_\mathrm{i}}}}\right)^2\times u^2\left(\overline{\Delta P_\mathrm{i}}\right)\right)=\sum_{i=1}^{n}\frac{u^2\left(\overline{\Delta P_\mathrm{i}}\right)}{4\overline{\Delta P_\mathrm{i}}} \quad \text{(F.11)}$$

$$\frac{u^2(\overline{v})}{\overline{v}^2}=\frac{u^2(K)}{K^2}+\frac{u^2(p_\mathrm{atm})+u^2\left(\overline{p_\mathrm{stat}}\right)}{4\times p_\mathrm{c}^2}+\frac{u^2(T_\mathrm{c})}{4\times \mathrm{T}_\mathrm{c}^2}+$$
$$\frac{\left(4\times10^{-5}\right)^2\times u^2\left(\phi_{\mathrm{O_2,d}}\right)+\left(16\times10^{-5}\right)^2\times u^2\left(\phi_{\mathrm{CO_2,d}}\right)+\left(10^{-4}\right)^2\times u^2\left(\phi_{\mathrm{H_2O}}\right)}{4\times M^2}+ \quad \text{(F.12)}$$
$$\frac{\sum_{i=1}^{n}\left[u^2\left(\overline{\Delta p_i}\right)/4\overline{\Delta p_i}\right]}{\left(\sum_{i=1}^{n}\sqrt{\overline{\Delta p_i}}\right)^2}$$

Result of the combined standard uncertainty of the mean velocity:

$u\left(\overline{v}\right)$ = 0,32 m/s

Result of expanded uncertainty:

$U_\mathrm{c}\left(\overline{v}\right)$ = ± 0,65 m/s (k = 2)

$U_\mathrm{c,rel}\left(\overline{v}\right)$ = ± 2,1 % (k = 2)

8.2.4 F.2.4: Calculation of uncertainty in reported values

8.2.4.1 F.2.4.1: Volume flow rate in the actual conditions of temperature, pressure, water vapour content and oxygen

Standard uncertainty associated with the volume flow rate in the actual conditions of temperature, pressure, water vapour content and oxygen is given by:

$$\frac{u^2\left(q_{V,\mathrm{w}}\right)}{q_{V,\mathrm{w}}^2}=\frac{u^2\left(\overline{v}\right)}{\overline{v}^2}+\frac{u^2(A)}{A^2} \quad \text{(F.13)}$$

— where in the case of a circular duct of diameter D:

$$\frac{u^2(A)}{A^2}=4\times\frac{u^2(D)}{D^2}$$

— in the case of a rectangular conduit on sides a and b:

$$\frac{u^2(A)}{A^2}=\frac{u^2(a)}{a^2}+\frac{u^2(b)}{b^2}$$

Calculation of combined standard uncertainty:

$$\frac{u^2(A)}{A^2} = 4 \times \frac{u^2(D)}{D^2} = 4 \times \frac{\left[\left(2 / 100 \times 4,5\right) / \sqrt{3}\right]^2}{4,5^2}$$

$u(q_{V,w})$ = 45 171 m^3/h

Calculation of the expanded combined standard uncertainty:

$U_c(q_{V,w})$ = ± 90 342m^3/h (k = 2)

$U_{c,rel}$ ($q_{V,w}$) = ± 5,05 % (k = 2)

9 Annexes B, C, D, E, G, H, I and J

No guidance required.

Annex A
(informative)

Degree of swirl determination example method

When using an S-type Pitot the swirl test is carried out using the following procedure:

a) Level and zero the manometer.

b) Connect an S-type Pitot tube to the manometer and leak-check the system.

c) Position the S-type Pitot tube at each traverse point, in succession, so that the planes of the face openings of the Pitot tube are perpendicular to the stack cross-sectional plane (when the S-type Pitot tube is in this position, it is at 0° reference).

d) Note the differential pressure reading at each traverse point.

e) If a null (zero) Pitot reading is obtained at 0° reference at a given traverse point, an acceptable flow condition exists at that point.

f) If the Pitot reading is not zero at 0° reference, rotate the Pitot tube (up to ± 90° yaw angle), until a null reading is obtained.

g) Determine the angle of rotation at each sample point.

   A device, such as a port adaptor, can be marked to show if the angle of rotation is < 15°. However, if the angle of rotation is measured to the nearest degree, it is necessary to use a device, such as an inclinometer.

h) Apply the swirl test to each sample point.

Annex B
(informative)

S-type Pitot leak check example method

To perform the leak check on an S-type pitot tube, pressurize the pitot impact opening until at least 7,6 cm H_2O (3 in. H_2O) velocity pressure, or a pressure corresponding to approximately 75 percent of the pressure device's measurement scale, whichever is less, registers on the pressure device; then, close off the impact opening. The pressure shall remain stable (±2,5 mm H_2O, ± 0,10 in. H_2O) for at least 15 s. Repeat this procedure for the static pressure side, except use suction to obtain the required pressure.

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