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Introduction

This draft standard is based on national and international discussions. Your comments on this draft are invited and will assist in the preparation of the consequent standard.

For international standards, comments will be reviewed by the relevant UK national committee before sending the consensus UK vote and comments to the international committee, which will then decide appropriate action. If the international standard is approved, it is usual for the text to be published as a British Standard.

For national standards, comments will be reviewed by the relevant UK national committee and the resulting standards published as a British Standard.

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Template for comments and secretariat observations

Date: xx/xx/20xx	Document: ISO/DIS xxxx
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1	2	(3)	4	5	(6)	7
MB	Clause No./ Subclause No./Annex (e.g. 3.1)	Paragraph/ Figure/Table/Note	Type of comment	Comment (justification for change) by the MB	Proposed change by the MB	Secretariat observations on each comment submitted
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	



DRAFT International Standard

ISO/DIS 16911-1

Stationary source emissions — Manual and automatic determination of velocity and volume flow rate in ducts —

Part 1: Manual reference method

*Émissions de sources fixes — Détermination manuelle et
automatique de la vitesse et du débit-volume d'écoulement dans
les conduits —*

Partie 1: Méthode de référence manuelle

ICS: 13.040.40

This document is circulated as received from the committee secretariat.

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Foreword

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

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

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 1, *Stationary source emissions*, in collaboration with the Technical Committee CEN/TC 264, *Air quality*, of the European Committee for Standardization (CEN).

This second edition cancels and replaces the first edition (ISO 16911-1:2013), which has been technically revised.

The main changes are as follows:

- The monitoring objectives with different uncertainty requirements, ranging from very stringent (Emission Trading Schemes and calibration of automated flow measuring systems) to less demanding (support of isokinetic sampling) have been clarified.
- The level of quality control in relation to the uncertainty requirements of the monitoring objective have been clarified.
- Monitoring objectives have been grouped based on the required quality control.
- The measurement techniques and the associated requirements have been described in more detail.
- Performance characteristics and requirements for differential pressure devices and vane anemometers have been adapted to the state of the art.
- The example uncertainty calculations have been improved and corrected.

A list of all parts in the ISO 16911 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document describes a method for periodic determination of the axial velocity and volume flow rate of gas within emissions ducts and stacks and a method for the calibration of automated flow measuring systems permanently installed on a duct or stack.

This document provides a method which uses point measurements of the flow velocity to determine the flow profile and mean velocity and volume flow rates. It also provides for alternative methods based on tracer gas injection, which can also be used to provide routine calibration for automated flow measuring systems. A method based on calculation from energy consumption is also described. This document provides guidance on when these alternative methods can be used.

Stationary source emissions — Manual and automatic determination of velocity and volume flow rate in ducts —

Part 1: Manual reference method

1 Scope

This document specifies a method for periodic determination of the axial velocity and volume flow rate of gas within emissions ducts and stacks. It is applicable for use in circular or rectangular ducts with measurement locations meeting the requirements of ISO 15259. Minimum and maximum duct sizes are driven by practical considerations of the measurement devices described within this document.

NOTE ISO 15259 is identical to EN 15259^[12].

This document requires all flow measurements to have demonstrable metrological traceability to national or international primary standards.

This document applies to a range of monitoring objectives with different uncertainty requirements, ranging from very stringent (Emission Trading Schemes and calibration of automated flow measuring systems) to less demanding (support of isokinetic sampling). The level of quality control within this document is determined by the uncertainty requirements of the monitoring objective. Monitoring objectives are grouped based on the required quality control. The document specifies which requirements and performance characteristics apply to specified measurement objectives and application areas.

The methods specified in this document can be used as a standard reference method, if the user demonstrates that the performance characteristics of the methods are equal to or better than the performance criteria specified in this document and that the expanded uncertainty of the measurement results obtained by the methods, expressed with a level of confidence of 95 %, is determined and reported. The results for each method defined in this document have different uncertainties within a range of 1 % to 10 % at flow velocities of 20 m/s.

Other methods can be used provided that the user can demonstrate equivalence, e.g. based on the principles of EN 14793^[11].

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 15259, *Air quality — Measurement of stationary source emissions — Requirements for measurement sections and sites and for the measurement objective, plan and report*

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

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

Pitot tube

device to measure flow velocity at a point, operating on the principle of differential pressure measurement

Note 1 to entry: A number of designs of Pitot tube can be used, including standard L-type, S-type, 2D and 3D Pitot tubes. [Annex A](#) describes a number of Pitot designs currently in use in Europe.

3.2

measurement line

line across the stack, on a measurement plane, along which flow measurements are made to characterize the flow velocity profile or to determine the average flow

3.3

measurement plane

plane normal to the centreline of the duct at the measurement location at which the measurement of flow velocity or volume flow rate is required

3.4

measurement point

sampling point

position in the measurement plane at which the sample stream is extracted or the measurement data are obtained directly

3.5

volume flow rate

volume flow of gas axially along a duct

Note 1 to entry: If not specifically stated, the term may be taken to mean the mean volume flow passing through the measurement plane.

Note 2 to entry: Volume flow rate is expressed in cubic metres per second or cubic metres per hour.

3.6

point flow velocity

local gas velocity at a point in the duct

Note 1 to entry: Unless otherwise specified, the term may be taken to mean the axial velocity at the measurement location.

Note 2 to entry: Point flow velocity is expressed in metres per second.

3.7

average flow velocity

<1> velocity which, when multiplied by the area of the measurement plane of the duct, gives the volume flow rate in that duct

<2> quotient of the volume flow rate in the duct and the area of the measurement plane of the duct

3.8

standard conditions

conditions for reference values for pressure (101,3 kPa) and temperature (273,15 K)

3.9

uncertainty (of measurement)

parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

3.10

uncertainty budget

statement of a measurement uncertainty, of the components of that measurement uncertainty, and of their calculation and combination

Note 1 to entry: For the purposes of this document, the sources of uncertainty are according to ISO 14956^[5] or ISO/IEC Guide 98-3.

3.11

standard uncertainty

uncertainty of the result of a measurement expressed as a standard deviation

3.12

expanded uncertainty

quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand

Note 1 to entry: In this document, the expanded uncertainty is calculated with a coverage factor of $k = 2$, and with a level of confidence of 95 %.

3.13

overall uncertainty

expanded uncertainty attached to the measurement result

Note 1 to entry: The overall uncertainty is calculated according to ISO/IEC Guide 98-3.

3.14

swirl

cyclonic flow

tangential component of the flow vector providing a measure of the non-axial flow at the measurement plane

3.15

automated measuring system

AMS

measuring system permanently installed on site for continuous monitoring of flow

Note 1 to entry: See ISO 16911-2.

3.16

metrological traceability

property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty

Note 1 to entry: The elements for confirming metrological traceability are an unbroken metrological traceability chain to an international measurement standard or a national measurement standard, a documented measurement uncertainty, documented measurement procedure, accredited technical competence, metrological traceability to the SI units, and calibration intervals.

4 Symbols and abbreviated terms

4.1 Symbols

A	area of the measurement plane	m^2
A_I	internal area of the measurement plane	m^2
B	number of component B	
α_1, α_2	angle between sensing holes	°
c	constant	
$f_{v,cor,i}$	velocity correction factor at measurement point i	
d	outer tube diameter	mm
dl	measuring rod length change	m
d_s	stack diameter	mm
$e_{(N)}$	net specific energy (NSE) of the fuel as received	MJ/kg
e_p	absolute error of measurement	
F	force acting on the vane wheel	N
f	vane frequency	s^{-1}
f_v	velocity factor	
f_{WA}	wall adjustment factor	
h_s	corrected height of the indicating fluid of a liquid manometer to standard temperature	
h_t	height of the indicating fluid at the temperature when read	
i	number of the measurement point	
K	coefficient of the Pitot tube which includes the Pitot calibration factor and constant values relating to the Pitot design	
$K(\rho_0, \eta_{dyn})$	non-linear calibration factor dependent on density ρ_0 , and viscosity η_{dyn}	
k	coverage factor	
L	length of the measuring section, i.e. the stack length between the two measurement levels	m
L_p	probe length	m
L_0	measuring rod initial length	m
M	molar mass of wet gas effluent	kg/mol
M_B	molar mass of component B	kg/mol
n	number of measurement points	

P	energy production	MW
p	flue gas pressure	kPa
$p_1 \dots p_5$	pressures at points $P_1 \dots P_5$	
p_2	stagnation point pressure	Pa
p_3	static pressure	Pa
p_{atm}	atmospheric pressure	Pa
p_c	absolute pressure in the duct in the measurement plane	Pa
p_{dyn}	dynamic pressure on the vane wheel	Pa
p_s	density of the indicating fluid of a liquid manometer at standard temperature	
p_t	density of the indicating fluid of a liquid manometer at the temperature when read	
$\overline{p_{\text{stat}}}$	average static pressure in the measurement section	Pa
Δp	differential pressure	Pa
$\overline{\Delta p_i}$	average dynamic pressure measured at the measurement point i of the measurement plane	Pa
$q_{m,t}$	tracer mass flow rate	kg/s
q_V	volume flow rate	m ³ /s
$q_{V,0d}$	dry volume flow rate, under standard conditions of temperature and pressure	m ³ /s
$q_{V,0d,O_2}$	dry volume flow rate, under standard conditions of temperature and pressure and on actual oxygen concentration	m ³ /s
$q_{V,0d,O_2,\text{ref}}$	dry volume flow rate, under standard conditions of temperature and pressure, and reference oxygen concentration	m ³ /s
$q_{V,0,O_2}$	stack gas flow rate at sample oxygen content and moisture under standard conditions	m ³ /s
$q_{V,w}$	volume flow rate under the conditions of temperature and pressure of the duct, on wet gas	m ³ /s
r_{Sp}	geometry of the vane wheel	
R	gas constant	8,314 J/(K mol)
t	transit time of the tracer pulse between the two measurement points	s
T	flue gas temperature	K
T_c	temperature of gas in the measurement plane	K
T_0	initial temperature of the rod at the start of the measurement	K
T_1	final temperature of the rod at the end of the measurement	K
v_0	start-up velocity	m/s

v_c	velocity corrected for flow direction	m/s
v_i	local velocity at measurement point i	m/s
v_{meas}	measured velocity	m/s
v_t	peripheral velocity, $v_t = \omega r_{\text{sp}}$	
$v_{f,\text{av}}$	average velocity of fixed device measurements	m/s
$v_{f,i}$	velocity of fixed measurement device at measurement point i	m/s
$v_{t,\text{cor},i}$	corrected velocity at measurement point i	m/s
$v_{t,i}$	velocity of traverse measurement device at measurement point i	m/s
v_∞	axial approach velocity	m/s
$\bar{v}$	mean velocity	m/s
$\bar{v}_c$	corrected mean velocity	m/s
$\bar{v}_p$	average of the point velocity measurements	m/s
$\bar{v}_v$	mean axial velocity	m/s
w_{ash}	ash yield mass fraction of solid fuel as received	
w_C	carbon mass fraction in fuel as received	
w_f	fuel mass fraction in fuel as received	
w_H	hydrogen mass fraction in fuel as received	
$w_{\text{H}_2\text{O}}$	moisture mass fraction in solid fuel as received	
w_N	nitrogen mass fraction in fuel as received	
w_O	oxygen mass fraction in fuel as received	
w_S	sulfur mass fraction in fuel as received	
α	linear expansion coefficient	m/(m K)
α	pitch of blade	
η	thermal efficiency	
η_{dyn}	dynamic viscosity	Pa s
θ_{meas}	measured angle	°
ρ	density of the gas effluent under ambient conditions of temperature and pressure of wet gas	kg/m ³
$\sigma_{\Delta p_i}$	standard deviation of the m dynamic pressure measurements in the measurement point i	
$\Phi_{(\text{N})\text{F}}$	process heat release	MW
φ_B	volume concentration of component B	%

$\varphi_{\text{CO}_2, \text{w}}$	CO ₂ volume concentration in the gas stream in wet gas	%
$\varphi_{\text{H}_2\text{O}}$	flue gas water vapour volume concentration, wet	%
φ_{O_2}	flue gas oxygen volume concentration, dry	%
$\varphi_{\text{O}_2, \text{d}}$	oxygen volume concentration measured in the duct during the exploration of the duct on dry gas	%
$\varphi_{\text{O}_2, \text{ref}}$	reference oxygen volume concentration	%
$\varphi_{\text{O}_2, \text{w}}$	oxygen volume concentration in the gas stream in wet gas	%
ω	angular frequency	s ⁻¹
ϖ	pulsatance	s ⁻¹

4.2 Abbreviated terms

AMS	automated measuring system
MO	monitoring objective
NSE	net specific energy
QAL2	second quality assurance level
SRM	standard reference method
QA	quality assurance
WAF	wall adjustment factor

5 Principle

5.1 General

This document provides a method for the determination of gas velocity and volume flow rate within an emissions duct. It describes a method to determine the velocity profile of the gas flow across a measurement plane in the duct, and a method to determine the total volume flow rate at a measurement plane in the duct based on a grid of point velocity measurements made across the measurement plane. In addition, alternative methods are described for the determination of volume flow rate based on the measurement of tracer dilution, tracer transit time, and by calculation from energy consumption.

Techniques for determining gas velocity at a point include a calibrated differential pressure device (Pitot tube, see [Annex A](#)) and a calibrated vane anemometer (see [Annex B](#)). Selection criteria for the use of different types of Pitot and the vane anemometer are given in [Clause 6](#). However, it is up to the user to ensure the method selected for a given application meets the performance criteria defined by this document. The volume flow rate within a duct is determined by measuring the duct axial gas velocity at a series of points along measurement lines across the duct on a single measurement plane. The number of measurement lines and measurement points required depends on the duct shape and size. The spacing of the measurement points is based on the principle of equal areas as defined in ISO 15259. The volume flow rate is calculated from the average axial velocity and the duct area at the measurement plane. If required a correction is applied to account for wall effects (see [10.4](#)).

Three alternative methods are also described to determine volume flow rate and average flow velocity:

- [Annex C](#) describes a method based on tracer dilution measurements. In this method, the volume flow rate is determined from the dilution of a known concentration of injected tracer.

- [Annex D](#) describes a method based on a tracer transit time measurement technique. The volume flow rate is determined from the time for a pulse of tracer gas to traverse between two measurement locations.
- [Annex E](#) describes a method to determine the volume flow rate using a calculation-based approach to derive the flow from the energy consumption of a combustion process.

The volume flow rate may be reported at stack conditions or may be expressed at standard conditions (273,15 K and 101,3 kPa) on either the wet or dry basis.

This document applies to a range of monitoring objectives (MO) with different uncertainty requirements, and it provides quality control checks to enable these to be met. The level and extent of quality control checks and the selection of performance characteristics and their criteria have been established and specified based on the monitoring objective uncertainty requirements.

5.2 Monitoring objectives

Monitoring objectives are grouped based on the required quality control. The grouping of monitoring objectives is as follows:

- MO1: periodic monitoring for regulatory compliance purposes according to ISO 15259 and/or pollution inventory reporting which involves the determination of mass emissions and for the control of isokinetic conditions during manual extractive sampling;
- MO2: periodic measurements under the requirements of Emission Trading Schemes and/or calibration of an AMS under ISO 16911-2 and/or flow profile characterization either to meet the requirements of Emission Trading Schemes or any other regulatory requirements.

For simplicity any reference throughout this document to MO1 or MO2 refers to the above list.

This document can be used for other monitoring objectives, but the user has to specify the required level of quality control based on the uncertainty requirement of the monitoring objective.

5.3 Principle of flow velocity determination at a point in the duct

The axial flow velocity at a point in the duct is determined using one of two techniques described in this document:

- differential pressure based measurement using Pitot tubes, and
- vane anemometry.

[Annex A](#) provides details for the use of differential pressure based techniques. [Annex B](#) describes the vane anemometer in detail.

The flow velocity is determined as the duct axial velocity at each point determined according to ISO 15259.

The differential pressure based techniques are based on the principle of the Pitot tube as defined in ISO 3966. [3] A probe with one or more pressure taps is inserted into the flow. The basic principle is that one pressure tap is impacted by the flowing gas, and one or more other pressure taps are exposed to the static pressure in the duct. The probe assembly allows the resultant pressure difference between these to be measured by an external differential pressure measuring device.

Different implementations of the differential pressure approach are available. These include standard L-type, S-type, and multi-axis Pitot tubes (3D and 2D Pitot tubes). Each has their own specific advantages and disadvantages, and these are described in this document. The methods used are based on those specified in ISO 10780, [4] ISO 3966, [3] and US EPA Method 2. [16] Performance requirements and quality assurance procedures are applied to achieve the uncertainties defined in this document.

If 2D Pitot tubes are to be used, information on the necessary QA/QC can be found in US EPA Method 2G [18].

5.4 Principle of measurement of volume flow rate

5.4.1 General

Volume flow rate can be determined from a series of measurements of the point velocity in a duct made across the measurement plane or by alternative techniques including tracer dilution, tracer transit time or calculation from energy consumption. [Annex C](#), [Annex D](#) and [Annex E](#) provide details of these alternative approaches.

5.4.2 Principle of volume flow rate determination from point velocity measurements

Volume flow rate is determined from a number of point measurements of the axial flow velocity over a measurement plane. Sufficient point measurements are made to characterize non-uniformities in the flow profile. The measurement points across the measurement plane are selected to be representative of regions of equal area. The average velocity passing through the measurement plane is calculated with good approximation as equal to the average of the point flow measurements. The procedures in ISO 15259 are used to determine the measurement points for circular or rectangular ducts. The tangential methodology provided in ISO 15259 is used for circular ducts as described in this document.

The reason why for circular ducts, the tangential methodology is preferred to the general method for determining equal areas (as specified in ISO 15259), is that in the tangential method the points provide a measure of the average flow in each equal area. The centre point in the general method does not provide a measure of the average flow in the centre area, but rather the maximum flow value. This can be useful for characterising the flow profile, but is not recommended for determining the average flow in the duct.

The measurement plane is selected to be representative of the required duct volume flow rate, and also to be in a region where it is uniform and stable. If non-axial flow (swirl or cyclonic flow) is expected at the measurement plane due to geometry of the duct or other upstream conditions, then the degree of swirl is determined using S-type, 3D or 2D Pitot tube measurements and if it is significant, as defined in this document, then it is taken into account through the use of additional measurement procedures, or a different measurement plane is selected.

If required, improved uncertainty in the results is achieved by taking wall effects into account following [10.4](#).

The volume flow rate q_V is determined by multiplying the average velocity by the area of the measurement plane (i.e. the internal area of the duct at the measurement plane) according to [Formula \(1\)](#):

$$q_V = \bar{v}_p A \quad (1)$$

where

$\bar{v}_p$ is the average of the point velocity measurements;
 A is the area of the measurement plane.

It is also possible to determine an array of volume flow rates, determined from the point measurements at each equal area multiplied by the area represented by each measurement point. Each measurement point area is, by definition, equal to the area of the measurement plane divided by the number of measurement points. The volume flow rate is then calculated according to [Formula \(2\)](#) which is equivalent to [Formula \(1\)](#):

$$q_V = \sum_{i=1}^n v_i \frac{A}{n} \quad (2)$$

where

v_i is the velocity at measurement point i ;
 A is the area of the measurement plane;
 n is the number of measurement points.

5.4.3 Determination of volume flow rate using tracer dilution measurements

Tracer gas injection is used to measure the volume flow rate by determining the dilution of the injected tracer by the stack gas flow. A known traceable flow rate of a tracer gas with specified composition is injected into the stack. The concentration of this tracer gas is measured at a location downstream, representative of the measurement plane, after adequate mixing of the tracer with the stack gas has occurred. Adequate mixing can be achieved when sampling from a test location that meets the homogeneity requirements of ISO 15259 for the tracer gas concentration. Guidance for achieving good tracer mixing quality are provided in [Annex C](#).

The dilution of the tracer gas by the stack gas provides a measurement of the volume flow rate, provided that:

- the tracer gas is well mixed in the stack gas;
- there is no tracer gas present in the stack gas prior to injection or the background concentration can be measured and subtracted accurately. Determination of volume flow rate using transit time tracer measurements

A small amount of tracer material is injected rapidly into the stack gas flow, to produce a short pulse of tracer. After the tracer pulse has moved over the cross-section of the flow, its transit time between two measurement points placed on a suitable straight duct section is measured. The volume flow rate is calculated by dividing the duct volume between the measurement points by the transit time. The flow determined using this technique is representative of a region of the duct defined by the pulse measurement locations, and these are chosen to be representative of the required measurement plane.

5.4.4 Determination of volume flow rate from plant thermal input

For most combustion sources the volume flow rate can be calculated from the stoichiometric flue gas volume, determined from the fuel composition and the thermal energy input rate. The possible calculation methods are described in EN 12952-15,^[7] which includes both direct and indirect methods. In a direct method the fuel flow is measured and the thermal input is calculated from the specific energy ("calorific value") of the fuel and the fuel flow. Use of an indirect method includes measurement of the energy produced and the thermal efficiency of the plant. Especially for heat generation, or combined heat and power plants, with a high net thermal efficiency of typically 90 %, the uncertainty of the indirect method to calculate the thermal input is very low.

To later determine the actual flue gas flow rate, the oxygen volume concentration at the measurement plane in many cases shall be used to take account of the excess air. The oxygen concentration can be determined using EN 14789.^[9] However, the calculation method can also provide results at reference oxygen volume concentration values without requiring the determination of the oxygen composition in the duct. The calculation approach determines the volume flow rate on a dry gas basis. It also can be used to determine the wet flue gas flow but the uncertainty in such cases increases.

6 Selection of measurement technique

6.1 Monitoring objective

This document provides methods that can be used for a number of different monitoring objectives. The user of these methods shall understand the monitoring objective and the associated maximum permissible expanded uncertainty before undertaking any measurements as required by ISO 15259. The selection of the method can depend on the monitoring objective. This document groups the monitoring objectives specified in [5.1](#) based on the required quality control. The monitoring objectives specified in [5.1](#) include specific measurement objectives that can require the use of one or more measurement techniques. [Table 1](#) outlines measurement techniques which can be used to achieve some example key measurement objectives that fall under one or more monitoring objectives.

Table 1 — Selection of measurement technique

Measurement objective	Suitable measurement techniques
Velocity measurement at a point	Point measurement: — differential pressure devices; — vane anemometer.
Determination of swirl at the measurement plane	Differential pressure device able to determine flow direction: — S-type Pitot tube; — 3D or 2D Pitot tube.
Periodic measurement of average velocity in duct	Grid of point velocity measurements; tracer dilution technique; tracer transit time technique; calculation approach based on energy consumption.
Calibration of AMS for average velocity or volume	Grid of point velocity measurements; tracer dilution technique; tracer transit time technique.

The point velocity measurement methods described in this document can be used to fulfil any of the above measurement objectives, subject to the performance requirements of the method to be met.

The alternative methods described in this document may be used for the determination of the volume flow rate and for the calibration of flow automated measuring systems (AMS), provided specific requirements are met. These are detailed in [6.3](#).

The objective of the flow measurement should be clearly defined before selecting the measurement technique. In particular, the required measurement and reference conditions, (e.g. stack gas or standard conditions, and wet or dry conditions) should be determined. These requirements can influence the selection of the measurement technique.

EXAMPLE If the flow measurements are used to calibrate an AMS which measures flow under stack conditions, then the flow is determined under these conditions to avoid additional uncertainties being introduced when converting between different conditions. Similarly, if mass emission rates are calculated using concentration data obtained on a dry basis, then flow values determined directly under dry conditions are preferred. It is not always possible to achieve this, and so this document provides procedures to convert the data to different reference conditions.

6.2 Choice of measurement technique to determine point flow velocity

A measurement technique able to determine point velocity shall be employed in order to carry out the following measurement objectives:

- velocity measurement at a point in the duct — this can be required as a part of another measurement method, e.g. for ensuring isokinetic sampling of particulates;
- flow profile measurement across a plane in the duct;
- determination of swirl.

These measurement techniques can also be employed to meet all other measurement objectives. This document allows the use of differential pressure devices or vane anemometer to determine point flow velocity.

The following provides some general advice on the selection of the point measurement technique. However, expert judgement and specific conditions inform the choice of the measurement technique on a case-by-case basis.

There are a number of different designs of Pitot tube which can be used. [Annex A](#) describes the use of these measurement techniques. These include the L-type, S-type and 2D and 3D Pitot tubes. Pitot tubes of different designs may be used provided that they meet the performance requirements given in this document, under

the conditions of use. However, certain designs of Pitot tube are more appropriate to certain stack and measurement conditions.

A vane anemometer may be used provided the performance requirements given in this document are met. [Annex B](#) provides a procedure for the use of this measurement technique.

The objective is to determine the axial velocity at one or more measurement points in the stack. Most point measurement devices, if aligned to the axis of the stack, measure the magnitude of the flow velocity vector if the angle of the flow to the axis is small ($<20^\circ$ is typical as observed in the laboratory validation studies). This implies these devices could overestimate the axial velocity by a factor equal to the reciprocal cosine of the angle of the flow velocity to the axis.

NOTE 1 If there is significant swirl in the duct flow, the 3D-type Pitot can be the appropriate technique. A procedure is given in [9.3.5](#) to determine the swirl and provides criteria to determine if the swirl is significant.

NOTE 2 In ISO 10780[4] and EN 13284-1,[8] it is stated that the S-type Pitot tube is more sensitive than the L-type to alignment to the flow vector. However, the laboratory evaluation carried out for this document did not observe this. Both the L- and S-type Pitot tubes were observed to have similar response to being misaligned to the flow vector. In both cases, the Pitot tubes could be misaligned by up to 15° to 20° without significant ($<1\%$) change to the velocity reading.

For small measurement ports, and for use in conjunction with sample probes, the S-type Pitot tube can be more appropriate. The S-type Pitot tube can also be more appropriate for use in cases where there are droplets or significant dust loading in the stack. In conditions of high dust loading, a vane anemometer is not recommended as it can become fouled, potentially invalidating its calibration.

For velocities less than 5 m/s or differential pressures less than 5 Pa, the vane anemometer has the potential to give smaller uncertainties than the differential pressure-based techniques.

6.3 Choice of the measurement technique for volume flow rate and average flow determination

The average velocity can be determined from the average of a grid of point velocity measurements. In such cases, the measurement plane shall meet the requirements of ISO 15259. [Annex C](#), [Annex D](#) and [Annex E](#) provide methods for the measurement of volume flow rate and average velocity. These methods are:

- tracer gas method by dilution;
- tracer method using transit time; and
- calculation from energy consumption for combustion processes.

The tracer gas methods can be used for the determination of volume flow rate and average velocity and for the calibration of an AMS used to determine these parameters.

NOTE 1 The use of the radioactive tracer time-of-flight can be restricted by national regulations on the use of radioactive tracers.

The section of duct where time of flight measurements is carried out shall be at least five hydraulic diameters of straight duct away from any disturbances/top of the stack.

Tracer gas methods require adequate mixing of the injected material and therefore the tracer gas methods require installation of an injection port at a suitable location and can require a port for the sensing element.

The calculation approach is suitable for the determination of volume flow rate from combustion sources or other processes, where the required process information is available as specified in [Annex E](#). The methods shall not be used for the calibration of an AMS. This method determines the flow based on measurements or assigned values for input parameters from the combustion process, e.g. fuel composition and fuel amount. Where input data are measured, the measurement systems used shall be under appropriate quality control

and shall be calibrated. For fuels with variable moisture content, a fuel sample per measurement period shall be taken and analysed.

NOTE 2 Fuel composition has only a small impact on the dry flow rate.

Methods which determine volume flow rate may also be used to determine average velocity at the measurement plane, through measurement of the stack diameter and the use of [Formula \(1\)](#), and vice versa.

7 Measuring equipment

7.1 General

Flow measurement can be carried out for a number of monitoring objectives, as described in [Clause 6](#). The equipment used depends on the measurement technique adopted and is detailed in the relevant normative annex.

7.2 Measurement of duct area

Measurements of the internal duct area shall be made using direct dimensional measurements. Care should be taken if external measurements are used to define the internal dimension, e.g. using external circumference for circular ducts or the measurement of sides of a rectangular duct. These approaches should only be used if the duct wall is constant in thickness, well defined and single skinned. The cladding thickness and wall thickness shall be subtracted from the internal diameter or the two sides of a rectangular duct, before the area is calculated.

Engineering drawings may only 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. The method(s) and equipment used to determine the internal duct area shall be reported and the plant operator shall be notified about any improvements required to improve the measurement. If engineering drawings are used the maximum acceptance criterion shall be used as the associated expanded uncertainty.

The expanded uncertainty of the internal area of duct at measurement plane shall not exceed the acceptance criterion given in [Table 2](#).

NOTE The dilution tracer method determines the stack flow rate directly and does not require an internal duct area measurement.

Table 2 — Acceptance criterion for the expanded uncertainty of the internal area of the duct at the measurement plane

Parameter	Acceptance criterion
Internal area of the duct at the measurement plane	≤ 2 % of value

The length of any ports and the thickness of the duct wall shall also be measured at each measurement port. The mean value of the length of all measurement ports (including wall thickness) can be used as the length value for each individual port as long as the difference of the individual port length including wall thickness with the mean of all measurements ports is less than 10 % of the mean, with a maximum difference allowed of 5 cm. If the length at each measurement port is more than 10 % of the mean or more than 5 cm on one or more of the measurement ports then the measurement points shall be marked differently for each measurement port to reflect the measurement port length including wall thickness.

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

A laser measurement device (see [Annex F](#)) or a suitable rigid measuring rod can be used to directly determine the internal diameter on at least two axes. Care should be taken to ensure the measurements are perpendicular to the stack axis and that internal stack fittings and ports do not affect the measurement.

In high-temperature stacks, temperature effects can be considered and taken account of if using a measuring rod. These can be accounted for by using [Formula \(3\)](#):

$$dl = L_0 \cdot \alpha \cdot (T_1 - T_0) \quad (3)$$

where

- dl is the change in length, in m;
- L_0 is the measuring rod initial length, in m;
- α is the linear expansion coefficient, in m/(m K);
- T_0 is the initial temperature of the rod at the start of the measurement, in K;
- T_1 is the final temperature of the rod at the end of the measurement, in K.

The linear expansion coefficient value depends on the measuring rod material. Regardless of whether the measuring rod length has been corrected for thermal expansion or not, temperature effects do not have to be accounted for within the uncertainty assessment. They are accounted for either through this correction or as a standard uncertainty which may be ignored as it accounts for less than 5 % of the maximum standard uncertainty.

8 Performance characteristics and requirements for differential pressure devices and vane anemometers

8.1 General

This document specifies performance requirements for the manual determination of the point velocity across a measurement plane within an emissions duct for differential pressure devices and vane anemometers. Other measurement techniques may be used, in which case, it shall be demonstrated that they meet the performance criteria given in this document. In some cases, in order to meet the uncertainty requirements of certain measurement objectives under MO2, the performance criteria specified in [Clause 8](#) should be more stringent.

8.2 Differential pressure devices

Differential pressure devices shall meet the performance requirements and the frequency specified in [Table 3](#).

Table 3 — Performance requirements of differential pressure readout devices

Checks	Frequency	Method of determination	Acceptance criteria
Standard deviation of repeatability of measurement in the laboratory	At least annually	Shall be carried out at one point, either close to the differential pressure expected during measurement or at 50 % of calibration range (can be carried out during calibration of the instrument)	≤ 1 Pa or 1,0 % of value, whichever is greater
Lack-of-fit (linearity)	At least annually	Shall be carried out over a minimum of five points	≤ 2 Pa or 2,0 % of value, whichever is greater
Calibration uncertainty	At least annually	From calibration certificate	≤ 5 Pa or 2,5 % of value, whichever is greater

The calibration certificate of differential pressure readout devices can be provided by an external calibration laboratory or internally by the testing laboratory by carrying out a calibration check against a reference standard. The calibration check carried out internally shall meet the performance criteria in [Table 3](#).

The resolution of an electronic pressure readout device shall have of at least 1 Pa (MO1) and at least one decimal place per Pascal (MO2). However, at very low differential pressures or very strict uncertainty requirements the use of two decimal places can be more appropriate. [Table 4](#) provides a list of resolutions and standard uncertainties in relation to differential pressure values and velocities.

Table 4 — Resolution and associated standard uncertainty of differential pressure readout devices

Differential pressure in Pa or Velocity in m/s	Resolution in Pa or m/s	Standard uncertainty	
		in Pa or m/s	percentage of value
5	0,01	0,003	0,058
	0,1	0,03	0,58
	1	0,3	5,8
10	0,01	0,003	0,029
	0,1	0,03	0,29
	1	0,3	2,9
20	0,01	0,003	0,014
	0,1	0,03	0,14
	1	0,3	1,4

NOTE The standard uncertainty associated with the resolution is derived through the formula $u = \frac{\alpha}{2\sqrt{3}}$, where α is the instrument resolution.

Pitot tubes shall meet the performance requirements and the frequency specified in [Table 5](#).

Table 5 — Performance requirements of Pitot tubes

Checks	Frequency	Method of determination	Acceptance criteria
Calibration uncertainty	— before first use — after repair	From calibration certificate	$\leq 2,5$ % of value or 0,02 (dimensionless uncertainty of Pitot coefficient), whichever is greater

The calibration certificate of Pitot tubes can be provided by an external calibration laboratory or internally by the testing laboratory by carrying out a calibration check against a reference standard. The calibration check carried out internally shall meet the performance criteria in [Table 5](#).

Density measurements and temperature and pressure measurement devices shall meet the performance requirements and the frequency specified in [Table 6](#).

Table 6 — Performance requirements for density measurements and temperature and pressure measurement devices

Checks	Frequency	Method of determination	Acceptance criteria
Calibration uncertainty of the measurement device for temperature which contains the temperature sensor and the temperature readout device	At least annually	From calibration certificate	$\leq 1,5 \text{ K}$ or $2,0 \%$ of absolute temperature value, whichever is greater, for combined system (temperature sensor and temperature readout device)
Calibration uncertainty of atmospheric pressure measurement device	At least annually	From calibration certificate	$\leq 0,5 \%$ of value
Uncertainty in stack gas density determination	For every field measurement	Flow uncertainty assessment	$\leq 0,05 \text{ kg/m}^3$

The calibration certificate of temperature and pressure measurement devices can be provided by an external calibration laboratory or internally by the testing laboratory by carrying out a calibration check against a reference standard. The calibration check carried out internally shall meet the performance criteria in [Table 6](#).

The lowest measurable flow by a differential pressure device is the minimum differential pressure measured or the limit of quantification, whichever is higher. Below 5 Pa differential pressure readout devices shall not be used.

NOTE 1 During the validation studies no sensitivity was detected for S-type misalignment effect from $-0,1^\circ$ up to 15° and for L-Type from 0° up to 15° .

NOTE 2 During the validation studies no sensitivity was detected for temperatures in the range of 20°C to 290°C for both L-Type and S-Type Pitot.

NOTE 3 Atmospheric pressure is unlikely to change significantly over a measurement. Therefore, the sensitivity of the system to atmospheric pressure is not significant.

NOTE 4 The acceptance criterion for the calibration uncertainty relates to an expanded uncertainty at a 95 % confidence level with $k = 2$.

NOTE 5 If the Pitot tube is used for isokinetic sampling and is attached on a sampling probe, it is preferable that the calibration is carried out under the same configuration (i.e. Pitot tube attached to sampling probe) to avoid the effect the proximity of the sampling probe can have on the Pitot coefficient. However, as the majority of test laboratories use interchangeable parts it is recognized that this is not always possible.

The uncertainty requirements specified in the individual standards (e.g. water vapour, oxygen, carbon dioxide) used for the determination of the density shall be applied.

8.3 Vane anemometers

The vane anemometer shall be calibrated at flow rates representative of the stack flow conditions, and the calibration points used to calibrate the vane anemometer shall encompass its range of operation (e.g. a maximum of twice the maximum flow plus fixed percentages of the maximum flow).

The calibration shall be a multiple point calibration spanning the velocity range of application. The calibration shall have metrological traceability. This may be achieved, for example, by the use of a flow facility with flow rates traceable to laser Doppler anemometry.

Vane anemometer devices shall meet the performance requirements and the frequency specified in [Table 7](#).

Table 7 — Performance requirements for vane anemometers

Checks	Frequency	Method of determination	Acceptance criteria
Standard deviation of repeatability of measurement in the laboratory	At least annually	Shall be carried out at one point, either close to the velocity expected during measurement or at 50 % of calibration range (can be carried out during calibration of the instrument)	1,0 % of value
Lack-of-fit (linearity)	At least annually	Shall be carried out over a minimum of five points	$\leq 2,0$ % of value
Calibration uncertainty	At least annually	From calibration certificate	$\leq 0,1$ m/s or 2,0 % of value, whichever is greater

The lowest measurable velocity by a vane anemometer is the minimum velocity measured or the limit of quantification, whichever is higher. Below the lowest range limit vane anemometers shall not be used. This value depends on flue gas characteristics and the design of the vane anemometer but is typically between 0,2 m/s to 0,5 m/s.

NOTE 1 Particulate concentrations (up to 50 mg/m³) have no influence on the performance of vane anemometers. Any fibre within the flue gas can affect the performance of the vane anemometer.

NOTE 2 Humidity has no influence on the performance of vane anemometers. However, any droplets in the stack gas can affect the performance of the vane anemometer.

NOTE 3 During the validation studies no sensitivity was detected for temperatures in the range of 20 °C to 290 °C.

9 Measurement procedure

9.1 Measurement strategy

9.1.1 Site survey before measurement

The measurement site shall meet the requirements of ISO 15259. A survey of the plant and the measurement section before the measurement is necessary to gain information on access to the measurement plane, measurement port number and dimension, workplace conditions, weather protection, obstruction, and power supply at measurement site. From the information collected, select a fit for purpose measurement system and define a measurement plan. The measurement plan should include dates, starting times and duration of the measurement periods. Record plant operating conditions during measurement periods.

The measurement objective shall be discussed with the plant operator. The measurements shall be conducted under plant operating conditions that are suitable for the measurement objective. The plant flow should be allowed to stabilise before any measurements are conducted unless the measurement objective requires otherwise.

9.1.2 Correction for time related flow variation for the characterisation of a velocity profile

If the measurement objective is characterizing a flow profile two measurement devices (one at a fixed point and one that traverses the measurement plane) shall always be used. This is because, if in this case flow variations are not considered, there is a risk that a flow profile can seem to be asymmetric when in fact it's not. This in turn can lead to incorrect decisions when it comes to confirming measurement plane suitability and/or selecting the type of flow AMS.

The fixed measurement device used can be a flow AMS as long as it has a valid QAL2 calibration function.

The correction factor to account for flow variations over time when using two devices can be determined by [Formula \(4\)](#):

$$f_{v,cor,i} = v_{f,av} / v_{f,i} \quad (4)$$

where

- $f_{v,cor,i}$ is the velocity correction factor at measurement point i ;
- $v_{f,av}$ is the average velocity of fixed device measurements, in m/s;
- $v_{f,i}$ is the velocity of fixed measurement device at measurement point i , in m/s.

The corresponding corrected velocity can be determined by [Formula \(5\)](#):

$$v_{t,cor,i} = C_{f,i} \times v_{t,i} \quad (5)$$

where

- $v_{t,cor,i}$ is the corrected velocity at measurement point i , in m/s;
- $v_{f,i}$ is the velocity of fixed measurement device at measurement point i , in m/s;
- $v_{t,i}$ is the velocity of traverse measurement device at measurement point i .

9.1.3 Consideration of flow measurement assembly surface area in relation to measurement plane area

The area of the flow measurement assembly (sensing element and probe) 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 the area of the flow measurement assembly (sensing element and probe) shall not obstruct more than 10 % of the measurement plane area for stack or duct areas of less or equal to 1,5 m² to account for the larger measurement assembly area resulting from the integrated sampling device. For ducts or stacks with a very small measurement plane area where it is not possible to carry out isokinetic sampling and measure flow at the same time because the area of the sampling equipment can obstruct more than 10 % of the stack or duct measurement plane area, the flow measurement can be carried out prior to the isokinetic sampling and the values derived from the flow traverse used to control isokinetic conditions.

NOTE A typical point measurement survey, in a duct requiring 20 measurement points, can take up to 1 h. During this time, it is desirable to have flow conditions which are as stable as possible, unless the measurement objective requires otherwise.

9.2 Determination of measurement plane and number of measurement points

The following requirements are applicable when a series of measurements are being made across the measurement plane, in order to determine the volume flow rate.

The measurement plane for the determination of volume flow rate shall conform to the requirements of ISO 15259. Any deviations from this document shall be reported.

If measurements are being carried out to characterize the flow conditions at the measurement plane, consideration shall be given to the need to characterize the flow under different process (load) conditions, as this can lead to different flow conditions. This is of particular concern when the measurements are being carried out to characterize the flow profile for the installation of a flow AMS or for the calibration of a flow AMS.

9.3 Checks before sampling

9.3.1 General

Depending on the measurement plan, the preliminary checks required by ISO 15259 shall be carried out before the start of sampling.

The following functional checks shall be carried out on the differential pressure readout device and/or the vane anemometer device before use:

- checking the zero value of the device,
- checking that the instrument responds to gas flow;
- ensuring if required that the correct input values are stored within the electronic differential pressure device when conversions from differential pressure to velocity are carried out internally;
- checking the internal damping time is fit for purpose in regard to the measurement task.

Measure the internal stack diameter (or stack width for rectangular/square stacks) and stack wall thickness at the measurement plane for each measurement line. The duct wall thickness should include the depth of the measurement port. Determine the required number of measurement lines and measurement points following the procedure given in ISO 15259, based on the equal area approach. For circular ducts, the tangential approach shall be used.

Calculate the position the probe should be inserted for each measurement point and mark the probe accordingly, taking account of the duct wall and port depth.

If required identify a suitable location for the fixed-point flow measurement system to check varying flow conditions with time. This may be a second flow measurement device, or a suitable flow AMS, provided it is located in a suitable position.

Before and after use Pitot tubes shall be checked for:

- deformities, burrs or damage to the tube;
- blockage of the pressure taps;
- leaks;
- cleanliness;
- straightness of the supporting tube.

Before and after use vane anemometers should be checked for:

- damage to the vane and housing;
- build-up of contamination on the vane blades;
- cleanliness;
- any sticking of the vane when gently blown on.

Any issues identified with the preceding two lists invalidate the calibration of the device. The Pitot tubes/vane anemometers affected shall not be used until the issues identified have been rectified (if possible) and the devices have been recalibrated.

9.3.2 Pre-test leak check

Before undertaking a series of measurements and each time the system is disconnected, a leak check shall be performed for Pitot tubes. This can be achieved by pressurizing the tube at least as high a differential 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 2 % of the value or 10 Pa, whichever value is lower (for at least 15 s).

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

The S-type Pitot tube shall be positioned perpendicular to the direction of the flow. The static pressure is then measured using both taps. The difference in the measured static pressure shall be less than

1 % of the range of the differential pressure readout device or 10 Pa whichever is greater. If the difference in readings exceeds this tolerance this can indicate local swirl, blockage of pitot, etc. In this case the reason should be investigated and rectified or a new Pitot tube used.

9.3.4 Tests of repeatability at a single point

If two measurement devices are being used, one fixed and one traverse, select one equal area location and make at least five paired readings of the velocity, using both measurement devices in the same equal area. Calculate the field repeatability from the standard deviation of the differences between these readings and compare to the field repeatability criterion in [Table 7](#), as a percentage of the measured velocity.

The test of repeatability at a single point is only required under M02.

9.3.5 Swirl or cyclonic flow

If swirl is either known to exist from previous measurements or is expected due to the geometry or stack conditions, then non-axial flow (indicating swirl within the duct) shall be assessed at each measurement point using differential pressure devices. An example method is provided in the informative [Annex K](#) (only applicable to S-Type Pitot). Self-compensating anemometer models may also be used for flow angles up to 30°. If any of the tangential flow angles is greater than 15° to the axial direction at any measurement point in the plane, then swirl can be assumed to have a significant impact on the measurements. In such cases, measurement of the velocity at each point should be made using devices which can provide the flow velocity and angle of flow at each point. These include 3D, 2D, and S-type Pitot tubes.

If the swirl angle is greater than 15° but lower or up to 40°, the axis of the Pitot tube head shall be parallel to the local flow direction and the axial velocities at each point (where swirl angle is greater than 15° but lower or up to 40°) determined by [Formula \(6\)](#) using the cosines of the measured angles above 15° in order to account for the angle of swirl:

$$v_c = v_m \cos \theta_m \quad (6)$$

where

- v_c is the axial velocity, in m/s;
- v_m is the velocity measured with the Pitot tube head parallel to the local flow direction, in m/s;
- $\cos \theta_m$ is the cosine of the swirl angle measured.

When carrying out isokinetic testing and swirl is identified above 15° the number of measurement points shall be doubled (up to a maximum of 20 measurement points) and no sampling shall be carried out on the non-compliant points (i.e., the points that the angle of swirl has been identified to be above 15°). A distance of at least 5 cm or 3 % of the length of the measurement axis, whichever is greater, shall always be maintained between the inner wall and the first and last measurement points on the measurement axis. This deviation from standard sampling conditions according to ISO 15259 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.

9.4 Quality control

A number of quality control and quality assurance procedures are required to ensure measurements made using differential pressure devices achieve the smallest measurement uncertainty. These are summarized in [Table 8](#).

Table 8 — Performance requirements during field measurements

Parameter	Criterion	Method of determination
Field repeatability	≤ 5 % of velocity	Determined before measurements (9.3.4) - only applicable to MO2
Angle of flow sensor to gas flow	$< 15^\circ$	During measurement
Leak check	$< 2,0$ % of the value or 10 Pa, whichever value is lower	Before undertaking a series of measurements and each time the system is disconnected (9.3.4)
Positional accuracy of flow sensor in stack	≤ 10 % of distance between adjacent measurement points	During field measurement - only applicable to MO2
Angle of the probe to measurement plane (pitch of probe)	$\leq 10^\circ$ from measurement plane	During field measurement - only applicable to MO2

Specific requirements for vane anemometers are specified in [Annex B](#).

9.5 Measurement of flow at locations within the measurement plane

The measurements of the velocity shall be carried out at each measurement point in the measurement plane.

The probe shall be inserted to the marked insertion depth. For differential pressure devices, at each measurement point, the average differential pressure shall be determined over at least 1 min, from the average of at least three instantaneous readings of the differential pressure. An electronic pressure readout device may be used to provide a direct reading of average differential pressure over at least a minute.

Sampling duration for the 3D Pitot tube can be significantly longer. It is important in such cases to ensure that temporal variations in the stack flow are considered.

If two flow measurement devices are used, the measurements from both devices shall be recorded in parallel.

The temperature at each measurement point shall be recorded, where appropriate. The measurements of oxygen, water vapour and carbon dioxide shall be recorded, if required, or the stack gas density determined by other means.

The atmospheric pressure shall be recorded.

The static pressure shall be recorded at least once for each measurement line.

9.6 Post-measurement quality control

For Pitot tubes a post-measurement leak check shall be carried out following the procedure in [9.3.2](#).

A blockage test is required for differential pressure devices.

This test is not required for an S-type Pitot tube. Its performance is required for each pressure tap of a 3D Pitot tube. It shall be carried out as a minimum after the measurement period. It is advisable to carry it out after each traverse as, if it is failed, all data since the previous test are invalidated.

Record the differential pressure at a location in the duct. When using 3D Pitot tube, purge it with pressurized air to clean the pressure taps. Repeat the measurement of the differential pressure at the same location. If the two readings are within 5 %, then the traverse data are acceptable. The fixed point readings shall be checked to ensure they do not vary by more than 2 % between these measurements. If they do, the blockage test readings may be corrected to account for the variation in flow.

10 Calculation of results

10.1 General

In the calculation which follows, the gas properties are assumed to be the same across all points of the measurement plane.

Results may be reported under stack conditions or reference conditions. The choice of conditions under which to express the results should be informed by the monitoring objective, and by available data. If the measurements are being carried out in order to calibrate an AMS, then the flow data should be expressed in the same units. Where the volume flow rate data are being used to calculate mass emissions, then the flow data and the concentration data shall be expressed in the same conditions. To avoid additional uncertainty components, unnecessary conversions between conditions should be avoided. This requirement implies that, for example, if it is possible to measure simultaneously both concentration and flow data under wet (stack) conditions, then this is preferable as there is then no requirement to measure water vapour concentration in order to convert measurements to dry conditions, and the uncertainty component due to this measurement is avoided.

10.2 Measurement of velocity

The velocity v_i at each measurement point i in the measurement plane is determined using the differential pressure device or vane anemometer (see [Annex A](#) and [Annex B](#)).

10.3 Determination of the mean velocity

The mean axial velocity $\bar{v}_v$ across the measurement plane is given by [Formula \(7\)](#):

$$\bar{v}_v = \frac{1}{n} \sum_{i=1}^n v_i \quad (7)$$

where

- $\bar{v}_v$ mean axial velocity across the measurement plane, in m/s
- i is the number of the measurement point, $i = 1 \dots n$;
- v_i is the local velocity at measurement point i , in m/s.

NOTE [Formula \(7\)](#) is only valid if the velocities are taken at equal area points.

10.4 Correction of average velocity for wall effects

The rapid curvature of the wall velocity profile is not fully captured by the relatively coarse measurement grid, defined according to ISO 15259, leading to a slight overestimate of flow rate. This document allows the operator to select a default wall adjustment factor (WAF), f_{WA} , which is used as a multiplier on the measured mean flow rate in a duct of circular cross-section according to [Formula \(8\)](#):

$$\bar{v}_c = \bar{v} f_{WA} \quad (8)$$

where

- $\bar{v}_c$ is the corrected mean velocity, in m/s;
- $\bar{v}$ is the mean velocity, in m/s;
- f_{WA} is the wall adjustment factor.

The use of WAF in measurements in support of isokinetic sampling is not required. The default WAF is 0,995 for smooth walled ducts or 0,99 for rough walled ducts constructed from brick or mortar. Application of the WAF therefore results in a 0,5 % to 1,0 % reduction in volume flow rate. For rectangular ducts with 5 straight duct hydraulic diameters upstream and downstream of the measurement section, a default WAF of 0,97 can be assumed. For rectangular ducts with less than 5 straight duct hydraulic diameters upstream and downstream a default WAF of 0,95 can be assumed because of the increased influence of the walls and

corner effects. It should be noted that rectangular ducts often contain side ribs and cross-bracing supports and, in solid fuel fired plant, dust build up in corners can alter the internal shape of the duct. Alternatively, factors for ducts of rectangular cross-section may be calculated using a procedure specified in US EPA CTM-041.^[15] This approach provides a more accurate factor but can need additional measurements in the duct and lengthy calculations.

NOTE US EPA Method 2H^[19] also specifies a method for calculating the WAF based on near wall velocity measurements in ducts of more than 1,0 m diameter, provided that the measured WAF is no lower than 0,97. US EPA CTM-041^[15] specifies a similar approach for ducts of rectangular cross-section, noting that the wall effect in these circumstances can be more significant since: the ratio of the perimeter to the cross-sectional area is greater; the test points are relatively further from the wall; and the corners of the duct are subject to increased wall effects from two adjoining walls.

10.5 Calculation of the volume flow rate from the average velocity

The volume flow rate $q_{V,w}$ under the conditions of temperature and pressure of the duct and on wet gas is given by [Formula \(9\)](#):

$$q_{V,w} = \bar{v} \times A_I \quad (9)$$

where

- $q_{V,w}$ is the volume flow rate under the conditions of temperature and pressure of the duct and on wet gas, in m³/s;
- $\bar{v}$ is the mean velocity, in m/s;
- A_I is the internal area of the measurement plane, in m².

10.6 Conversion of results to standard conditions

10.6.1 General

If required, the volume flow rate is converted to standard conditions according to the calculations in [10.6.2](#) to [10.6.4](#).

10.6.2 Conversion of the volume flow rate to standard conditions

The volume flow rate shall be expressed at standard conditions, as a dry gas, where the standard conditions for temperature and pressure, i.e. 273,15 K and 101,3 kPa, respectively, shall be used.

If the pollutant is expressed to a reference oxygen concentration, the volume flow rate shall also be calculated under the same conditions.

The calculation of the uncertainty of the normalized flow rate shall take account of the uncertainties of related measurements to these conversions.

10.6.3 Dry volume flow rate in standard conditions

The dry volume flow rate $q_{V,0d}$ under standard conditions of temperature and pressure is given by [Formula \(10\)](#):