



BSI Standards Publication

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

Part 1: Manual reference method

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National foreword

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Foreword

This document (EN ISO 16911-1:2013) has been prepared by Technical Committee CEN/TC 264 "Air quality", the secretariat of which is held by DIN, in collaboration with Technical Committee ISO/TC 146 "Air quality".

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by September 2013, and conflicting national standards shall be withdrawn at the latest by September 2013.

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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.

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ISO 16911-1 was prepared by the European Committee for Standardization (CEN) in collaboration with ISO Technical Committee TC 146, *Air quality*, Subcommittee SC 1, *Stationary source emissions*.

ISO 16911 consists of the following parts, under the general title *Stationary source emissions — Manual and automatic determination of velocity and volume flow rate in ducts*:

- *Part 1: Manual reference method*
- *Part 2: Automated measuring systems*

Introduction

EN ISO 16911-1 describes a method for periodic determination of the axial velocity and volume flow rate of gas within emissions ducts and stacks and for the calibration of automated flow monitoring systems permanently installed on a stack.

EN ISO 16911-1 provides a method which uses point measurements of the flow velocity to determine the flow profile and mean 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-monitoring systems. A method based on calculation from energy consumption is also described. EN ISO 16911-1 provides guidance on when these alternative methods may be used.

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

Part 1: Manual reference method

1 Scope

EN ISO 16911-1 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 EN 15259. Minimum and maximum duct sizes are driven by practical considerations of the measurement devices described within EN ISO 16911-1.

EN ISO 16911-1 requires all flow measurements to have demonstrable metrological traceability to national or international primary standards.

To be used as a standard reference method, the user is required to demonstrate that the performance characteristics of the method are equal to or better than the performance criteria defined in EN ISO 16911-1 and that the overall uncertainty of the method, expressed with a level of confidence of 95 %, is determined and reported. The results for each method defined in EN ISO 16911-1 have different uncertainties within a range of 1 % to 10 % at flow velocities of 20 m/s.

Methods further to these can be used provided that the user can demonstrate equivalence, based on the principles of CEN/TS 14793.^[10]

2 Normative references

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

ISO 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)*

EN 14789, *Stationary source emissions — Determination of volume concentration of oxygen (O₂) — Reference method — Paramagnetism*

EN 14790, *Stationary source emissions — Determination of the water vapour in ducts*

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

3 Terms and definitions

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

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 may 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

reference value a pressure 101,325 kPa and a 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 EN ISO 16911-1, 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 EN ISO 16911-1, 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 combined standard 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 EN 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, 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 section	m^2
A_S	cross-sectional area of stack	ft^2
B	number of component B	

a_1, a_2	angle between sensing holes	°
c	constant	
d	outer tube diameter	mm
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
$F_1(i)$	pitch angle ratio at traverse point i	1
$F_2(i)$	3D probe velocity calibration coefficient at traverse point i	1
f	vane frequency	s ⁻¹
f_v	velocity factor	
f_{WA}	wall adjustment factor	
i	i th measurement point	
K	coefficient of the Pitot tube which includes the Pitot calibration factor and constant values relating to the Pitot design	
K_p	conversion factor, 85.49 ft/s[(lb/lb-mol)(inHg)/(R)/(inH ₂ O)] ^{0.5}	
$K(\rho_{0,\eta_{\text{dyn}}})$	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	molar mass of wet gas effluent	kg/mol
M_B	molar mass of component B	kg/mol
M_d	molar mass of gas, dry basis	lb-lb/mol
M_s	molar mass of gas, wet basis	lb-lb/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

$(p_1 - p_2)_i$	velocity differential pressure at traverse point i	inH ₂ O
$(p_4 - p_5)_i$	pitch differential pressure at traverse point i	inH ₂ O
p_{atm}	atmospheric pressure	inHg
p_c	absolute pressure in the duct, in the measurement section	Pa
p_{dyn}	dynamic pressure on the vane wheel	Pa
p_g	static pressure	inH ₂ O
p_s	stack absolute pressure	inHg
p_{std}	standard absolute pressure	29.92 inHg
$\overline{p_{\text{stat}}}$	average static pressure in the measurement section	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 O ₂ content and moisture under standard conditions	m ³ /s
$q_{V,\text{sd}}$	average dry-basis stack gas volume flow rate corrected to standard conditions	dscf/h
$q_{V,\text{sw}}$	average wet-basis stack gas volume flow rate corrected to standard conditions	wscf/h
$q_{V,w}$	volume flow rate under the conditions of temperature and pressure of the duct, on wet gas	m ³ /s
R	gas constant	8,314 J/(K mol)
r_{Sp}	geometry of the vane wheel	
T	flue gas temperature	K
T_c	temperature of gas in the measurement section	K
$T_{s(\text{avg})}$	average absolute stack gas temperature across stack	R
$T_{s(i)} ^\circ\text{F}$	stack gas temperature at traverse point i	$^\circ\text{F}$
$T_{s(i)} \text{ R}$	absolute stack gas temperature at traverse point i	R
T_{std}	standard absolute temperature	528 R
t	transit time of the tracer pulse between the two measurement points	s

$u(v)$	uncertainty of measurement of the flow velocity	m/s
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_∞	axial approach velocity	m/s
$\bar{v}$	mean velocity	m/s
$\bar{v}_v$	mean axial velocity	m/s
$\bar{v}_c$	corrected mean velocity	m/s
$\bar{v}_p$	average of the point velocity measurements	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	pitch of blade	
Δp	differential pressure	Pa
$\overline{\Delta p_i}$	average dynamic pressure measured at the point i of the measurement section	Pa
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 point i	
$\Phi_{(\text{N})\text{F}}$	process heat release	MW

φ_B	volume fraction of component B	volume fraction
$\varphi_{CO_2, w}$	concentration of CO ₂ in the gas stream in wet gas	% volume fraction
φ_{H_2O}	flue gas water content, wet	% volume fraction
φ_{O_2}	flue gas oxygen content, dry	% volume fraction
$\varphi_{O_2, d}$	oxygen concentration measured in the duct during the exploration of the duct on dry gas	% volume fraction
$\varphi_{O_2, ref}$	reference oxygen concentration	% volume fraction
$\varphi_{O_2, w}$	concentration of O ₂ in the gas stream in wet gas	% volume fraction
ω	angular frequency	s ⁻¹
ϖ	pulsatance	s ⁻¹

4.2 Abbreviated terms

AMS	automated measuring system
NSE	net specific energy
SRM	standard reference method
QA	quality assurance
WAF	wall adjustment factor

5 Principle

5.1 General

EN ISO 16911-1 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) and a calibrated vane anemometer. 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 EN ISO 16911-1. 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 EN 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.

EN ISO 16911-1 provides quality control checks for the verification of the conditions for accurate measurements.

The volume flow rate may be reported at stack conditions or may be expressed at standard conditions (273,15 K and 101,325kPa) on either the wet or dry basis.

5.2 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 EN ISO 16911-1: differential pressure based measurement using Pitot tubes and vane anemometry. The annexes describe the techniques in detail, [Annex A](#) provides for the use of differential pressure based techniques, [Annex B](#) describes the vane anemometer.

The flow velocity is determined as the duct axial velocity at each point determined according to EN 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 EN ISO 16911-1. The methods used are based on those defined in ISO 10780,^[4] ISO 3966,^[3] and US EPA Method 2.^[14] Performance requirements and quality assurance procedures are applied to achieve the uncertainties defined in EN ISO 16911-1.

If 2D Pitot tubes are to be used, then they should be subject to QA/QC as defined in US EPA Method 2G.^[16]

5.3 Principle of measurement of volume flow rate

5.3.1 General

Volume flow rate may 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. [Annexes C, D](#) and [E](#) provide details of these alternative approaches.

5.3.2 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 EN 15259 are used to determine the measurement points for circular or rectangular ducts. The tangential methodology provided in EN 15259 is used for circular ducts as described in EN ISO 16911-1.

The reason that for circular ducts, the tangential methodology is preferred from the two schemes for determining equal areas provided for in EN 15259, is that this scheme has points which provide

measures of the average flow in each equal area. The central point in the general method does not provide a measure of the average flow in the central area, but rather the maximum value. This may be useful for reconstructing 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 EN ISO 16911-1, 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 a procedure based on the US EPA Method 2H^[17] for circular ducts, and US EPA CTM-041^[13] for rectangular ducts.

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).

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

where

$\bar{v}_p$ is the average of the point velocity measurements;

A is the area of the measurement plane.

NOTE 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 sample point. Each sample point area is, by definition, equal to the area of the measurement plane divided by the number of points. The volume flow rate is then

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

where

v_i is i th point measurement;

A is the area of the measurement plane;

n is the number of measurement points.

which is equivalent to Formula (1).

5.3.3 Determination of volume flow rate using tracer dilution measurements

Trace 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 calibrated tracer gas is injected into the stack. The concentration of this tracer gas is measured at a location downstream, representative of the measurement plane, after complete mixing of the tracer with the stack gas has occurred. The dilution of the tracer gas by the stack gas provides a measurement of the volume flow rate, provided that:

- the tracer gas is fully 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.

5.3.4 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 mixed 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.

5.3.5 Determination of volume flow rate from plant thermal input

For most combustion sources the volume flow rate may 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 concentration at the measurement plane in many cases shall be used to take account of the excess air. The oxygen concentration is determined using EN 14789. However, the calculation method can also provide results at reference oxygen 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 may be used to determine the wet flue gas flow but the uncertainty in such cases increases.

6 Selection of monitoring approach

6.1 Monitoring objective

EN ISO 16911-1 provides methods that can be used for a number of different objectives. The user of this method shall understand the objective of the measurement task before undertaking the measurements as required by EN 15259, as the selection of the method to use can depend on the measurement objective.

Measurement objectives include:

- a) velocity measurement at a point in the duct — this may be required as a part of another measurement method, e.g. for ensuring isokinetic sampling of particulates;
- b) flow profile measurement across a plane in the duct;
- c) determination of swirl;
- d) calibration of a flow AMS — this calibration may be by volume flow rate or velocity;
- e) periodic determination of volume flow rate passing through a measurement plane.

[Table 1](#) outlines the techniques which can be used to achieve measurement objectives a) to e).

Table 1 — Selection of measurement technique

Aim of measurement	Suitable techniques to realize measurement
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 EN ISO 16911-1 may be used to fulfil any of the above objectives, subject to the performance requirements of this method being met.

The alternative methods described in EN ISO 16911-1 may be used to determine volume flow rate and for the calibration of flow automated measuring systems (AMSs), provided specific requirements under which they may be used are met. These are detailed in [6.3](#).

The objective of the flow measurement should be clearly defined before selecting the monitoring approach. In particular, the required basis of the measurements, stack gas conditions or reference conditions, on a wet or dry basis should be understood, as the selection of the measurement technique may be influenced by this.

EXAMPLE If the flow measurements are to be used to calibrate an AMS which measures flow under stack conditions, then the flow should be determined under these conditions to avoid additional uncertainties being introduced when converting between different conditions. Similarly, if mass emission rates are to be calculated using concentration data obtained in a dry basis, then flow values determined directly under dry conditions would be preferred. It is not always possible to achieve this, and so EN ISO 16911-1 provides procedures to convert the data to different reference conditions.

6.2 Choice of technique to determine point flow velocity

In order to fulfil objectives 6.1 a) to c), a technique able to determine point velocity shall be employed. These techniques may also be employed to meet all other measurement objectives. EN ISO 16911-1 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 monitoring technique. However, expert judgement and specific conditions inform the choice of technique on a case-by-case basis.

There are a number of different designs of Pitot tube which may be used to carry out this method. [Annex A](#) describes the use of these 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 EN ISO 16911-1, under the conditions of use. However, certain designs of Pitot tube are more appropriate to certain stack and measurement conditions.

A vane anemometer technique may be used provided the performance requirements given in EN ISO 16911-1 are met. [Annex B](#) provides a procedure for the use of this technique.

The objective is to determine the axial velocity at one or more 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° 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 method. 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 EN ISO 16911-1 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 access 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 may become fouled, affecting the calibration.

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

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

The average velocity may be determined from the average of a grid of point flow measurements. In such cases, the measurement plane shall meet the requirements of EN 15259. [Annexes C, D, E](#) to EN ISO 16911-1 provide methods for the measurement of volume flow rate and average duct 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 may be used for the determination of volume flow rate and average velocity and for the calibration of AMSs 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. It is also a requirement that there is a straight section of duct long enough to provide adequate time of flight measurements.

Tracer methods require complete mixing of the injected material and therefore the tracer methods require installation of an injection port at a suitable location, and may 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 defined in [Annex E](#). The methods shall not be used for the parallel calibration of automated flow measurement systems. 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 may be carried out for a number of objectives, as described in [Clause 6](#). The equipment used depends on the 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. The use of engineering drawings or specifications without verification by measurements is not allowed. 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 depth of any ports and the depth of the duct wall shall also be measured at each measurement port. If not significantly different, the mean value of these may be used. A laser measurement device (see [Annex I](#)) or a suitable rigid measuring rod may 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 shall be considered and taken account of if using a measuring rod.

Performance requirements are given in [Table 2](#).

Table 2 — Performance requirements

Parameter	Criterion	Method of determination
Internal area of duct at measurement plane	≤ 2 % of value	Performance evaluation of measurement method — note temperature may have a significant influence

8 Performance characteristics and requirements

EN ISO 16911-1 defines performance requirements for the manual determination of the point velocity across a measurement plane within an emissions duct. Other techniques may be used, in which case, it shall be demonstrated that they meet the performance standards given in EN ISO 16911-1.

The performance characteristics defined in [Table 3](#) shall be met by velocity flow determination techniques.

Table 3 — Performance requirements

Parameter	Criterion	Method of determination
Standard deviation of repeatability of measurement in the laboratory	< 1 % of value	Performance evaluation in wind tunnel at values spanning measured level
Lack-of-fit (linearity)	< 2 % of value	Maximum deviation from linear fit at five velocity levels in wind tunnel
Uncertainty due to calibration	< 2 % of full scale	From calibration certificate for measurement equipment
Lowest measureable flow (limit of quantification)	No criterion, but should be determined	This parameter shall be determined, but is not a performance requirement. The sensor shall not be used to measure flows below its limit of quantification
Sensitivity to ambient temperature Note: Only external components are affected by ambient conditions.	≤ 2 % of range per 10 K	Performance evaluation of measurement device
Sensitivity to atmospheric pressure	≤ 2 % of range per 2 kPa	Performance evaluation of the measurement device
Effect of angle of sensor to flow	≤ 3 % at 15°	Performance evaluation of measurement device

9 Measurement procedure

9.1 Site survey before testing

The setting of the sampling location shall be according to EN 15259. A survey of the plant and sampling plane before the measurement is necessary to gain information on access to the sampling location, sampling port number and dimension, work place conditions, weather protection, obstruction, and power supply at sampling location. From the information collected, select the proper sampling device and define a schedule of the test procedure. The measurement schedule should include dates, starting times and duration of the test periods. Make sure that plant operation conditions during test periods or volume flow rate measurement should be communicated to control room staff and plant management.

The measurement should be conducted under conditions as close to steady-state operation as possible. To achieve operating conditions that are as close to representative as possible, discuss the purpose of the measurement with the plant management. If periodicity in the flow is expected (peak to peak variation >10 % of the average flow conditions), the measurement plan should be developed to average out these variations.

The area of the flow measurement assembly (sensing element and probe) shall not obstruct more than 5 % of the stack sampling plane area.

NOTE A typical point measurement survey, in a duct requiring 20 measurement locations, could take up to 1 h to complete. During this time, it is desirable to have flow conditions which are as stable as possible.

9.2 Determination of sampling plane and number of measurement points

The requirements in this subclause 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 EN 15259; any deviations from EN ISO 16911-1 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 sampling location 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 monitoring plan, the preliminary inspections required in EN 15259 shall be carried out before the start of sampling.

When using an electronic pressure reading device, a calibration check shall be made by comparing the output with measurements from a liquid manometer device or calibrated pressure sensor, with an uncertainty better than the measurement device. The two results shall agree to within the uncertainty of the electronic device, if they differ by more than this, the cause shall be investigated and rectified. The resolution of the electronically pressure device shall be at least 2 decimal places per pascal.

Measure the internal stack diameter and stack wall thickness at the measurement plane for each measurement line. The duct wall thickness should include the depth of the port. The use of engineering drawing for the determination of the internal diameter is possible. The data, however, should be made plausible. Determine the required number of measurement lines and measurement points following the procedure given in EN 15259:2007, [Annex D](#), 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 point and mark the probe accordingly, taking account of the duct wall and port depth.

Identify a suitable location for the fixed-point flow determination 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;
- internal leakage between the stagnation and static pressure taps for L-type or stagnation and reference for other Pitot tubes;
- 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 with the preceding two lists invalidate the calibration of the device.

9.3.2 Pre-test leak check

Before undertaking a series of measurements or each time the system is disconnected, whichever is the more frequent, a leak check should be performed for Pitot tubes. This can be achieved by pressurizing the tube at least as high as the static pressure in the stack and sealing the pressure taps. The pressure reading device should indicate no drop in pressure over a 5 min period.

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 10 Pa.

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 4](#), as a percentage of the measured velocity.

If only one device is being used, calculate the repeatability from the standard deviation of five consecutive 1 min readings of the velocity.

NOTE The test for repeatability when only one flow measurement device is used includes the influence of changes in the stack flow as well as the repeatability of the flow device. This is intentional, as it is only intended that a single device be used when the flow conditions are stable.

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 in accordance with methods provided in ISO 10780.^[4] If any of the tangential flow angles is greater than 15 ° to the axial direction at any measurement point in the

plane, then swirl may 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 is $>15^\circ$, then the velocity corrected for flow direction, v_c , is given by:

$$v_c = \cos \theta_{\text{meas}} v_{\text{meas}}$$

where

$\cos \theta_{\text{meas}}$ is the cosine of the angle measured;

v_{meas} is the velocity measured.

NOTE 1 This corrects for flow direction and does not correct the reading of velocity.

NOTE 2 US EPA Method 2[14] describes a procedure for determination of swirl.

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 4](#).

Table 4 — Performance requirements during field measurements

Parameter	Criterion	Method of determination
Field repeatability	≤ 5 % of velocity	Determined before measurements (9.3.4)
Angle of flow sensor to gas flow	$<15^\circ$	During measurement
Stack internal area	2 % of value	Determined before measurements
Positional accuracy of flow sensor in stack	≤ 10 % of distance between adjacent measurement points	During field measurement
Angle of the probe to measurement plane (pitch of probe)	$\leq 10^\circ$ from measurement plane	During field measurement
Uncertainty in flow measurement device calibration	≤ 1 % of value	Calibration certificate
Uncertainty in differential pressure-reading device calibration ^a	≤ 1 % of value	Calibration certificate for manometer or pressure sensor
Uncertainty in stack gas density ^a	$\leq 0,05$ kg/m ³	During field measurement
^a Only applicable to differential pressure devices.		

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

9.5 Measurement of flow at locations within the measurement plane

Carry out measurements of the velocity at each sampling point in the measurement plane.

Insert the probe to the marked insertion depth, in accordance with the measurement locations defined in [9.2](#). For differential pressure devices, at each measurement point, determine the average differential pressure over at least 1 min, from the average of at least three instantaneous readings of the differential pressure. An electronic manometer may be used to provide a direct reading of average differential pressure over at least a minute.

Measurement times for the 3D Pitot tube method 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 being used, record the measurements from both devices in parallel.

Record the temperature at each measurement point, where appropriate. Record measurements of oxygen, water vapour and CO₂, if required, or determine the stack gas density by other means.

Record the atmospheric pressure.

Record the static pressure at least once for each measurement line.

9.6 Post-measurement quality control

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 section.

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 intended use of the measurements, and by available data. If the measurements are being made 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 at each point i in the measurement plane, v_i , is determined using the differential pressure device or vane anemometer (see [Annexes A](#) and [B](#)).

10.3 Determination of the mean velocity

The mean axial velocity, $\bar{v}_v$, in m/s, across the measurement plane is given by:

$$\bar{v}_v = \frac{1}{n} \sum_{i=1}^n v_i \quad (3)$$

where

$i, i = 1 \dots n$ is the i th measurement point;

v_i is the local velocity at measurement point i , in m/s.

NOTE Formula (3) 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 EN 15259, leading to a slight overestimate of flow rate. EN ISO 16911-1, in line with US EPA Method 2H,^[17] 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. 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. Default factors for ducts of rectangular cross-section may be calculated using a procedure defined in US EPA CTM-041.^[13]

$$\bar{v}_c = \bar{v} f_{WA} \quad (4)$$

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.

NOTE US EPA Method 2H^[17] also defines 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^[13] defines 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 under the conditions of temperature and pressure of the duct, and on wet gas, $q_{V,w}$, in m³/s, is given by Formula (5):

$$q_{V,w} = \bar{v} A_i \quad (5)$$

where

$\bar{v}$ is the mean velocity, in m/s;

A_i is the internal area of the measurement section, 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 [10.6.3](#) to [10.6.4](#).

10.6.2 Conversion of the volume flow rate to standard conditions

The volume flow rate may be expressed as a dry gas, under standard conditions for temperature and pressure, i.e. 273,15 K and 101,325 kPa, respectively.

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, under standard conditions of temperature and pressure, $q_{V,0d}$, in m³/s, is given by:

$$q_{V,0d} = q_{V,w} \times \frac{p_c}{101,325} \times \frac{273,15}{T_c} \times \frac{100 - \varphi_{H_2O}}{100} \quad (6)$$

where

- $q_{V,w}$ the volume flow rate under the conditions of temperature and pressure of the duct, on wet gas, in m³/s;
- p_c is the absolute pressure in the duct, on the measurement section, in kPa;
- T_c is the temperature of gas, in the measurement section, in K;
- φ_{H_2O} is the water vapour content of gas in the duct, expressed as a percentage volume fraction.

10.6.4 Conversion of the volume flow rate to a reference oxygen concentration

The dry volume flow rate, under standard conditions and on reference oxygen concentration, $q_{V,0d,O_2ref}$, in m³/s, is given by:

$$q_{V,0d,O_2ref} = q_{V,0d,O_2} \times \frac{21 - \varphi_{O_2,d}}{21 - \varphi_{O_2,ref}} \quad (7)$$

where

- $q_{V,0d,O_2}$ is the dry volume flow rate, under standard conditions and on actual oxygen concentration, in m³/s;
- $\varphi_{O_2,ref}$ is the reference oxygen concentration, expressed as a percentage volume fraction;
- $\varphi_{O_2,d}$ is the oxygen concentration measured in the duct during the exploration of the duct on dry gas expressed as a percentage volume fraction.

11 Establishment of the uncertainty of results

An uncertainty budget shall be determined for the reported results in accordance with the principle of the calculation of the overall uncertainty as specified in ISO/IEC Guide 98-3 and ISO 20988.

- Determine the standard uncertainties attached to the performance characteristics to be included in the calculation of the uncertainty budget by means of laboratory and field tests, according to ISO/IEC Guide 98-3.
- Calculate the uncertainty budget by combining all the standard uncertainties according to ISO/IEC Guide 98-3, including the uncertainties in the calibration of the measurement devices, and any uncertainties due to conversion to reported conditions. If required uncertainties due to wall effects and swirl shall be taken into account.
- Values of standard uncertainty that are less than 5 % of the maximum standard uncertainty may be neglected.
- Calculate the overall uncertainty at the measured value, at the reported conditions.
- Uncertainty contributions due to the determination of the stack area shall be considered. This should take account of uncertainties due to the measurement device and stack non-uniformities. An example is given in [Annex D](#).
- Uncertainty contributions due to wall effects may be determined by considering the use of the fixed factor specified in [10.4](#).
- The uncertainty contributions due to swirl may be discounted if the procedures for aligning the flow measuring devices given in EN ISO 16911-1 are followed.

NOTE The laboratory assessment of point measurement devices showed that the maximum effect due to 15° of flow was less than 1 % of the measured velocity.

An illustrative uncertainty budget for measurements made using differential pressure reading devices is given in [Annex E](#), examples for other volume flow rate determination methods are given in the respective annexes.

12 Evaluation of the method

The techniques described in EN ISO 16911-1 were assessed during three validation studies (Reference [\[26\]](#)).

The validation studies were subdivided into two parts:

- laboratory tests at a wind tunnel site with a series of test runs involving manual methods (SRM) and automatic measuring methods (AMS);
- field tests at two plants site with a series of test runs involving manual methods (SRM) and automatic measuring methods (AMS).

Full reports on the validation studies are available through the CEN/TC 264 Secretariat, and are described in overview in [Annex G](#).

The assessment of the field validation data in accordance to ISO 20988 provides the following results. The standard uncertainty of the result measurement y from the application of a manual flow measurement techniques in the range 17,8 m/s to 21,2 m/s, is $u(y) = 0,49$ m/s. The expanded 95 % of result of measurement y using a manual flow measurement method in the range 17,8 m/s to 21,2 m/s is $U_{0,95}(y) = 0,98$ m/s.

The 95 % confidence interval $[y_R - U_{0,95}(y) : y_R + U_{0,95}(y)]$ is expected to encompass $P = 95$ % of the measured points. It was found to encompass $P = 97,5$ % of the evaluated 62 measurement results $y(k,j)$. Therefore, the expanded uncertainty $U_{0,95}(y) = 0,98$ m/s is considered to be a reasonable measure of the uncertainty.

The uncertainties determined are therefore applicable to the measurement of average flow for an emissions duct in m/s formed by taking a grid of samples of point flow measurements.