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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

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 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 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	ith 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_20)]$^{0.5}$	
$K\left(\rho_{0,\eta\ dyn}\right)$	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
$p_1 \ldots p_5$	pressures at points $P_1 \ldots P_5$	
p_2	stagnation point pressure	Pa
p_3	static pressure	Pa

$(p_1 - p_2)_i$	velocity differential pressure at traverse point *i*	inH_2O
$(p_4 - p_5)_i$	pitch differential pressure at traverse point *i*	inH_2O
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_2O
p_s	stack absolute pressure	inHg
p_{std}	standard absolute pressure	29.92 inHg
$\overline{p_{stat}}$	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
$q_{V,0d,O_2,ref}$	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
$q_{V,sd}$	average dry-basis stack gas volume flow rate corrected to standard conditions	dscf/h
$q_{V,sw}$	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
$T_{s(avg)}$	average absolute stack gas temperature across stack	R
$T_{s(i)}$ °F	stack gas temperature at traverse point *i*	°F
$T_{s(i)}$ 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, $v_t = \varpi r_{Sp}$	
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_{H_2O}	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*	
$\Phi_{(N)F}$	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).

$$q_V = \bar{v}_p A \tag{1}$$

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

$$q_V = \sum_{i=1}^{n} v_i \frac{A}{n} \tag{2}$$

where

v_i is ith 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°, then the velocity corrected for flow direction, v_c, is given by:

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

where

$\cos \theta_{meas}$ 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°	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)	≤10° 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]	≤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 CO_2, 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:

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

where

i, $i = 1 \ldots n$ is the ith 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]

$$\bar{v}_c = \bar{v} f_{WA} \tag{4}$$

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 m^3/s, is given by Formula (5):

$$q_{V,w} = \bar{v} A_I \tag{5}$$

where

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

A_I is the internal area of the measurement section, in m^2.

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 m^3/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 m^3/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 m^3/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 m^3/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 F, 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.

Annex A
(normative)

Measurement of velocity using differential pressure based techniques

A.1 Principle of differential pressure based technique

The principle of the determination of velocity in a gas using differential pressure measurement is described in ISO 3966.[3] A Pitot tube provides a means to determine the differential pressure within a region of the measurement plane. Figure A.2 is a schematic diagram of an L-type Pitot tube, though the principles are the same for all Pitot tube designs.

At least two pressure taps are aligned in the flow stream, one directly impacted by the flow, measuring the stagnation point pressure, p_2, and one or more measuring the static pressure, p_3. The static pressure tap may consist of a ring of holes around the Pitot tube in an L-type design, or a single 'wake' pressure tap as in an S-type design. In 3D Pitot tubes, additional separate pressure taps, may be present to measure the flow vector in three dimensions. The pressure at these orifices is transmitted by the tubing of the Pitot probe to a differential pressure meter mounted outside the stack. The difference in pressure is measured at this point. The measurement of the differential pressure may be carried out by either a digital manometer or a manual inclined liquid manometer.

Formula (A.1) is used to derive velocity from the differential pressure.

A.2 Measuring equipment

A.2.1 Pitot tubes

A.2.1.1 L-type

This type is a basic Pitot tube, which consists of a tube pointing directly into the fluid flow. As this tube contains fluid, a pressure can be measured. The moving fluid is brought to rest (stagnates) as there is no outlet to allow flow to continue. This pressure is the stagnation pressure of the fluid, also known as the total pressure or (particularly in aviation) the Pitot pressure.

Figure A.1 illustrates the measurement principle of the L-type Pitot tube.

A.2.1.2 S-type

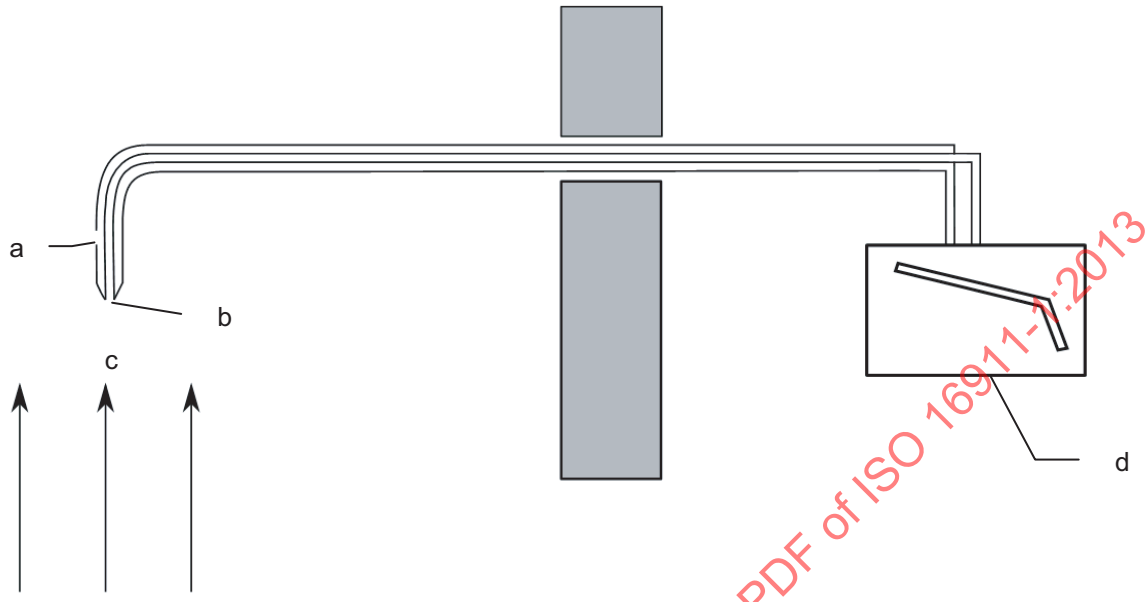
This type is also a basic Pitot tube, which measures directly in the flow. The working principle is similar to that of the L-type. The velocity is calculated on the same way as for the L-type. The S-type has to be calibrated against a reference method because the measured "static" pressure is not the real static pressure.

Figure A.3 is a schematic diagram of an S-type Pitot tube.

A.2.1.3 3D

This type of probe consists of five pressure taps in a spherical (or prism-shaped, which was not used on laboratory tests) sensing head. The pressure taps are numbered 1 to 5, with the pressures measured at each hole referred to as p_1, p_2, p_3, p_4, and p_5, respectively.

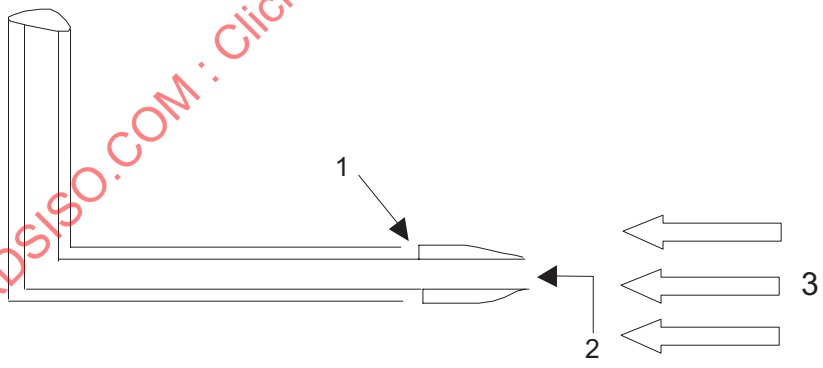
The differential pressure $p_2 - p_3$ is used to yaw null the probe and determine the yaw angle; the differential pressure $p_4 - p_5$ is a function of pitch angle; and the differential pressure $p_1 - p_2$ is a function of total velocity. A typical spherical 3D Pitot tube is shown in Figure A.4.



Key

a	p_3	static pressure	c	v	flow
b	p_2	stagnation pressure point	d	Δp	differential pressure measurement

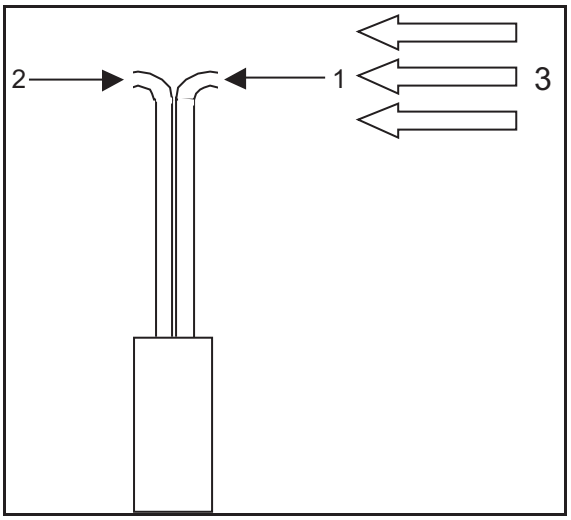
Figure A.1 — Principle of differential pressure-based velocity determination



Key

1	p_3	static pressure	3	v	flow direction
2	p_2	total or stagnation pressure			

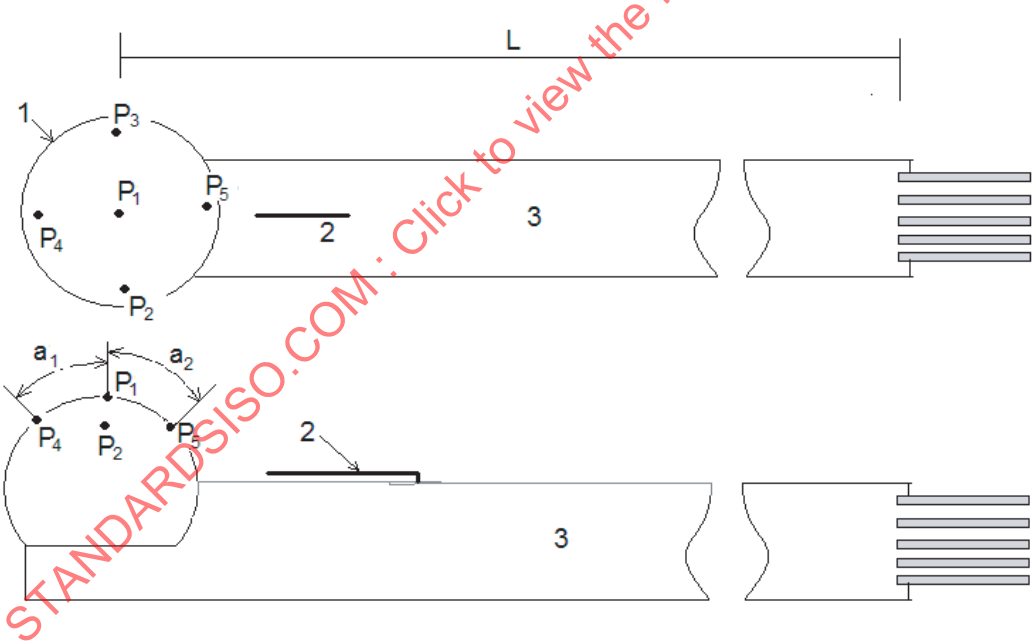
Figure A.2 — Schematic diagram of an L-type Pitot tube



Key

1	p_2	total or stagnation pressure	3	v	flow direction
2	p_3	static pressure			

Figure A.3 — Schematic diagram of an S-type Pitot tube



Key

1	sphere of diameter 38,1 mm (1,5 inch)	a_1	angle between sensing holes of 44°
2	type K thermocouple	a_2	angle between sensing holes of 44°
3	tube of diameter 19,05 mm (0,75 inch)	L_p	probe length of 1,067 m (42 inch)
		P_1 ... P_5	taps (sensing holes) at which pressures are p_1 ... p_5

Figure A.4 — 3D (spherical) Pitot tube

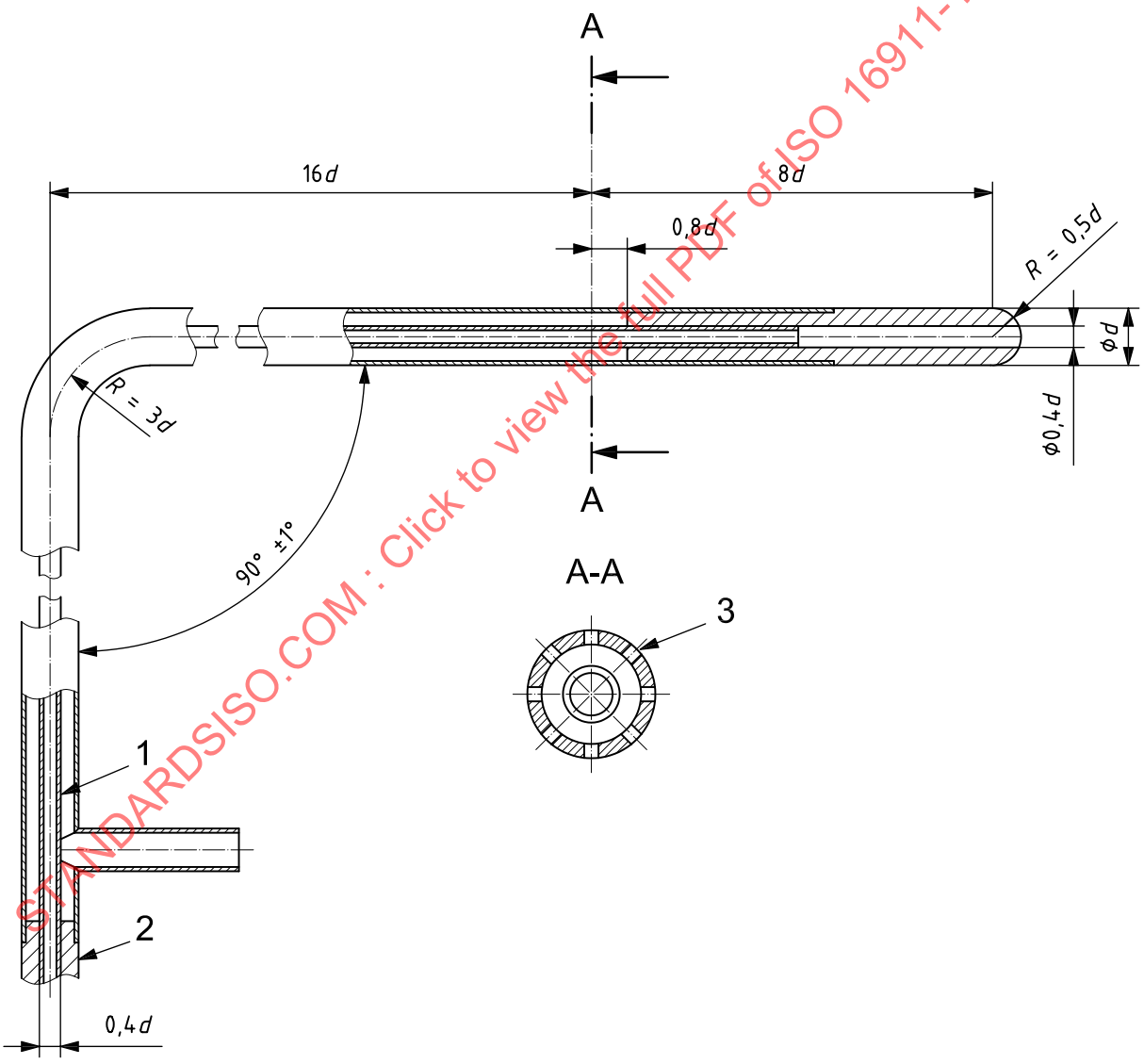
A.2.1.4 2D

A 2D probe measures the velocity pressure and the yaw angle of the flow velocity vector in a stack or duct. Alternatively, these measurements may be made by operating one of the 3D probes described in A.2.1.3, in the yaw determination mode only. From these measurements and a determination of the stack gas density, the average near-axial velocity of the stack gas is calculated. The near-axial velocity accounts for the yaw, but not the pitch, component of flow. The average gas volume flow rate in the stack or duct is then determined from the average near-axial velocity.

A.2.1.5 Examples of Pitot tube designs

A.2.1.5.1 AMCA-type

See Figure A.5.



Key

1 inner tube diameter

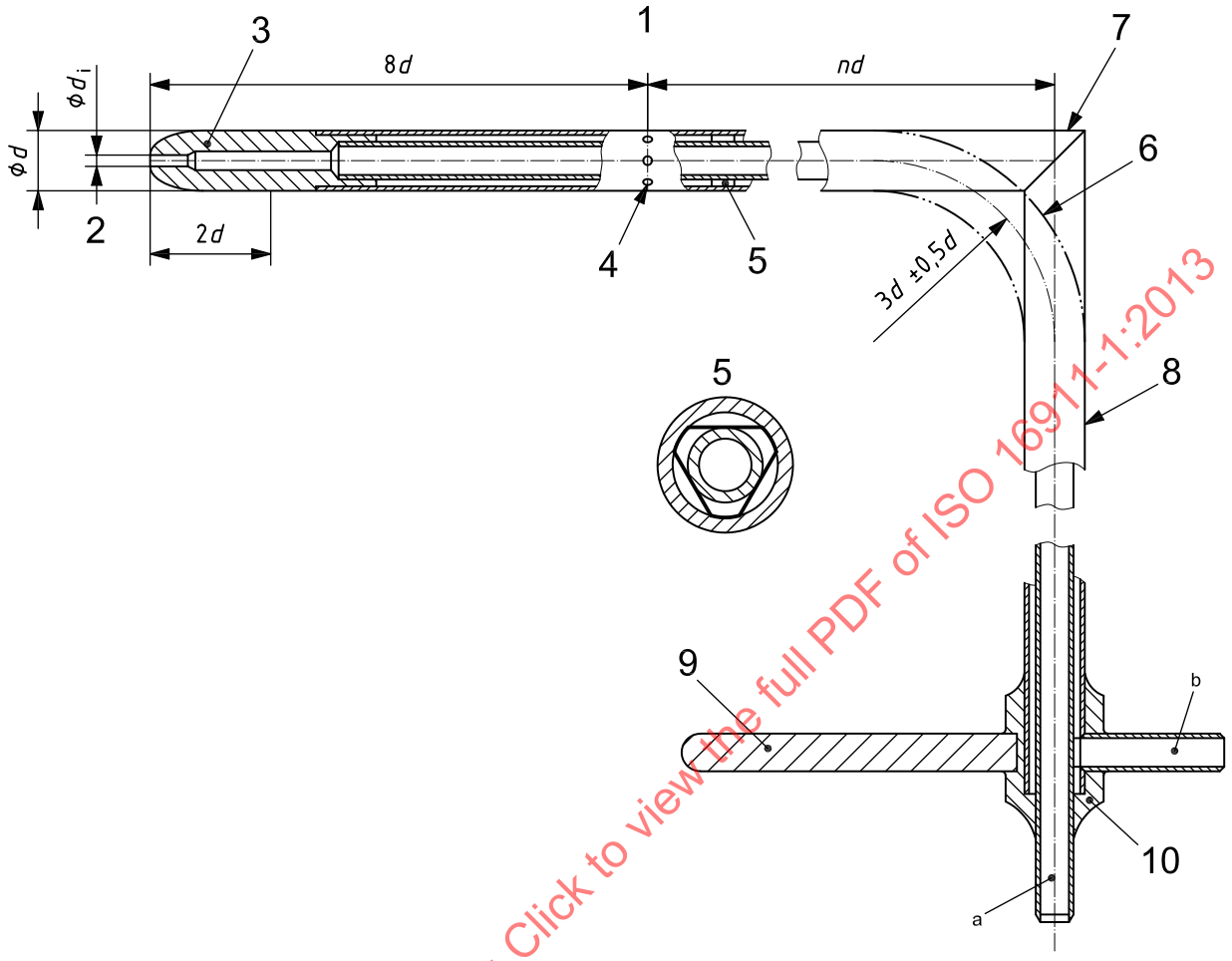
2 outer tube diameter

3 eight holes of diameter 0,13*d*, not to exceed 1 mm diameter maximum, equally distributed and free of burrs

Figure A.5 — AMCA-type Pitot tube

A.2.1.5.2 NPL-type

See Figure A.6.



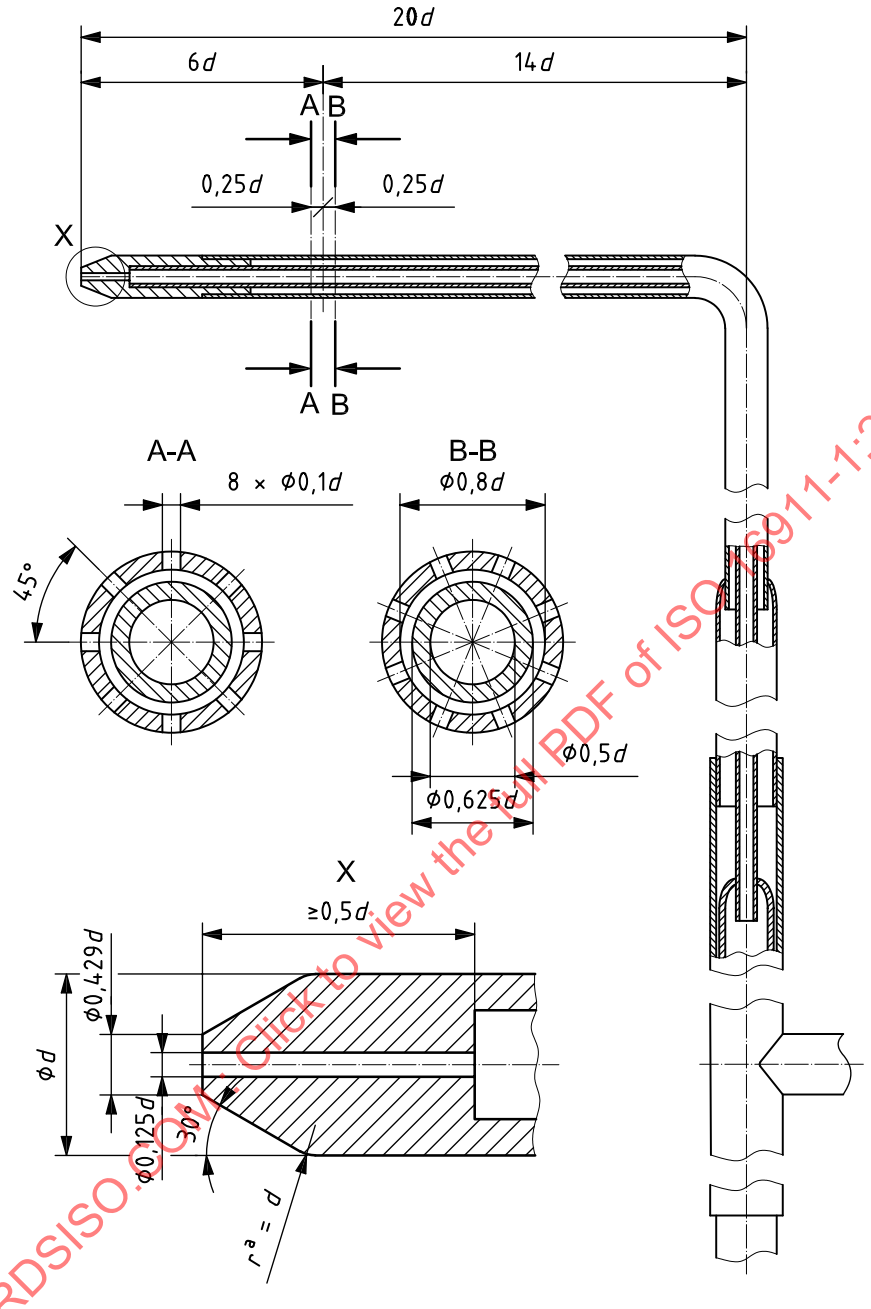
Key

1	head	6	alternative curved junction
2	total pressure hole	7	mitred junction
3	modified ellipsoidal nose	8	stem
4	static pressure holes	9	alignment arm
5	spacer	10	pressure tapping
d	outer tube diameter	a	Total pressure.
		b	Static pressure.

Figure A.6 — NPL-type Pitot tube

A.2.1.5.3 CETIAT-type

See Figure A.7.



Key

d outer diameter

[a] The radius is only useful when the Pitot tube is used in liquids in order to avoid cavitation.

NOTE Static pressure taps may be limited to those indicated on section A–A, in which case section A–A shall be placed at 6*d* from the tube tip.

Figure A.7 — CETIAT-type Pitot tube

A.2.2 Differential pressure flow measurement equipment

A.2.2.1 General

The differential pressure at representative locations across the stack is measured by inserting a probe, with a Pitot tube at the end, into the stack. The probe transfers the differential pressure between the static and stagnation pressure taps, to the differential pressure device.

The measurement of gas velocity by differential pressure at a location in the stack therefore requires:

a) differential pressure sensing head — Pitot tube, generally of S- (A.2.1.2), L-type (A.2.1.1) design or a 3D Pitot tube, e.g. of spherical (A.2.1.3) or US EPA Method 2G[16] design;

b) probe — usually integral to the Pitot head, but extension tubes may be used, provided they are fully leak checked prior to use;

c) differential pressure measuring device — either an inclined manometer or digital manometer meeting the requirements of Table A.1;

d) stack gas temperature sensor;

e) atmospheric pressure sensor.

For simultaneous measurements of the traverse and fixed point velocities, two sets of items a) to e) are required. Where only a single device is available, e.g. due to access port restrictions or duct dimensions, then measurements at the fixed point location need to be made periodically during the measurements. A flow AMS may be used to provide the fixed point readings. In addition, an accurate measurement of the stack internal diameter and wall thickness are required.

NOTE In the case of a 3D Pitot sensor, the pressures at the pressure taps are transferred in a number of tubes to three differential pressure measurement devices.

A.2.2.2 Pitot tube

The Pitot tube shall meet the performance requirements specified in Table A.1. It may be one of the designs described in this annex, or any other design meeting the performance requirements of EN ISO 16911-1. For many applications a 1D Pitot tube (e.g. S- or L-type design) may be used. Where there is significant non-axial flow or swirl, a 3D Pitot tube, e.g. spherical, can deliver smaller uncertainty values.

The probes and Pitot tube heads shall be made of material that is not affected mechanically by the temperatures within the stack.

The elements of the Pitot tube probe which remain external to the stack shall have a mechanism to identify the tube orientation within the stack and a methodology to mark the distances that the probe has been inserted into the stack. This enables the correct positioning of the sensing head within the required measurement points inside the duct.

The Pitot tube shall be calibrated at flow rates representative of the stack flow conditions, and the calibration points used 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.

If a Pitot tube (commonly an S-type) is used in a configuration with a closely coupled gas-sampling probe, then the device shall be calibrated in this configuration.

The use of standard Pitot calibration factors and performance based purely on Pitot tube design criteria is not allowed within EN ISO 16911-1. Devices shall be calibrated and have been subject to suitable performance evaluation.

Any other flow conditions affecting the differential pressure (e.g. turbulence in the case of S-type tubes) shall be properly taken into account in calibration.

NOTE The calibration requirement can be fulfilled by a corresponding traceable certificate prepared by the manufacturer according to EN ISO 16911-1. If no mechanical damage of the tube occurs, a repeated calibration is not necessary.

A.2.2.3 Differential pressure measurement device

The measurement of the differential pressure between the pressure taps of the Pitot sensor is made using a differential pressure meter; this may either be an inclined manometer or an electronic differential-pressure gauge.

A correction for ambient temperature is required for an inclined manometer.

The differential pressure gauge shall be calibrated in a range appropriate for the application. The calibration shall be metrologically traceable to SI.

The upper limit of the calibration range of the device shall not exceed three times the maximum differential pressure that it is required to measure.

A damping device may be required if the stack conditions cause oscillations in the readout of the differential pressure which make it impossible to achieve the required uncertainty in the pressure reading. Damping is required if the magnitude of the fluctuations in the differential pressure reading (peak-to-peak) are >10 % of the mean reading at the measurement location. The damping device may consist of a damping pot or a capillary tube installed in a liquid manometer, or other device provided or recommended by the manufacturer. The damping device shall have been demonstrated not to cause a systematic effect on the differential pressure reading.

NOTE ISO 3966:2008,[3] Annex D, describes a methodology for damping a liquid manometer system using a capillary tube.

The frequency of calibration of the differential pressure gauge depends on its use. The user may demonstrate that the calibration function of differential pressure gauge is still valid by periodic checks of the differential pressure gauge.

A.2.2.4 Measurements of stack gas conditions

The calculation of stack gas velocity from the differential pressure measurements made with a Pitot tube requires knowledge of the stack gas density, which is determined from the temperature, static pressure and gas molar mass.

In order to refer the measured flow to standard conditions (see 10.6) measurements of the following parameters of the stack gas are required:

— temperature;

— water vapour;

— where necessary, measurements of the oxygen or CO_2 content.

These data may be obtained from calibrated automated monitoring instruments installed on the stack.

A temperature sensor shall be used to measure the stack gas temperature at the Pitot measurement location. This sensor shall be calibrated and shall be able to meet the performance requirements given in Table A.1.

The measurement of oxygen concentration within the stack gas shall be made in accordance with EN 14789.

The measurement of water vapour within the stack gas shall be made in accordance with EN 14790.

In the case of dry air (<1 % humidity) the molar mass may be assumed to be 29 kg/kmol.

Table A.1 — Performance requirements for differential pressure-based flow measurement

Parameter	Criterion	Method of determination
Minimum differential pressure	5 Pa	Performance evaluation of differential pressure-reading device
Calibration uncertainty of the measurement device for temperature which contains the temperature sensor and the indicator	≤1 % of value	Performance evaluation for temperature sensor from thermocouple standards
Calibration uncertainty of the differential pressure sensor used for the measurement of the dynamic pressure and of the static pressure	≤1 % of value or 20 Pa whichever is greater	Performance evaluation of differential pressure reading device

A.3 Calculation

A.3.1 Determination of velocity using differential pressure devices

The principle of the determination the velocity of a gas at a point of the measurement section, by means of a Pitot tube, consists of measuring the dynamic pressure at this point with a Pitot tube associated with a manometer. The local velocity at measurement point i, v_i, in m/s, is then calculated according to Formula (A.1):

$$v_i = K\sqrt{\frac{2\overline{\Delta p_i}}{\rho}} \tag{A.1}$$

where

$\overline{\Delta p_i}$ is the average dynamic pressure measured at the point i of the measurement section, in Pa;

K is the coefficient of the Pitot tube which includes the Pitot calibration factor and constant values relating to Pitot design;

ρ is the density of the gas effluent under the conditions of temperature and pressure of wet gas, in kg/m^3.

The average dynamic pressure $\overline{\Delta p_i}$ is equal to the arithmetic mean of the n measurements of dynamic pressure carried out at each point i:

$$\overline{\Delta p_i} = \frac{1}{n}\sum_{i=1}^{n}\Delta p_i \tag{A.2}$$

Direct determination of $\overline{\Delta p_i}$ is possible using a suitable digital manometer which provides an average reading of dynamic pressure over the required averaging period.

Formulae (A.3) to (A.10) are used to calculate the velocity, the yaw, the pitch and the gas volume flow rate with 3D US EPA Method 2F.[15]

$$F_1(i) = \frac{(p_1 - p_2)_i}{(p_4 - p_5)_i} \tag{A.3}$$

$$F_2(i) = Cp\sqrt{\frac{\Delta p_{\text{std}}}{(p_1 - p_2)_i}} \tag{A.4}$$

$$M_s = M_d(1 - \varphi_{ws}) + 18\varphi_{ws} \tag{A.5}$$

$$p_s = p_{atm} + \frac{p_g}{13.6} \tag{A.6}$$

$$T_{s(i)}\,R = 460 + T_{s(i)}\,°F \tag{A.7}$$

$$v_{a(i)} = K_p F_2(i) \sqrt{\frac{(p_1 - p_2)_i\, T_{s(i)}}{p_s M_s}} \left[\cos\Theta_{y(i)}\right]\left[\cos\Theta_{p(i)}\right] \tag{A.8}$$

$$q_{V,sw} = 3{,}600 v_{a(avg)} A_s \left[\frac{T_{std}}{T_{s(avg)}}\right]\left(\frac{p_s}{p_{std}}\right) \tag{A.9}$$

$$q_{V,sd} = q_{V,sw}(1 - \varphi_{ws}) \tag{A.10}$$

where

A_s cross-sectional area of stack, in ft2;

φ_{ws} water vapour proportion by volume;

K_p conversion factor, 85.49 ft/s[(lb/lb-mol)(inHg)/(R)/(in$H_2$0)]$^{0.5}$;

M_d molar mass of gas, dry basis, in lb-lb/mol;

M_s molar mass of gas, wet basis, in lb-lb/mol;

p_{atm} atmospheric pressure, in inHg;

p_g static pressure, in inH_2O;

p_s stack absolute pressure, inHg;

p_{std} Standard absolute pressure, 29.92 inHg;

$q_{V,sd}$ Average dry-basis volumetric stack gas flow rate corrected to standard conditions, in dscf/h;

$q_{V,sw}$ Average wet-basis stack gas volume flow rate corrected to standard conditions, in wscf/h;

$T_{s(avg)}$ Average absolute stack gas temperature across stack, in R;

$T_{s(i)}$ °F Stack gas temperature at traverse point i, in °F;

$T_{s(i)}$ R absolute stack gas temperature, in R;

T_{std} Standard absolute temperature, 528 R;

$F_1(i)$ pitch angle ratio at traverse point *i*, dimensionless;

$F_2(i)$ 3D probe velocity calibration coefficient at traverse point *i*, dimensionless;

$(p_1 - p_2)_i$ velocity differential pressure at traverse point *i*, in inH_2O;

$(p_4 - p_5)_i$ pitch differential pressure at traverse point *i*, in inH_2O.

A.3.2 Density of the stack gas

In the duct, the density of the gas effluent under ambient conditions of temperature and pressure, ρ, in kg/m^3, is given by

$$\rho = \frac{M p_c}{R T_c} \tag{A.11}$$

where

M is the molar mass of wet gas effluent, in kg/mol;

p_c is the absolute pressure in the duct in the measurement section, in Pa;

R is the gas constant, i.e. 8,314 J/(K mol);

T_c is the gas temperature in the duct, in K.

A.3.3 Absolute pressure of gas

The absolute pressure in the duct is given by the measurement of the atmospheric pressure on the site and the static pressure measured in the duct. The static pressure shall be measured in at least one point of each measurement line.

To improve quality of measurement, it is recommended that several instantaneous measurements of the static pressure be made to take into account the variability of the pressure and the repeatability of measuring.

The static pressure, which is used in the calculation of the absolute pressure, is the arithmetic mean of the average static pressures recorded on each measurement line (two diameters in the case of a circular duct) therefore the arithmetic mean of the whole of the recorded values of static pressure.

$$p_c = p_{atm} + \overline{p_{stat}} \tag{A.12}$$

where

p_c is the absolute pressure in the duct in the measurement section, in Pa;

p_{atm} is the atmospheric pressure, in Pa;

$\overline{p_{stat}}$ is the average static pressure in the measurement section, in Pa.

The average static pressure is equal to the arithmetic mean of the average static pressures measured at each point (at least one per measurement line), in Pa

$$\overline{p_{stat}} = \frac{1}{n_1} \sum_{i_1=1}^{n_1} \overline{p_{stat,i_1}} \tag{A.13}$$

where

$$\overline{P_{stat,i_1}} = \frac{1}{n_2} \sum_{i_2=1}^{n_2} p_{stat,i_1,i_2} \tag{A.14}$$

where

p_{stat,i_1,i_2} , $i_2 = 1 \ldots n_2$ is the i_2th measurement of static pressure at the point i_1, in Pa;

$\overline{p_{stat,i_1}}$, $i_1 = 1 \ldots n_1$ is the mean static pressure at the point i_1, in Pa — n_1 is at least equal to the number of measurement lines explored in the measurement section

A.3.4 Molar mass of gas

The molar mass of wet gas effluent under the conditions of pressure and temperature of the duct, M, in kg/mol, is given by Formula (A.15):

$$M = 10^{-3} \times \sum_{B=1}^{q} \left(M_B \varphi_B \right) \quad \text{(A.15)}$$

where

M_B is the molar mass of component B, in kg/mol, for component number $B = 1 \ldots q$;

φ_B is the volume fraction of component B, for component number $B = 1 \ldots q$.

The molar mass of gas is given, in general, with a good approximation starting from measurements of the contents of O_2, CO_2, and water vapour, by applying Formula (A.15).

The bias introduced by this approximation of the density is variable according to the nature and concentrations of the components not taken into account

$$M = 10^{-5} \times \left[32\varphi_{O_2,w} + 44\varphi_{CO_2,w} + 18\varphi_{H_2O} + 28 \times \left(100 - \varphi_{O_2,w} - \varphi_{CO_2,w} - \varphi_{H_2O} \right) \right] \quad \text{(A.16)}$$

where

M is the molar mass of wet gas stream in kg/mol;

$\varphi_{O_2,w}$ is the concentration of O_2 in the gas stream, expressed as a percentage volume fraction, in wet gas;

$\varphi_{CO_2,w}$ is the concentration of CO_2 in the gas stream, expressed as a percentage volume fraction, in wet gas;

φ_{H_2O} is the concentration of water vapour in the gas stream, expressed as a percentage volume fraction, in wet gas;

$\left(100 - \varphi_{O_2,w} - \varphi_{CO_2,w} - \varphi_{H_2O} \right)$ corresponds to the nitrogen content, assuming that the components other than O_2, CO_2 and water vapour, expressed as percentage volume fractions in wet gas, are insignificant.

This assumption holds true for most combustion sources.

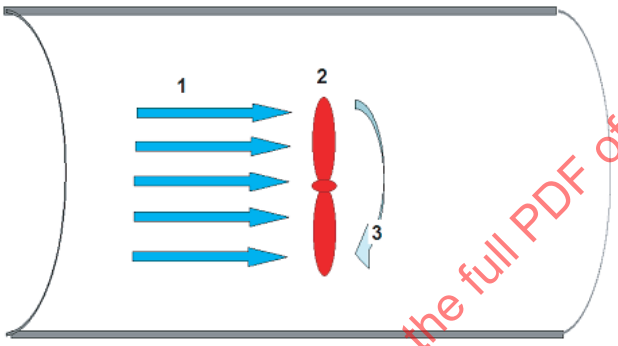
Annex B
(normative)

Vane anemometer

B.1 Principle of vane anemometer

The measuring principle of the vane anemometer depends on the proportionality of the rotating velocity to the flow velocity v_∞ of the fluid into which it is inserted.

The simplified principle of a vane anemometer is shown in Figure B.1.



Key

1	v_∞	m/s	flow velocity
2			vane
3	f	s^{-1}	number of revolutions per time

Figure B.1 — Vane anemometer

Assuming no friction and a massless vane wheel, the resulting characteristic is purely geometric.

Given input variables are:

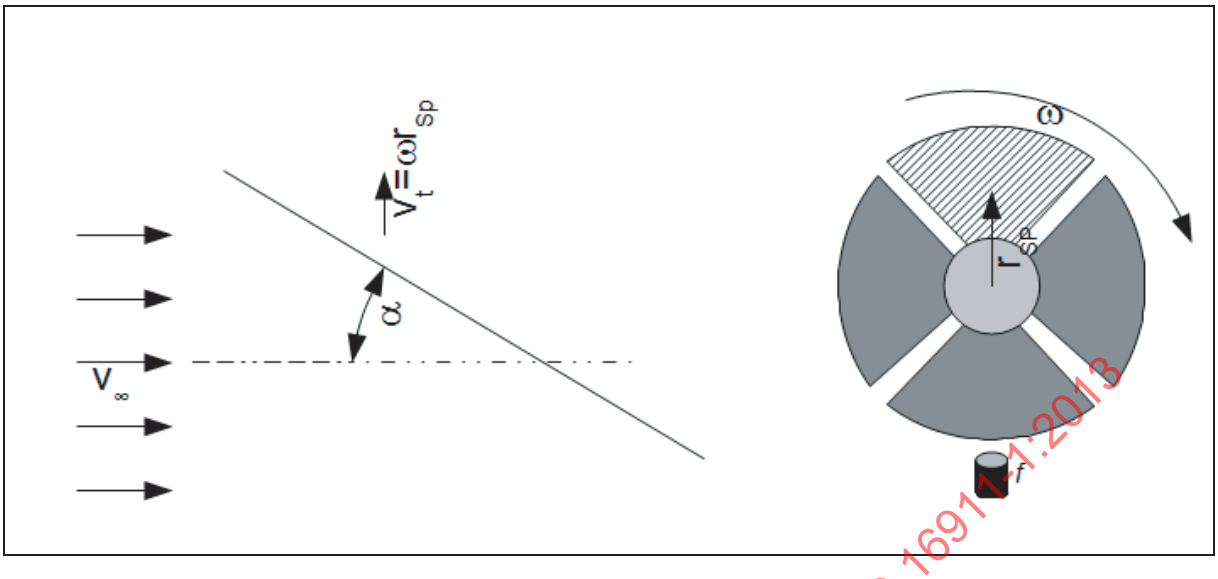
a) approach velocity v_∞ in axial direction;

b) frequency of the characteristic, f;

c) geometry of the vane wheel or a vane wheel blade with its centre in spherical coordinates, r_{Sp};

d) number of blades e.g. $n_F = 4$.

Pulsatance, $\varpi = 2\pi(f/n_F)$, and peripheral velocity, $v_t = \varpi r_{Sp}$, are also used for the calculation. See Figure B.2.



Key

v_∞ flow velocity

α pitch of blade

f scan frequency

ω angular frequency

r_{Sp} geometry of the vane wheel

v_t peripheral velocity

Figure B.2 — Vane anemometer principle

The correct value for the r_{Sp} of the blade is of particular importance. Given that the acting compressive force can be determined as a constant acting force over the total area, this can be replaced by an acting single force in the centre of the blade, ruled area.

The vane wheel is activated via an inductive proximity switch. With the introduction of a second inductive switch, the rotational direction can be measured and the direction of flow determined. This type of angular frequency measurement has no braking effect on the vane wheel. Contamination has no impact on the pulse recognition. Due to the low mass of the vane wheel, depending on type in the 10th of gram range, it adjusts its angular frequency in the millisecond range to the velocity variations.

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.

Performance requirements for vane anemometers are given in Table B.1.

Table B.1 — Performance requirements for vane anemometers

Parameter	Criterion	Method of determination
Minimum velocity	0,2 m/s to 0,5 m/s	Depending on gas and vane specifications
Influence of particles	Process media shall be fibre-free at all times. Clean gas particulate matter concentrations (up to 50 mg/m^3) have no influence	
Temperature influence	No influence in the specified range	Applications at temperatures for which short-term operation is specified, should only last a matter of minutes, thus avoiding damage to the sensor.
Influence of humidity	No influence of humidity, droplets have to be avoided	
Uncertainty of meaurement of flow velocity, $u(v)$	0,01 m/s to 0,02 m/s ± 0,02 m/s to 0,08 m/s	Depending on vane type
Absolute error of measurement (reproducibility of output quantities) e_p	0,01 m/s to 0,02 m/s	Depending on vane type
Uncertainty of measurement of the scan frequency,[a] $k\,u(f)$	±0,02 m/s to ±0,08 m/s	Depending on vane type
[a] $k = 2$ for tested Höntzsch-type vane anemometers.		

B.2 Calculation

B.2.1 Background

The characteristic axial velocity in the frictionless case, v_∞, can be calculated using Formula (B.1):

$$v_\infty = \frac{v_t}{\tan\alpha} = \frac{\varpi r_{Sp}}{\tan\alpha} \tag{B.1}$$

where

v_t is the peripheral velocity, $v_t = \varpi r_{Sp}$;

α is the pitch of blade;

r_{Sp} is the geometry of the vane wheel.

B.2.2 Lowest range limit

However, in practice, friction and mass play a significant role. As a result, the lowest range limit is a minimum velocity, the so-called start-up velocity, v_0, to overcome friction in the bearings and inertia of the vane wheel. Below this, the measurement fails.

Furthermore, the basic Formula (B.1) can be expanded to

$$v_{\infty} = K\left(\rho_0, \eta_{\mathrm{dyn}}\right)\frac{v_{\mathrm{t}}}{\tan\alpha} + v_0 \tag{B.2}$$

where a non-linear calibration factor $K\left(\rho_0, \eta_{\mathrm{dyn}}\right)$ is introduced, which depends on density, ρ_0, and dynamic viscosity, η_{dyn}.

B.2.3 Highest range limit

The upper limit for measuring flow velocity with a vane wheel is specified by the manufacturer and based on the demand for a defined lifetime of the sensor in respect of increasing mechanical stress caused by increasing velocity, the capacity of the manufacturer's calibration facilities and the signal output unit of the vane wheel sensor.

The rotation of a vane wheel is, according to B.2.2, only dependent on the density and viscosity of the medium. Ambient pressure, temperature, humidity or possible dust particles only have an influence on the characteristic axial velocity when density or viscosity alter significantly and play a significant role only in durability, i.e. susceptibility to wear.

Relevant for the force acting on the vane wheel, F, and the resultant peripheral velocity v_{t} is the dynamic pressure on the vane wheel, p_{dyn}:

$$F \approx p_{\mathrm{dyn}} = \frac{\rho}{2} v_{\infty}^2 = c \tag{B.3}$$

where

ρ is the density;

v_{∞} is the axial velocity;

c is a constant.

If, when measuring in air or gases, the actual density ρ_1 deviates from the density during calibration ρ_0, then values displayed from the vane wheel $v_{\infty,0}$ when measuring in gases with medium density ρ_1 equate to an actual velocity

$$v_{\infty,1} = v_{\infty,0} - \Delta v_{0-1} \tag{B.4}$$

where

$v_{\infty,1}$ axial velocity;

$v_{\infty,0}$ measured value of axial velocity at vane;

Δv_{0-1} adjustment of characteristic curve:

$$\Delta v_{0-1} = v_{0,0} - v_{0,1} = v_{0,0}\left(1 - \sqrt{\frac{\rho_0}{\rho_1}}\right) \tag{B.5}$$

where

$v_{0,0}$ specified value of start of range;

$v_{0,1}$ real start of range;

ρ_0 specified density;

ρ_1 real density.

This means that the characteristic (B.2) is offset by the difference of the start-up velocity.

B.3 Calculation of the uncertainty and calibrations

The uncertainty is affected by the precision of the measurement of the angular frequency (and thus of the scan frequency) and by the reproducibility of the output quantities.

For a vane anemometer with four blades, the precision is (ω/4) ± 1 impulse, where ω is angular frequency.

The uncertainty of measurement of flow velocity, $u(v)$, of a vane anemometer results from the absolute error of measurement (reproducibility of output quantities), e_P, and the uncertainty of the measurement of the scan frequency, $u(f)$, in hertz:

$$u(f) = (f+1)\frac{(v_{max} - v_{min})}{f_{max}} + v_{min} - (f-1)\frac{(v_{max} - v_{min})}{f_{max}} - v_{min} \tag{B.6}$$

or

$$u(f) = 2 \times \frac{(v_{max} - v_{min})}{f_{max}} \tag{B.7}$$

where

f is the scan frequency;

v_{max} is the maximum speed of the vane type;

v_{min} is the minimal speed of the vane type (start velocity);

f_{max} is the maximum frequency of the vane type;

e_P is between 0,01 and 0,02 m/s, for the vane anemometers tested.

NOTE The value of e_P depends on the design of the vane. It can be estimated, for example, according to DIN 1319-3.[20] The manufacturer is required to provide the value.

In sum, the uncertainty of flow measurement is

$$u(v) = u(f) \pm e_P \tag{B.8}$$

B.3.1 Example

Minimum velocity, v_{min} = 0,5 m/s

Maximum velocity, v_{max} = 40 m/s

e_p = 0,02 m/s

Diameter of vane, $2r_{Sp}$ = 22,8 mm

Ratio (f/v) = 29,25

Maximum frequency of vane, f_{max} = 1 770 Hz

$$u(f) = 2 \times \frac{(v_{max} - v_{min})}{f_{max}} = 2 \times \frac{(40 - 0{,}5)}{1\,770} = 0{,}04 \quad \text{(B.9)}$$

$$u(v) = u(f) \pm e_p = 0{,}02 \pm 0{,}04 \quad \text{(B.10)}$$

Linear regression data for manual methods from laboratory test data

Method:	**Technique**	**Slope**	**Intercept**, m/s
Vane anemometer, vane 1	Vane anemometer	0,975	0,227
Vane anemometer, vane 1	Vane anemometer	0,992	0,226

Uncertainty analysis according to ISO 20988 for manual method in laboratory assessment:

Technique:	**Bias**	**Bias criteria**	**uncertainty**	**Expanded uncertainty**	**Cover factor**
Vane anemometer	0,000 4	0,236	0,021	0,042	2

Lack of fit determined from laboratory test:

Technique:	**Lack of fit of testing range of** 25 m/s, %	**Criteria** (EN 15267-3[11]), %
Vane 1	1,05	3
Vane 2	0,38	3

Annex C
(normative)

Tracer gas dilution method determination of volume flow rate and average velocity

C.1 Tracer gas by dilution

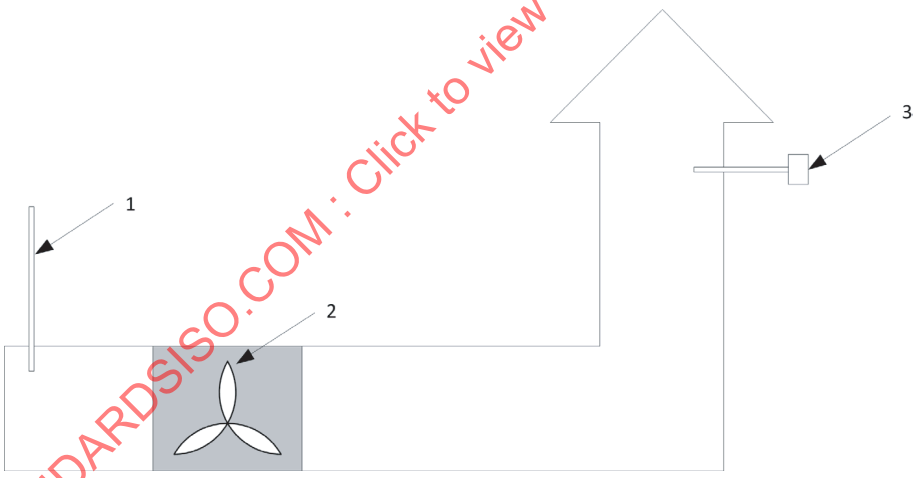
C.1.1 Principle of the use of tracer gas injection

Tracer gas injection is used to measure the volume flow rate in a duct. A tracer gas that is not usually present in the flue gas is injected at a known constant rate (Figure C.1, label 1). The tracer gas is mixed over the cross-section of duct, mixing is enhanced by obstructions such as fans or bends, which create extra turbulence (Figure C.1, label 2). The diluted tracer gas is measured downstream of the injection point to give the volume flow rate (Figure C.1, label 3), provided that:

— the tracer gas is well mixed in the stack gas;

— there is no loss of tracer gas from adsorption on to duct walls or removal from plant abatement;

— there is no tracer gas present in the stack gas prior to injection or the background concentration can be measured accurately.



Key

1 tracer injection lance
2 process fan
3 tracer sampling and analysis

Figure C.1 — Tracer gas dilution principle

C.1.2 Tracer gas injection

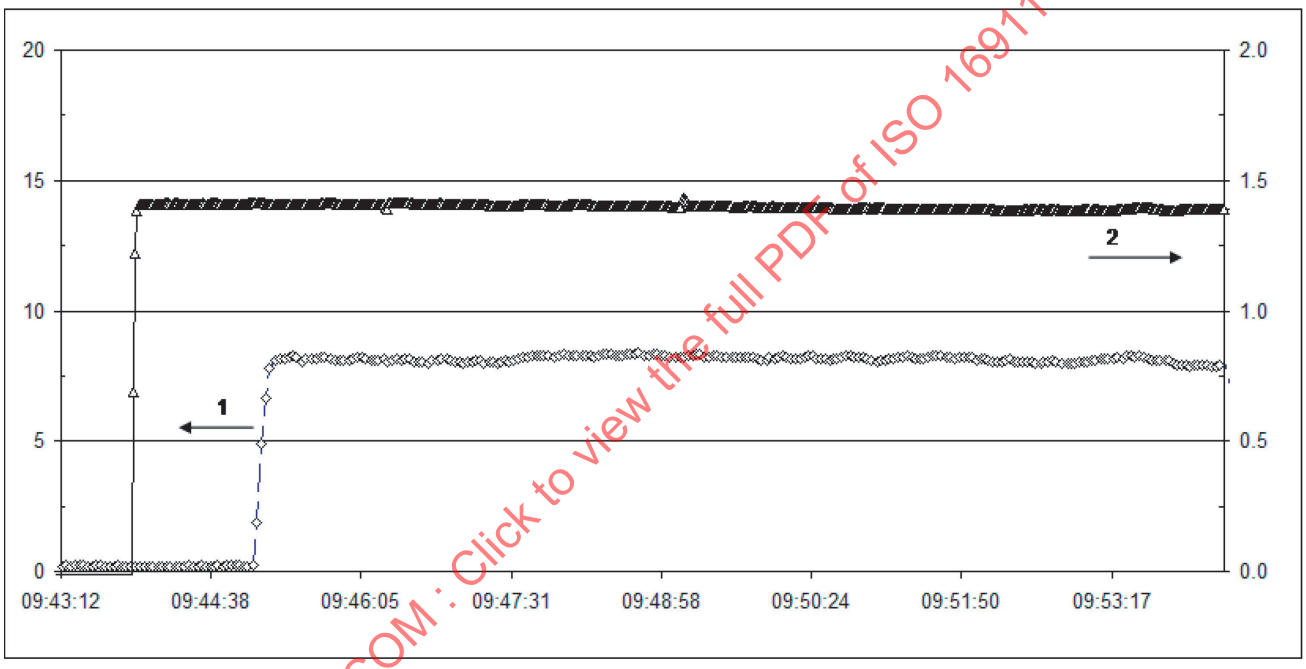
A controlled injection of the tracer gas is required. The tracer injection flow rate is calibrated to traceable standards.

Select an upstream location for introducing the tracer gas into the stack duct flow in order to promote mixing of the tracer with the duct flow. As a guideline, the injection point(s) should ideally be located

at least $10d_s$, where d_s is stack diameter, upstream of the tracer concentration measurement location. If possible, the tracer injection should be upstream of a source of mixing such as a fan or bends in the duct. The tracer injection shall be downstream of any process operation that may affect the tracer concentration.

For a given injection arrangement, it shall be demonstrated that there is no significant stratification of the tracer gas at the downstream location by means of a one off multi-point duct survey conducted according to EN 15259. There should ideally be no additional flow inputs between the injection and the measurement locations, and no leaks from the duct. However, in-leakage that is fully mixed prior to the concentration measurement (as confirmed by the duct survey), or out-leakage that takes place after the tracer is fully mixed, would not cause a measurement error.

The duration of the injection shall be at least $4t_r$, where t_r is the response time of the tracer gas analyser used for the measurement of the tracer gas, to ensure that a meaningful stable concentration response can be obtained. See Figure C.2 for example.



Key

1	$\varphi \times 10^6$	volume fraction	tracer concentration
2	q_V	kg/h	injection flow rate

Figure C.2 — Typical tracer gas response

Injection may be accomplished using a single lance or by multiple lances connected to a manifold off the tracer flow meter. Flow through each lance should be approximately equal and each lance may have either a single or multiple release points. The injection system shall be leaktight.

C.1.3 Tracer gas concentration measurement

The tracer gas measurement equipment consists of a gas monitor (the analyser used for the measurement of the tracer gas) and suitable sampling equipment. The sampling system shall not react with or otherwise alter the concentration of the tracer gas. The tracer analyser shall not be significantly affected by other components in the stack gas. The tracer gas analyser shall be calibrated at a suitable frequency to ensure acceptable drift across the test period.

The tracer gas concentration shall have a traceable calibration. The choice of tracer gas should include consideration of the components of the stack gas, both in terms of the tracer gas itself and any interferents to the measurement of the tracer gas. The selection of the tracer gas is also influenced by the availability

of measurement equipment able to measure it with a sufficient level of certainty. The release of the tracer gas shall also have negligible environmental impact.

The tracer gas concentration may be measured either on a dry basis, following removal of water vapour from the sample to a dew point less than 5 °C, or on a wet basis using a heated sample and analysis train. This needs to be accounted for when calculating the stack flow rate. The stack flow rate is determined under the same conditions that the measurement is made, i.e. if the tracer is measured on a dry basis the flow determined is also on a dry basis.

The sample probe may be single or multi-hole, provided that there is no significant stratification of the tracer at the measurement location. Multi-hole is preferred since this compensates for residual stratification.

C.1.4 Tracer gas calibration equipment

C.1.4.1 Tracer gas injection

A controlled injection of the tracer gas is required. The injection flow rate shall be determined using a mass or volume flow rate meter with a traceable calibration. The expanded uncertainty of the tracer flow rate measurement shall be ≤1 % of value based on the calibration relationship and taking into account any relevant influencing parameters such as ambient temperature. The tracer injection line shall be leak tested in the field, from the flow meter inlet to the injection lance.

C.1.4.2 Tracer gas concentration measurement

The tracer gas measurement equipment consists of a gas concentration analyser and suitable sampling equipment. The sampling system shall not react with or otherwise alter the concentration of the tracer gas. The tracer gas analyser shall not be affected by other components in the stack gas. The tracer gas analyser shall be calibrated before each flow measurement.

Following the flow rate measurement, the tracer analyser shall be checked using calibration gas at the span value, in order to correct for allowable drift. Table C.1 gives the performance requirements of the tracer gas analyser.

Table C.1 — Tracer gas concentration measurement performance requirements

Parameter	Criterion	Method of determination
Calibration gas concentration	≤1 % of value	Traceable calibration gas standard (standard uncertainty)
Linearity	≤1,5 % relative to the calibration gas concentration	Laboratory evaluation according to EN 14181[9] using traceable calibration gases or a calibrated dilution system. The five levels are 0, 25 %, 50 %, 75 % and 100 % of the calibration gas volume fraction
Repeatability	≤1 % of calibration gas concentration	Laboratory evaluation using calibration gas (standard deviation)
Interference	≤2 % of calibration gas concentration	Cross-interferences of stack gas components determined from instrument certification or laboratory evaluation according to EN 15267-3[11]
Leak or sample loss	≤2 % of calibration gas concentration	Field evaluation — passing calibration gas through sampling system
Drift	≤2 % of calibration gas concentration	Field evaluation by periodic calibration gas check. Correct drift if >2 % and declare invalid if >5 %

C.1.4.3 Calculation of stack gas flow rate from tracer injection results

$$q_{V,0,O_2} = \frac{q_{m,t}}{\rho_{t,0}} \frac{1}{\varphi_t} \quad \text{(C.1)}$$

where

$q_{V,0,O_2}$ stack gas flow rate at sample O_2 content and moisture under standard conditions, in m^3/s;

$q_{m,t}$ tracer mass flow rate, in kg/s;

$\rho_{t,0}$ tracer density under standard conditions, in kg/m^3;

φ_t tracer volume fraction at sample O_2 content and moisture content.

C.2 Uncertainty of the calibration result

C.2.1 General

The uncertainty of the derived stack flow rate is simply the combined uncertainty of the injection mass flow rate, $q_{m,t}$, and the tracer volume fraction, φ_t. The uncertainty of the tracer volume fraction shall include the uncertainty related to the mixing quality of the tracer within the stack gas.

C.2.2 Uncertainty of concentration measurement

The performance characteristics considered in the uncertainty analysis are dependent upon the technology employed for the tracer concentration measurement.

The common contributions are: calibration gas uncertainty, u_{cal}, and ambient temperature effects, u_{temp}, both assigned a rectangular probability distribution to give the absolute standard uncertainty as follows:

$$u_{cal} = \frac{(\%\, x_{cal}/100)\, x_{cal}}{\sqrt{3}}$$

where x_{cal} is the calibration value.

For a temperature range, T_{min} to T_{max}, and a baseline calibration temperature of, T_{cal}, in K:

$$u_{temp} = \left(\frac{\%\, T_{max} - T_{min}}{100} \right) (T_{max} - T_{min}) \sqrt{\frac{(T_{max} - T_{cal})^2 + (T_{max} - T_{cal})(T_{min} - T_{cal}) + (T_{min} - T_{cal})^2}{3}}$$

Other performance characteristics can be included in this analysis, e.g. linearity and cross-interference, if these are significant. Linearity errors can be minimized by selecting a calibration value that is close to the expected tracer concentration value.

C.2.3 Uncertainty of tracer gas mixing

The standard uncertainty due to imperfect mixing of the tracer gas is calculated from an EN 15259 tracer concentration survey conducted when injecting the tracer at a constant flow rate.

The standard relative uncertainty, u_{mix}, is the coefficient of variation of the measured grid values:

$$u_{\text{mix}} = \frac{s_{\text{grid}}}{\bar{\varphi}_{\text{grid}}}$$

A more accurate assessment can be obtained by correcting for temporal variations in the process (determined from the fixed reference measurement required under EN 15259). Temporal variations can be accounted for by first normalizing each grid concentration measurement using the normalization factor, f_{n}:

$$f_{\text{n}} = \frac{\bar{\varphi}_{\text{ref}}}{\varphi_{\text{ref},i}}$$

where

$\varphi_{\text{ref},i}$ is the reference volume fraction (fixed location) corresponding to the sampling periods at each grid point;

$\bar{\varphi}_{\text{ref}}$ is the mean reference volume fraction from all of the sampling periods.

A velocity measuring instrument can be used as the reference if a second tracer gas analyser is not available. In this case, since the tracer volume fraction is inversely proportional to the flow, the normalization factor is inverted:

$$\frac{v_{\text{ref},i}}{\bar{v}_{\text{ref}}}$$

Following normalization, the relative uncertainty is calculated as before using the normalized volume fractions:

$$u_{\text{mix}} = \frac{s_{\text{n,grid}}}{\bar{\varphi}_{\text{n,grid}}}$$

The standard uncertainty due to mixing is then combined with other standard uncertainties for the volume fraction measurement to give the overall standard uncertainty of the volume fraction measurement:

$$u_{\varphi_{\text{t}}} = \sqrt{u_{\text{cal}}^2 + u_{\text{temp}}^2 + u_{\text{mix}}^2 \ldots}$$

C.2.4 Uncertainty of tracer injection rate

The performance characteristics considered in the uncertainty analysis are dependent upon the technology employed for the flow measurement which shall have a traceable calibration. Common contributions are considered below.

The uncertainty contribution from the calibration of the instrument is based on the average error declared on the calibration certificate, assigned a rectangular probability distribution in this example:

$$u_{\text{cal}} = \frac{\left(\%\, x_{\text{range}} / 100\right) x_{\text{range}}}{\sqrt{3}}$$

where x_{range} is the range.

The uncertainty contribution due to temperature variation of the tracer gas passing through the mass flow meter is also assigned a rectangular probability distribution:

$$u_{\text{temp}} = \left(\frac{\%\, T_{\max} - T_{\min}}{100} \right) \left(T_{\max} - T_{\min} \right) \sqrt{\frac{\left(T_{\max} - T_{\text{cal}} \right)^2 + \left(T_{\max} - T_{\text{cal}} \right)\left(T_{\min} - T_{\text{cal}} \right) + \left(T_{\min} - T_{\text{cal}} \right)^2}{3}}$$

where $T_{\max}$ and $T_{\min}$ are the maximum and minimum gas temperatures and T_{cal} the temperature at calibration.

The uncertainty of the combined sensor and transducer includes the uncertainty related to linearity and repeatability.

$$u_{\text{comb}} = \frac{\left(\%\, x_{\text{value}} / 100 \right) x_{\text{value}}}{\sqrt{3}}$$

where x_{value} is the value.

The combined mass flow rate uncertainty, $u_{q_{m,\text{t}}}$, is the sum of the squares of the standard uncertainties.

$$u_{q_{m,\text{t}}} = \sqrt{u_{\text{cal}}^2 + u_{\text{temp}}^2 + u_{\text{comb}}^2 \ldots}$$

C.2.5 Uncertainty of stack flow rate

The standard uncertainty of the stack volume flow rate measurement is based on the combined uncertainty of the measured tracer volume fraction, u_{φ_t}, and the mass flow rate, $u_{q_{m,\text{t}}}$. In general, a sensitivity coefficient, C_{sens}, is applied to each uncertainty and this can be obtained from the partial derivatives with respect to the parameter under consideration, e.g.

$$C_{\text{sens},q_{m,\text{t}}} = \frac{\partial q_V}{\partial q_{m,\text{t}}}$$

The overall standard uncertainty is then the sum of the squares of each uncertainty contribution multiplied by its sensitivity coefficient:

$$u_{q_V}^2 = \left(\frac{q_V}{q_{m,\text{t}}} \right)^2 u_{q_{m,\text{t}}}^2 + \left(\frac{-q_{m,\text{t}}}{\rho \varphi_t^2} \right)^2 u_{\varphi_\text{t}}^2$$

In this instance, since the stack flow is simply proportional to each of the parameters, it is acceptable to combine the relative standard uncertainties directly:

$$u_{q_V}^2 = \left(\frac{u_{\varphi_\text{t}}}{\varphi_t} \right)^2 + \left(\frac{u_{q_{m,\text{t}}}}{q_{m,\text{t}}} \right)^2$$

The standard uncertainty obtained in this way is then multiplied by a coverage factor of $k = 2$ to give the expanded uncertainty at 95 % confidence.

Annex D
(normative)

Transit time tracer gas method determination of average velocity

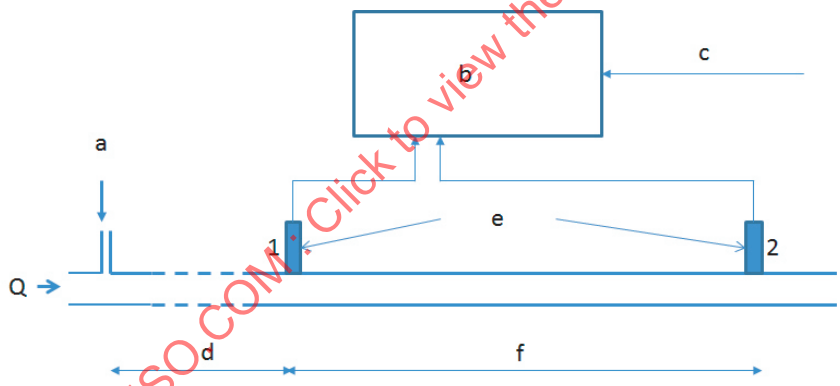
D.1 Existing standards

Even though heavily outdated as to measuring equipment, BS 5857-1.4:1980[18] and BS 5857-2.4:1980[19] give a thorough view of the physical background of the method. ASME MFC-13M-2006[12] gives only a short qualitative description on the use of the transit time method.

D.2 Transit time method

D.2.1 Principle of the method

A very small amount of tracer material is momentarily injected into the stack gas flow. 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 as given in D.2.3. The measurement principle is shown schematically in Figure D.1.



Key

a	tracer pulse input	c	AMS signal	e	measurement points
b	data logging unit	d	mixing length	f	measurement section

Figure D.1 — Principle of tracer time of flight flow measurement technique

D.2.2 Choice of the tracer

The tracer shall follow the stack gas flow in the duct. It may be gas or sufficiently small particles. It may be radioactive or inactive. The radioactive tracer has the advantage that it can be detected through the stack wall. The disadvantage is the possible difficulty or delay in getting a licence from the national radiation safety authorities for use, even when a radiotracer with a very short half-life is used.

Suitable inactive tracers need no safety licence, but are from a technical point of view more difficult to implement. The inactive tracer shall be such that the time constant in its detection is of the order of few milliseconds or less. This requirement comes from the fact that the transit times to be measured accurately are in the range from a couple of seconds to some fractions of a second. In the case of stack gas ducts, it is fairly simple to make connections through which the detector can be pushed into the

contact with the flow. This enables the use of inactive tracers, detectable for instance by ultrasound or by optical methods.

D.2.3 AMS flow calibration procedure

The reference flow value obtained by the transit time method is compared with the simultaneous AMS flow signal. In order to obtain the calibration result on a flow level, several measurement repetitions (normally 7 to 15) are made. The number of flow levels should preferably be 2 to 3 to obtain a good and representative calibration result.

D.2.4 Calculation of the reference values

The average stack gas velocity is derived as:

$$v = \frac{L}{t} \tag{D.1}$$

where

v is the average velocity, in m/s;

L is the length of the measuring section, i.e. the stack length between the two measurement levels, in m;

t is the transit time of the tracer pulse between the two measurement points, in s.

The volume flow rate, q_V, in m^3/s, is derived as:

$$q_V = vA \tag{D.2}$$

where A is the duct cross-section area, in m^2.

D.2.5 Provisions for measurement site

D.2.5.1 Duct area

The duct cross-section area shall be constant between the two measurement points.

D.2.5.2 The length of the measurement section

The duct between the two measurement points shall be straight to allow accurate determination of the volume. For transit time measurements with maximum accuracy, the duct length between the detection points should be $\geq 10 d_d$, where d_d is the duct diameter.

D.2.6 Flow condition

The flow shall be turbulent. This condition is by definition always fulfilled in stack gas ducts.

D.3 Minimum requirements

D.3.1 Tracer

The tracer shall be able to fully mix over the cross-section of the stack gas flow, then having the same average velocity as the stack gas. No significant adsorption of tracer on the duct walls is admissible.

D.3.2 Mixing

Tracer shall be mixed over the flow cross-section when it arrives at the measurement section. The degree of mixing required depends on the characteristics of the tracer concentration measurement used. If the measurement yields values that are well averaged over the flow cross-section, the mixing in a rough scale is sufficient. Concentration measurement in a point of the cross-section is the opposite case and requires more thorough mixing of the tracer over the cross-section. Insufficient mixing is normally indicated also as a significant increase of the variation between the measurement repetitions.

D.3.3 Measurement section

The measurement section where the tracer transit time is measured shall be straight duct section with constant cross-section with sufficient total length. The minimum total length depends on the length of the tracer pulse on the measurement section, stack gas flow velocity, duct diameter, desired measurement uncertainty level, etc. For maximum accuracy, the measurement section shall be $\geq 10 d_{\mathrm{d}}$. This is, in practice, no limitation because the high stacks provide an ideal measurement section for transit time measurement.

The volume of the tracer measurement section may be determined easily and accurately by using laser measurement for both inner diameter and the length of the measurement section.

D.3.4 Tracer concentration measurement

The concentration of the tracer pulse is measured at the two measurement locations. The method of concentration measurement shall be shown to be linear.

The concentration measurement shall not be disturbed by possible rapid variations in stack gas characteristics or in the measurement environment.

D.4 Performance requirements

D.4.1 Injection

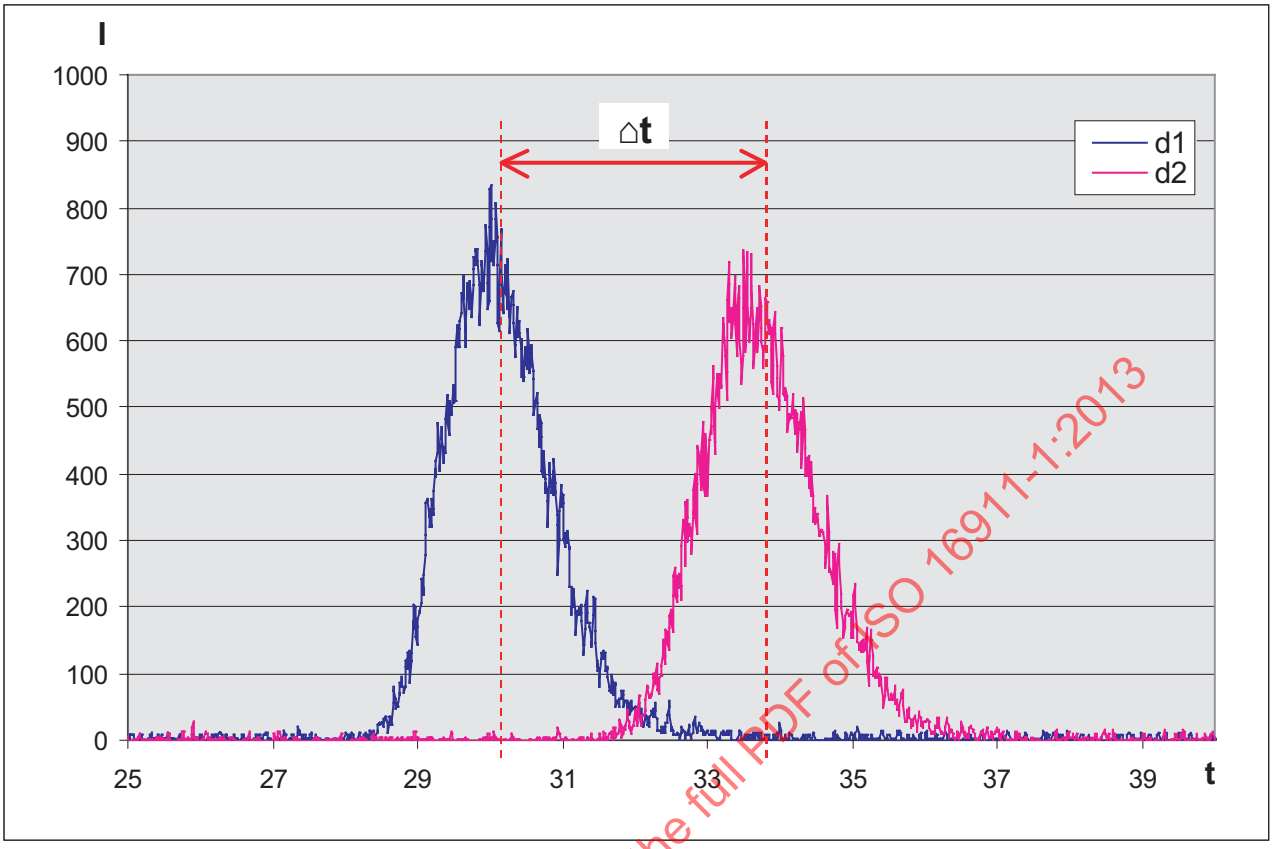
The tracer pulse injected into the stack gas flow should be so short that it does not dominate the pulse length on the measurement section. Injection times of 0,5 s to 1 s are normally sufficiently short.

D.4.2 Measurement of the tracer pulse

The transit times to be measured are normally between some 0,5 s and a few seconds. The time constant of tracer concentration measurement and the data collection interval shall of the order of some milliseconds to allow accurate reconstruction of the tracer pulse. A concentration measurement that gives an averaged value over the duct cross-section is to be preferred because it, compared with point measurement, is more tolerant to non-complete mixing and disturbed flow profiles.

D.4.3 Calculation of the transit time

The transit time is calculated as the time difference of the concentration pulses measured in the beginning and the end of the measuring section. The time difference is calculated by using the pulse medians that divides the pulse in two parts having equal areas, see Figure D.2.



Key

I	pulses/s	measured radiation intensity
t	s	time
Δt	s	transit time
d1, d2		radiation detector

Figure D.2 — The determination of the transit time

The physically correct way of calculating the time difference is by using the gravity points of the pulses. Pulse medians, however, are recommended because they are less sensitive to the correct background subtraction. In normal measurement circumstances, i.e. a straight measurement section and a duct with constant cross-section, the difference between the velocities of the pulse gravity point and median has been shown to be insignificant.

D.4.4 Calculation of the flow reference value

The velocity reference value is obtained by dividing L, the length of the measuring section, by the transit time, t. The reference value for the flow rate is obtained by multiplying the velocity reference value by the duct inner cross-section.

L is measured by using a calibrated measurement band or a calibrated laser distance meter. The inner cross-section is normally determined by measuring the inner diameter of a circular stack. The diameter is obtained with the most reliability by measuring it in two perpendicular directions by using a laser distance meter.

D.5 Uncertainty of the calibration result

D.5.1 The calculation principle

The measurement uncertainty is calculated at a confidence level of 95 % as described in these instructions. The method of calculation of uncertainty is in accordance with EA-4/02.[21]

The uncertainty of the calibration result is divided into two parts:

a) the uncertainty of the reference flow rate originating from the determination of the volume of the measurement section and the equipment's measurement of time;

b) the uncertainty of the comparison of the reference flow rate and the indication of the AMS to be calibrated, including the random uncertainty.

D.5.2 Uncertainty of determination of the volume and measurement of time

In stack emission measurements, the volume of the measurement section is normally determined by measuring L, the length of the measurement section and D, the inner diameter of the duct. In this case, the equation for the reference volume flow rate is:

$$q_V = \frac{\pi D^2}{4}\frac{L}{t} \tag{D.3}$$

The partial derivatives with respect to the different input quantities are:

$$\frac{\partial q_{V,\mathrm{ref}}}{\partial L} = \frac{\pi}{4}\frac{D^2}{t} \tag{D.4}$$

$$\frac{\partial q_{V,\mathrm{ref}}}{\partial D} = \frac{\pi}{2}\frac{LD}{t} \tag{D.5}$$

$$\frac{\partial q_{V,\mathrm{ref}}}{\partial t} = -\frac{\pi}{4}\frac{LD^2}{t^2} \tag{D.6}$$

The standard uncertainty $u_{q_{V,\mathrm{ref}}}$ of the reference volume flow rate is obtained by quadratic summing of the standard uncertainties $u(x_i)$ of the different input quantities x_i multiplied by the corresponding sensitivity coefficients ci.

$$u^2_{q_{V,\mathrm{ref}}} = \sum\left[c_i u(x_i)\right]^2 = \sum\left[\frac{\partial q_{V,\mathrm{ref}}}{\partial x_i}u(x_i)\right]^2 \tag{D.7}$$

The standard uncertainties of the input quantities are obtained as in a) and b).

a) For a quantity which is obtained as an average of several independent observations with adequate resolution, standard uncertainty is obtained by dividing the experimental standard deviation with the square root of the number of observations. (EA-4/02:1999,[21] type A).

b) For calibrated measurement equipment, the standard uncertainty is obtained from the calibration certificates by dividing the expressed uncertainty with the coverage factor k, which typically equals 2 (EA-4/02:1999,[21] type B).

In the case of transit time measurement, the standard uncertainties are obtained as follows.

— $u(L)$. Calibrated measurement tapes or laser distance measurement device are used to the measurement of L. The uncertainty caused by field circumstances is however, significantly larger than the small uncertainties specified by equipment manufacturers and attainable under laboratory conditions.

— $u(D)$. Under stack conditions, the preferred way to determine D is by using a laser distance measurement device. The measurement should be carried out, if possible, of perpendicular diameters to detect any possible ovality of the stack.

— $u(t)$. Measurement of time by the calibration equipment in itself is easily and accurately calibrated and thus the hardware-based uncertainty is negligible (<0,01 %). The uncertainty of the calculated transit time is dominantly stochastic in nature. It is therefore included in the total statistical uncertainty of the calibration and discussed in the following in relation to the uncertainty of the comparison of reference flow rate and the AMS indication.

D.6 Numerical example of uncertainty calculation in stack flow calibration

D.6.1 The uncertainty of $q_{V,\,\mathrm{ref}}$

Length L (in this example 62,577 m):

a) specifications for measuring tape, class 2: $U = \pm(1 + 0{,}2L[\mathrm{m}])$ mm = >±13,2 mm.

b) tape stretch by other than nom. 50 N force: U = ±20 N × (5 µm/N)L[m] = >±6,3 mm.

c) tape stretch by temperature; u = ±10 °C × (12 µm/°C)L[m] = >±7,5 mm.

d) transfer of the tape reading value to detector positions; u = ±100 mm.

All these uncertainty components associated with L are given by upper and lower limits and probability distribution between the limits is assumed to be rectangular (EA-4/02:1999,[21] 3.3.2, type B, case c). Standard uncertainty of each of these input estimate components is obtained by dividing the limit values by √3. The square root of the sum of the squares of these uncorrelated values gives standard uncertainty for L, u_{L} = 58,5 mm (transfer of tape reading is predominant).

Inside diameter D (= 3 580 mm).

1) Specifications for laser distance meter (distance up to 30 m), u = ±3 mm.

2) Gauge 0-point setting transfer to stack inside wall; u = ±2 mm.

3) Uncertainty components 1) and 2) associated with D are given by upper and lower limits with rectangular probability distribution (type B, case c) — the standard uncertainty of each of these input estimate components is obtained by dividing the limit values by √3.

4) Focusing of measuring spot on opposite wall has been evaluated according to the EA-4/02:1999,[21] type A method. Comprehensive tests have given for this part of the measurement method, an experimental variance of 20 mm^2 and a normal distribution. In this calibration, the measurement of D is based on limited number, five, of repetitions. An experimental variance of 20 mm^2 based on comprehensive tests is used here as a pooled estimate of variance. This gives for component 3) standard uncertainty, $u = \sqrt{(20/5)}$ = 2,0 mm.

No ovality of the stack was detected in this case.

The square root of the sum of the squares of these uncorrelated components 1) to 3) gives standard uncertainty for D, u_{D} = 2,9 mm.

Transit time t (average, 3,645 s).

— Detectors and the signal amplifiers have a small deviation of response time. Associated (expanded) uncertainty with them is u = 1 ms, (normal distribution, k = 2).

— Data-logging apparatus has time-measuring (expanded) uncertainty u = 100 µs or 0,01 % of the length of the time interval (normal distribution, k = 2).

These uncertainties associated with transit time measurement represent EA-4/02:1999,[21] 3.2, type A evaluation. Standard uncertainty of each of these input estimate components is obtained by dividing the given u values by the coverage factor, k = 2. The square root of the sum of the squares of these uncorrelated values gives standard uncertainty for t, u_t = 0,53 ms.

Correlation of input quantities associated with $q_{V,\,ref}$: none of the input quantities for definition of $q_{V,\,ref}$ are considered to correlate to any significant extent.

Combined uncertainty associated with $q_{V,\,ref}$: the effect of each component u_L, and u_t on $q_{V,\,ref}$ is calculated by multiplying each u_i with the corresponding sensitivity coefficient c_i. The square root of the sum of the squares of these effects gives the standard uncertainty for $q_{V,\,ref}$, $u_{q_V,ref}$ = 0,32 m³/s.

D.6.2 The total uncertainty

See Table D.1.

The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k = 2,37, which for a t-distribution with ν_{eff} = 8 effective degrees of freedom corresponds to a coverage probability of approximately 95 %. The standard uncertainty of measurement has been determined in accordance with EA-4/02.[21]

Table D.1 — Uncertainty budget

Quantity	Estimate	Unit	Standard uncertainty	Unit	Probability distribution	Sensitivity coefficient	Unit	Uncertainty contribution	Unit
X_i	x_i		$u(x_i)$			c_i		$u_i(y)$	
Definition of $q_{V,ref}$									
L	62,557	m	58,5	mm	rectangular	2,762	m²/s	0,161	m³/s
—measurement tape base uncertainty			7,6		rectangular				
—measurement tape stretch by pull force			3,6		rectangular				
—measurement tape stretch by temperature			4,3		rectangular				
—measurement transfer tape→detectors			57,7		rectangular				
D	3 580	mm	2,9	mm	rectangular + normal	96,521	m²/s	0,279	m³/s
—laser base uncertainty			1,7		rectangular				
—0 point setting			1,2		rectangular				
—measurement spot focusing			2,0		normal				
t	3,645	s	0,53	ms	normal	−47,404	m³/s	−0,025	m³/s
—detection uncertainty			0,50		normal				
—data-logging uncertainty			0,18		normal				
Combined									
$u_{q_V,ref}$								0,323	m³/s

Annex E
(normative)

Calculation of flue gas volume flow rate from energy consumption

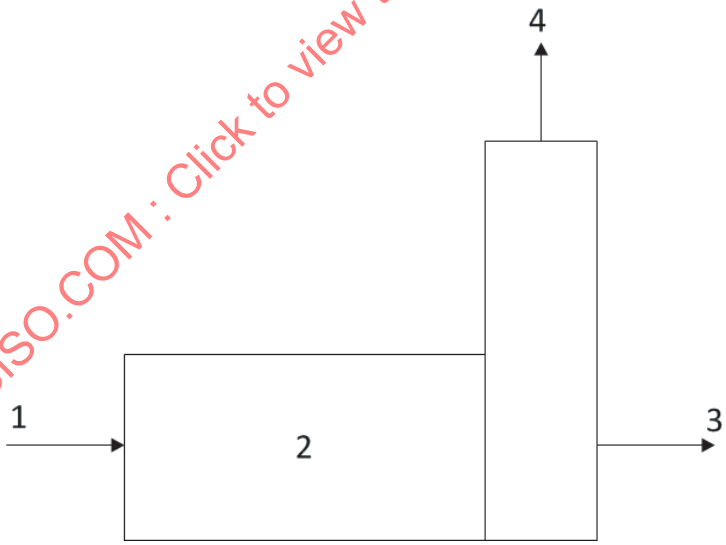
E.1 Principle

This annex describes a procedure for the calculation of flue gas volume flow rate. The general method is to multiply the energy consumption by a fuel factor in order to obtain the dry stoichiometric stack gas flow rate at standard reference conditions (0 % O_2, 273,15 K and 101,325 kPa). The energy consumption may be determined directly, by measurement of fuel flow rate and specific energy, or indirectly from the plant output and thermal efficiency.

For mass emissions reporting, the dry stoichiometric flow rate rate is then corrected to a given reference oxygen content, for subsequent multiplication by emissions concentrations reported at the same reference conditions.

For dispersion modelling, and a number of other purposes, the dry stoichiometric flow rate is recalculated to the prevailing or expected stack conditions of oxygen, moisture content, temperature and pressure.

The required inputs, calculation steps and outputs are shown in Figure E.1 and are specified in later sections of this annex.



Key

1 inputs: fuel flow, $q_{m,\,F}$, in kg/s, with net specific energy, $e_{(N)}$, in MJ/kg; input: gas release (fuel factor), S [m^3/MJ]

2 calculation: process heat release, $\Phi_{(N)F}$ [MW] = $q_{m,\,F}\, e_{(N)} = P/\eta$

3 inputs (alternative): energy production, P, in MW, with thermal efficiency η

4 calculation: flue gas volume flow rate $q_{V,0d}$ [m^3/s] = $S\, \Phi_{(N)F}$ (at 273,15 K, 101,325 kPa, 0 % volume fraction O_2, 0 % volume fraction H_2O)

Figure E.1 — Principle of calculation of stack gas flow from energy consumption

E.2 Fuel factor

E.2.1 Fixed factors for commercially traded fossil fuels

The volume of flue gas generated by the combustion of a known quantity of fuel is required. On a thermal input basis, the fuel factor does not vary substantially for a given fuel type and a fixed value is often sufficient. The volume of dry, stoichiometric flue gas per MJ of net supplied energy, *S*, is given in Table E.1 for a range of fuels. An estimate of the uncertainty of the fuel constant is also given in the table based on a comparison of the correlated values with an exact mass balance approach for a wide range of samples. The fuel factors have been derived in accordance with EN 12952-15.[7]

The natural gas fuel factor is appropriate for Group H natural gas (EN 437:2003)[6] provided that this is also natural gas as defined in Directive 2010/75/EU,[25] in which the methane content is higher than 80 %.

Table E.1 — Fossil fuel factors

Fuel factor *S*	Fuel type			
	Natural gas	Gas oil	Fuel oil	Hard coal
m^3/MJ at 0 % O_2 dry 273,15 K, 101,325 kPa	0,240	0,244	0,248	0,256
$U_{rel,95\ \%}$, %	±0,7	±1,0	±1,0	±2,0

NOTE Relative uncertainty, U_{rel}, is quoted at 95 % confidence assuming a normal data distribution and a coverage factor of 1,96 unless otherwise stated.

The gas oil factor is suitable for gas oil, diesel, light distillate and kerosene. The fuel oil factor is appropriate for other commercially available petroleum products from light to heavy fuel oil.

The hard coal factor is appropriate for commercially traded hard coal and pure biomass fuel with a moisture content of less than 25 % mass fraction.

A lower uncertainty may be achieved for these fuels by applying a correction for the net specific energy (NSE) or by deriving a fuel factor from the fuel composition as described below.

Fuel factors for wet biomass are given in Table E.2, again derived in accordance with EN 12952-15.[7] The uncertainty relates to a moisture content variation of ±10 %, e.g. a moisture content of 30 % mass fraction covering a range of moisture contents from 20 % to 40 %. The uncertainty increases non-linearly at high moisture contents.

Table E.2 — Biomass fuel factors

Fuel moisture (% mass fraction)	20	30	40	50	60
Fuel factor, *S*, m^3/MJ at 0 % O_2 dry	0,260	0,267	0,276	0,290	0,314
Uncertainty, $U_{rel,95\ \%}$, % (±10 % mass fraction moisture)	2,8	3,6	5,0	7,7	13,9

E.2.2 Factors corrected for specific energy

A wider range of fuels may be considered, and a lower uncertainty can be achieved, by applying a correction for the NSE of the as-received fuel. “As-received” indicates that the fuel heating value is reported on the basis that all moisture and ash-forming minerals are present.

The NSE correction is derived from EN 12952-15:2003,[7] Annex A:

$$S = \frac{a}{e_{(N)}} + b \tag{E.1}$$

where

$e_{(N)}$ is the NSE of the as-received fuel, in MJ/kg;

a, b correction factors, see Table E.3.

Table E.3 — NSE correction factors

Parameter	Fuel type		
	Gas	Liquid	Solid
a	0,649 72	1,764 35	$-0{,}060\ 18 w_f$
b	0,225 53	0,200 60	$0{,}254\ 37 (1 + 2{,}442\ 5\ w_{H_2O} / e_{(N)})$

For gaseous fuels, it may be more convenient to employ the volumetric NSE (MJ/m^3 at 0 °C) in Formula (E.1) in which case a = 0,2 and b = 0,234. This approach is not suitable for low specific energy fuel gases for which the fuel factor shall be determined from the gas composition according to EN 12952-15,[7] Section 8.

For liquid fuels, this approach is suitable only for light petroleum fractions. Other liquid fuels should be assessed using the measured composition and heating value as described in E.2.3.

For solid fuels, the mass fractions of ash yield, w_{ash}, and moisture, w_{H_2O}, in the as-received fuel need to be taken into account using the dry, ash free, fuel mass fraction, w_f, where:

$$w_f = 1 - w_{ash} - w_{H_2O} \tag{E.2}$$

If the NSE of the fuel stream is variable, the uncertainty associated with the fuel variability shall be estimated from multiple fuel samples. This method is not suitable for fuels with an ash yield greater than 20 % mass fraction, in which case the assessment should be based upon the measured composition and heating value as described in E.2.3.

E.2.3 Factors derived from fuel composition

For solid and liquid fuels, EN 12952-15:2003,[7] 8.3.4.2 also defines a method for determining the mass specific fuel factor, $q_{V,0d}$, in m^3/kg, from the as-received fuel composition based on an ultimate analysis:

$$q_{V,0d} = 8{,}893\ 0 w_C + 20{,}972\ 4 w_H + 3{,}319\ 0 w_S - 2{,}642\ 4 w_O + 0{,}799\ 7 w_N \tag{E.3}$$

where w is the mass fraction of an individual fuel component in the supplied fuel (as received) and C, H, S, O and N are the elements carbon, hydrogen, sulfur, oxygen, and nitrogen, respectively.

This is then divided by $e_{(N)}$ to obtain the energy specific fuel factor S:

$$S = \frac{q_{V,0d}}{e_{(N)}} \tag{E.4}$$

For inhomogeneous solid fuels, for which it is difficult to obtain representative samples, it is recommended that the measured specific energy be checked using a calculated value of $e_{(N)}$, in MJ/kg, using the following formulas.

$$e_{(N)} = e_{(G)} - 21{,}22w_H - 0{,}08 \times (w_O + w_N) - 2{,}442\,5\,w_{H_2O} \tag{E.5}$$

Formula (E.5) is from ISO 1928[2] and requires $e_{(G)}$, the gross specific energy, either measured or calculated as follows.

$$e_{(G)} = 34{,}1w_C + 132{,}2w_H + 6{,}86w_S - 12w_O - 12w_N - 1{,}53w_{ash} \tag{E.6}$$

Formula (E.6) is from Reference [27]. Note that methods for obtaining the fuel composition on an "as-received" basis are described in ISO 1170.[1]

If the composition of the fuel stream is variable, the uncertainty associated with the fuel variability shall be estimated from multiple fuel samples. In any case, it is recommended that multiple fuel samples be considered in order to minimize the uncertainty contribution associated with the analysis of composition.

E.3 Energy consumption

For gas and liquid fuels, the energy consumption, $\Phi_{(N)F}$, in MW, may be determined directly from the metered fuel consumption, $q_{m,F}$, in kg/s, and the measured or supplied NSE, $e_{(N)}$, in MJ/kg.

$$\Phi_{(N)F} = q_{m,F}e_{(N)} \tag{E.7}$$

Quality ensured metering and specific energy determination has an estimated worst case expanded uncertainty of ±1,6 %, although lower values may be used if justified.

For solid fuels with a directly measured fuel consumption rate using, for example, calibrated gravimetric feeders, and a stable fuel composition (specific energy), a similar uncertainty is achievable. However, in many situations, the instantaneous fuel consumption and specific energy are not available, in which case the energy consumption shall be derived from the plant energy production, P, in MW, and the fractional thermal efficiency, η:

$$\Phi_{(N)F} = \frac{P}{\eta} \tag{E.8}$$

The uncertainty of the thermal efficiency shall be justified for compliance purposes. For example, a coal-fired power plant, with an established heat accountancy and fuel management system, has an expanded uncertainty of the instantaneous thermal efficiency of circa ±5 %. This may be reduced to circa ±3 % with online correction of the efficiency calculation to account for changes in plant operation and ambient conditions. For heat-producing plants with typical thermal efficiencies of about 90 %, this uncertainty is below 1 %. A biomass steam-generating plant has a higher absolute thermal efficiency and can therefore achieve a lower thermal input expanded uncertainty of typically 2 % to 3 %, provided that the heat output measurement has a low uncertainty.

E.4 Calculation of flue gas volume flow rate

The stoichiometric dry flue gas volume flow rate at 273,15 K and 101,325 kPa, $q_{V,0d}$, in m^3/s, is calculated from the fuel factor, S, and the thermal input $\Phi_{(N)F}$:

$$q_{V,0d} = S\,\Phi_{(N)F} \tag{E.9}$$

For mass emission reporting, this flue gas volume flow rate is corrected to the required standard reference oxygen content:

$$q_{V,0d,O_2,ref} = \frac{0{,}2095 \times q_{V,0d}}{0{,}2095 - \varphi_{O_2,ref}} \tag{E.10}$$

where $\varphi_{O_2,ref}$ is the dry oxygen reference condition for the plant as a dry volume fraction. For boilers, this is normally 0,03 for gas and liquid fuels and 0,06 for solid fuels and for gas turbines this is normally 0,15.

Additional corrections are required when calculating the flue gas flow rate at the free stream conditions in the flue:

$$q_V = \frac{0{,}2095}{\left(0{,}2095 - \varphi_{O_2}\right)} \frac{1}{\left(1 - \varphi_{H_2O}\right)} \frac{T}{273{,}15} \frac{101{,}325}{p} q_{V,0d} \tag{E.11}$$

where

φ_{O_2} is the flue gas oxygen content, dry volume fraction;

φ_{H_2O} is the flue gas water content, wet volume fraction;

T is the flue gas temperature, in K;

p is the flue gas pressure, in kPa.

E.5 Performance requirements

The target overall performance requirement for the dry flue gas flow rate is given by fuel type in Table E.4 or which the method of determination is calculation (E.4) from fuel factor (E.2) and energy consumption (E.3). The performance requirements are given as expanded uncertainties at 95 % confidence.

Table E.4 — Performance requirements of the calculation approach

Fuel	Criterion
Gas	≤2,0 % of flow rate
Liquid	≤3,0 % of flow rate
Solid	≤7,5 % of flow rate

The performance requirements for the main calculation inputs are given in Table E.5.

Table E.5 — Performance requirements of main input parameters

Parameter	Criterion	Method of determination
Energy input — from fuel consumption		
Fuel flow rate	≤1,5 % of value	Mass or volume flow meter with traceable calibration certificate
Net specific energy	≤0,5 % of value	Determination or instrument calibration by a laboratory accredited to, for example, ISO/IEC 17025
Energy input — from energy production		
Electrical power	≤0,5 % of value	Electricity meter
Net thermal efficiency	≤5,0 % of value	Heat balance verified by performance testing or annual fuel consumption and energy production
Fuel factor		
Gas	≤1,0 % of value	Determination from fuel composition, NSE or a defined constant fuel factor
Liquid	≤1,5 % of value	
Solid	≤7,5 % of value	

E.6 Example of uncertainty calculations

E.6.1 Example 1 — Coal-fired power plant

The flue gas volume flow rate at a reference condition of 6 % volume fraction oxygen, dry, 273,15 K, 101,325 kPa is required at the base load operating condition for calculation of a mass release.

The oxygen correction is

$$\frac{0{,}2095}{0{,}2095-0{,}06} = 1{,}40$$

The fuel factor, S = 0,256, for hard coal is given in Table E.1 and the thermal input is determined from the plant electrical output, P = 500 MW electric, and thermal efficiency, η = 0,40, to give, at reference conditions, the volume flow rate:

$$q_V = 1{,}4 S \frac{P}{\eta} = 1{,}4 \times 0{,}256 \times \frac{500}{0{,}4} = 448\ \mathrm{m^3/s}$$

Since the relationship between the parameters is linearly proportional, it is sufficient to combine the standard relative uncertainties using a simple root mean square approach and a coverage factor of 2,0.

Fuel factor, S, standard uncertainty for hard coal (Table E.1): 1,0 %

Power output, P, standard uncertainty: 0,25 %

Thermal efficiency, η, standard uncertainty: 2,5 %

Combined flue gas flow, q_V, expanded uncertainty: $2 \times \sqrt{1{,}0^2 + 0{,}25^2 + 2{,}5^2} = 5{,}4\ \%$

E.6.2 Example 2 — Biomass fired combined heat and power plant

The flue gas volume flow rate at a reference condition of 8 % volume fraction oxygen, dry, 273,15 K, 101,325 kPa is required for the calculation of a mass release rate.

The oxygen correction is

$$\frac{0{,}2095}{0{,}2095-0{,}08} = 1{,}62$$

The biomass fuel has a mean moisture content of 50 % mass fraction with a typical variation of ±10 %. Since the uncertainty associated with the moisture variation (Table E.2) is higher than desired, the deliveries are sampled and a moisture analysis is performed on each delivery to an expanded uncertainty of 5 % (reported by the laboratory). The ash yield is consistently low (2 % mass fraction on a dry basis) and the specific energy and the ultimate analysis of the dry fuel is invariable (a homogeneous biomass source). The standard uncertainty of the fuel factor for each measurement may be estimated as follows.

a) Multiply the gross specific energy (GSE), $e_{(G)}$, of the dry ash free (DAF) material by $\left(1-w_{ash}-w_{H_2O}\right)$ to obtain the gross specific energy of the wet fuel sample. For a sample with 48 % moisture content and 2 % ash yield, with a DAF GSE of 20 MJ/kg, the actual GSE is then 20(1 – 0,02 – 0,48) = 10 MJ/kg. Repeat for the ±5 % moisture values of 45,6 % moisture (10,48 MJ/kg) and 50,4 % moisture (9,52 MJ/kg).

b) Calculate the NSE from the gross specific energy using Formula (E.5):

$$e_{(N)} = e_{(G)} - 21{,}22w_H - 0{,}08\left(w_O + w_N\right) - 2{,}4425w_{H_2O}$$

The fuel mass fractions used in this formula are calculated from the DAF values using the measured moisture and ash, using the same multiplier as before $(1-w_{ash}-w_{H_2O})$. The DAF fuel H fraction is 0,06 and the (O + N) fraction is 0,421 for this fuel. The $e_{(N)}$ values then range from 8,852 MJ/kg (45,6 % moisture) to 7,855 MJ/kg (50,4 % moisture) with a value of 8,354 MJ/kg at 48 % moisture content.

c) Calculate the fuel factor for each moisture value from Formula (E.1) using the associated $e_{(N)}$ values and the parameters, *a* and *b*, for solid fuel. These parameters also require the appropriate moisture and ash yields to be employed. The fuel factor range is then 0,282 8 to 0,290 5 with a fuel factor of 0,286 4 m^3/MJ at 48 % moisture content. The relative standard uncertainty is calculated from the half range in the usual way:

[(0,290 5 – 0,282 8)/2/√3]/0,286 4

giving 0,78 %. This is combined with an additional standard uncertainty of 0,55 %, associated with the use of Formula (E.5), to give 0,96 %.

Note that the composition and/or specific energy of the samples may need to be determined for a less homogeneous fuel.

The thermal input is determined from the plant steam output (P = 20 MW thermal) and the thermal efficiency (η = 0,9) to give, under reference conditions, the volume flow rate:

$$q_V = 1{,}62S\frac{P}{\eta} = 1{,}62\times 0{,}286\,4\times\frac{20}{0{,}90} = 10{,}31\ \mathrm{m^3/s}$$

Since the relationship between the parameters is linearly proportional, it is sufficient to combine the standard relative uncertainties using a simple root mean square approach and a coverage factor of 2,0.

Fuel factor, *S*, standard uncertainty for biomass sample (see above): ~1,0 %

Thermal output, *P*, standard uncertainty from flow meters and thermocouple calibrations: 2,5 %

Thermal efficiency, η, standard uncertainty from boiler efficiency analysis: 2,0 %

Combined flue gas volume flow rate, q_V, expanded uncertainty: $2\times\sqrt{1^2+2{,}5^2+2^2}=6{,}7\%$

E.6.3 Example 3 — Natural gas fired gas turbine plant

The flue gas volume flow rate at a reference condition of 15 % oxygen volume fraction, dry, 273,15 K, 101,325 kPa is required for the calculation of a mass release rate.

The oxygen correction is

$$\frac{0{,}2095}{0{,}2095-0{,}15}=3{,}521$$

The fuel factor, S = 0,240, for natural gas is given in Table E.1 and the thermal input is determined from the metered fuel input, $q_{m,\,F}$ = 10 kg/s, and the measured NSE, $e_{(N)}$ = 50 MJ/kg, to give, under reference conditions, the volume flow rate:

$$q_V = 3{,}521 \times Sq_{m,\,F}e_{(N)} = 3{,}521 \times 0{,}240 \times 10 \times 50 = 422{,}5\ \text{m}^3/\text{s}$$

Since the relationship between the parameters is linearly proportional, it is sufficient to combine the standard relative uncertainties using a simple root mean square approach and a coverage factor of 2,0.

Fuel factor, S, standard uncertainty for natural gas (Table E.1): 0,35 %

Thermal input, P, standard uncertainty from fiscal flow meter and gas chromatograph: 0,8 %

Combined flue gas volume flow rate, q_V, expanded uncertainty: $2\times\sqrt{0{,}7^2+0{,}8^2}=2{,}1\%$

Annex F
(informative)

Example of uncertainty budget established for velocity and volume flow rate measurements by Pitot tube

F.1 Process of uncertainty estimation

F.1.1 General

The procedure for calculating measurement uncertainty is based on the law of propagation of uncertainty laid down in ISO 14956[5] or ISO/IEC Guide 98-3. The calculation procedure presents different steps (F.1.2 to F.1.5).

F.1.2 Determination of model function

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

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

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

F.1.3 Quantification of uncertainty components

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

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

F.1.4 Calculation of the combined uncertainty

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

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

F.1.5 Other sources of errors

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

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

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

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

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

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

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

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

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

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

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

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

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

F.2 Example uncertainty calculation

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

— duct with a diameter 1 m, explored in five points by means of an L-type Pitot: uncertainty in the measurement of the diameter of the duct is calculated starting from the maximum permissible error equal to 2 % of the diameter;

— temperature of gases on the measurement section: 150 °C = 423 K — accurate to within 1 % of the absolute temperature, in K (as mentioned in ISO 10780[4]);

— atmospheric pressure: 101 080 Pa — uncertainty in the atmospheric pressure is calculated starting from the maximum permissible error which is 300 Pa and the error due to the reading estimated at 20 Pa;

— composition of gases:

  — oxygen content measured in the conduit: 11,8 % volume fraction on dry gas ±6 % relative (k = 2),

  — carbon dioxide content measured in the conduit: 9,1 % volume fraction on dry gas ±6 % relative (k = 2),

— water vapour content: 10,8 % volume fraction on wet gas ±20 % relative (k = 2);

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

Value	Point i				
	1	2	3	4	5
1	190	205	221	208	195
2	189	198	227	215	188
3	195	203	225	213	186
4	194	200	219	216	195
5	192	203	220	210	194
$\overline{\Delta p_i}$	192	202	222	212	192

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

Value	Diameter	
	1	2
1	–160	–158
2	–165	–162
3	–166	–164
4	–170	–159
5	–159	–161
$\overline{p_{\mathrm{stat},k}}$	–164	–161

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

$$\overline{p_{\mathrm{stat}}} = \frac{1}{2}\left(\overline{p_{\mathrm{stat},1}} + \overline{p_{\mathrm{stat},2}}\right) = -162\ \mathrm{Pa}$$

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

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

— molar mass gases: $M = 28{,}6 \times 10^{-3}$ kg/mol

— density of gases: ρ = 0,82 kg/m^3 in actual conditions of temperature and pressure, on wet gas

— absolute pressure: p_c = 100 918 Pa

— local velocities, in m/s:

Velocity	Point *i*				
	1	2	3	4	5
v_i	21,72	22,27	23,38	22,85	21,70
mean velocity: $\bar{v}$ = 22,38 m/s					

— volume flow rate:

  — $q_{V,w}$ = 63 292 m³/h in actual conditions of temperature and pressure and on wet gas,

  — $q_{V,0d}$ = 32 371 m³/h in standard conditions and on dry gas,

  — $q_{V,0d,O2ref}$ = 29 755 m³/h in standard conditions, on dry gas and to a reference oxygen concentration.

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

$$\frac{u^2(v_i)}{v_i^2} = \frac{u^2(K)}{K^2} + \frac{u^2\left(\overline{\Delta p_i}\right)}{4\times\overline{\Delta p_i}^2} + \frac{u^2(\rho)}{4\rho^2} \qquad \text{(F.1)}$$

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

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

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

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

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

where

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

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

$C_f, f = 1 \ldots r$ are the corrections to the dynamic pressure measurements.

The standard deviation $\sigma_{\Delta p_i}$ is calculated as follows:

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

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

where

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

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

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

— If the number of measurements is greater than 10:

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

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

The corrections to dynamic pressure measurements are related to:

— the resolution of the sensor used;

— its uncertainty of calibration;

— its drift;

— its linearity;

— hysteresis.

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

— range: 0 Pa to 1 000 Pa;

— resolution: 1 Pa;

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

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

— lack of fit: 0,06 % of the range.

$$u^2(\overline{\Delta p_i}) = \frac{\sigma^2_{\Delta p_i}}{m} + \left(\frac{1}{2\sqrt{3}} \right)^2 + \left(\frac{2}{2} \right)^2 + \left[\frac{(0{,}1/100) \times 1\,000}{\sqrt{3}} \right]^2 + \left[\frac{(0{,}06/100) \times 1\,000}{\sqrt{3}} \right]^2$$

Value, Pa	Point i				
	1	2	3	4	5
$\overline{\Delta p_i}$	192	202	222	212	192
$\sigma_{\Delta p_i} = d_n\left(\Delta p_{i,\max} - \Delta p_{i,\min}\right)$	2,58	3,01	3,44	3,44	3,87
$\sigma_{\Delta p_i} / \sqrt{m}$	1,15	1,35	1,54	1,54	1,73
$u\left(\overline{\Delta p_i}\right)$	1,69	1,83	1,98	1,98	2,13

F.2.2.3 Standard uncertainty associated with the density of the gas effluent

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

where

ρ is the density of the gas effluent under the conditions of temperature and pressure of gas, in kg/m^3;

M is the molar mass of wet gas effluent, in kg/mol;

p_c is the absolute pressure in the duct in the measurement section, in Pa;

T_c is the gas temperature in the duct, in K.

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

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

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

Sensitivity coefficients:

$$\frac{\partial M}{\partial \varphi_{O_2,w}} = 4 \times 10^{-5} \qquad \sigma_{\Delta p_i} = d_n \times \left(\Delta p_{j,\max} - \Delta p_{j,\min}\right) \qquad \frac{\partial M}{\partial \varphi_{H_2O}} = -10^{-4}$$

Standard uncertainty

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

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

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

$$\varphi_{O_2,w} = \varphi_{O_2,d} \times \frac{100 - \varphi_{H_2O}}{100} = 11{,}8 \times \frac{100 - 10{,}8}{100} = 10{,}5\,\%\ \text{volume fraction}$$

$$\varphi_{CO_2,w} = \varphi_{CO_2,d} \times \frac{100-\varphi_{H_2O}}{100} = 9,1 \times \frac{100-10,8}{100} = 8,1\,\%\ \text{volume fraction}$$

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

$$u\left(\varphi_{H_2O}\right) = \frac{20}{2\times 100} \times 10,8 = 1,08\,\%\ \text{volume fraction on wet gas}$$

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

$$u\left(\varphi_{O_2,w}\right) = 10,5 \times \sqrt{\left(\frac{\frac{6}{2\times 100}\times 11,8}{11,8}\right)^2 + \left(\frac{\frac{20}{2\times 100}\times 10,8}{100-10,8}\right)^2} = 0,34\,\%\ \text{volume fraction water vapour}$$

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

$$u\left(\varphi_{CO_2,w}\right) = 8,1 \times \sqrt{\left(\frac{\frac{6}{2\times 100}\times 9,1}{9,1}\right)^2 + \left(\frac{\frac{20}{2\times 100}\times 10,8}{100-10,8}\right)^2} = 0,26\,\%\ \text{volume fraction}$$

$$u(M) = 1,17\times 10^{-4}\ \text{kg/mol}$$

F.2.2.3.2 Standard uncertainty associated with the temperature T_c

Uncertainty associated with the temperature measurement is dependent:

— with the resolution of the temperature sensor used;

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

— with the drifts of the measuring equipment;

— with the linearity-measuring equipment;

— with the hysteresis-measuring equipment.

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

The standard uncertainty $u(T_c)$ is thus equal to:

$$u\left(T_c\right) = \frac{4,23}{2} = 2,11\,\text{K}$$