INTERNATIONAL STANDARD

ISO 16911-2

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

Part 2:
Automated measuring systems

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

Partie 2: Systèmes de mesure automatiques

Reference number
ISO 16911-2:2013(E)

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Foreword

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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 16911-2 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*

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Introduction

EN ISO 16911-2 describes the quality assurance (QA) procedures related to automated measuring systems (AMSs) for the determination of the volume flow rate of flue gas with a total uncertainty that accords with the requirements of Commission Decision of 2007-07-18.[4]

The calibration and validation of flow AMSs are performed by parallel measurements with the reference manual method described in EN ISO 16911-1.

The purpose of EN ISO 16911-2 is to secure flow monitoring with a minimized uncertainty for use according to EU Directive 2000/76/EC,[1] EU Directive 2001/80/EC,[2] and EU Directive 2010/75/EU.[5]

The purpose of EN ISO 16911-2 is also to secure flow monitoring with an overall uncertainty equal to or less than stipulated in Commission Decision of 2007-07-18[4] and establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC.[3]

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INTERNATIONAL STANDARD **ISO 16911-2:2013(E)**

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

Part 2:
Automated measuring systems

1 Scope

EN ISO 16911-2 describes specific requirements for automated measuring system (AMS) flow monitoring. It is partly derived from EN 14181 which is the general document on the quality assurance of AMSs and is applicable in conjunction with that document.

EN ISO 16911-2 specifies conditions and criteria for the choice, mounting, commissioning and calibration of AMSs used for determining the volume flow rate from a source in ducted gaseous streams. EN ISO 16911-2 is applicable by correlation with the manual reference methods described in EN ISO 16911-1.

EN ISO 16911-2 is primarily developed for monitoring emissions from waste incinerators and large combustion plants. From a technical point of view, it can be applied to other processes for which flow rate measurement is required with a defined and minimized uncertainty.

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 14956, *Air quality — Evaluation of the suitability of a measurement procedure by comparison with a required measurement uncertainty*

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

EN 14181:2004, *Stationary source emissions — Quality assurance of automated measuring systems*

EN 15267-3:2007, *Air quality — Certification of automated measuring systems — Part 3: Performance criteria and test procedures for automated measuring systems for monitoring emissions from stationary sources*

EN 15259, *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 terms and definitions given in EN 14181 and the following apply.

3.1
automated measuring system
AMS
measuring system permanently installed on site for continuous monitoring of flow

Note 1 to entry: An AMS is a monitoring technology which is traceable to a reference method.

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Note 2 to entry: The AMS is a complete system for measuring flow rate, and includes the features required for conducting regular functional checks.

3.2

cross-sensitivity

response of the AMS to determinants other than flow rate, e.g. caused by the presence of particulate matter, changes in gas composition, duct temperature

3.3

linearity

lack of fit

systematic deviation, within the range of application, between the accepted value of a flow reference material applied to the measuring system and the corresponding measurement result produced by the AMS

Note 1 to entry: The linearity test is described in EN 15267-3:2007, Annex B.

3.4

limit of detection

minimum value of the measurand for which the measuring system is not in the basic state, with a stated probability

Note 1 to entry: Basic state is normally the zero reading or the minimum measured by the instrument.

3.5

period of unattended operation

maintenance interval

maximum interval of time for which the performance characteristics remain within a predefined range without external servicing, e.g. calibration or adjustment

3.6

reproducibility under field conditions

measure of the agreement between two measurements in field tests at a level of confidence of 95 % expressed as the standard deviation of the difference of paired measurements:

$$s_D = \sqrt{\frac{\sum_{i=1}^{n}(x_{1i} - x_{2i})^2}{2n}} \tag{1}$$

where

x_{1i} is the ith measurement result of AMS 1;

x_{2i} is the ith measurement result of AMS 2;

n is the number of parallel measurements.

Note 1 to entry: The absolute reproducibility in the field, $R_{f,abs}$, is calculated according to:

$$R_{f,abs} = t_{0,05(N-1)} \times s_D \tag{2}$$

where

$t_{0,05(N-1)}$ is the two-sided Student t-factor at a confidence level of 0,05, with $N - 1$ degrees of freedom.

Note 2 to entry: Adapted from EN 15267-3:2007.

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3.7
standard reference method
SRM

method described and standardized to define an air quality characteristic, temporarily installed on site for verification purposes

Note 1 to entry: For the purposes of EN ISO 16911-2, the manual reference methods are described in EN ISO 16911-1.

3.8
flow reference material

surrogate for flow for testing the AMS performance

Note 1 to entry: A surrogate for flow is normally the parameter measured directly by the instrument, e.g. pressure, time delay, temperature, heat dissipation or frequency.

3.9
lower reference point

output of the instrument in response to an internally generated function, intended to represent a defined amount of the measured flow at or close to the lowest flow rate that the system can measure with a given uncertainty

3.10
upper reference point

output of the instrument in response to an internally generated function, intended to represent a defined amount of the measured flow at or close to the highest flow rate the system is intended to measure in a given installation

3.11
flow profile

represented by two diagrams showing the gas velocity in the axial direction along a line across the duct passing through the centre of gravity of the duct, and a line perpendicular to the first

Note 1 to entry: The gas velocity is expressed in m/s.

3.12
crest factor
peak-to-average ratio

characteristic of a flow profile, calculated from the measured peak value of each flow profile divided by the average value of each flow profile in the primary and secondary monitoring paths

Note 1 to entry: If the measurement is made according to EN ISO 16911-1 and EN 15259, each measurement represents the same area of flow in the duct, and the crest factor divisor can be calculated from a simple average of the individual measurements.

Note 2 to entry: Crest factor shall be calculated for both flow profiles, the primary and secondary monitoring paths, which are perpendicular to each other.

3.13
skewness

measure of asymmetry defined as the total flow to the left of the centre of the duct divided by the total flow to the right of the centre of the duct, or the inverse thereof, whichever is larger than 1,00

Note 1 to entry: If the measurement is made according to EN ISO 16911-1 and EN 15259, each measurement represents the same area of flow in the duct, and the skewness can be calculated from a simple average of the individual measurements, not including a possible measurement in the centre of the duct.

Note 2 to entry: Skewness shall be calculated for both flow profiles, perpendicular to each other.

3.14
swirl

also referred to as cyclonic flow, is the tangential component of the gas velocity vector

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3.15
certification range
range over which the flow monitor has been tested

Note 1 to entry: The certification range is normally from zero, if the instrument reads zero, or from the lower reference point, if the instrument does not read zero.

Note 2 to entry: The flow monitor is tested according to EN 15267-3 and EN ISO 16911-2.

3.16
primary monitoring path
P
line across the duct through the centre and where the maximum velocity is expected to be found

3.17
secondary monitoring path
S
line across the duct through the centre perpendicular to the primary monitoring path

3.18
Reynolds number
Re

$$Re = \rho v_m \frac{d}{\eta_{\mathrm{dyn}}} \tag{3}$$

where

ρ is the gas density, in kg/m^3;

v_m is the gas velocity, in m/s;

d is the duct diameter, in m;

η_{dyn} is the dynamic viscosity, in Pa s

4 Symbols and abbreviations

4.1 Symbols

a	intercept of the calibration function
b	slope of the calibration function
D_i	difference between measured SRM value y_i and calibrated AMS value $\hat{y}_i$
D_{AVG}	average of D_{i}
D	amount by which the AMS has to be adjusted when drift is detected
d	duct diameter
k_{v}, $k_{\mathrm{v}}(N)$	test value for variability (based on a χ^2-test, with a β-value of 50 %, for N numbers of paired measurements)
n	number of paired samples in parallel measurements
q_V	volume flow rate

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R^2	coefficient of determination from a linear regression
Re	Reynolds number
$R_{\mathrm{f.abs}}$	absolute reproducibility in the field
s_{D}	standard deviation of the differences D_i in parallel measurements
$t_{0,95(N-1)}$	two-sided Student *t*-factor at a confidence level of 95 % with $N - 1$ degrees of freedom
$t_{0,05(N-1)}$	two-sided Student *t*-factor at a confidence level of 5 %, with $N - 1$ degrees of freedom
v_{AVG}	weighted average of velocity across a monitoring path
$v_{\mathrm{L,\,AVG}}$	weighted average of velocity to the left of the centreline
$v_{\mathrm{L,\,12\,\%}}$	velocity measured at a point 12 % of the diameter from the duct wall to the left of the centreline, $\mathrm{L}_{12\,\%}$
v_{PEAK}	peak velocity value on the monitoring path
v_m	gas velocity, in m/s
$v_{\mathrm{R,\,AVG}}$	weighted average of velocity to the right of the centreline
$v_{\mathrm{R,\,12\,\%}}$	velocity measured at a point 12 % of the diameter from the duct wall to the right of the centreline, $\mathrm{R}_{12\,\%}$
x	measured signal obtained with the AMS at AMS measuring conditions
x_i	*i*th measured signal obtained with the AMS at AMS measuring conditions
x_{AVG}	average of AMS measured signals x_{i}
x_{1i}	*i*th measurement result of AMS 1
x_{2i}	*i*th measurement result of AMS 2
y	result obtained with the SRM
y_{AVG}	average of the SRM results y_{i}
y_{cal}	best estimate for the “true value”, calculated from the AMS measured signal x by means of the calibration function
η_{dyn}	dynamic viscosity, in Pa s
ρ	gas density, in kg/m^3
σ_0	uncertainty derived from requirements of legislation

4.2 Abbreviations

AMS	automated measuring system
AST	annual surveillance test according to EN 14181
CFD	computational fluid dynamics
ELV	emission limit value

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SRM	standard reference method
QA	quality assurance
QAL1	quality assurance level 1 according to EN 14181
QAL2	quality assurance level 2 according to EN 14181
QAL3	quality assurance level 3 according to EN 14181

5 Principle

5.1 General

To achieve the uncertainty required by the relevant EU Directives[1]–[3][5] and the EU Commission Decision,[4] the focus of EN ISO 16911-2 is the systematic error.

EN ISO 16911-2 allows three different ways of achieving high accuracy:

- assuring correct installation by means of a pre-investigation, see 7.2;
- establishing that a fully developed flow profile is present, see 7.3;
- assuring correct measurement by a quality assurance level 2 (QAL2), see 7.4.

Noting that, if a pre-investigation has been performed, the subsequent QAL2 and annual surveillance test (AST) may be reduced in scope, see 9.1 b).

EN ISO 16911-2 also introduces some extra requirements to type testing according to EN 15267-3, see Clause 6.

5.2 Importance of minimizing systematic errors

The uncertainties required in Commission Decision of 2007-07-18,[4] 2.1.3, are dependent on the “tier” of the plant and shall be:

- 10 % for tier 1;
- 7,5 % for tier 2;
- 5 % for tier 3;
- 2,5 % for tier 4.

These uncertainties include the uncertainty for both concentration monitoring and volume flow rate monitoring, and are uncertainties for the yearly mass emission.

The uncertainty of any measurement is combined from the uncertainties originating from random errors and systematic errors.

Since the random error component can be reduced by repeated measurements, and the factor it is reduced by, according to the general theory of propagation of errors, is the square root of the numbers of measurements, the random error component of the yearly average is negligible. For example, the yearly average is combined of (ideally) up to 17 520 half-hourly averages, in which case the uncertainty originating from the random error component carried from the individual half-hourly average is reduced by a factor of around 132.

However, the systematic error is not reduced by repeated measurements.

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In flow monitoring, systematic errors originate from a series of sources, e.g. changing flow profiles under plant operating conditions not covered by the calibration function or changes in the monitoring system, caused by contamination, blocking of holes, drift in electronics, and general wear and tear.

EN ISO 16911-2 therefore focuses on reducing the systematic error of each individual measurement.

Specifically, a pre-investigation test is recommended in order to assess whether the flow profile changes under different plant operating conditions and this test is used for the selection and configuration of the AMS.

5.3 Relationship to EN 14181

EN ISO 16911-2 is applicable in conjunction with the general document, EN 14181, on quality assurance (QA) of AMSs and provides indications which are specific to flow measurements.

EN ISO 16911-2 follows, as far as possible, the structure of EN 14181, with the caveat that the emission limit value (ELV) and the uncertainty limit specified as a 95 % confidence interval for flow monitoring are not stated in any EU Directive. Since these data are required by the procedure prescribed in EN 14181, suggestions for surrogate values are given in EN ISO 16911-2.

If a pre-investigation has been performed, the number of paired measurement points required for a calibration is reduced.

An alternative calibration method has been added (method D) using linear regression and forcing the regression line through the zero point.

6 Type testing, quality assurance level 1 data

6.1 Introduction

6.1.1 General

According to EN 14181 and EN 15267,[6] the flow monitoring system shall consist of all necessary parts to keep the flow monitor operating within a specified uncertainty. These components shall include, but are not limited to, necessary air-purging systems and auxiliary equipment to control continued operation within the stipulated uncertainty.

Either 6.1.2 or 6.1.3 applies as appropriate.

6.1.2 Requirements within the European Economic Area

The relevant performance characteristics of the AMS shall be documented by the manufacturer and/or his European representative by suitability tests performed according to the relevant European Standards.

6.1.3 Requirements outside the European Economic Area

The relevant performance characteristics of the AMS shall be documented by the manufacturer by suitability tests performed according to the relevant standards.

6.1.4 Conclusion

These tests are usually carried out in the framework of certification or type approval procedures according to EN 15267,[6] and the AMS delivered to the plant shall have the same characteristics as the tested devices. The tests comprise of a separate laboratory test and a 3 month field test in a typical application.

The test report shall include the total AMS uncertainty calculated according to EN 14181 and ISO 14956.

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6.2 Performance criteria

The requirements for the test results are developed from EN 15267-3 and stated in Table 1 and Table 2.

EN 15267-3 requires the manufacturer to describe, and the test laboratory to assess, the quality assurance level 3 (QAL3) functionality.

EN ISO 16911-2 also requires the manufacturer to describe and the test laboratory to assess the capability of the AMS to be linearity tested as a part of the functional test. If another test, other than the linearity test, is assessed and certified by a test laboratory, that test is sufficient as part of the functional test.

The manufacturer shall declare and quantify any influencing parameters known to affect instrument uncertainty, e.g. gas temperature, change in specific mass and/or specific heat capacity, gas composition, gas pressure, as well as any method of compensation.

Interference tests shall be performed and the sensitivity coefficients shall be calculated and reported according to EN 15267-3.

Using test results from the type approval certificate according to EN 15267-3 and ISO 14956, the total uncertainty, systematic and random, of the results obtained for the flow AMS shall be calculated and reported.

6.3 Flow reference material or procedure

Most volume flow rate monitors measure flow indirectly using an associated parameter, e.g. differential pressure, heat loss or transit time, in which case a flow reference material or procedure is used to test these parameters.

The part of the monitor not tested by the reference material or procedure shall be tested by a procedure described by the manufacturer and assessed and documented during the type approval.

The test laboratory shall assess whether the flow reference procedure provided for testing the AMS functionality challenges all or as much of the AMS as possible with a repeatable reference value and a specified uncertainty, see Table 1 and 2.

Table 1 — Automated measuring system performance criteria in laboratory tests

Performance characteristic	Performance criteria
Response time	≤60 s
Repeatability standard deviation at lower reference point	≤2,0 %[a]
Repeatability standard deviation at upper reference point	≤2,0 %[a]
Lack of fit	≤3,0 %[a]
Lower reference point shift due to ambient temperature change from 20 °C within specified range	≤5,0 %[a]
Upper reference point shift due to ambient temperature change from 20 °C within specified range	≤5,0 %[a]
Influence of voltage at +15 % and at −10 % from nominal supply voltage	≤2,0 %[a]
Influence of vibration	≤2,0 %[a]
Assessment of QAL3 check capability	Pass[b]
Assessment of linearity check capability	Pass[b]

[a] Percentage value as percentage of the upper limit of the certification range.

[b] The test house shall assess the possibility for the test procedure as described in 6.2.

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Table 2 — Automated measuring system performance criteria in field tests

Performance characteristic	Performance criteria
Coefficient of determination of calibration function, R^2	≥0,90
Response time	≤60 s
Period of unattended operation (maintenance interval)	≥8 days
Lower reference point drift within maintenance interval	≤2 %[a]
Upper reference point drift within maintenance interval	≤4 %[a]
Availability	≥95 %
Reproducibility, R_f	≤3,3 %

[a] Percentage value as percentage of the upper limit of the certification range.

6.4 Quality assurance level 1 calculation

6.4.1 General

Either 6.4.2 or 6.4.3 applies as appropriate.

6.4.2 Requirements within the European Economic Area

The AMS shall be approved and certified according to EN 15267-3 and the additional requirements in EN ISO 16911-2.

6.4.3 Requirements outside the European Economic Area

The AMS shall meet the requirements specified in EN 15267-3 and the additional requirements in EN ISO 16911-2.

6.4.4 Conclusion

The instrument configuration shall be audited by the test laboratory during type testing, and this auditing shall include the geometrical configuration, including measurement of the duct cross-sectional area and any reference quantity with an influence on the flow monitoring result, e.g. changes in flow profile, changes in temperature, changes in pressure, changes in gas composition, and contamination.

All of these influences shall be estimated within a combined expanded uncertainty, calculated as described in ISO 14956.

The test laboratory shall assess the influence of the change in flow profile on the flow monitor reading.

NOTE This facilitates the end user to estimate the expected flow profile influence, when the result of the pre-investigation is known.

6.5 Velocity check points and quality assurance level 3

EN 15267-3 requires the manufacturer to provide a description of the methodology used by the AMS to determine whether it is operating according to its product specification. This is made up of AMS checks (automatic or manual internal zero point or lower reference point and upper reference point), combined with an additional procedure, if the instrument checks do not challenge the whole measurement chain.

The test laboratory shall assess whether the mechanism for determining the internal reference points, being at zero or defined lower reference velocity and upper reference velocity points, is as comprehensive as is practical for the measurement technique used. The internal control combined with a procedure shall be capable of detecting instrument malfunction, including problems caused by contamination and internal drift.

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The manufacturer shall provide details of this procedure in the instruction manual describing how to ensure the correct operation of the parts of the measurement not tested by the internal reference point checks.

The QAL3 test shall be made up of the reference point checks and, if required, the results of the inspection procedure.

7 Selection of automated measuring system location

7.1 General

The axial position of the AMS on the duct (normally vertical) as well as its circumferential position on the duct perimeter may have a significant influence on the AMS performance.

It is strongly recommended that a pre-investigation be performed as described in Clause 8 in order to characterize the flow so that the AMS can be located in a position where changes in the flow profile do not adversely affect AMS performance.

NOTE To reduce costs, the pre-investigation can be done together with the investigation of the homogeneity test required by EN 15259.

The pre-investigation also enables the operator to determine whether a point AMS, probe AMS or cross-duct AMS measurement satisfies the uncertainty requirements of EN ISO 16911-2, see Table 2.

NOTE The EU Directive 2010/75/EU[5] states in Article 38, Section 3, and in Article 48, Section 3, that "The competent authority shall determine the location of the sampling or measurement points to be used for the monitoring of emissions".

This section is intended to be a guideline for operators to enable them to make a good engineering decision.

If more than one AMS is being used, the AMSs shall be mounted so that they do not interfere with one another.

7.2 Selection based upon pre-investigation

A pre-investigation shall be performed according to Clause 8.

The location shall be chosen to give a representative measurement that also minimizes influence of changes in the flow profile on the flow measurement uncertainty.

The proposed location and monitoring path(s) shall be determined based upon the recorded change in flow profile, quantified using the crest factor and skewness of the flow profile as described in Annex F.

The installer shall select the AMS measurement location in accordance with the instructions given by the manufacturer or in consultation with the manufacturer's representative. The operator is advised to liaise with the competent authority to ensure this location meets with their approval.

7.3 Selection based upon a predictable flow profile

The position of an AMS may be decided without a pre-investigation if it can be positioned in a place where the flow profile is fully developed and cannot change, and if it is accepted by the competent authority.

This is normally achieved if all of the following criteria are fulfilled:

— the monitoring point is at least 25 times the hydraulic diameter, away from any upstream disturbance, and at least five times the hydraulic diameter from any downstream disturbance;

— the flow has a Reynolds number larger than 10 000;

— the duct has no movable dampers or guide vanes;

— the duct does not have multiple feeds;

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— the duct does not have off centre feeds.

If the above conditions are all met, any AMS should be suitable, including measurement at a single point.

NOTE For a fully developed turbulent flow, in a duct with a circular cross-section, the average flow is expected to be identical to the flow at a point 12 % of the diameter from the wall.

In this case the QAL2 procedure may be performed according to Clause 9 with a reduced number of data points.

If this installation does not pass the QAL2 procedure, as specified in Clause 9, even though the above conditions are fulfilled, the procedure described in 7.4 shall be used, or a pre-investigation shall be carried out as described in Clause 8.

7.4 Qualifying the automated measuring system calibration through a type 2 quality assurance level 2 procedure

An operator may opt not to perform a pre-investigation, e.g. where there is pre-existing equipment installed, provided that a type 2 QAL2 procedure is performed and passed.

The installation can be approved according to EN ISO 16911-2 without having made a pre-investigation, if the QAL2 calibration is performed with measurement points spread from the highest flow rate the plant is designed to operate at continuously, down to the lowest flow rate the plant is designed to operate at continuously (at least the flow rate so low, that is occurring lower no more than 10 % of the plant's normal operation time or the point of minimum stable load), and the calibration passes the criteria described in Clause 9.

NOTE This subclause does not remove the requirement of the operator to perform the duct investigation tests as described in EN 15259.

7.5 Ports and working platforms

The measurement ports and platforms for the parallel measurements shall be located to ensure that there is no measurable interference between the SRM and the AMS.

Working platform(s) shall provide an easy and safe access to the AMS, to allow inspection and the implementation of QA procedures (QAL2, AST and QAL3).

The working platform for the SRM shall comply with EN 15259 requirements related to the manual method.

8 Pre-investigation of flow profile

8.1 General

The stability of the flow profiles, as the plant operating conditions change, is a major concern with regards to flow monitor calibration. If the flow profile changes as the plant load condition changes, or as dampers are operated, or as different duct inlets are brought into operation, this shall be taken into account when deciding on the type of flow AMS to install, and when performing the calibration.

In order to minimize any systematic error associated with a non-representative measurement, it is recommended that the plant operator measure or calculate any change in the cross-duct flow profile at the AMS location as the plant operating conditions are changed. Therefore, either a CFD calculation or pre-investigation by measurement of the change in flow profile under different flow conditions at the AMS location shall be undertaken enabling the plant operator to make an informed engineering decision on whether a single point AMS, an AMS with a limited path length, cross-duct single path AMS or cross-duct

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double path AMS measurement principle is sufficient for minimizing systematic error under the likely conditions of the plant at the intended location, i.e. at different plant operating conditions and flow levels.

NOTE 1 The predominant source of systematic error is the change in the flow profile. The major sources of changes in flow profile are changes to the disturbances in the duct, or large changes in flow rate. At high gas velocities, the flow profile is expected to be fully developed, and not to change profile even at higher gas velocities, see Annex B for details of flow profile characterization. At lower gas velocities, the flow profile might develop asymmetry and/or a higher crest factor, and consequently the relation between a point or line measurement and the volume flow rate changes, which is identical to a change in calibration function.

The pre-investigation shall establish the main characteristics of the flow profile at the planned AMS installation position and establish if changes in profile are likely to occur and the severity of their influence on the calibration function.

The pre-investigation shall always be undertaken as a part of the design phase before an AMS flow monitor is acquired and mounted.

NOTE 2 Part of the pre-investigation process is identical to the EN 15259 investigation, and can be combined with that to minimize costs.

A pre-investigation may be omitted as described in 7.2, in which case a type 2 calibration procedure as described in Clause 9 shall be used for any subsequent QAL2 and AST calibration.

A type 1 QAL2 and AST calibration procedure as described in Clause 9 may only be used if a pre-investigation according to Clause 8 has been performed.

NOTE 3 The choice of not performing a pre-investigation according to Clause 8 does not in any way influence the obligation to test the duct condition according to EN 15259.

8.2 Pre-investigation by measurement

8.2.1 General

The pre-investigation shall consist of at least two measurements performed according to EN ISO 16911-1, each establishing the flow profile in the primary monitoring axis, and an axis perpendicular to this.

The two measurements shall be performed at two different plant operating conditions:

a) one where the flow profile is expected to be the most uniform, i.e. close to the highest possible flow rate and with the least possible obstruction to the flow path;

b) one where the flow rate is so low, that it is not occuring lower more than 10 % of the plant's normal operation time or the point of minimum stable operation, combined with the maximum obstruction to the flow path, e.g. closure of dampers or regulation of the fan blowers.

NOTE 1 Least possible obstruction means that the effects of any non-permanent obstructions are minimized or removed.

If a plant has not yet been commissioned, the lowest flow level shall be estimated from plant design data.

NOTE 2 If an AMS is installed in a multi-inlet duct, it may be necessary to calibrate the AMS at different production configurations since changes to the relative contributions of the individual inlets can produce different calibration functions.

From the two measurements at high and low flow rates, the reproducibility of the normalized flow calculated for each of the measuring planes shall be calculated, and crest factor and skewness shall be calculated for each of the four profiles.

From these data the AMS selection is evaluated as described in 8.4.

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At complicated installations, or those with the potential for the flow profiles to change with the operating conditions (e.g. flow splitting immediately upstream of the duct), further investigations may be required to fully describe the flow profile complexity.

8.2.2 Measuring flow profiles in a duct

The flow profile shall be measured in accordance with EN ISO 16911-1 which specifies that the measurement points are selected in accordance with EN 15259 along the primary and secondary measurement paths. EN 15259 also requires that the velocity is measured simultaneously at a fixed reference point. The flow profile is calculated by correcting the individual measurements with the reference point flow.

8.2.3 Measurement method

The flow profiles shall be measured with an SRM as described in EN ISO 16911-1 and the measurement plan shall be in accordance with EN 15259.

After completion of the two profile measurements along the primary and secondary measurement paths, all of the measurement results shall be corrected to account for changes in the fixed point reference velocity.

This procedure shall be performed at a high flow rate and a low flow rate, as described in 8.2.1.

An example is shown in Annex F.

8.3 Pre-investigation by computational fluid dynamics (CFD)

A physical pre-investigation as described in 8.2.1 may be replaced by a CFD assessment to establish the flow profiles, which are assessed as described in Annex G, if a physical pre-investigation is not possible or is likely not to yield a sufficient result.

NOTE A CFD pre-investigation is acceptable e.g. if the plant is not yet built, or if the duct configuration is so complicated, that conditions for SRM-measurements cannot be fulfilled.

CFD is an established method for pre-investigation of the flow conditions in a duct or a pipeline.

The CFD requires accurate information about the route and the geometrical dimensions of the ductwork including the upstream section. Furthermore, important basic design parameters have to be considered (e.g. the number and position of the duct inlets, the plant load and the gas velocity range).

Based on this information, the flow is modelled using specialized software. The results of the computer simulation are processed and evaluated using two- or three-dimensional graphics from which the flow profiles can be created.

This can be used:

- to determine the expected flow profile changes as the plant operation conditions are changed;
- to assist the selection of the AMS type (single point AMS, a single probe AMS with limited path length, one path cross-duct AMS, two path cross-duct AMS etc.);
- to determine the optimal position of the AMS.

The accuracy of the CFD depends strongly on the quality and quantity of the input data (geometry and process conditions) and the use of a suitable model for the calculation.

The CFD shall be used to characterize the flow as described in 8.1.

The input data and the results of the pre-investigation by CFD shall be retained by the operator for inspection by the competent authority.

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8.4 Automated measuring system selection guide

Based upon the results of reproducibility, skewness and crest factor, an example is shown in Annex F, the plant operator may select the measurement type for the AMS using Table 3. The flow reproducibility is a measure of the difference in flow profiles at the two test flow rates. The crest factor and skewness to be used are the maximum values derived from the two measured flow profiles.

The guideline is informative, and the configuration shall be chosen in cooperation with the manufacturer. The installation shall in any case pass the QAL2 requirements of EN ISO 16911-2.

The test for the presence of swirl shall be performed in accordance with EN ISO 16911-1.

Table 3 — Skewness and crest factor

Reproducibility of normalized profile%	Crest factor	Skewness	Measurement type	Comments
<5,0 %	<1,3	<1,2	Point measurement or measurement with limited path length	Flow profile not likely to change
>5,0 %	<1,3	<1,2	One cross-duct monitoring path	Flow profile is expected to change with flow rate
	>1,3	<1,2	One cross-duct monitoring path in the plane with the highest skewness	Flow profile is expected to change considerably with flow rate
	>1,3	>1,2	Two cross-duct monitoring paths (along the primary and secondary measurement paths)	A skewed flow profile, possibly due to swirl, i.e. the point in the profile with the maximum flow rate is rotating and the best way to secure a representative average is to monitor in a cross or across two chords

8.5 Quality assurance level 2 requirements

If subsequently the chosen configuration does not meet the requirement of QAL2, as specified in Clause 9, a more representative measurement approach, as exemplified in the informative Annex C, shall be used.

It is recommended in these cases that an accredited duct test laboratory and the AMS manufacturer be consulted.

9 Calibration and validation of the automated measuring system (quality assurance level 2 and annual surveillance test)

9.1 Selection of calibration method

Calibration of a volume flow rate monitor can be performed in two different ways, depending upon whether the pre-investigation is conducted in accordance with Clause 8:

a) a type 1 QAL2 and AST calibration procedure if the pre-investigation has been performed or the conditions of 7.3 are fulfilled;

b) a type 2 QAL2 and AST calibration procedure if a pre-investigation has not been performed and the conditions of 7.3 are not fulfilled.

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This clause covers both calibration procedures.

NOTE EN ISO 16911-2 prescribes the QA/QC procedure for flow monitors following EN 14181 as closely as possible, noting that EN 14181 does not specifically apply to flow monitors. This includes recommendations for surrogate values for the ELV and uncertainty derived from requirements of legislation, σ_0, in order to perform the variability test as part of the calibration acceptance test.

9.2 Selection of calibration method, if calculation methods are used

9.2.1 Fuel based

When the AMS is based on a calculation method, this shall follow EN ISO 16911-1:2013, Annex E and the calculation shall be verified according to this clause by means of a QAL2 and checked yearly by means of an AST in accordance with EN 14181. If QAL2 or AST fails, the calculation procedure shall be investigated and if necessary rectified prior to retesting by QAL2.

9.2.2 Surrogate based

When the AMS is based on a surrogate approach, such as a fan characteristic or the pressure drop across a plant component, the AMS shall be calibrated according to this clause by means of a QAL2 and checked yearly by means of an AST in accordance with EN 14181. If QAL2 or AST fails, the calculation procedure shall be investigated and if necessary rectified prior to retesting by QAL2.

9.3 Calibration procedure

EN 14181:2004, 6.1 and 8.1 apply with the following modifications.

The calibration of an AMS volume flow rate monitor is performed as described in EN 14181, with the exception that the flow monitor shall be calibrated in units of volume flow rate, m^3/s, under the actual operating conditions.

The quality assurance level 1 (QAL1) documentation shall, further to the certification of the AMS to EN 15267-3 and the requirements given in Table 1 and 2, include an assessment by the test laboratory, performing the QAL2, in consultation with the competent authority, that the configuration of the AMS is suitable for this specific flow profile, as recommended in Clause 7.

9.4 Functional tests

EN 14181:2004, 6.2 and 8.1 apply with the following modifications.

A functionality test, using reference materials or surrogates, as certified according to EN 15267-3 shall be performed according to EN 14181.

The instrument configuration shall be audited by the test laboratory before any QAL2 or AST measurement. The auditing shall include the geometrical configuration, including measuring the duct cross-sectional area and assessing the uncertainty, due to variation in operation, of any reference quantity with an influence on the flow monitoring result, e.g. temperature, pressure, gas composition.

9.5 Parallel measurements with a standard reference method

EN 14181:2004, 6.3 and 8.2 apply with the following modifications.

EN 14181 states that the results obtained from the SRM shall be expressed under the same conditions as those measured by the AMS, which is normally m/s.

NOTE 1 The calibration is normally expressed in m^3/s in operation condition if the dilution tracer method is used.

The SRM method for volume flow rate shall be performed in accordance with EN ISO 16911-1.

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The tracer transit time method measures the average velocity directly, and the tracer dilution method measures the volume flow rate directly.

None of the tracer methods give any information of the flow profile. If, however, calibration of flow monitors is the only purpose of the measurement campaign, the tracer methods may be used.

NOTE 2 The vane anemometer is especially suited for low flow velocity conditions.

The Pitot tube and vane anemometer method performed in accordance with EN ISO 16911-1 provide information of the flow profile, from which the volume flow rate is calculated.

NOTE 3 Pitot tube and vane anemometer methods are slower when compared to the tracer methods. They can, however, be combined with measurement of pollutant concentration, and therefore still be economically advantageous.

In order to ensure that the calibration function is valid for the range of conditions within which the plant is to operate, the flow rate during the calibration shall be varied as much as possible within the operations of the plant during the calibration.

If a pre-investigation has proven that the flow monitor reads correctly at volume flow rates so low that it is occurring lower no more than 10 % of the plant's normal operation time or the point of minimum stable load, it is acceptable to perform a calibration even if the data points are not spread out.

The pre-investigation together with the functional test ensures that the calibration of the AMS is valid over as large a range as possible, and also that it covers most operational situations and flow profiles.

If a pre-investigation has not been performed, the range during calibration shall span from maximum volume flow rate the plant is designed for under normal operation down to a volume flow rate so low that it is occurring lower no more than 10 % of the plant's normal operation time or the point of minimum stable load. This is to prove that the flow monitor is correctly calibrated in this range.

The minimum numbers of paired data points (traverses if a point velocity technique is used) are listed in Table 4.

Table 4 — Method overview

Condition to be met	**Type 1**	**Type 2**
	Pre-investigation has been performed	Pre-investigation has not been performed
Minimum number of paired data points for QAL2 calibration	9	15
Minimum number of paired data points for AST	4	5
Upper limit of calibration range	No restrictions	Maximum flow rate for normal operation
Lower limit of calibration range	No restrictions	Flow rate not fallen below more than 10 % of the plant's normal operation time

The QAL2 and AST procedure shall be performed to obtain data points that are evenly spread out over a minimum of 5 h.

The EN 14181 minimum requirement of performing the calibration over a minimum of 3 days is not required.

9.6 Wall effects

When the calibration of the AMS is based on a velocity profile measurement, a wall adjustment factor shall be applied as specified in EN ISO 16911-1.

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9.7 Automated measuring system flow calibration procedure with transit time tracer

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 at a given flow rate, several measurement repetitions (normally 7 to 15) are made. The number of flow rates tested should preferably be 2 to 3 to obtain a good and representative calibration result.

Since transit time measurements are very fast, noting that several measurements can be made every minute, it is of paramount importance that the flow monitor set up be changed to enable it to output with an averaging time of a few seconds, since with longer time constants simultaneous comparison becomes more difficult and tends to increase the stochastic uncertainty component in the calibration. Furthermore, the time delay of the gas flow from the flow AMS to the measurement point shall be considered when the comparison is performed, if there is a long physical distance between them.

When calibrating an AMS, its flow signal is to be registered by the transit time measurement equipment with short time intervals in order to allow simultaneous comparison of the volume flow determined by the trransit time method with the flow value given by the AMS.

9.8 Data evaluation

EN 14181:2004, 6.4 and 8.3 apply with the following modifications.

Since a special source of uncertainty for some flow monitor technologies is the relation between the actual total volume flow rate (measured in m^3/s) and the parameter monitored (e.g. averaged gas flow in m/s at one or more points or averaged over a line or a section of an area), the calibration function shall always be tested for non-linearity. If a polynomial calibration function results in a higher coefficient of determination of calibration function, R^2, and/or lower variability, the polynomial calibration line may be used.

NOTE A linear calibration function may also be used, if it passes the R^2 and variability criteria. It is the choice of the plant operator in consultation with the competent authority.

Since the duct area is an important factor to calculate volume flow rate from average gas velocity the result of the measurement or auditing of the duct area shall be noted in the test report, and any deviation exceeding the tolerance stated in Clause 6 from the values already used by the plant shall be investigated and reported.

9.9 Calibration function of the automated measuring system and its validity

9.9.1 General

EN 14181:2004, 6.5 applies with the modification in 9.9.2.

9.9.2 Linear calibration function (method D)

If the spread of data is less than 30 % of the maximum SRM value, a calibration function calculated as a linear regression forced through the lower reference point (which is zero point if the AMS reads zero) may be used provided the functional test has proven that the volume flow rate monitor is linear down to the lower reference point or zero.

NOTE A linear calibration function forced through zero may be used, even if the spread of data is more than 30 %, provided the variability and R^2 requirement are fulfilled and the competent authority agrees to the choice.

The valid calibration function is extrapolated upwards to 120 % of the highest value of the volume flow rate during the QAL2 or AST and downwards to the lowest test point of the functionality test. If the flow AMS can measure at zero, the lowest test point shall be zero.

If the flow AMS is based upon monitoring differential pressure, the calibration range downwards is in any case limited to a flow rate corresponding to a differential pressure of 5 Pa.

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The historical data for the AMS shall be examined and these shall be consistent with plant conditions (e.g. shut down) within the past 6 months.

9.9.3 Polynomial calibration function

If a polynomial calibration function results in a higher R^2 and/or lower variability than a linear calibration function, the polynomial calibration function may be used.

NOTE It is always acceptable according to EN ISO 16911-2 to use a linear calibration function, even if the R^2 are lower and/or the variability is higher, if it passes the test criteria. It is the choice of the plant operator in consultation with the competent authority.

When using a polynomial calibration function, the behaviour of the calibration function, outside the range where paired measurement points are available, is unpredictable and special precautions shall be taken. These are specified in Annex D.

9.10 Calculation of variability

EN 14181:2004, 6.6 and 8.4 shall apply with the following modification.

Since volume flow rate has no ELV prescribed in an EU Directive, 120 % of the maximum volume flow rate during the QAL2 test shall be used as the ELV, but not lower than 10 m/s, unless the competent authority has given other instructions.

NOTE 1 This corresponds to the top of the valid calibration range.

Since flow rate has no prescribed uncertainty in an EU Directive, σ_0 = 4 % in operation condition shall be used, unless the competent authority has given other instructions.

NOTE 2 The σ_0 in EN 14181 from the relevant EU Directive refers to concentrations in normalized conditions, but in EN ISO 16911-2 σ_0 is calculated in the condition of the duct gas at the time of the calibration.

Outliers may be removed in accordance with good engineering practice, but the calibration curve shall still be based upon the required number of independent parallel measurements, and outliers shall be reported and shown in the diagrams.

9.11 Test of variability and annual surveillance test of validity of the calibration function

EN 14181:2004, 6.7 and 8.5 shall apply.

9.12 Test of R^2

Further to the requirements of EN 14181, but in accordance with the test criterion of EN 15267-3, a calculation of R^2 shall be performed, and the calibration shall pass the criterion of Table 2, i.e. $R^2 > 0{,}90$.

If a pre-investigation has been performed, and the method D calibration is based upon a very tight cluster, where the spread of data in both SRM and AMS values are both less than 15 % of the corresponding average value during the calibration, fulfilment of the R^2 condition is not required.

NOTE Pearson's coefficient of correlation, the R^2 calculation, is based upon data points being widely spaced. If it is calculated for a tight cluster of data points, it is possible that the data set does not exhibit any correlation and consequently R^2 can be very low. However, this may produce an acceptable calibration within the terms of EN 14181. If data are widely spaced, the R^2 calculation is a good indicator of the quality of the calibration.

9.13 Quality assurance level 2 and annual surveillance test report

EN 14181:2004, 6.8 and 8.6 apply with the following modifications.

The QAL2 and AST report shall specifically focus on an evaluation of the total systematic uncertainty, including that from changes in flow profile, and the method chosen for minimizing this.

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All measurement points shall be reported in a table as well as in a diagram which also shows the chosen regression function.

Outliers, not used in the calculation of the regression function, shall be shown in the diagram together with the rest of the measurement points and the regression function, and the method or reason for identifying outliers shall be reported.

Since the changes in flow profile are the major source of systematic error, the flow profiles measured during the QAL2 or AST procedure shall always be reported in a diagram for each measurement series (traverse) and evaluated by the test laboratory.

NOTE If a tracer method is used, the flow profile cannot be established.

10 Commissioning documentation

After commissioning, the configuration documentation, the functional test and QAL2 documentation shall be stored and available for audit by the responsible authority.

Changes and periodic verifications, e.g. after the AST, referenced back to commissioning or the last QAL2 shall also be recorded in an auditable manner.

11 On-going quality assurance during operation (quality assurance level 3)

QAL3 shall be performed in accordance with the requirements of EN 14181. In addition, the following applies.

QAL3 internal reference point measurements shall be performed at least at a time interval corresponding to the maintenance interval, as established during the type test according to EN 15267-3.

12 Assessment of uncertainty in volume flow rate

The overall uncertainty of the AMS measured values shall be calculated in accordance with ISO 14956 on the basis of the performance characteristics determined during the general performance test and shall meet the uncertainty required for the measurement objective.

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Annex A
(informative)

Example of calculation of the calibration function (data from tests in Copenhagen and Wilhelmshaven)

A.1 Calculation of calibration data according to method A (data from Copenhagen)

This is an example of calibration using S-type Pitot tubes according to EN ISO 16911-1.

Calibration procedure is made as a linear least square regression, and the spread of data is so low that the R^2 test is not required. See Table A.1.

Table A.1 — Example of calibration made in accordance with method A (data from Copenhagen)

No.	AMS m/s x	SRM m/s y	$x - x_{avg}$	$y - y_{avg}$	$(x - x_{avg})^2$	$(y - y_{avg})^2$	y_{cal}	D	$(D - D_{avg})^2$
1	20,89	19,84	0,60	0,16	0,36	0,03	20,104	−0,264	0,069 5
2	21,00	20,05	0,71	0,37	0,50	0,14	20,182	−0,132	0,017 4
3	20,62	20,38	0,33	0,70	0,11	0,49	19,911	0,469	0,219 7
4	20,50	20,32	0,21	0,64	0,04	0,41	19,826	0,494	0,244 3
5	19,21	19,03	−1,08	−0,65	1,18	0,42	18,907	0,123	0,015 2
6	19,98	19,44	−0,31	−0,24	0,10	0,06	19,455	−0,015	0,000 2
7	20,17	19,38	−0,12	−0,30	0,02	0,09	19,591	−0,211	0,044 4
8	20,08	19,31	−0,21	−0,37	0,05	0,14	19,527	−0,217	0,046 9
9	20,43	19,76	0,14	0,08	0,02	0,01	19,776	−0,016	0,000 3
10	20,06	19,28	−0,23	−0,40	0,05	0,16	19,512	−0,232	0,054 0
av	20,29	19,68						0,0	

N =	10	
Min	19,21	19,03
Max	21,00	20,38
SP	9 %	7 %
R^2-test?		**No**

b =	0,712 5
a =	5,219 5
R^2 =	0,632 2

s_D =	0,281 m/s
σ_0 =	4 %
k_v =	0,962 9
Max s_D =	0,942 m/s
Variability ok	

SRM: Measurements from standard reference method
AMS: Measurements from continuous working flow monitor
av: Average from the column above.
b: Regression line gradient
a: Regression line intercept
R^2: Coefficient of determination
Min: The lowest value measured from the column above
Max: The highest value measured from the column above
SP: Spread of data determined max. minus min., divided by the average value
N: Number of measurements (traverses)
Max s_D: The maximum allowable s_D calculated from the number of measurements and a σ_0 of 4 %

The result is shown in Figure A.1.

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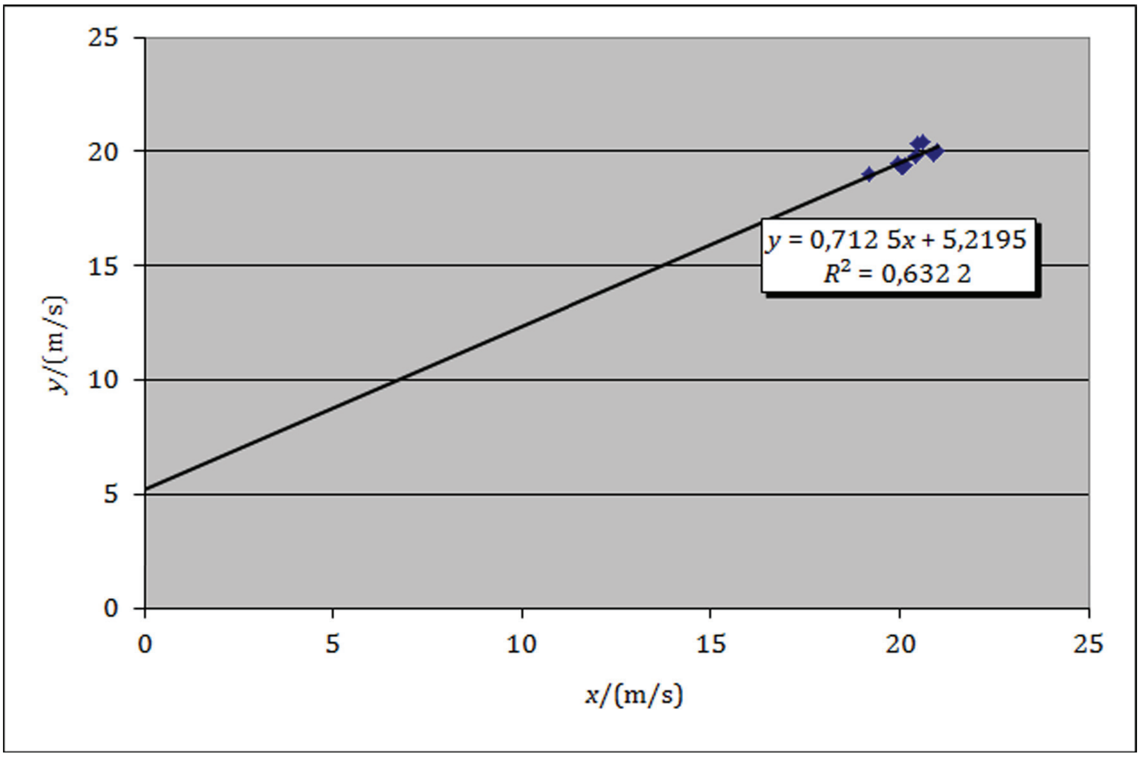

Key

CPH	data from Copenhagen validation test
S2	SRM performed with S-type Pitot tubes
A	calibration procedure A (least squares regression)
y	measurements from standard reference method (SRM)
x	measurements from continuous working flow monitor (AMS)

Figure A.1 — Example of calibration made in accordance with method A (data from Copenhagen)

A.2 Calculation of calibration data according to method D (data from Copenhagen)

This is an example of calibration using S-type Pitot tubes according to EN ISO 16911-1.

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Calibration procedure is made as a linear least squares regression with the regression line forced through zero, and the spread of data is so low, that the R^2 test is not required. See Table A.2.

Table A.2 — Example of calibration made in accordance with method D (data from Copenhagen)

No.	AMS m/s x	SRM m/s y	$x - x_{avg}$	$y - y_{avg}$	$(x - x_{avg})^2$	$(y - y_{avg})^2$	y_{cal}	D	$(D - D_{avg})^2$
1	20,89	19,84	0,60	0,16	0,36	0,03	20,253	−0,413	0,173 7
2	21,00	20,05	0,71	0,37	0,50	0,14	20,360	−0,310	0,098 3
3	20,62	20,38	0,33	0,70	0,11	0,49	19,991	0,389	0,148 2
4	20,50	20,32	0,21	0,64	0,04	0,41	19,875	0,445	0,194 7
5	19,21	19,03	−1,08	−0,65	1,18	0,42	18,624	0,406	0,161 6
6	19,98	19,44	−0,31	−0,24	0,10	0,06	19,371	0,069	0,004 3
7	20,17	19,38	−0,12	−0,30	0,02	0,09	19,555	−0,175	0,032 0
8	20,08	19,31	−0,21	−0,37	0,05	0,14	19,468	−0,158	0,026 1
9	20,43	19,76	0,14	0,08	0,02	0,01	19,807	−0,047	0,002 6
10	20,06	19,28	−0,23	−0,40	0,05	0,16	19,448	−0,168	0,029 6
av	20,29	19,68						0,0	

N =	10	
Min	19,21	19,03
Max	21,00	20,38
SP	9 %	7 %
R^2-test?		**No**

b =	0,969 5
a =	0,000 0
R^2 =	0,549 9

s_D =	0,311 m/s
σ_0 =	4 %
k_v =	0,962 9
Max s_D =	0,942 m/s
Variability ok	

SRM: Measurements from standard reference method
AMS: Measurements from continuous working flow monitor
av: Average from the column above.
b: Regression line gradient
a: Regression line intercept
R^2: Coefficient of determination
Min: The lowest value measured from the column above
Max: The highest value measured from the column above
SP: Spread of data determined as max. minus min., divided by the average value
N: Number of measurements (traverses)
Max s_D: The maximum allowable s_D calculated from number of measurements and σ_0 of 4 %

The result is shown in Figure A.2.

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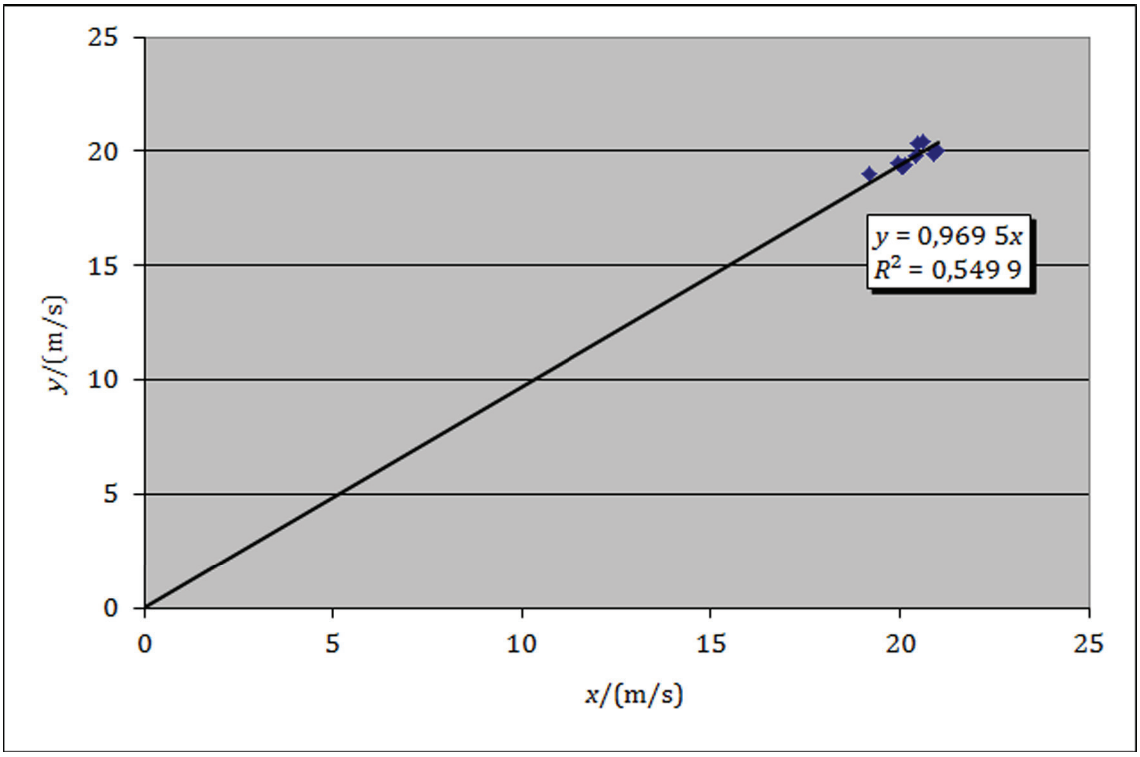

Key

CPH	data from Copenhagen validation test
S2	SRM performed with S-type Pitot tubes
D	calibration procedure D (least square regression forced through zero)
y	measurements from standard reference method (SRM)
x	measurements from continuous working flow monitor (AMS)

Figure A.2 — Example of calibration made in accordance with method D (data from Copenhagen)

A.3 Calculation of calibration data according to method A (data from Wilhelmshaven)

This is an example of calibration using L-type Pitot tubes according to EN ISO 16911-1.

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Calibration procedure is made as a linear least squares regression and the spread of data is sufficiently high for the R^2 test to be required. See Table A.3.

Table A.3 — Example of calibration made in accordance with method A (data from Wilhelmshaven)

No.	AMS m/s x	SRM m/s y	$x - x_{avg}$	$y - y_{avg}$	$(x - x_{avg})^2$	$(y - y_{avg})^2$	y_{cal}	D	$(D - D_{avg})^2$
1	28,88	28,31	2,61	2,77	6,79	7,67	28,266	0,044	0,001 9
2	24,65	23,78	−1,62	−1,76	2,64	3,10	23,841	−0,061	0,003 8
3	30,69	30,37	4,42	4,83	19,50	23,32	30,160	0,210	0,044 2
4	24,35	23,57	−1,92	−1,97	3,70	3,88	23,528	0,042	0,001 8
5	24,40	23,74	−1,87	−1,80	3,51	3,24	23,580	0,160	0,025 6
6	24,51	23,57	−1,76	−1,97	3,11	3,88	23,695	−0,125	0,015 6
7	24,47	23,68	−1,80	−1,86	3,26	3,46	23,653	0,027	0,000 7
8	29,56	28,87	3,29	3,33	10,79	11,08	28,978	−0,108	0,011 6
9	27,99	27,07	1,72	1,53	2,94	2,34	27,335	−0,265	0,070 4
10	24,79	23,92	−1,48	−1,62	2,20	2,63	23,988	−0,068	0,004 6
11	24,73	24,07	−1,54	−1,47	2,39	2,16	23,925	0,145	0,021 0
av	26,27	25,54						0,0	

N =	11	
Min	24,35	23,57
Max	30,69	30,37
SP	24 %	27 %
R^2-test?		**Yes**

b =	1,046 1
a =	−1,944 5
R^2 =	0,997 0
R^2 ok	

s_D =	0,142 m/s
σ_0 =	4 %
k_v =	0,966 5
Max s_D =	1,409 m/s
Variability ok	

SRM: Measurements from standard reference method

AMS: Measurements from continuous working flow monitor

av: Average from the column above

b: Regression line gradient

a: Regression line intercept

R^2: Coefficient of determination

Min: The lowest value measured from the column above

Max: The highest value measured from the column above

SP: Spread of data determined as max. minus min., divided by the average value

N: Number of measurements (traverses)

Max s_D: The maximum allowable s_D calculated from number of measurements and σ_0 of 4 %

The result is shown in Figure A.3.

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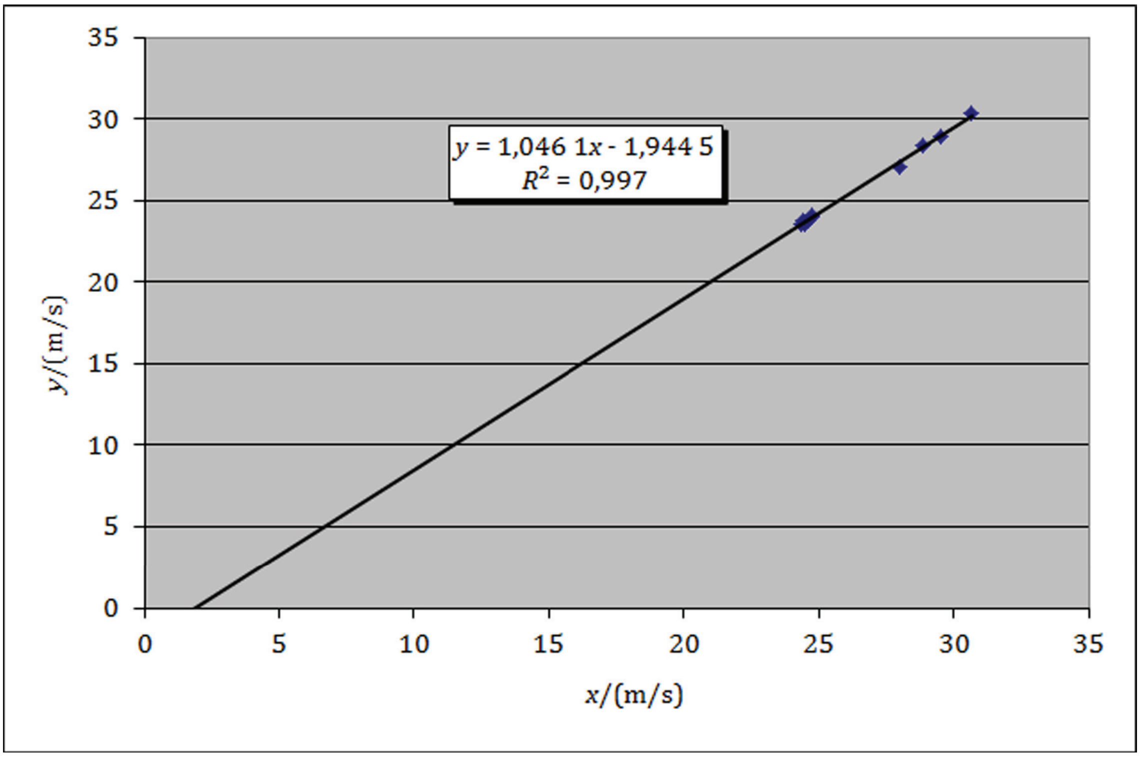

Key

WIH	data from Wilhelmshaven validation test
L1	SRM performed with L-type Pitot tubes
A	calibration procedure A (least square regression)
y	measurements from standard reference method (SRM)
x	measurements from continuous working flow monitor (AMS)

Figure A.3 — Example of calibration made in accordance with method A (data from Wilhelmshaven)

A.4 Calculation of calibration data according to method D (data from Wilhelmshaven)

This is an example of calibration using L-type Pitot tubes according to EN ISO 16911-1.

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Calibration procedure is made as a linear least squares regression with regression line forced through zero, and the spread of data is so high that the R^2 test is required. See Table A.4.

Table A.4 — Example of calibration made in accordance with method D (data from Wilhelmshaven)

No.	AMS m/s x	SRM m/s y	$x - x_{avg}$	$y - y_{avg}$	$(x - x_{avg})^2$	$(y - y_{avg})^2$	y_{cal}	D	$(D - D_{avg})^2$
1	28,88	28,31	2,61	2,77	6,79	7,67	28,092	0,218	0,055 1
2	24,65	23,78	−1,62	−1,76	2,64	3,10	23,977	−0,197	0,032 7
3	30,69	30,37	4,42	4,83	19,50	23,32	29,852	0,518	0,285 3
4	24,35	23,57	−1,92	−1,97	3,70	3,88	23,685	−0,115	0,009 8
5	24,40	23,74	−1,87	−1,80	3,51	3,24	23,734	0,006	0,000 5
6	24,51	23,57	−1,76	−1,97	3,11	3,88	23,841	−0,271	0,064 8
7	24,47	23,68	−1,80	−1,86	3,26	3,46	23,802	−0,122	0,011 2
8	29,56	28,87	3,29	3,33	10,79	11,08	28,753	0,117	0,017 8
9	27,99	27,07	1,72	1,53	2,94	2,34	27,226	−0,156	0,019 5
10	24,79	23,92	−1,48	−1,62	2,20	2,63	24,113	−0,193	0,031 3
11	24,73	24,07	−1,54	−1,47	2,39	2,16	24,055	0,015	0,001 0
av	26,27	25,54						0,0	

N =	11	
Min	24,35	23,57
Max	30,69	30,37
SP	24%	27%
R²–test?		**Yes**

b =	0,972 7
a =	0,000 0
R^2 =	0,992 0
R² ok	

s_D =	0,230 m/s
σ_0 =	4%
k_v =	0,966 5
Max s_D =	1,409 m/s
Variability ok	

SRM: Measurements from standard reference method
AMS: Measurements from continuous working flow monitor
av: Average from the column above
b: Regression line gradient
a: Regression line intercept
R^2: Coefficient of determination
Min: The lowest value measured from the column above
Max: The highest value measured from the column above
SP: Spread of data determined as max. minus min., divided by the average value
N: Number of measurements (traverses)
Max s_D: The maximum allowable s_D calculated from number of measurements and σ_0 of 4 %

The result is shown in Figure A.4.

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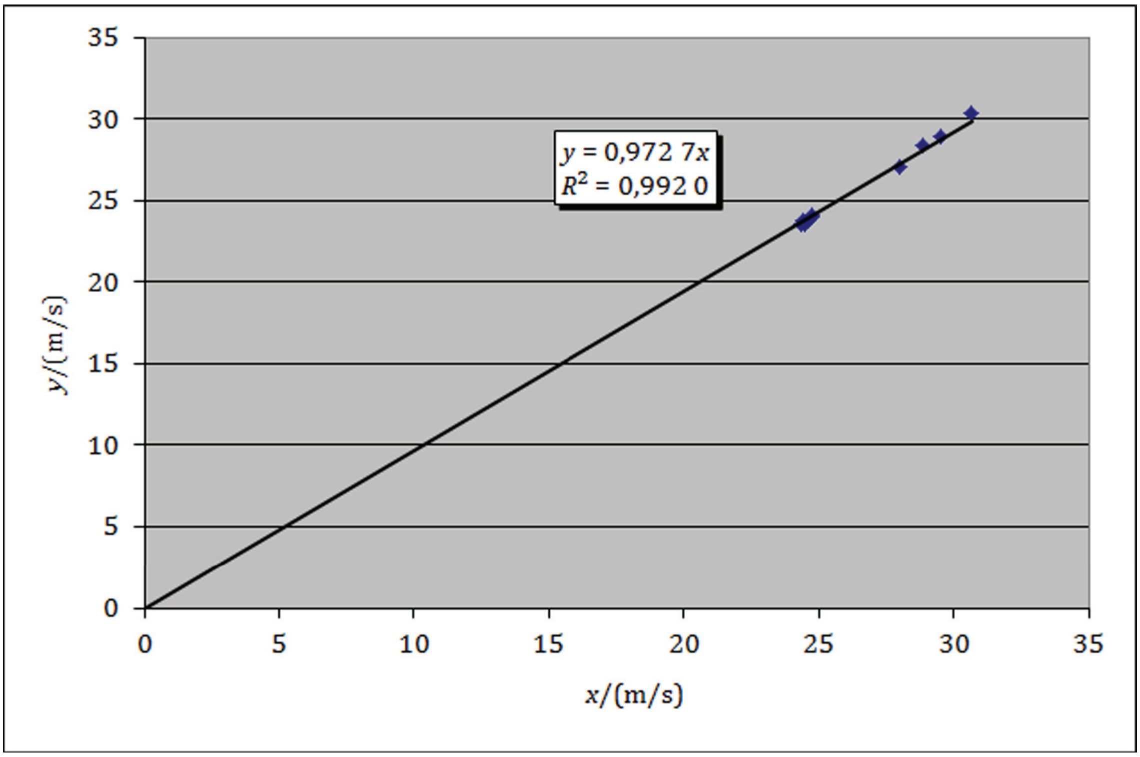

Key

WIH	data from Wilhelmshaven validation test
L1	SRM performed with L-type Pitot tubes
A	calibration procedure A (least squares regression)
y	measurements from standard reference method (SRM)
x	measurements from continuous working flow monitor (AMS)

Figure A.4 — Example of calibration made in accordance with method D (data from Wilhelmshaven)

A.5 Calculation of calibration data according to method A (data from Copenhagen)

This is an example of calibration using the time-based tracer method according to EN ISO 16911-1.

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Calibration procedure is made as a linear least squares regression, and the spread of data is so low, that the R^2 test is not required. See Table A.5.

Table A.5 — Example of calibration made in accordance with method A (data from Copenhagen)

No.	AMS m/s x	SRM m/s y	$x - x_{avg}$	$y - y_{avg}$	$(x - x_{avg})^2$	$(y - y_{avg})^2$	y_{cal}	D	$(D - D_{avg})^2$
1	21,75	20,59	1,34	1,39	1,79	1,94	20,369	0,221	0,048 7
2	21,62	20,07	1,21	0,87	1,46	0,76	20,255	−0,185	0,034 3
3	21,41	20,41	1,00	1,21	1,00	1,47	20,071	0,339	0,114 9
4	21,29	19,64	0,88	0,44	0,77	0,20	19,966	−0,326	0,106 1
5	19,39	18,32	−1,02	−0,88	1,05	0,77	18,299	0,021	0,000 5
6	19,90	18,55	−0,51	−0,65	0,26	0,42	18,746	−0,196	0,038 5
7	19,67	18,71	−0,74	−0,49	0,55	0,24	18,544	0,166	0,027 4
8	20,37	19,22	−0,04	0,02	0,00	0,00	19,159	0,061	0,003 8
9	19,90	18,85	−0,51	−0,35	0,26	0,12	18,746	0,104	0,010 8
10	20,44	19,07	0,03	−0,13	0,00	0,02	19,220	−0,150	0,022 5
11	20,80	19,48	0,39	0,28	0,15	0,08	19,536	−0,056	0,003 1
12	19,38	18,25	−1,03	−0,95	1,07	0,89	18,290	−0,040	0,001 6
13	20,51	19,27	0,10	0,07	0,01	0,01	19,281	−0,011	0,000 1
14	20,23	19,16	−0,18	−0,04	0,03	0,00	19,036	0,124	0,015 5
15	20,05	18,63	−0,36	−0,57	0,13	0,32	18,878	−0,248	0,061 4
16	20,77	19,56	0,36	0,36	0,13	0,13	19,509	0,051	0,002 6
17	20,07	18,83	−0,34	−0,37	0,12	0,13	18,895	−0,065	0,004 3
18	19,95	19,01	−0,46	−0,19	0,21	0,03	18,790	0,220	0,048 4
19	20,53	18,89	0,12	−0,31	0,01	0,09	19,299	−0,409	0,167 2
20	20,45	19,57	0,04	0,37	0,00	0,14	19,229	0,341	0,116 5
21	20,18	19,03	−0,23	−0,17	0,05	0,03	18,992	0,038	0,001 5
av	20,41	19,20						0,0	

N =	21	
Min	19,38	18,25
Max	21,75	20,59
SP	12 %	12 %
R^2-test?		**No**

b =	0,877 4
a =	1,286 7
R^2 =	0,893 7

s_D =	0,204 m/s
σ_0 =	4 %
k_v =	0,982 4
Max s_D =	0,971 m/s
Variability ok	

SRM: Measurements from standard reference method
AMS: Measurements from continuous working flow monitor
av: Average from the column above
b: Regression line gradient
a: Regression line intercept
R^2: Coefficient of determination
Min: The lowest value measured from the column above
Max: The highest value measured from the column above
SP: Spread of data determined as max. minus min., divided by the average value
N: Number of measurements (traverses)
Max s_D: The maximum allowable s_D calculated from number of measurements and σ_0 of 4 %

The result is shown in Figure A.5.

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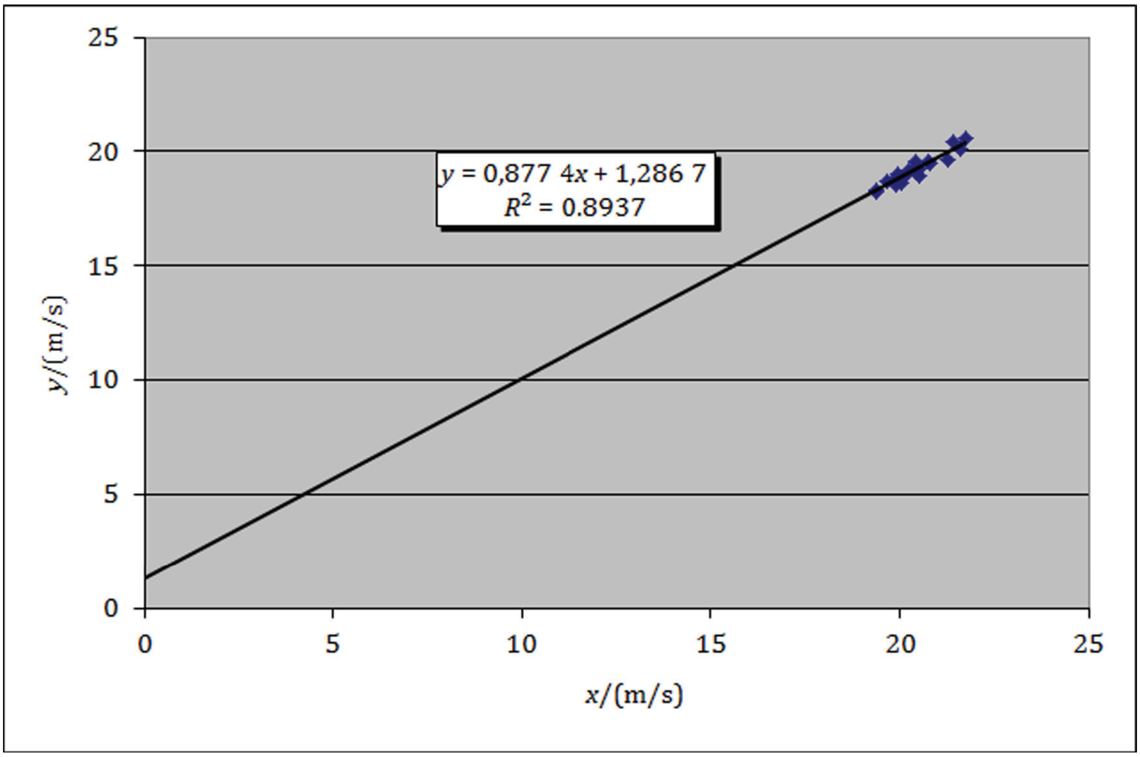

Key

CPH	data from Copenhagen validation test
TT	SRM performed with time based tracer method
A	calibration procedure A (least square regression)
y	measurements from standard reference method (SRM)
x	measurements from continuous working flow monitor (AMS)

Figure A.5 — Example of calibration made in accordance with method A (data from Copenhagen)

A.6 Calculation of calibration data according to method D (data from Copenhagen)

This is an example of calibration using the time-based tracer method according to EN ISO 16911-1.

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Calibration procedure is made as a linear least squares regression with the regression line forced through zero, and the spread of data is so low, that the R^2 test is not required. See Table A.6.

Table A.6 — Example of calibration made in accordance with method D (data from Copenhagen)

No.	AMS m/s x	SRM m/s y	$x - x_{avg}$	$y - y_{avg}$	$(x - x_{avg})^2$	$(y - y_{avg})^2$	y_{cal}	D	$(D - D_{avg})^2$
1	21,75	20,59	1,34	1,39	1,79	1,94	20,452	0,138	0,018 6
2	21,62	20,07	1,21	0,87	1,46	0,76	20,329	−0,259	0,068 2
3	21,41	20,41	1,00	1,21	1,00	1,47	20,132	0,278	0,076 3
4	21,29	19,64	0,88	0,44	0,77	0,20	20,019	−0,379	0,145 1
5	19,39	18,32	−1,02	−0,88	1,05	0,77	18,232	0,088	0,007 3
6	19,90	18,55	−0,51	−0,65	0,26	0,42	18,712	−0,162	0,026 9
7	19,67	18,71	−0,74	−0,49	0,55	0,24	18,496	0,214	0,045 1
8	20,37	19,22	−0,04	0,02	0,00	0,00	19,154	0,066	0,004 1
9	19,90	18,85	−0,51	−0,35	0,26	0,12	18,712	0,138	0,018 5
10	20,44	19,07	0,03	−0,13	0,00	0,02	19,220	−0,150	0,023 0
11	20,80	19,48	0,39	0,28	0,15	0,08	19,558	−0,078	0,006 4
12	19,38	18,25	−1,03	−0,95	1,07	0,89	18,223	0,027	0,000 6
13	20,51	19,27	0,10	0,07	0,01	0,01	19,286	−0,016	0,000 3
14	20,23	19,16	−0,18	−0,04	0,03	0,00	19,022	0,138	0,018 4
15	20,05	18,63	−0,36	−0,57	0,13	0,32	18,853	−0,223	0,050 6
16	20,77	19,56	0,36	0,36	0,13	0,13	19,530	0,030	0,000 8
17	20,07	18,83	−0,34	−0,37	0,12	0,13	18,872	−0,042	0,001 9
18	19,95	19,01	−0,46	−0,19	0,21	0,03	18,759	0,251	0,062 0
19	20,53	18,89	0,12	−0,31	0,01	0,09	19,304	−0,414	0,173 3
20	20,45	19,57	0,04	0,37	0,00	0,14	19,229	0,341	0,114 9
21	20,18	19,03	−0,23	−0,17	0,05	0,03	18,975	0,055	0,002 8
av	20,41	19,20						0,0	

N =	21	
Min	19,38	18,25
Max	21,75	20,59
SP	12 %	12 %
R^2-test?		**No**

b =	0,940 3
a =	0,000 0
R^2 =	0,889 0

s_D =	0,208	m/s
σ_0 =	4 %	
k_v =	0,982 4	
Max s_D =	0,971	m/s
Variability ok		

SRM: Measurements from standard reference method

AMS: Measurements from continuous working flow monitor

av: Average from the column above

b: Regression line gradient

a: Regression line intercept

R^2: Coefficient of determination

Min: The lowest value measured from the column above

Max: The highest value measured from the column above

SP: Spread of data determined as max. minus min., divided by the average value

N: Number of measurements (traverses)

Max s_D: The maximum allowable s_D calculated from number of measurements and σ_0 of 4 %

The result is shown in Figure A.6.

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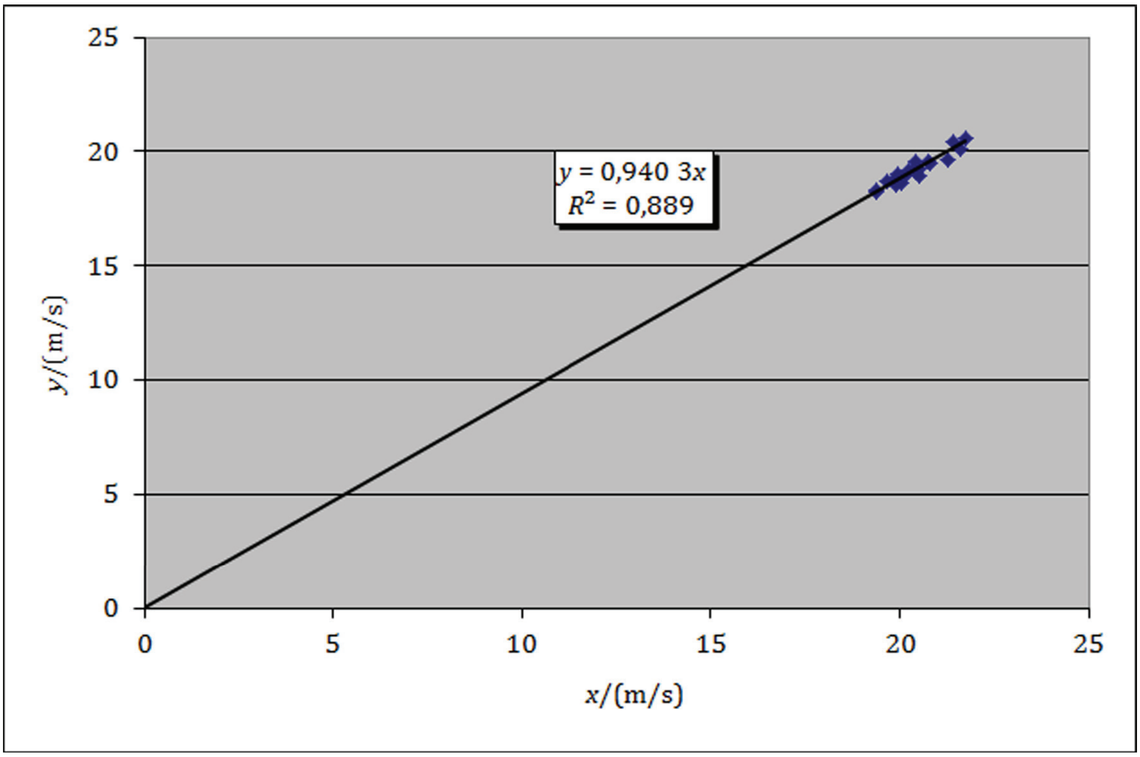

Key

CPH	data from Copenhagen validation test
TT	SRM performed with time based tracer method
D	calibration procedure D (least square regression forced through zero)
y	measurements from standard reference method (SRM)
x	measurements from continuous working flow monitor (AMS)

Figure A.6 — Example of calibration made in accordance with method D (data from Copenhagen)

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Annex B
(informative)

Flow profile characteristics

B.1 General

In EN ISO 16911-2, the term “flow profile” is used to describe a diagram showing the gas velocity, in m/s, along a line across the duct passing through the centre of the duct.

The actual flow profile has a large influence on the expected uncertainty, since a fully developed flow profile is expected not to change with higher average flow rate, while a less developed flow profile and an asymmetrical flow profile is expected to change, and may consequently introduce systematic uncertainties compared with a calibration made at a higher flow rate.

The following examples are characterized by the following parameters, derived from the measured point velocities:

a) the average velocity across the diameter, v_{AVG};

b) the peak velocity across the diameter, v_{PEAK};

c) the crest factor, $v_{\mathrm{PEAK}}/v_{\mathrm{AVG}}$;

d) the average velocity across the left half of the diameter, $v_{\mathrm{L,\ AVG}}$;

e) the average velocity across the right half the diameter, $v_{\mathrm{R,\ AVG}}$;

f) the skewness, being the ratio $v_{\mathrm{L,\ AVG}}/v_{\mathrm{R,\ AVG}}$ or the ratio $v_{\mathrm{R,\ AVG}}/v_{\mathrm{L,\ AVG}}$, whichever is larger than 1,00;

g) the velocity, $v_{\mathrm{L,\ 12\ \%}}$, at 12 % of the duct diameter from the left side wall, the $\mathrm{L}_{12\ \%}$ point;

h) the velocity, $v_{\mathrm{R,\ 12\ \%}}$, at 12 % of the duct diameter from the right side wall, the $\mathrm{R}_{12\ \%}$ point.

B.2 Fully developed flow profile

See Figure B.1.

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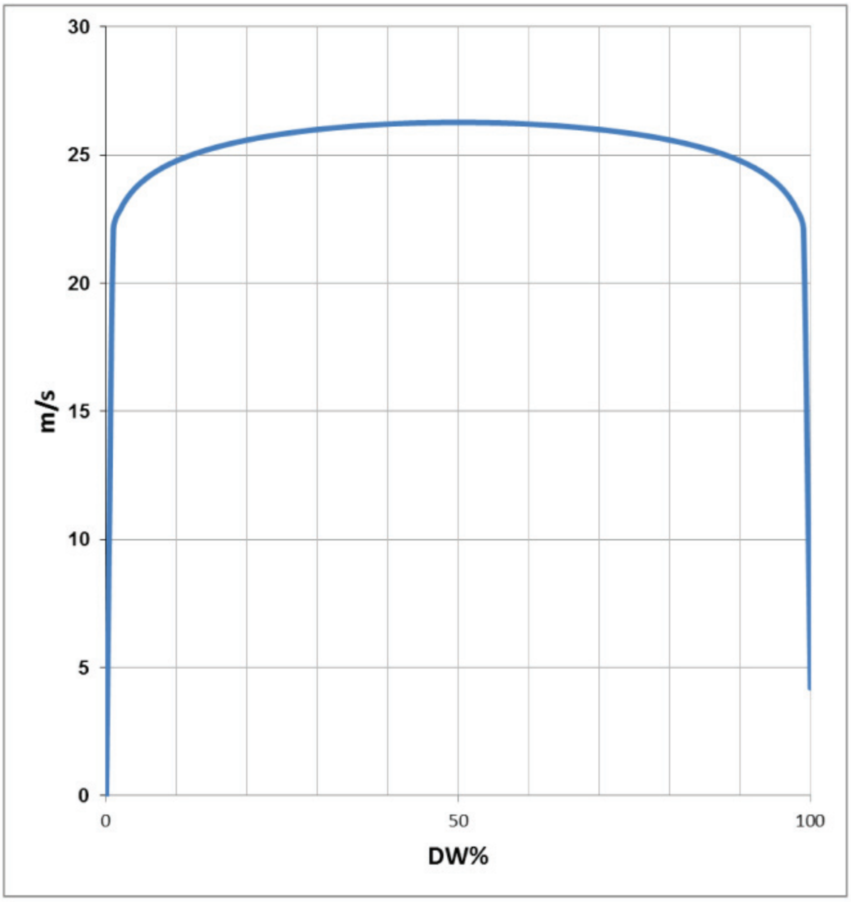

Key

DW%	distance from the inner stack wall as a percentage of the stack inner diameter	
AV	average flow across the duct	25,00 m/s
TFL	total flow velocity to the left of the centreline	25,47 m/s
TFR	total flow velocity to the right of the centreline	25,56 m/s
SK	skewness	0,997
$L_{12\,\%}$	left 12 % point at which the flow velocity is $v_{L,\,12\,\%}$	$v_{L,\,12\,\%}$ = 25,00 m/s
$R_{12\,\%}$	right 12 % point at which the flow velocity is $v_{R,\,12\,\%}$	$v_{R,\,12\,\%}$ = 25,00 m/s
CF	crest factor	105,1 %

Figure B.1 — Fully developed flow profile

A fully developed flow profile is characterized by being symmetrical along the centre of the duct, being rather flat, but falling towards zero in the vicinity of the duct wall, and (in a circular duct) having a flow equal to the average flow at a distance of 12 % of the diameter from the duct wall.

A fully developed profile is typical achieved with a long distance downstream of any disturbance or bend in the duct, and with a rather high Reynolds number.

B.3 Less developed symmetrical flow profile

See Figure B.2.

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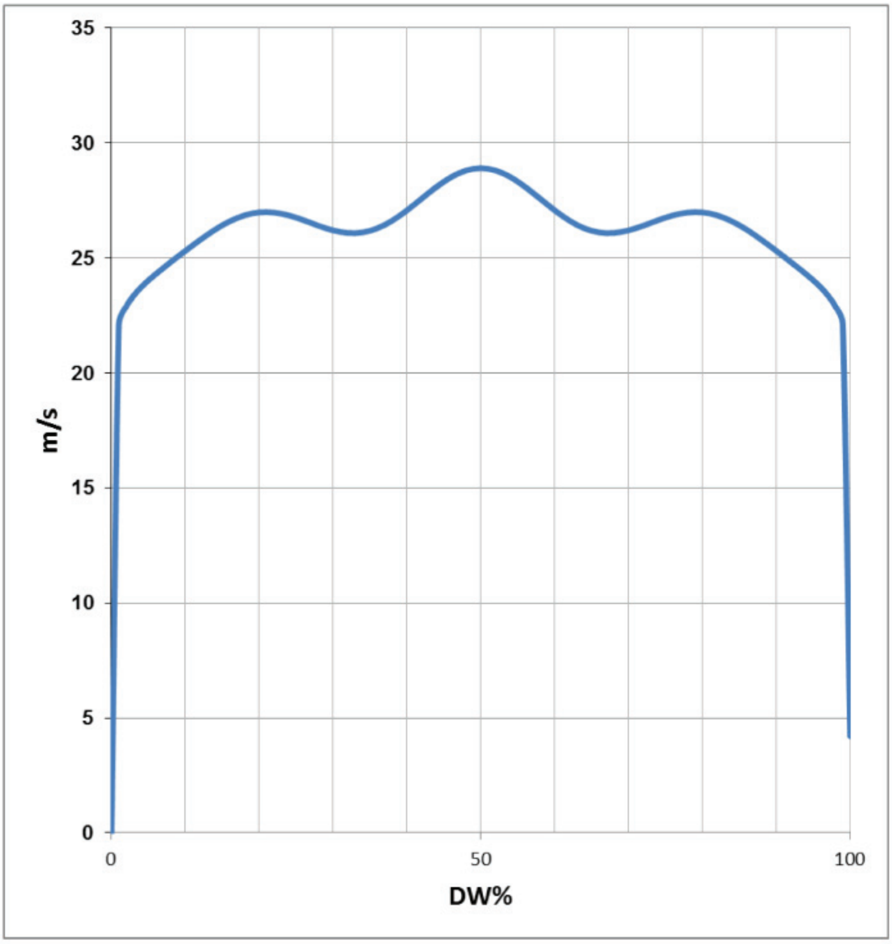

Key

DW%	distance from the inner stack wall as a percentage of the stack inner diameter	
AV	average flow across the duct	25,85 m/s
TFL	total flow velocity to the left of the centreline	26,36 m/s
TFR	total flow velocity to the right of the centreline	26,44 m/s
SK	skewness	0,997
$L_{12\ \%}$	left 12 % point at which the flow velocity is $v_{L,\ 12\ \%}$	$v_{L,\ 12\ \%}$ = 25,79 m/s
$R_{12\ \%}$	right 12 % point at which the flow velocity is $v_{R,\ 12\ \%}$	$v_{R,\ 12\ \%}$ = 25,79 m/s
CF	crest factor	111,8 %

Figure B.2 — Less developed symmetrical profile

This less developed profile may be fairly uniform but with a higher crest factor, or may be uneven across the monitoring path.

It is seen that the shape is still symmetrical, skewness is very low, but crest factor has risen.

B.4 Asymmetrical flow profile

See Figure B.3.

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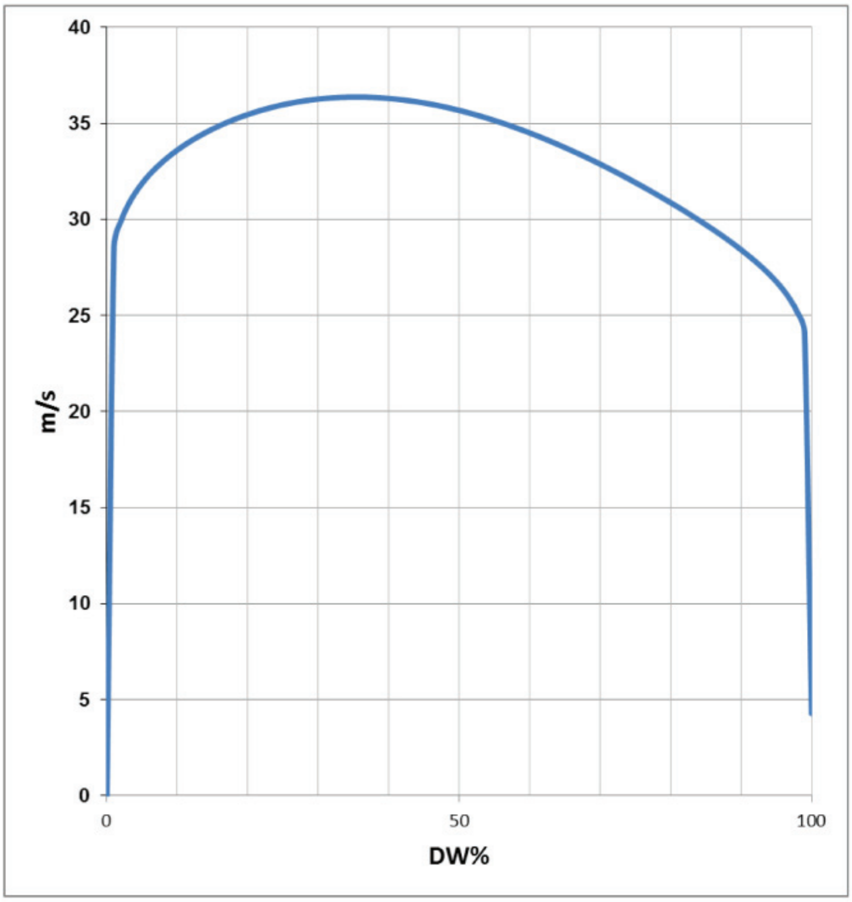

Key

DW%	distance from the inner stack wall as a percentage of the stack inner diameter	
AV	average flow across the duct	32,60 m/s
TFL	total flow velocity to the left of the centreline	34,97 m/s
TFR	total flow velocity to the right of the centreline	31,60 m/s
SK	skewness	1,107
$L_{12\ \%}$	left 12 % point at which the flow velocity is $v_{\mathrm{L,\ 12\ \%}}$	$v_{\mathrm{L,\ 12\ \%}}$ = 34,11 m/s
$R_{12\ \%}$	right 12 % point at which the flow velocity is $v_{\mathrm{R,\ 12\ \%}}$	$v_{\mathrm{R,\ 12\ \%}}$ = 28,97 m/s
CF	crest factor	111,6 %

Figure B.3 — Asymmetrical flow profile

Any flow profile in a duct with a one-sided inlet is likely to asymmetrical, however, if the duct is long, the asymmetry is often small.

If, however, the flow profile shows clear signs of asymmetry, as defined by the skewness, and as shown in the preceding, this shall be considered when the flow monitoring is planned and performed.

It is also evident that average velocity is no longer read at the 12 % point, and skewness and crest factor have risen.

B.5 Less developed and asymmetrical flow profile

See Figure B.4.

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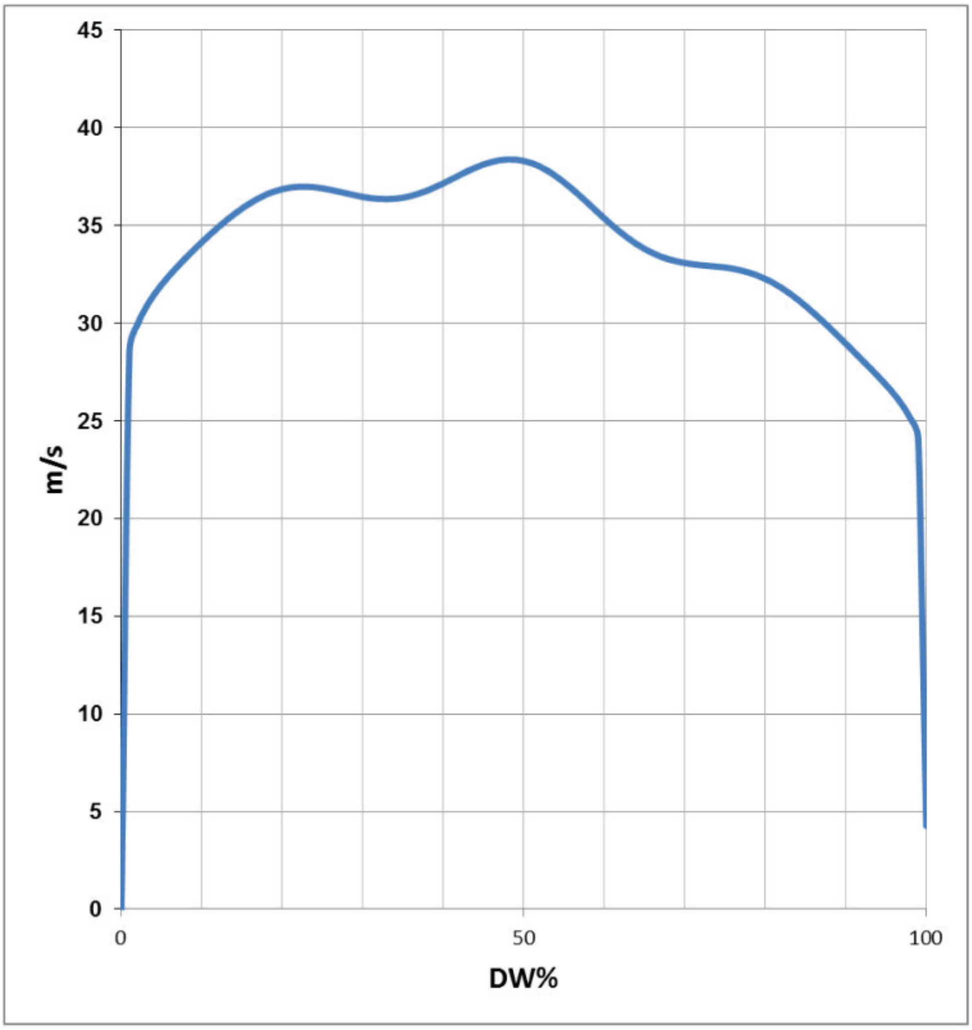

Key

DW%	distance from the inner stack wall in percentage of the stack inner diameter	
AV	average flow ocross the duct	33,45 m/s
TFL	total flow left of the centreline	35,86 m/s
TFR	total flow right of the centreline	32,49 m/s
SK	skewness	1,104
$L_{12\ \%}$	left 12 % point at which the flow velocity is $v_{L,\ 12\ \%}$	$v_{L,\ 12\ \%}$ = 34,90 m/s
$R_{12\ \%}$	right 12 % point at which the flow velocity is $v_{R,\ 12\ \%}$	$v_{R,\ 12\ \%}$ = 29,77 m/s
CF	crest factor	114,7 %

Figure B.4 — Less developed and asymmetrical flow profile

In this example of an uneven and asymmetrical flow profile, average velocity is not read at the 12 % points, and both skewness and crest factor have risen.

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Annex C

(informative)

Determination of measuring points and/or paths

C.1 Single point monitor

If the requirements of 7.3 are fulfilled, a sensing element of a single point monitor may be mounted at a point situated 12 % from the inner diameter from the duct wall anywhere along the circumference that is free of local upstream disturbances. If the flow profile is fully developed, this position has a flow rate very close to the average over the cross-sectional area.

C.2 Limited path length monitor

Some technologies, like multi-point differential pressure monitors, thermal mass monitors, and ultrasound monitors, are also obtainable as probes inserted from one side of the duct with a limited measurement path length. These typically have an effective monitoring length from 0,25 m to 1 m, and may be used as a good and less expensive alternative in ducts with a small diameter or ducts where the access to two diametrically opposite positions is limited. They may also be used as single point monitors, where the diameter is considerably greater than the monitoring length.

C.3 Primary monitoring path in a circular duct

The primary monitoring path, P, shall be the path in which the maximum velocity is expected to be found. That is, in a straight line through the centre of the duct, and lying in the plane defined by the centreline of the duct being monitored and the centreline of the inlet upstream of the monitoring point. See Figure C.1.

If the centreline of the inlet does not cross the centreline of the duct, the plane should be determined by the centreline of the duct and a line through the centre of the duct and parallel with the centreline of the inlet.

If there is more than one inlet, not in the same plane, P should include the point where the maximum velocity is found based upon the pre-investigation results.

C.4 Secondary monitoring path in a circular duct without dominant asymmetric swirl

If swirl is not dominant asymmetric, and increased accuracy is required, it is recommended that two monitoring paths be used, parallel to P and to each other, and spaced symmetrically at 0,3 of the diameter from the centre of the duct. See Figure C.2.

This spacing corresponds approximately to the point where a theoretical laminar flow and well-developed turbulent flow have the same velocity, and consequently the calibration curve changes minimally, even if the flow profile develops further [see Figure C.3 in which a laminar flow (highest curve) is compared with different turbulent flows].

C.5 Secondary monitoring path in a circular duct with dominant asymmetric swirl

The point in the duct where the maximum velocity is located rotates if swirl is dominant asymmetric, and consequently a monitoring path which includes the point where the maximum velocity is found cannot be determined.

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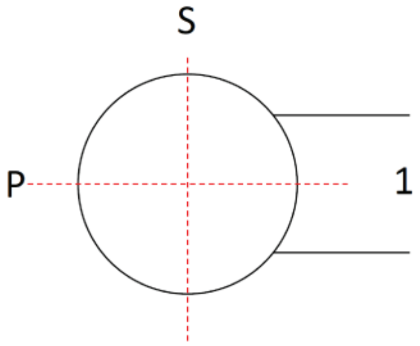
In this case, the secondary monitoring path, S, shall be a straight line through the centre of the duct, lying in a plane perpendicular to P, see Figure C.1.

With a rotating pattern, the sum of averages of the measurement results in these two measuring paths give the best estimate.



Key

1 inlet

P primary monitoring path

S secondary monitoring path

Figure C.1 — Position of primary and secondary monitoring paths

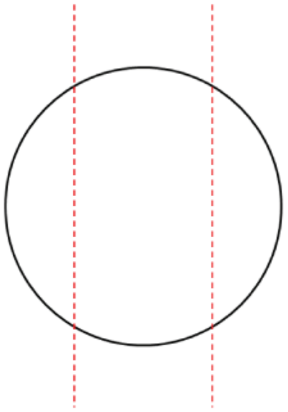


Figure C.2 — Position of two monitoring paths

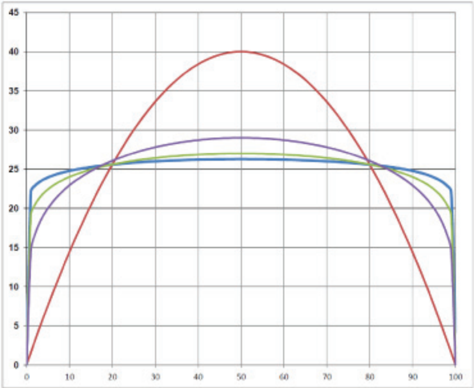


Figure C.3 — Intersection of flow profile for fully developed and fully laminar flow

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C.6 Primary monitoring path in a rectangular duct

P should be a straight line through the centre of the duct, lying perpendicular to the side panel, where the flanges are mounted.

This should preferably be in the plane defined by the centreline of the duct being monitored and the centreline of the inlet upstream of the monitoring point, or a line through the centre of the duct and parallel with the centreline of the inlet.

If this is not possible or if there is more than one inlet, not in the same plane, P should include the point of maximum velocity found in the pre-investigation results, and should be determined after consulting an accredited test laboratory and the flow monitor manufacturer.

If there is more than one inlet, not in the same plane, P should include the point of maximum velocity from the pre-investigation results.

C.7 Secondary monitoring path in a rectangular duct with swirl

The point of maximum velocity within the duct rotates if swirl is present and consequently a monitoring path which includes this point may not be determined. In this case, S should be a straight line through the centre of the duct, lying in a plane perpendicular to P. With a rotating pattern, the sum of averages of the measurement results in these two measuring paths gives the best estimate.

C.8 Other configurations

If flow monitoring in two paths as described in the preceding does not give sufficient accuracy to pass the QAL2 calibration, other configurations may be used.

Three paths may be used in a configuration as shown in Figure C.4: P and two further parallel paths, spaced 0,3 of the diameter from the centre path.

If swirl is dominant, a higher accuracy may be obtained, by the other configuration shown in Figure C.4: P and two paths shifted 60 ° from P.

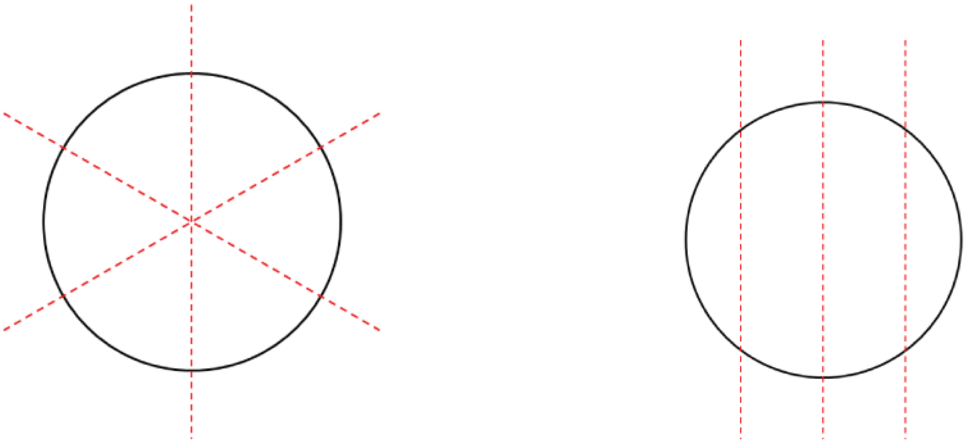

Figure C.4 — Position of three monitoring paths

C.9 Single path not in the primary monitoring path

If the duct is very large or the duct gas temperature is very high, it may be necessary to monitor in a secant line of the circular duct, with an offset of 0,25 to 0,3 times the duct diameter, as shown in Figure C.5.

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Special considerations should be given to the possible change in flow profile with changing load, to secure successful calibration/QAL2.

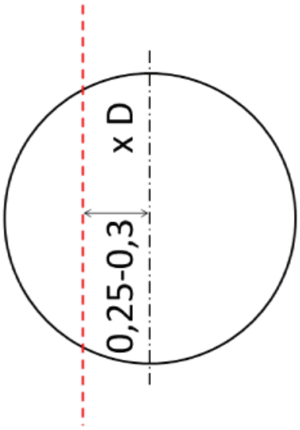

Figure C.5 — Single path not in the primary monitoring path

C.10 Other cases

If the duct is neither rectangular nor circular, or in cases where any other obstacle upstream in the duct is likely to disturb the flow profile, P and S shall be determined after consultations with an accredited test laboratory and the flow monitor manufacturer, and subsequently approved by the competent authorities.

In general, whenever a monitoring path is added, the measurement reproducibility is reduced. An example with four measurement paths is shown in Figure C.6.

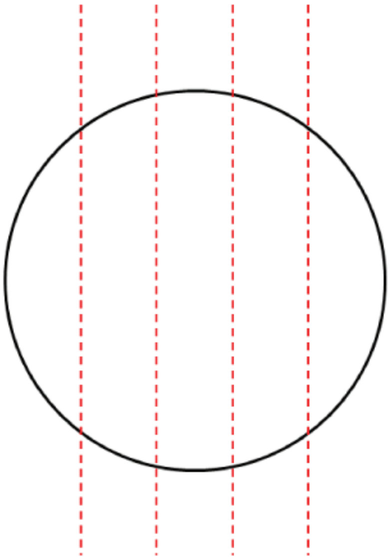

Figure C.6 — Position of four monitoring paths

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Annex D
(normative)

Treatment of a polynomial calibration function

Additional care shall be taken when using a polynomial calibration function.

When using a polynomial calibration function, the valid calibration range may be extrapolated downwards to 80 % of the minimum volume flow rate and upwards to 120 % of the maximum volume flow rate recorded as an SRM value during the last QAL2.

This valid calibration range may be extrapolated further at a subsequent AST according to EN 14181, if the polynomial calibration function is recalculated to include the extra paired measurement points.

If the AMS value falls below the lowest point or increases above the highest point of calibration function from the last QAL2 calibration or AST, a warning or error message shall be recorded in accordance with Table D.1.

If the AMS value falls below the valid calibration range as specified above, the lowest point of the valid calibration range shall be used as a surrogate value for the flow rate, an error message shall be recorded and values calculated based upon this shall be tagged.

If the AMS value rises above the valid calibration range as specified in the preceding, the highest point of the valid calibration range shall be used as a surrogate value for the flow rate, an error message shall be recorded, and values calculated based upon this shall be tagged as such.

Table D.1 — Treatment of a polynomial calibration function

Measured value, q_V	**Value used in data acquisition and handling system**	**Action in data acquisition and handling system**
q_V < 80 % of lowest QAL2/AST	80 % of lowest last QAL2 or AST, values tagged	Error message
80 % of lowest last QAL2/AST < q_V < 100 % of lowest QAL2/AST	Read value	Warning message
100 % of lowest last QAL2/AST < q_V < 100 % of highest last QAL2/AST	Read value	None
100 % of highest last QAL2/AST < q_V < 120 % of highest last QAL2/AST	Read value	Warning message
q_V > 120 % of highest last QAL2/AST	120 % of highest last QAL2 or AST, values tagged	Error message

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Annex E
(normative)

Values of $k_v(N)$ and $t_{0,95(N-1)}$

Table E.1 — Values of $k_v(N)$ and $t_{0,95(N-1)}$ (Source: CEN/TR 15983:2010,[7] Annex C)

Number of parallel measurements, N	$k_v(N)$	$t_{0,95(N-1)}$
3	0,832 6	2,92
4	0,888 1	2,353
5	0,916 1	2,132
6	0,932 9	2,015
7	0,944 1	1,943
8	0,952 1	1,895
9	0,958 1	1,86
10	0,962 9	1,833
11	0,966 5	1,812
12	0,969 5	1,796
13	0,972 1	1,782
14	0,974 2	1,771
15	0,976 1	1,761
16	0,977 7	1,753
17	0,979 1	1,746
18	0,980 3	1,74
19	0,981 4	1,734
20	0,982 4	1,729
25	0,986 1	1,711
30	0,988 5	1,701

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Annex F
(informative)

Example of a pre-investigation measurement

F.1 Flow profile monitoring

An example is a flow profile measured according to EN 15259 at highest possible and lowest possible flow rate. A pre-investigation shall perform these measurements along the primary, P, and secondary, S, monitoring paths; here only the result along P is shown. See Tables F.1 and F.2, and Figure F.1.

The flow velocities at the individual measurement points are corrected to give the "corrected flow" velocity using a correction factor, which is the ratio between the velocity at the measurement point (raw flow value) and the velocity at a fixed reference point, as described in 8.2.2.

Table F.1 — Example with 21 measurement points along one path at the highest possible flow rate

Side	No.	DW%	F	RF	CF	CrF	AF
			m/s	m/s		m/s	m/s
LS	1	1,23	16,40	15,06	1,009	16,55	19,75
	2	3,80	18,08	15,36	0,989	17,88	
	3	6,52	18,50	15,03	1,011	18,71	
	4	9,42	18,39	14,38	1,057	19,44	
	5	12,55	19,26	14,54	1,045	20,14	
	6	15,96	21,13	15,48	0,982	20,74	
	7	19,76	20,61	14,83	1,025	21,12	
	8	24,10	21,84	15,70	0,968	21,14	
	9	29,34	19,47	14,19	1,071	20,86	
	10	36,47	19,38	14,11	1,077	20,88	
	11	50,00	23,21	16,13	0,942	21,87	
RS	12	63,53	21,45	16,71	0,910	19,51	17,19
	13	70,66	18,68	15,05	1,010	18,87	
	14	75,90	17,46	14,14	1,075	18,77	
	15	80,24	19,50	16,03	0,948	18,49	
	16	84,04	18,19	15,42	0,986	17,93	
	17	87,45	18,45	16,29	0,933	17,22	
	18	90,58	17,96	16,58	0,917	16,47	
	19	93,48	14,99	14,47	1,051	15,74	
	20	96,20	15,78	15,98	0,951	15,01	
	21	98,77	13,26	14,46	1,051	13,94	
			ARF	15,20	AF:	18,63	

DW%: Distance from the inner stack wall expressed as a percentage of the stack inner diameter

F: Flow velocity measurement at individual traverse points (uncorrected)

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RF: Reference flow velocity measurement at a fixed point during traversing

CF: Correction factor: average reference flow velocity divided by the individual reference flow velocity

CrF: Flow velocity measurement at individual traverse points corrected using the reference flow velocity

AF: Average corrected flow to the left or right side of the stack centre

LS: Data from the left side of stack centre

RS: Data from the right side of stack centre

ARF: Average of reference flow velocity

AF: Average flow velocity over the stack diameter.

Table F.2 — Example with 21 measurement points along the same path as Table F.1, but at the lowest possible flow rate

Side	No.	DW%	F	RF	CF	CrF	AF
			m/s	m/s		m/s	m/s
LS	1	1,23 %	12,53	11,68	1,010	12,66	16,63
	2	3,80 %	13,76	11,79	1,001	13,77	
	3	6,52 %	14,27	11,51	1,025	14,63	
	4	9,42 %	16,19	11,90	0,992	16,06	
	5	12,55 %	16,55	11,68	1,010	16,71	
	6	15,96 %	17,60	11,66	1,012	17,81	
	7	19,76 %	17,60	11,53	1,023	18,01	
	8	24,10 %	18,76	11,76	1,003	18,82	
	9	29,34 %	18,70	11,74	1,005	18,79	
	10	36,47 %	18,73	11,61	1,016	19,03	
	11	50,00 %	20,71	11,76	1,003	20,77	
RS	12	63,53 %	18,99	11,60	1,017	19,31	18,15
	13	70,66 %	19,25	11,92	0,990	19,05	
	14	75,90 %	18,36	11,66	1,012	18,58	
	15	80,24 %	18,41	11,52	1,024	18,85	
	16	84,04 %	18,70	11,84	0,997	18,64	
	17	87,45 %	18,29	11,72	1,007	18,42	
	18	90,58 %	18,06	11,75	1,004	18,13	
	19	93,48 %	17,72	11,73	1,006	17,83	
	20	96,20 %	16,96	11,80	1,000	16,96	
	21	98,77 %	15,82	11,88	0,993	15,71	
			ARF	11,80	AF:	17,55	

DW%: Distance from the inner stack wall in percentage of the stack inner diameter

F: Flow measurement in individual points during traversing uncorrected as measured.

RF: Reference flow measurement in reference point stationary during traversing.

CF: Correction factor: average reference flow velocity divided by the individual reference flow velocity.

CrF: Flow measurement in individual points during traversing corrected with the reference flow.

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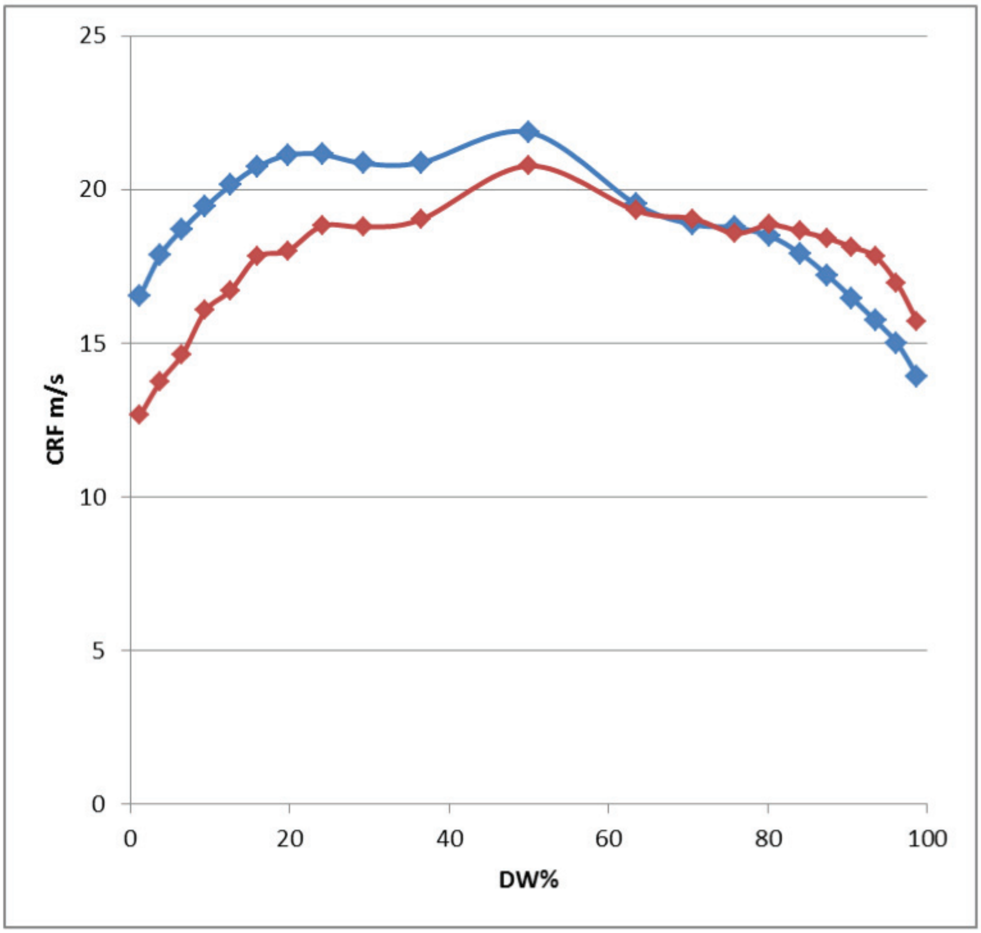
AF: Average flow in left and right side of the stack centre.

LS: Data from the left side of stack centre

RS: Data from the right side of stack centre



Key

See Table F.1 or Table F.2

Figure F.1 — Profile for the higher flow rate (at left) with an average value of 18,63 m/s and the lower flow rate (at left) with an average value of 17,55 m/s

F.2 Crest factor

The crest factor or peak-to-average ratio, $v_{\text{PEAK}}/v_{\text{AVG}}$, is a measurement of a flow profile, calculated as the ratio between the measured peak value of the flow profile and the average value of the flow profile.

For the high flow profile, the crest factor is:

$$\frac{v_{\text{PEAK}}}{v_{\text{AVG}}}=\frac{21,87}{18,63}=1,174 \qquad \text{(F.1)}$$

For the low flow profile, the crest factor is:

$$\frac{v_{\text{PEAK}}}{v_{\text{AVG}}}=\frac{20,77}{17,55}=1,184 \qquad \text{(F.2)}$$

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NOTE If the measurement is made according to EN ISO 16911-1 and EN 15259, as in this example, each measurement represents the same area of flow in the duct, and the average value can be calculated from a simple average of the individual measurements.

F.3 Skewness

Skewness is a measure of asymmetry, and in this case is defined as the relative difference in the total flow to the left of the centre of the duct divided by the total flow to the right of the centre of the duct, $v_{\mathrm{L,\,AVG}}/v_{\mathrm{R,\,AVG}}$.

Skewness for the high flow profile is:

$$\frac{v_{\mathrm{L,AVG}}}{v_{\mathrm{R,AVG}}}=\frac{19{,}75}{17{,}19}=1{,}149 \tag{F.3}$$

Skewness for the low flow profile is:

$$\frac{v_{\mathrm{R,AVG}}}{v_{\mathrm{L,AVG}}}=\frac{18{,}15}{16{,}63}=1{,}091 \tag{F.4}$$

NOTE 1 If the measurement is made according to EN ISO 16911-1 and EN 15259, following this example, each measurement represents the same area of flow in the duct, and the skewness can be calculated from a simple average of the individual measurements, either side of the centreline, not counting any measurements at the centre of the duct.

NOTE 2 If an even number of measurement points are used, all left and right points are used. If an uneven number of measurements points are used, as in this example, the centre point is omitted.

F.4 Reproducibility

The reproducibility is calculated from the measurement results at each traverse point, chosen according to EN 15259, at the highest possible flow rate and at the lowest possible flow rate, as described in 8.1.

The purpose of the calculation is to quantify the amount of change between the flow profiles measured at the highest and lowest flow rate the plant is likely to operate under. The flow profiles are normalized to compensate for the change in average flow. In this way, the reproducibility only measures the change in flow profile and not the change in average flow.

The procedure is performed in both P and S, but only one example is shown here.

The flow profiles are normalized by dividing by the average flow rate at each condition, thereby producing two flow profiles with an average flow rate of 1, see Table F.3.).

The reproducibility is expressed as the standard deviation of the differences of paired measurements (from EN 15267-3).

The reproducibility in the field, R_{f}, is calculated according to:

$$R_{\mathrm{f}} = t_{0,95(N-1)} \times s_{\mathrm{D}} \tag{F.5}$$

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$$s_D = \sqrt{\frac{\sum_{i=1}^{n} \left(x_{1i} - x_{2i}\right)^2}{2n}} \qquad \text{(F.6)}$$

where

x_{1i} is the ith measurement result of flow profile high flow;

x_{2i} is the ith measurement result of flow profile low flow;

n is the number of traverse measurements in each flow profile;

$t_{0,95(N-1)}$ is the two-sided Student t-factor at a confidence level of 0,95 with $N - 1$ degrees of freedom, as given in Annex E.

NOTE If the measurement is made according to EN ISO 16911-1 and EN 15259, following this example, each measurement represents the same area of flow in the duct, and the reproducibility can be calculated from the flow profile divided by the average flow. If this is not the case, each measurement has to be normalized to the average flow rate and area weighted in relation to the total volume flow rate.

An example is given in the following.

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Table F.3 — Calculation of reproducibility from normalized flow profiles from examples in this annex

CFH		CFL		$(x_1 - x_2)^2$
x_1		x_2		
m/s	normalized	m/s	normalized	
16,55	0,888 2	12,66	0,721 4	0,027 83
17,88	0,959 8	13,77	0,784 7	0,030 68
18,71	1,004 0	14,63	0,833 7	0,029 01
19,44	1,043 3	16,06	0,915 1	0,016 42
20,14	1,080 8	16,71	0,952 4	0,016 49
20,74	1,113 3	17,81	1,014 7	0,009 72
21,12	1,133 6	18,01	1,026 2	0,011 55
21,14	1,134 7	18,82	1,072 2	0,003 91
20,86	1,119 4	18,79	1,070 7	0,002 37
20,88	1,120 6	19,03	1,084 3	0,001 32
21,87	1,173 7	20,77	1,183 8	0,000 10
19,51	1,047 4	19,31	1,100 2	0,002 79
18,87	1,012 7	19,05	1,085 8	0,005 33
18,77	1,007 3	18,58	1,058 6	0,002 63
18,49	0,992 3	18,85	1,074 2	0,006 72
17,93	0,962 4	18,64	1,062 2	0,009 95
17,22	0,924 1	18,42	1,049 8	0,015 80
16,47	0,883 8	18,13	1,033 0	0,022 26
15,74	0,845 1	17,83	1,015 8	0,029 15
15,01	0,805 5	16,96	0,966 3	0,025 88
13,94	0,748 0	15,71	0,895 0	0,021 61
AF				
18,63	1,00	17,55	1,00	
			s_D	0,083 31
			R_f	0,144
				14,4 %

CFH: Corrected flow rate high

CFL: Corrected flow rate low

AF: Average flow rate

Figure F.2 illustrates the two normalized flow profiles.

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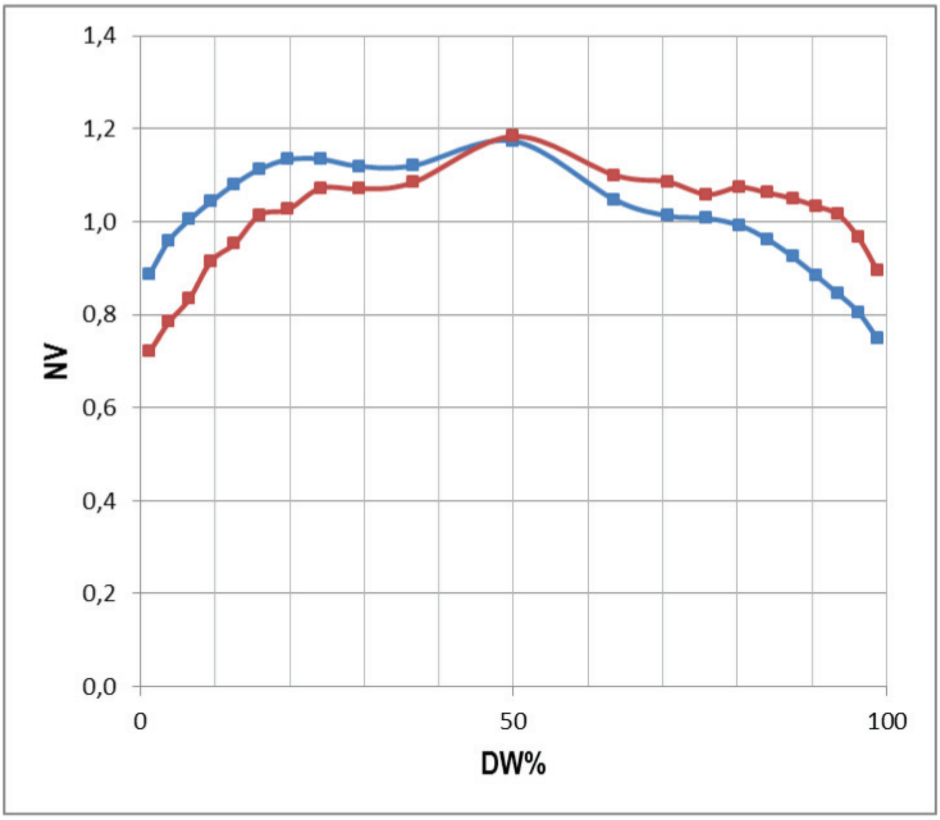

Key

NV	normalized flow: high (upper line at left); low (lower line at left)
DW%	distance from the inner wall, expressed as a percentage of the inner diameter

Figure F.2 — Comparison of two normalized flow profiles

The normalization compares the changes in flow profile only, and not the change in average flow rate.

Since the reproducibility calculated in Table F.3 is more than 5 %, it is considered to be a significant change.

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Annex G
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Computational fluid dynamics issues

G.1 General

CFD modelling is a complex subject and this annex describes aspects found to be important when using CFD procedures for the pre-investigation of duct flow conditions. It is not a procedural guideline.

Before starting a simulation, it is wise to think carefully about what it is that should be predicted and what physical phenomena affect the results. The pre-investigation with CFD is a prediction of what could be installed in the real world. Any factors that could influence an engineering decision or the measurement accuracy have to be included in the computational model.

The engineer has to consider, decide on, and report the specific CFD points in G.2 to G.6.

G.2 Numerical considerations

Use at least a second order accurate scheme for the flow variables. Some codes require a first order scheme for the turbulence in order to converge well. This might be sufficient for the turbulence variables only, but a second order scheme is preferable.

G.3 Convergence criteria

To know when a solution is converged is not always simple. Prior experience of the CFD code and the application is required in order to judge when a simulation is converged. For normal flow simulations without resolved walls, i.e. with wall functions or inviscid Euler simulations, convergence can most often be assessed by examining the residuals. The required value of the residuals depends on the computational details of the CFD code and how the residuals are scaled. Guidance is given in the code manuals and the residuals from a few global parameters should be plotted in order to decide on convergence. However, it should be noted that that general purpose CFD codes often list overly conservative convergence criteria. For simulations with resolved walls, it is likewise important to examine the convergence of the relevant global quantities, such as total pressure losses from the inlet to the outlet. With very well resolved walls, it can sometimes take 10 times longer for the thermal field to converge as the solution is non-isothermal.

G.4 Sources of errors and uncertainties

CFD requires the user to have a good understanding of uncertainties and errors that might invalidate the CFD simulation. CFD simulations therefore need to be interpreted by an experienced user in order to produce a credible solution. Errors can occur at different points in the process:

- definition of the problem — what needs to be analysed?
- selection of the solution strategy — what physical models and numerical tools should be used?
- development of the computational model — how should the geometry and the numerical tools be set up?
- analysis and interpretation of the results — how should the model be analysed and the results be interpreted?

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There exist many different definitions on errors. In this guide the errors are classified into four source types:

- problem definition;
- model;
- numerical;
- user and code.

These errors and guidelines on how to minimize their influence are given in G.5.

G.5 Errors

G.5.1 Problem definition errors

G.5.1.1 General

Problem definition errors are the most common type of error. In order to obtain useful results, a CFD simulation needs to analyse the correct problem, to have suitable boundary conditions and to be based on the correct geometry.

G.5.1.2 Simulation (wrong type of simulation)

It is essential to have an overview of the physics involved and how the problem can best be analysed. Running a 2D simulation in order to understand secondary flows, or running a steady simulation in order to understand transient behaviour, is evidently incorrect. When assessing a CFD simulation, the first thing to consider is which physical phenomena are important and if the type of simulation selected is suitable for resolving these phenomena.

G.5.1.3 Boundary conditions (incorrect or uncertain boundary conditions)

A common source of errors is that incorrect boundary conditions are used. The boundary conditions should be specified in sufficient detail to resolve all of the important physical features.

G.5.1.4 Geometrical errors

G.5.1.4.1 General. It is usually necessary to simplify the geometry in some way. When assessing a CFD simulation, the way in which geometrical simplifications affect the key physical phenomena requires considration. Typical geometrical errors are given in G.5.1.4.2 to G.5.1.4.4.

G.5.1.4.2 Simplifications. Small geometrical features, e.g. fillets, small steps or gaps, can often be disregarded. When disregarding this type of feature, the way in which they might affect the important physics (e.g. flow development or tracer mixing) requires consideration.

G.5.1.4.3 Tolerances and manufacturing discrepancies. If the geometry has very large tolerances or is manufactured in a way that might produce a non-ideal shape or position, it can be necessary to perform additional CFD simulations in order to cover the range of possible real geometries.

G.5.1.4.4 Surface conditions: roughness, welds, steps, gaps etc. Often CFD simulations assume a perfectly smooth surface. A non-smooth surface which might have welds, steps or even gaps produces different results. If the physical phenomena of interest might depend on the surface conditions, these should be considered. Typical phenomena that might be dependent on this type of error are transition prediction (flow regime), penetration and mixing of leakage flows.

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G.5.2 Computational model errors

G.5.2.1 Wrong physical models

Once the type of simulation has been selected, the next step is to select which type of physical models the simulation should use. The following points should be considered:

- gas data (incompressible/compressible, perfect gas/real gas, ...);
- turbulence modelling (type of model, type of near-wall treatment, ...);
- other models (combustion, sprays, ...).

When assessing model-related errors, it is important to know the features of the selected model and think carefully how these features and possible shortcomings might affect the predicted physical behaviour. Using the wrong turbulence model can completely invalidate the results of a CFD simulation.

G.5.2.2 Numerical errors

Errors related to the numerical solution of the developed model. Typical examples of numerical errors are discretization errors, convergence errors, and round-off errors.

G.5.2.3 Discretization errors

Discretization errors can either be spatial or temporal.

Spatial discretization errors are what people normally call discretization errors. These errors are due to the difference between the exact solution and the numerical representation of the solution in space. Describing the different discretization schemes used by different codes and their associated errors is not possible here. Instead some general rules to avoid these errors can be summarized as in the following.

- Use at least a second order accurate scheme, preferably a third order accurate scheme. Some general purpose codes have a first order upwind scheme as default, this is a very diffusive scheme that often overly smoothes the results.
- For new applications, always run a simulation with a finer mesh to assess the grid dependency of the solution.
- Be aware of checkerboard errors. Checkerboard errors occur close to large discontinuities and can be seen as a wavy pattern with a wavelength of two cells. Some schemes, especially those that behave like central differencing schemes, are more prone to checkerboard effects. Upwind schemes are somewhat better and schemes like total variation diminution are better still.

The quality of the meshing can have a large influence on the accuracy of the results. There should be a sufficient number of cells across boundary layers and in any other regions of large flow gradients and the mesh should be adapted to the type of turbulence wall model being used.

Temporal discretization errors mainly affect transient simulations. However, some codes use a time-marching method also for steady simulations and then a temporal discretization error might affect the final steady solution slightly. The discretization in time can be done with first or second order schemes or a Runge–Kutta method, which is more accurate and saves memory. Some codes can adapt the time-step, but it is often necessary to prescribe a time-step in advance. Regard the time-step as a time-based grid and ensure that the grid-resolution in time is fine enough to resolve the highest flow frequencies. To avoid problems with temporal discretization errors the following should be considered.

- Use at least a second order scheme in time.
- Estimate the typical frequencies of the important flow phenomena and select a time-step that is fine enough to properly resolve these frequencies. Also examine the frequencies captured by the simulation and make sure that they are well resolved by the chosen time-step.

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- For new applications, try a finer time-step to ensure that your solution in time is fairly grid independent in time.

G.5.2.4 Convergence errors

To judge when a CFD simulation is converged is not always simple. Different codes and different applications behave very differently. Aside from assessing the residuals, global parameters, like static pressure distributions, total pressure losses, skin friction, and heat transfer, should be evaluated as the solution progresses.

G.5.2.5 Round-off errors

Care needs to be taken to avoid round-off errors when using single precision. Inviscid Euler simulations and simulations using wall-function meshes can most often be performed in single precision. For well resolved boundary layers (Y + ~1) it is often necessary to use double precision. If using double precision for the solver with very fine mesh resolutions, ensure that the mesh is also created in double precision. Sometimes a single precision solver converges more slowly than a double precision solver due to numerical errors caused by rounding. When using advanced physical models like free-surface simulations, spray, and transient simulations with rapid mesh movement it is also often necessary to use double precision.

G.5.3 User and code errors

Such errors are related to bugs in the code or mistakes made by the CFD engineer.

G.6 What to trust and what not to trust

While CFD is generally quite good at predicting many common flow features, predicting flow separation and reattachment, for example, is challenging and the results should be interpreted with care.

Heat transfer is often very difficult to predict accurately and it is common to obtain heat-transfer coefficients that are 100 % wrong or more. Validation data are critical in order to be able to trust heat transfer simulations.

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Annex H
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The use of time of flight measurement instruments based on modulated laser light

EN ISO 16911-2 requires a control of the physical dimensions of the duct, where the flow monitor is being calculated, and such a control may be performed by the use of a non-tactile optical instrument, using modulated laser light, beamed from the instrument to an opposing surface and re-emitted to the instrument. The emitted and the re-emitted (returned) signals are compared, and since laser light is modulated with a wavelength ranging from a few to several hundred metres, the distance can be calculated from the phase shift of the two signals.

The method offers a high accuracy, often in the range of a standard deviation below 1 mm, if precautions a) to d) are taken.

a) The surface on which the measurement is performed should be non-reflective, preferably matt, re-emitting the laser signal in “all” directions. If the laser hits a “reflective” surface, like polished stainless steel, the laser beam is reflected and hits another surface before it is received by the instrument, and thereby the distance measured is greater than that intended.

b) It is best to measure from one flange across the duct to another flange, where a piece of cardboard or wood can be held against the flange to secure a firm and well-defined surface from which to measure.

c) Although many light switches use reflective tape or reflectors to measure against, many distance measurements overload the receiver circuitry and introduce a considerable measurement error; a range of 10 % to 30 % has been experienced. An instrument with a specific signal overload alarm is to be preferred.

d) Since the measurement depends on the speed of light in air, and gas temperature and air pressure do have an influence, a correction may be necessary if the gas is very warm, the stack is very large and an accurate measurement is required. The influence of temperature is approximately 1×10^{-6}/K, and that of pressure is about $0,3 \times 10^{-6}$/hPa, and if the light runs faster than the instrument assumes, it measures too short. A measurement in 200 °C gas and 10 m diameter accordingly measures $200 \times 10\,000 \times 1/1\,000\,000 = 2$ mm too short.

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Annex I
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Relationship between this International Standard and the essential requirements of EU Directives

This International Standard has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association and supports Essential Requirements of the European Directive 2000/76/EC,[1] the European Directive 2001/80/EC,[2] the European Directive 2003/87/EC,[3] and the European Industrial Emissions Directive (IED) 2010/75/EC.[5]

WARNING — Other requirements and other EU Directives may be applicable to the product(s) falling within the scope of this standard.

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[2] Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants. *Off. J. Eur. Union* 2001-11-27, **L309**, pp. 1–21

[3] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. *Off. J. Eur. Union* 2003-10-25, **L275**, pp. 32–46

[4] Commission Decision of 18 July 2007 establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council (2007/589/EC). *Off. J. Eur. Union* 2007-08-31, **L229**, pp. 1–85

[5] Directive 2010/75/EC of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). *Off. J. Eur. Union* 2010-12-17, **L334**, pp. 17–119

[6] EN 15267 (all parts), *Air quality — Certification of automated measuring systems*

[7] CEN/TR 15983:2010, *Stationary source emissions — Guidance on the application of EN 14181:2004*

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