INTERNATIONAL STANDARD

ISO 16911-1

First edition
2013-03-01

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

Part 1:
Manual reference method

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

Partie 1: Méthode de référence manuelle

Reference number
ISO 16911-1:2013(E)

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Published in Switzerland

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Foreword

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

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

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

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

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

— *Part 1: Manual reference method*

— *Part 2: Automated measuring systems*

Introduction

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

EN ISO 16911-1 provides a method which uses point measurements of the flow velocity to determine the flow profile and mean and volume flow rates. It also provides for alternative methods based on tracer gas injection, which can also used to provide routine calibration for automated flow-monitoring systems. A method based on calculation from energy consumption is also described. EN ISO 16911-1 provides guidance on when these alternative methods may be used.

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

Part 1:
Manual reference method

1 Scope

EN ISO 16911-1 specifies a method for periodic determination of the axial velocity and volume flow rate of gas within emissions ducts and stacks. It is applicable for use in circular or rectangular ducts with measurement locations meeting the requirements of EN 15259. Minimum and maximum duct sizes are driven by practical considerations of the measurement devices described within EN ISO 16911-1.

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

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

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

2 Normative references

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

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

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

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

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

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

3 Terms and definitions

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

3.1
Pitot tube
device to measure flow velocity at a point, operating on the principle of differential pressure measurement

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

3.2
measurement line
line across the stack, on a measurement plane, along which flow measurements are made to characterize the flow velocity profile or to determine the average flow

3.3
measurement plane
plane normal to the centreline of the duct at the measurement location at which the measurement of flow velocity or volume flow rate is required

3.4
measurement point
sampling point
position in the measurement plane at which the sample stream is extracted or the measurement data are obtained directly

3.5
volume flow rate
volume flow of gas axially along a duct

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

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

3.6
point flow velocity
local gas velocity at a point in the duct

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

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

3.7
average flow velocity
<1> velocity which, when multiplied by the area of the measurement plane of the duct, gives the volume flow rate in that duct
<2> quotient of the volume flow rate in the duct and the area of the measurement plane of the duct

3.8
standard conditions
reference value a pressure 101,325 kPa and a temperature 273,15 K

3.9
uncertainty (of measurement)
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

3.10

uncertainty budget

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

Note 1 to entry: For the purposes of EN ISO 16911-1, the sources of uncertainty are according to ISO 14956[5] or ISO/IEC Guide 98-3.

3.11

standard uncertainty

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

3.12

expanded uncertainty

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

Note 1 to entry: In EN ISO 16911-1, the expanded uncertainty is calculated with a coverage factor of $k = 2$, and with a level of confidence of 95 %.

3.13

overall uncertainty

expanded combined standard uncertainty attached to the measurement result

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

3.14

swirl

cyclonic flow

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

3.15

automated measuring system

AMS

measuring system permanently installed on site for continuous monitoring of flow

Note 1 to entry: See EN ISO 16911-2.

3.16

metrological traceability

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

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

4 Symbols and abbreviated terms

4.1 Symbols

A	area of the measurement plane	m^2
A_I	internal area of the measurement section	m^2
A_s	cross-sectional area of stack	ft^2
B	number of component B	

a_1, a_2	angle between sensing holes	°
c	constant	
d	outer tube diameter	mm
d_s	stack diameter	mm
$e_{(N)}$	net specific energy (NSE) of the fuel as received	MJ/kg
e_P	absolute error of measurement	
F	force acting on the vane wheel	N
$F_1(i)$	pitch angle ratio at traverse point i	1
$F_2(i)$	3D probe velocity calibration coefficient at traverse point i	1
f	vane frequency	s^{-1}
f_v	velocity factor	
f_{WA}	wall adjustment factor	
i	ith measurement point	
K	coefficient of the Pitot tube which includes the Pitot calibration factor and constant values relating to the Pitot design	
K_p	conversion factor, 85.49 ft/s[(lb/lb-mol)(inHg)/(R)/(inH$_2$0)]$^{0.5}$	
$K\left(\rho_{0,\eta\ \mathrm{dyn}}\right)$	non-linear calibration factor dependent on density, ρ_0, and viscosity, η_{dyn}	
k	coverage factor	
L	length of the measuring section, i.e. the stack length between the two measurement levels	m
L_p	probe length	
M	molar mass of wet gas effluent	kg/mol
M_B	molar mass of component B	kg/mol
M_d	molar mass of gas, dry basis	lb-lb/mol
M_s	molar mass of gas, wet basis	lb-lb/mol
n	number of measurement points	
P	energy production	MW
p	flue gas pressure	kPa
$p_1 \dots p_5$	pressures at points P$_1$ ... P$_5$	
p_2	stagnation point pressure	Pa
p_3	static pressure	Pa

$(p_1 - p_2)_i$	velocity differential pressure at traverse point *i*	$\mathrm{inH_2O}$
$(p_4 - p_5)_i$	pitch differential pressure at traverse point *i*	$\mathrm{inH_2O}$
p_{atm}	atmospheric pressure	inHg
p_{c}	absolute pressure in the duct, in the measurement section	Pa
p_{dyn}	dynamic pressure on the vane wheel	Pa
p_{g}	static pressure	$\mathrm{inH_2O}$
p_{s}	stack absolute pressure	inHg
p_{std}	standard absolute pressure	29.92 inHg
$\overline{p_{\mathrm{stat}}}$	average static pressure in the measurement section	Pa
$q_{m,\mathrm{t}}$	tracer mass flow rate	kg/s
q_V	volume flow rate	$\mathrm{m^3/s}$
$q_{V,\mathrm{0d}}$	dry volume flow rate, under standard conditions of temperature and pressure	$\mathrm{m^3/s}$
$q_{V,\mathrm{0d,O_2}}$	dry volume flow rate, under standard conditions of temperature and pressure and on actual oxygen concentration	$\mathrm{m^3/s}$
$q_{V,\mathrm{0d,O_2,ref}}$	dry volume flow rate, under standard conditions of temperature and pressure, and reference oxygen concentration	$\mathrm{m^3/s}$
$q_{V,\mathrm{0,O_2}}$	stack gas flow rate at sample $\mathrm{O_2}$ content and moisture under standard conditions	$\mathrm{m^3/s}$
$q_{V,\,\mathrm{sd}}$	average dry-basis stack gas volume flow rate corrected to standard conditions	dscf/h
$q_{V,\,\mathrm{sw}}$	average wet-basis stack gas volume flow rate corrected to standard conditions	wscf/h
$q_{V,\mathrm{w}}$	volume flow rate under the conditions of temperature and pressure of the duct, on wet gas	$\mathrm{m^3/s}$
R	gas constant	8,314 J/(K mol)
r_{Sp}	geometry of the vane wheel	
T	flue gas temperature	K
T_{c}	temperature of gas in the measurement section	K
$T_{\mathrm{s(avg)}}$	average absolute stack gas temperature across stack	R
$T_{\mathrm{s}(i)}$ °F	stack gas temperature at traverse point *i*	°F
$T_{\mathrm{s}(i)}$ R	absolute stack gas temperature at traverse point *i*	R
T_{std}	standard absolute temperature	528 R
t	transit time of the tracer pulse between the two measurement points	s

$u(v)$	uncertainty of measurement of the flow velocity	m/s
v_0	start-up velocity	m/s
v_c	velocity corrected for flow direction	m/s
v_i	local velocity at measurement point i	m/s
v_meas	measured velocity	m/s
v_t	peripheral velocity, $v_\mathrm{t} = \varpi r_\mathrm{Sp}$	
v_∞	axial approach velocity	m/s
$\bar{v}$	mean velocity	m/s
$\bar{v}_\mathrm{v}$	mean axial velocity	m/s
$\bar{v}_\mathrm{c}$	corrected mean velocity	m/s
$\bar{v}_\mathrm{p}$	average of the point velocity measurements	m/s
w_ash	ash yield mass fraction of solid fuel as received	
w_C	carbon mass fraction in fuel as received	
w_f	fuel mass fraction in fuel as received	
w_H	hydrogen mass fraction in fuel as received	
$w_\mathrm{H_2O}$	moisture mass fraction in solid fuel as received	
w_N	nitrogen mass fraction in fuel as received	
w_O	oxygen mass fraction in fuel as received	
w_S	sulfur mass fraction in fuel as received	
α	pitch of blade	
Δp	differential pressure	Pa
$\overline{\Delta p_i}$	average dynamic pressure measured at the point i of the measurement section	Pa
η	thermal efficiency	
η_dyn	dynamic viscosity	Pa s
θ_meas	measured angle	°
ρ	density of the gas effluent under ambient conditions of temperature and pressure of wet gas	kg/m^3
$\sigma_{\Delta p_i}$	standard deviation of the m dynamic pressure measurements in the point i	
$\Phi_\mathrm{(N)F}$	process heat release	MW

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

4.2 Abbreviated terms

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

5 Principle

5.1 General

EN ISO 16911-1 provides a method for the determination of gas velocity and volume flow rate within an emissions duct. It describes a method to determine the velocity profile of the gas flow across a measurement plane in the duct, and a method to determine the total volume flow rate at a measurement plane in the duct based on a grid of point velocity measurements made across the measurement plane. In addition, alternative methods are described for the determination of volume flow rate based on the measurement of tracer dilution, tracer transit time, and by calculation from energy consumption.

Techniques for determining gas velocity at a point include a calibrated differential pressure device (Pitot) and a calibrated vane anemometer. Selection criteria for the use of different types of Pitot and the vane anemometer are given in Clause 6. However, it is up to the user to ensure the method selected for a given application meets the performance criteria defined by EN ISO 16911-1. The volume flow rate within a duct is determined by measuring the duct axial gas velocity at a series of points along measurement lines across the duct on a single measurement plane. The number of measurement lines and measurement points required depends on the duct shape and size. The spacing of the measurement points is based on the principle of equal areas as defined in EN 15259. The volume flow rate is calculated from the average axial velocity and the duct area at the measurement plane. If required a correction is applied to account for wall effects (see 10.4).

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

- Annex C describes a method based on tracer dilution measurements. In this method, the volume flow rate is determined from the dilution of a known concentration of injected tracer.
- Annex D describes a method based on a tracer transit time measurement technique. The volume flow rate is determined from the time for a pulse of tracer gas to traverse between two measurement locations.
- Annex E describes a method to determine the volume flow rate using a calculation-based approach to derive the flow from the energy consumption of a combustion process.

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

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

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

The axial flow velocity at a point in the duct is determined using one of two techniques described in EN ISO 16911-1: differential pressure based measurement using Pitot tubes and vane anemometry. The annexes describe the techniques in detail, Annex A provides for the use of differential pressure based techniques, Annex B describes the vane anemometer.

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

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

Different implementations of the differential pressure approach are available. These include standard L-type, S-type, and multi-axis Pitot tubes (3D and 2D Pitot tubes). Each has their own specific advantages and disadvantages, and these are described in EN ISO 16911-1. The methods used are based on those defined in ISO 10780,[4] ISO 3966,[3] and US EPA Method 2.[14] Performance requirements and quality assurance procedures are applied to achieve the uncertainties defined in EN ISO 16911-1.

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

5.3 Principle of measurement of volume flow rate

5.3.1 General

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

5.3.2 Principle of volume flow rate determination from point velocity measurements

Volume flow rate is determined from a number of point measurements of the axial flow velocity over a measurement plane. Sufficient point measurements are made to characterize non-uniformities in the flow profile. The measurement points across the measurement plane are selected to be representative of regions of equal area. The average velocity passing through the measurement plane is calculated with good approximation as equal to the average of the point flow measurements. The procedures in EN 15259 are used to determine the measurement points for circular or rectangular ducts. The tangential methodology provided in EN 15259 is used for circular ducts as described in EN ISO 16911-1.

The reason that for circular ducts, the tangential methodology is preferred from the two schemes for determining equal areas provided for in EN 15259, is that this scheme has points which provide measures of the average flow in each equal area. The central point in the general method does not provide a measure of the average flow in the central area, but rather the maximum value. This may be useful for reconstructing the flow profile, but is not recommended for determining the average flow in the duct.

The measurement plane is selected to be representative of the required duct volume flow rate, and also to be in a region where it is uniform and stable. If non-axial flow (swirl or cyclonic flow) is expected at the measurement plane due to geometry of the duct or other upstream conditions, then the degree of swirl is determined using S-type, 3D or 2D Pitot tube measurements and if it is significant, as defined in EN ISO 16911-1, then it is taken into account through the use of additional measurement procedures, or a different measurement plane is selected.

If required, improved uncertainty in the results is achieved by taking wall effects into account, following a procedure based on the US EPA Method 2H[17] for circular ducts, and US EPA CTM-041[13] for rectangular ducts.

The volume flow rate, q_V, is determined by multiplying the average velocity by the area of the measurement plane (i.e. the internal area of the duct at the measurement plane).

$$q_V = \bar{v}_\mathrm{p} A \tag{1}$$

where

$\bar{v}_\mathrm{p}$ is the average of the point velocity measurements;

A is the area of the measurement plane.

NOTE It is also possible to determine an array of volume flow rates, determined from the point measurements at each equal area multiplied by the area represented by each sample point. Each sample point area is, by definition, equal to the area of the measurement plane divided by the number of points. The volume flow rate is then

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

where

v_i is ith point measurement;

A is the area of the measurement plane;

n is the number of measurement points.

which is equivalent to Formula (1).

5.3.3 Determination of volume flow rate using tracer dilution measurements

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

- the tracer gas is fully mixed in the stack gas;
- there is no tracer gas present in the stack gas prior to injection or the background concentration can be measured and subtracted accurately.