INTERNATIONAL STANDARD

ISO 12569

Second edition
2012-12-01

Thermal performance of buildings and materials — Determination of specific airflow rate in buildings — Tracer gas dilution method

Performance thermique des bâtiments et des matériaux — Détermination du débit d'air spécifique dans les bâtiments — Méthode de dilution de gaz traceurs

Reference number
ISO 12569:2012(E)

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Foreword

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ISO 12569 was prepared by Technical Committee ISO/TC 163, *Thermal performance and energy use in the built environment*, Subcommittee SC 1, *Test and measurement methods*.

This second edition cancels and replaces the first edition (ISO 12569:2000), which has been technically revised.

Introduction

The aim of ventilation is to maintain a proper hygienic status of the room by introducing outdoor air into a room, diluting contaminants, heat, moisture or odour generated in the room, and evacuating them. In terms of energy savings, it is also important to keep the ventilation at the required rate, in order to reduce heat loss and heat gain under air conditioning as much as possible. Measurement of airflow rates is often necessary, for example to check if the performance of a ventilation system is as intended, to assess the source strength of contaminants, to ensure that contaminants are properly eliminated, etc. The methods described here can be used to measure the ventilation rate or the specific airflow rate.

Thermal performance of buildings and materials — Determination of specific airflow rate in buildings — Tracer gas dilution method

1 Scope

This International Standard establishes an engineering standard by which to obtain the ventilation rate/specific airflow rate, using a tracer gas in a building space, which is considered to be of a single zone.

The measurement method is valid in spaces where the combined conditions concerning the uniformity of tracer gas concentration, measurement of the exhaust gas concentration, effective mixed zone and/or fluctuation of ventilation are satisfied.

This International Standard provides three measurement methods using a tracer gas: (1) concentration decay method, (2) continuous dose method, and (3) constant concentration method.

NOTE Specific measurement conditions are given in Table 1.

2 Terms and definitions

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

2.1
single zone
V
space where the ventilation rate/specific airflow rate is measured and which only exchanges air with the outside

NOTE 1 Measured in cubic metres.

NOTE 2 Conditions needed for measurement are different for each measurement method, and details are given in Clause 4.

2.2
effective mixed zone
V_{emz}
space within a single zone, excluding sealed furniture or storage space, in which tracer gas supplied to the zone is regarded as uniformly distributed

NOTE 1 Measured in cubic metres.

NOTE 2 Forced mixing of air in the zone is often needed to keep uniform tracer gas concentration.

2.3
ventilation rate
Q_v
total volume of air passing through the zone to the outdoor air per unit of time

NOTE Measured in m^3/s or m^3/h.

2.4
specific airflow rate
N
ratio of the Qv to the volume of the effective mixed zone, per second or per hour

2.5
building envelope
boundary or barrier separating the interior volume of a building from the outside environment

2.6
tracer gas
gas that can be mixed with air and measured in very small concentration in order to study airflow rate

NOTE The tracer gas volume is defined as the value of exhaust temperature converted into density. When the room air is mixed well, the room temperature approximately matches the exhaust temperature.

2.7
concentration decay method
method by which the specific airflow rate is obtained from the decaying curve of concentration observed after the end of the injection of tracer gas.

2.8
continuous dose method
method by which the ventilation rate is obtained from the concentration resulting from continuous generation or injection of the tracer gas

2.9
constant concentration method
method by which the ventilation rate is obtained from the injection rate of tracer gas dosed for constant concentration in the space

3 Measurement method and its selection

3.1 General

One of the three measurement methods concentration decay method, continuous dose method and constant concentration method, is used to measure the ventilation rate/specific airflow rate. Selection of a measurement method and data processing depends on a building structure, ventilation system and measurement instrument employed. The concentration decay method has a limited measurement time of up to several hours while the continuous dose and constant concentration methods can provide a longer measurement time up to several weeks. The guideline of selection of the method and what is measured by the method is listed in Table 1.

In order to improve the accuracy of measuring the ventilation rate/specific airflow rate, it is sometimes necessary to devise measures that approximate prerequisite conditions demanded of measurement methods. In particular, if a measurement method were used that requires uniformity of concentration in the effective mixed zone, it would be preferable to forcibly mix the internal air. In general, forced mixing of internal air has little effect on ventilation rate/specific airflow rate, but there is a risk that forced mixing affects the measured ventilation rate if natural ventilation due to temperature differences predominates and the temperature within the room is distributed significantly, or if airflow emitted from a fan for the purpose of mixing air directly impinges on the leakage areas in buildings. In such instances, a mixing system needs to be improved or it would be recommended to select a measurement method that could ensure uniformity of concentration without mixing.

In Table 1, specifications for the various applications are described as follows:

— “Room concentration can be maintained uniform at initial stage only” means making the concentration in the effective mixed zone uniform by a method such as forced mixing when supplying a tracer gas into the zone, but allowing the concentration to be distributed in principle with the measurement.

— If it is specified that “room concentration can be maintained uniform at all times”, continuous forced mixing of air in the effective mixed zone is preferable. However, if the constant concentration method is used, and if concentration is controlled by injecting the tracer gas at several places and air is sampled at several locations, it is possible to assume that concentration is uniform without mixing.

— "Average exhaust concentration can be measured" may either mean instances in which concentration in an effective mixed zone is made uniform using mixing, or instances whereby the pressure inside a zone is kept lower than the outside when using the exhaust ventilation system, or the leakage area is extremely low so the exfiltration rate may be ignored, and exhaust pathways may be specified beforehand.

— When using measurement methods that require the "known volume of an effective mixed zone", the volume of the effective mixed zone can be estimated using room dimensions. However, when using the corresponding average inverse concentration method and average concentration method, if a sufficiently long time is taken to evaluate the ventilation rate, high accuracy for estimating the volume of an effective mixed zone is not needed.

— Measurement methods that can be applied in instances where "fluctuation in ventilation rate can be ignored", are designed on the assumption that the ventilation rate/specific airflow rate over time does not change.

Table 1 — Method, application and measured quantities

Method		**Application and measured quantities**						
		Application					**What is measured**	
		Room concentration can be maintained uniform at initial stage only	Room concen-tration can be maintained uniform at all times	Average exhaust concen-tration can be measured	Known volume of effective mixed zone	Fluctuation in ventilation rate can be ignored	Ventilation rate or specific airflow rate	Flexibility to transient ventilation rate
Concentration decay method	2-point decay method		○				Specific air-flow rate	Δ
	Multi-point decay method		○			○	Specific air-flow rate	
	Step-down exhaust concentration method	○		○		○	Specific air-flow rate	
	Pulse method			○		○	Ventilation rate	

NOTE In addition to the measurement methods above, there is an intermittent dose method that allows the measurement the volume of an effective mixed zone and ventilation rate at the same time. For measurement of ventilation rate among the other measurements, if volume of an effective mixed zone is known, the ventilation rate can be obtained by multiplying the volume of the effective mixed zone by the specific airflow rate, and then converting to ventilation rate. The measurement methods marked with "Δ" in the "flexibility to transient ventilation rate" column can apply, in principle, to the case where changes in ventilation rate/specific airflow rate cannot be ignored, however, because the measurement is based on time-mean ventilation rate/specific airflow rate, it indicates that it does not meet the measurement of transient ventilation rate/specific airflow rate. The constant concentration methods marked with "○" indicate it meets measurement of transient ventilation rate if the dose of the tracer gas responds accurately to the transient ventilation rate with internal concentration maintained at a constant level.

Table 1 *(continued)*

Method		Application and measured quantities						
		Application					What is measured	
		Room concentration can be maintained uniform at initial stage only	Room concentration can be maintained uniform at all times	Average exhaust concentration can be measured	Known volume of effective mixed zone	Fluctuation in ventilation rate can be ignored	Ventilation rate or specific airflow rate	Flexibility to transient ventilation rate
Continuous dose method	Average of inverse concentration method		○		○		Ventilation rate	Δ
	Average concentration method		○		○	○	Ventilation rate	
	Stationary concentration method			○		○	Ventilation rate	
Constant concentration method			○				Ventilation rate	○

NOTE In addition to the measurement methods above, there is an intermittent dose method that allows the measurement the volume of an effective mixed zone and ventilation rate at the same time. For measurement of ventilation rate among the other measurements, if volume of an effective mixed zone is known, the ventilation rate can be obtained by multiplying the volume of the effective mixed zone by the specific airflow rate, and then converting to ventilation rate. The measurement methods marked with “Δ” in the “flexibility to transient ventilation rate” column can apply, in principle, to the case where changes in ventilation rate/specific airflow rate cannot be ignored, however, because the measurement is based on time-mean ventilation rate/specific airflow rate, it indicates that it does not meet the measurement of transient ventilation rate/specific airflow rate. The constant concentration methods marked with “○” indicate it meets measurement of transient ventilation rate if the dose of the tracer gas responds accurately to the transient ventilation rate with internal concentration maintained at a constant level.

3.2 Concentration decay method

3.2.1 General

At the start of measurement, the tracer gas is supplied in the zone to be measured, and ventilation rate/specific airflow rate is evaluated based on the concentration decay data obtained. In case of the forced mixing for uniform distribution or if the average exhaust concentration can be measured, the measurement point can be limited to one. The amount of tracer gas needed is very small for one measurement, and it is not required to accurately measure the amount of injected gas except for the pulse method.

The basic equation that can be commonly applied to the methods is as follows:

$$\frac{dV_{\text{gas}}(t)}{dt} = -C_{\text{E}}(t)Qv(t) \quad (\text{m}^3/\text{h or m}^3/\text{s}) \tag{1}$$

where

t is time, hours or seconds;

$V_{gas}(t)$ is total volume of tracer gas in a zone at time "t" ($= \iiint_V C(x,t)dV$) (m³);

x is location in a zone;

$C(x, t)$ is concentration at "t", "x" in a zone (m^3/m^3);

$Qv(t)$ is ventilation rate at "t" (m^3/h);

$C_E(t)$ is average exhaust concentration at "t" (m^3/m^3).

NOTE Formula (1) assumes that indoor-outdoor air density difference, mostly resulting from temperature difference can be neglected.

3.2.2 2-point decay method

With the concentration in an effective mixed zone continuously made uniform, the time-mean air charge rate is calculated from the measurement start point to the end point. It is not necessary for the specific airflow rate to be constant during measuring.

The following equation is established from the above conditions.

$$V_{gas}(t) = V_{emz} \cdot C(t)$$

$$C_E(t) = C(t) \quad (2)$$

where

$C(t)$ is concentration in an effective mixed zone (uniform distribution) at t (m^3/m^3);

V_{emz} is volume of an effective mixed zone (no time changes are assumed) $[= \iiint_V C(x,t)dV / C_E(t)]$ (m^3).

Formula (1) and Formula (2) provide Formula (3) to give Formula (4).

$$\int_{t1}^{t2} \frac{dC}{C(t)} = -\int_{t1}^{t2} \frac{Q(t)}{V_{emz}} dt \quad (3)$$

$$\bar{N} = \frac{1}{t2 - t1} \log_e \frac{C(t1)}{C(t2)} \quad (4)$$

where

t is time (t_1: Measurement start point, t_2: Measurement end point) (h);

$\bar{N}$ is time-mean specific airflow rate $\left(= \frac{1}{t2-t1} \int_{t1}^{t2} \frac{Q(t)}{V_{emz}} dt\right)$ (1/h).

Based on the measured concentration data of two different time points, the time-mean specific airflow rate is calculated for that period. During the measurement period the concentration in the effective mixed zone must be uniformly maintained. It is necessary for the accurate measuring of specific airflow rate that the difference in concentration between the measurement start point and end point be sufficiently greater than the concentration measurement error.

3.2.3 Multipoint decay method

Specific airflow rate is calculated when the concentration distribution in an effective mixed zone is maintained uniform and the ventilation rate does not fluctuate over time.

Formula (5) is obtained when the ventilation rate in Formula (3) is made constant and the equation is transformed.

$$\log_e C(t) = \log_e C(t_1) - N(t - t_1) \quad (5)$$

where N is specific airflow rate (h).

Specific airflow rate is calculated by applying the measured data of concentration using the least square method to a straight line shown in Formula (5). The precondition that specific airflow rate does not fluctuate over time is confirmed when $\log_e C(t)$ is plotted against t and there is a linear relationship. Lack of a linear relationship indicates that ventilation rate is not constant, so the specific airflow rate obtained using this method is not the time-mean specific airflow rate. In this instance the 2-point decay method should be applied.

3.2.4 Step-down exhaust concentration method

The specific airflow rate is calculated when the average exhaust concentration is measurable, the distribution of the concentration in an effective mixed zone at the measurement start point is uniform, and the ventilation rate does not fluctuate over time. It can also be applied when the concentration is distributed after the start of measuring. Simultaneous measurement with the mean age of air distribution is possible.

When time is integrated up to ∞ by making constant the ventilation rate in Formula (1), Formula (6) is obtained

$$\int_{t_1}^{\infty} dV_{gas}(t) = Qv \int_{t_1}^{\infty} C_E(t)\,dt \quad (6)$$

If the concentration in an effective mixed zone is made uniform at the measurement start point, the result is

$$V_{gas}(t_1) = V_{emz} \cdot C(t_1)$$

and after sufficient time has elapsed the result is

$$V_{gas}(\infty) = 0$$

which provides Formula (7).

$$N = \frac{C(t_1)}{\int_{t_1}^{\infty} C_E(t)\,dt} \quad (7)$$

That is, the reciprocal value to the mean local age of air in the exhaust outlet becomes the specific airflow rate in the room. In the event of multiple exhaust outlets, the average exhaust concentration weighted depending on the exhaust airflow rate at each exhaust outlet is used.

NOTE Refer to Annex F if the difference between the exhaust temperature and room temperature cannot be ignored.

3.2.5 Pulse method

The ventilation rate is calculated when the average exhaust concentration is measurable and the ventilation rate does not fluctuate over time. The tracer gas volume supplied at the measurement start point needs to be accurately evaluated, but the concentration distribution in a zone does not need to be uniform.

In this instance, in Formula (6), $V_{gas}(t_1)$ is already known, and after sufficient time has elapsed, the result is

$$V_{gas}(\infty) = 0$$

which provides Formula (8).

$$Qv = \frac{V_{gas}(t_1)}{\int_{t_1}^{\infty} C_E(t)\,dt} \tag{8}$$

where $V_{gas}(t)$ is tracer gas volume (= supplied tracer gas volume) retained in the room at the measurement start time t_1 (m^3).

NOTE For the tracer gas volume, a value of exhaust temperature converted into density is used.

3.3 Continuous dose method

3.3.1 General

With the tracer gas being supplied continuously in the zone, the ventilation rate is measured by the amount of the dosage and concentration measurement data. If a measurement method that requires uniformly distributed concentration throughout the effective mixed zone with the tracer gas supplied is used, it normally requires multiple concentration monitoring points to verify the uniform distribution of the concentration. The amount of the tracer gas supplied increases as the measurement time extends, however, the method can be applied to measurement that extends for a long time. The passive measurement that uses carbon dioxide generated by exhalation of residents as the tracer gas, is also one of the continuous concentration methods.

The basic equation that can be commonly applied to the methods is as follows:

$$\frac{dV_{gas}(t)}{dt} = m(t) - C_E(t)Qv(t) \tag{9}$$

where $m(t)$ is dosage of tracer gas at “t” (m^3/h).

3.3.2 Average inverse concentration method

The time-mean specific airflow rate is calculated from the start to the end of measuring, where the concentration distribution in an effective mixed zone is maintained uniform. It is not necessary for the ventilation rate to be constant during measuring, but the instantaneous concentration during measurement, the instantaneous dosage of tracer gas, and the volume of the effective mixed zone are required.

The following equation is established based on the assumed conditions.

$$\begin{aligned} V_{gas}(t) &= V_{emz} \cdot C(t) \\ C_E(t) &= C(t) \end{aligned} \tag{10}$$

where

$C(t)$ is concentration in an effective mixed zone (uniform distribution) at t (m^3/m^3);

V_{emz} is volume of an effective mixed zone (m^3).

Formula (9) and Formula (10) provide Formula (11), which gives Formula (12).

$$V_{emz}\int_{t_1}^{t_2} \frac{dC}{C(t)} = \int_{t_1}^{t_2} \frac{m(t)}{C(t)}dt - \int_{t_1}^{t_2} Qv(t)\,dt \tag{11}$$

$$\overline{Qv} = \overline{\left[\frac{m}{C}\right]} + \frac{V_{\text{emz}}}{t_2 - t_1} \log_e \frac{C(t_1)}{C(t_2)} \tag{12}$$

where

t is time (t_1: Measurement start point, t_2: Measurement end point) (h);

$\overline{Qv}$ is time-mean specific airflow rate $\left(= \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} Qv(t)dt\right)$ (m^3/h);

$$\overline{\left[\frac{m}{C}\right]} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{m(t)}{C(t)} dt \quad (m^3/h).$$

$\overline{(m/C)}$ is in general different to $(\overline{m}/\overline{C})$. When the tracer gas dose during measuring is constant and is m, $\overline{(m/C)}$ is replaced by $m\overline{(1/C)}$. When there is sufficient measuring time, the effect of the second term on the right side in Formula (12) is diminished, so in such circumstance this method may be applied also to instances where sufficient accuracy is not obtained for estimation of the volume of the effective mixed zone. Immediately after the start of tracer gas dosing, the concentration is generally small, which tends to have a strong effect of delaying the response to the concentration measurement system including the sampling system, and causing errors in the measured concentration value, so at this point data must not be used for calculating the ventilation rate.

3.3.3 Average concentration method

The ventilation rate that does not fluctuate over time when the concentration distribution in an effective mixed zone has been made constantly uniform is calculated. When there is sufficient measuring time, calculation is possible using only the time-mean tracer gas dose and time-mean concentration during the measuring.

Once Formula (10) is supposed for Formula (9), integration in the measuring time provides Formula (13).

$$\int_{t_1}^{t_2} C(t)Q(t)dt = \int_{t_1}^{t_2} m(t)dt - V_{\text{emz}} \int_{t_1}^{t_2} dC \tag{13}$$

If $Q_v(t) = Q_v$ without the ventilation rate changing over time, Formula (14) is obtained.

$$Q = \frac{\overline{m}}{\overline{C}} - \frac{V_{\text{emz}}}{t_2 - t_1} \left[\frac{C(t_2) - C(t_1)}{\overline{C}}\right] \tag{14}$$

where

$$\overline{m} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} m(t)dt \quad (m^3/h);$$

$$\bar{C} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} C(t)\,dt \quad (\mathrm{m^3/m^3}).$$

When there is sufficient measuring time, the effect of the second term in Formula (14) is relatively minor and can be ignored. However, in the event that the ventilation rate changes over time, if the mean value theorem in Formula (13) were applied, Formula (15) would be obtained.

$$Qv(\xi) = \frac{\bar{m}}{\bar{C}} - \frac{V_{\mathrm{emz}}}{t_2 - t_1}\left[\frac{C(t_2) - C(t_1)}{\bar{C}}\right], \quad t_1 \le \xi \le t_2 \tag{15}$$

The ventilation rate obtained in Formula (15) provides the ventilation rate at a time during measuring, but it does not end up as the time-mean ventilation rate. The ventilation rate obtained from Formula (15) is suitable in cases where the purpose is to simulate generation of the contaminating substance in the room using tracer gas dosing, and estimate the time-mean concentration to which the inhabitant is exposed. Therefore, when it is possible to measure the instantaneous concentration and instantaneous dosage of tracer gas for the purpose of measuring the mean ventilation rate, the inverse concentration method should be used.

3.3.4 Stationary concentration method

The ventilation rate is calculated when the ventilation rate does not fluctuate over time, under conditions in which the average exhaust concentration is measurable. It can also be applied when concentration in a zone is distributed.

Formula (16) is obtained when a stationary state is reached and there are no temporal changes in Formula (9).

$$Qv = \frac{m}{C_{\mathrm{E}}} \tag{16}$$

where

m is tracer gas dose ($\mathrm{m^3/h}$);

C_{E} is average exhaust concentration ($\mathrm{m^3/m^3}$);

That is, the ventilation rate is obtained by dividing the constant concentration by the tracer gas dose.

3.4 Constant concentration method

In order to make the concentration in an effective zone regularly constant at targeted value, the tracer gas dose should be controlled and the ventilation rate evaluated from the dosage of tracer gas. Even when the internal air is not uniformly mixed, by establishing multiple tracer gas dose points and measuring points, it is possible to make the concentration distribution uniform. Special equipment is necessary to control the tracer gas dose.

The basic equation to be applied is as follows (background concentration has been set at 0 for ease of understanding).

$$0 = \frac{dV_{\mathrm{gas}}(t)}{dt} = m(t) - C_{\mathrm{target}}Q(t) \tag{17}$$

where

C_{target} is target concentration for constant concentration method (m^3/m^3);

$Qv(t)$ is ventilation rate at time t (m^3/h);

$m(t)$ is tracer gas dose at time t (m^3/h);

Accordingly, ventilation rate is calculated using the following equation,

$$Q(t) = \frac{m(t)}{C_{target}} \tag{18}$$

3.5 Type of tracer gas

Six types of tracer gas as listed in Table 2 are used to measure the ventilation rate in a zone.

Table 2 — Types of tracer gas

Type of gas	Helium [a]	Carbon dioxide [b]		Sulfur hexafluoride [c]		Perfluoro carbon [d]	Ethylene [e]	Nitrogen monoxide [f]
Chemical symbol	He	CO_2 [b]		SF_6 [c]		CF_4(PFC-14) C_2F_6(PFC-16)	C_2H_4	N_2O
Measurement method	GC-TCD	Infrared gas absorption	GC-ECD	Infrared gas absorption	GC	GC-ECD	Infrared gas absorption & FID & GC	Infrared gas absorption
Example of lower limit detection	300×10^{-6}	1×10^{-6}	70×10^{-6}	$0{,}001 \times 10^{-6}$		—	$0{,}1 \times 10^{-6}$	$0{,}1 \times 10^{-6}$
Permissible concentration	—	$5\ 000 \times 10^{-6}$		$1\ 000 \times 10^{-6}$		—	—	25×10^{-6}
Relative density against air [-]	0,138	1,545		5,302		Example, PFC-14: 3,06 PFC-16: 4,80	0,974	1,53
Global warming potential (GWP)	—	1		23 900		Example, PFC-14: 6 500 PFC-16: 9 200	—	310

NOTE 1 In addition to those gases above, nitrogen, carbon monoxide, ethane, methane, isobutene, cyclobutanoctofluoride, Bromomethanetrifluoride, dichlorodifluoridemethane, and dichlorotetrafluoridemethane can be also used as tracer gas.

NOTE 2 The GC in the table indicates general Gas Chromatography, the GC-TCD is the gas chromatography using Thermal Conductivity Detector and GC-ECD using Electron Capture Detector.

NOTE 3 The Global Warming Potential is defined as relative green house effect potential per weight against carbon dioxide.

NOTE 4 Infrared gas absorption includes both TS (transmission spectroscopy) and PAS (photoacoustic spectroscopy).

[a] Helium is chemically stable.

[b] CO_2 is dissolved in water and can be adsorbed with building materials or furniture, and is not suited for precise measurement. However, if the measurement does not require critical accuracy, CO_2 is often used. CO_2 generated by occupants or any other internal source shall be taken into account. If this CO_2 emission rate is not known, this tracer cannot be used.

[c] SF_6 has a large global warming potential and should not be used in a large amount. SF_6 is an inactive gas. If it is heated to 500 °C it generates toxic gases. Therefore, it should not be used in a space where a fan heater is used and SF_6 flows through the heat source.

[d] PFC has a large Global Warming Potential and should not be used in large amounts.

[e] Ethylene is flammable and should be handled with a great care.

[f] N_2O has a large Global Warming Potential and should not be used in large amounts. N_2O is dissolved in water, and reacts with aluminium. It ignites at a high temperature. Great care must be exercised not to use it over its permissible concentration as it affects health.

3.6 Measurement apparatus

3.6.1 General

Measurement instruments required are listed in Table 3 in accordance with the group of measurement methods listed in Table 1. Each apparatus is defined as a means of dosing and distributing the tracer gas, collecting air samples, serving as an analyser to measure gas concentration, and other measurement devices.

Table 3 — Group of measurement methods and measurement instruments

Measurement method			Measurement instrument: Tracer gas generator	Tracer gas distributor	Tracer gas collector	Tracer gas concentration instrument	Other equipment
Concentration decay method	**2-point decay method**		Cylinder and valve with flow meter [a]	Blower for mixture	Manual suction and bag made of polyvinylidene fluoride	Gas concentration detector or gas concentration analyzer	Reader or recorder
	Multi-point decay method		Cylinder and valve with flow meter [a]	Blower for mixture or pipe for distribution and duct mesh	Teflon tube and gas suction pump	Concentration analyser	2-point decay method
	Step-down method at exhaust concentration		Cylinder and valve with flow meter [a]	Blower for mixture [f]	Teflon tube and gas suction pump	Concentration analyser	Recorder and PC
	Pulse method		Container of known volume [c]	Not required	Teflon tube and gas suction pump	Gas concentration analyser	Recorder and PC
Continuous dose method	**Average of inverse concentration method**		Precision flow meter system and cylinder [b]	Blower for mixture	Teflon tube and gas suction pump	Concentration analyser	Recorder and PC
	Average concentration method	**a. Active method**	Precision flow meter system and cylinder [b]	Blower for mixture	Teflon tube and gas suction pump	Concentration analyser	Recorder and PC
		b. Passive method	Specific generator (doser) [d]	N.A.	Specific sampler [g]	Concentration analyser	N.A.
	Stationary concentration method		Precision flow meter system and cylinder	Not required	Teflon tube and gas suction pump	Concentration analyser	Recorder and PC
Constant concentration method			Cylinder with feedback control [e]	Blower for mixture	Teflon tube and gas suction pump	Concentration analyser	Process controller

[a] Including a float type flow meter.

[b] Including valve with accurate orifice flow meter or electronic mass-flow controller. Generally, the cylinder should have a pressure of 1 MPa, and capacity of 10 l to 15 l and a weight of between 5 kg and 10 kg.

[c] Ex: graduated syringe or mass flow meter with timing controller.

[d] Including aluminium tube of finger size for dosing carbon hydride by evaporating it gradually.

[e] Doser of compressed tracer gas, having a combination of a flow meter and feedback control system for concentration in the zone.

[f] Mixing is needed only at the initial stage of the measurement.

[g] Activated carbon tubes adsorb evaporated carbon hydride.

3.6.2 Tracer gas dosing device

3.6.2.1 General

The dosing rate must be accurately measured. Table 3 outlines the combinations, but a suitable volume should be chosen in accordance with each test method in Table 1 and the tracer gas used in Table 2. When the gas flow rate is measured, the temperature is simultaneously measured for the gas mass flow rate estimation. A valve with a heater attached should be prepared to prevent cooling and freezing at the valve in case a large volume of carbon dioxide etc. is emitted.

The following measures are needed for promoting a uniform mixing.

3.6.2.2 Fan for mixing

Fans for properly mixing inside a testing zone are needed. However, this is not desirable when temperature layers exist in the zone that would affect the ventilation rate and specific airflow rate.

3.6.2.3 Synchronous emission of tracer gas

Piping and duct system etc. for distribution/emission by branched piping when multiple outlets are prepared.

3.6.3 Tracer gas sampling apparatus

3.6.3.1 Materials for sampling apparatus

Materials used for the tracer gas sampling system, which are mainly piping and tubes, shall be non-absorbent, non-reactive, and non-diffusive to the tracer gas in use. Glass, copper, and stainless steel etc. are preferable. Metal foil is suitable for flexible containers. Other permissible materials are polypropylene, polyethylene, and polyamide. Fluorine-coated tubing, so-called Teflon tubing, is often used. Depending on the tracer gas, materials to avoid include soft plastics. Tubes (especially plastic tubes) used once for injecting the pure tracer should never be used for air sampling.

3.6.3.2 Portable sampler

This includes gas tight syringes, flexible bottles, and sample packs having the capacity of at least three times the minimum air concentration sample in the gas analyser. The portable sampler must have been made airtight so that the sample air is not diluted or does not become contaminated.

3.6.3.3 Sampling network for on-site analysis

The tube network comprises manifold for directing multiple sample pipes to the gas analyser, a changeover switch, and a pump that leads to the analyser, but normally it is integrated and programmed so that the sample air is suctioned at determined time intervals, and directly connected to the gas analyser.

3.6.4 Gas analyser

The gas analyser must be suitable for the tracer gas and supposed concentrations. The analyser must also be strictly calibrated and kept within a measuring error of ± 5 %. If there is a concern about analyser drift, the analyser should be calibrated at the beginning and end of the test. The advantage of a gas analyser is the possibility of measuring continuous real time indoor contaminants, e.g. CO_2, TVOC, CO, Formaldehyde.

4 Procedure

4.1 Building preparations

The measurement method in this International Standard deals with the single zone ventilation measurement. In case the zone needs uniform concentration with multiple rooms, all internal doors in the rooms may be open and an appropriate mixing device may used, in order to achieve the uniform concentration in the rooms.

If measuring were to be performed on a single room within the building, even if internal doors and doors leading to an adjacent room were intentionally sealed so that there may be no leakage from an adjacent room, in many instances air would pass into an adjacent room via leakage areas in the ceiling so it may be difficult to limit it to just the target room.

4.2 Ancillary measurements

In addition to the zone subject to ventilation measurement, the air temperature of adjacent rooms connected by openings, cracks, ducts and pits is measured and recorded. Data on external air temperature, wind speed, and wind direction are collected using the nearest meteorological observation station or portable weather observation apparatus. The building ventilation system operating condition and the size of envelope openings are measured. If the measurement method requires the volume of Vemz, the dimensions of the zone must be measured.

4.3 Concentration decay method

4.3.1 Calculation of 2-point and multi-point methods

In 4.3.1.1 and 4.3.1.2 the calculation of the 2-point and multi-point method are described.

4.3.1.1 2-point decay method

With the measurement of room concentration at two points, the average specific airflow rate on a time basis is given from Formula (19).

$$\bar{N} = \frac{1}{t_2 - t_1} \log_e \frac{C(t_1)}{C(t_2)} \quad (1/\mathrm{h}) \tag{19}$$

where

$\overline{N}$ is mean time specific airflow rate (1/h or 1/s);

$C(t_1)$ is room concentration at “t_1” (m^3/m^3);

$C(t_2)$ is room concentration at “t_2” (m^3/m^3);

t_1 is start point of measurement (h);

t_2 is end point of measurement (h).

4.3.1.2 Multi-point concentration decay method

The multiple-point concentration decay method can be used when the gas concentration decay process can be measured multiple times at intervals ranging from several minutes to around one hour. The least square method is applied to the gas concentration when at least three points are measured, and the predicted value for the specific airflow rate (N) is calculated using the following equation.

$$N = \frac{\left(\sum_{j=1}^{np} t_j\right) \cdot \sum_{j=1}^{np} \log_e C(t_j) - n_p \cdot \sum_{j=1}^{np} t_j \cdot \log_e C(t_j)}{n_p \cdot \sum_{j=1}^{np} t_j^2 - \left(\sum_{j=1}^{np} t_j\right)^2} \quad (20)$$

where

N is the estimated specific airflow rate;

t_j is the j-th elapsed time from the decay process starting $t_1 = 0$;

$C(t_j)$ is the measured gas concentration at time (t_j);

n_p is the total number of measured elapsed time points (n_p is ≥ 3).

By using period T, where multiple measured elapsed points can be obtained, and n_p, the total number of measured elapsed time points, the measurement errors that cause an estimated error in the specific airflow rate N can be minimized. This can be realized if we take the product NT_m from the curve shown in Annex E, where T_m is an optimum period realizing minimized error of N.

4.3.2 Procedure of 2-point and multi-point methods

In each method, the decaying process of gas concentration is measured after the initial concentration is high in the zone being measured, with the following steps:

Step 1: Mix the tracer gas after it is dosed or released and distributed, and check the uniformity of concentration in the space with obtained samples of initial condition.

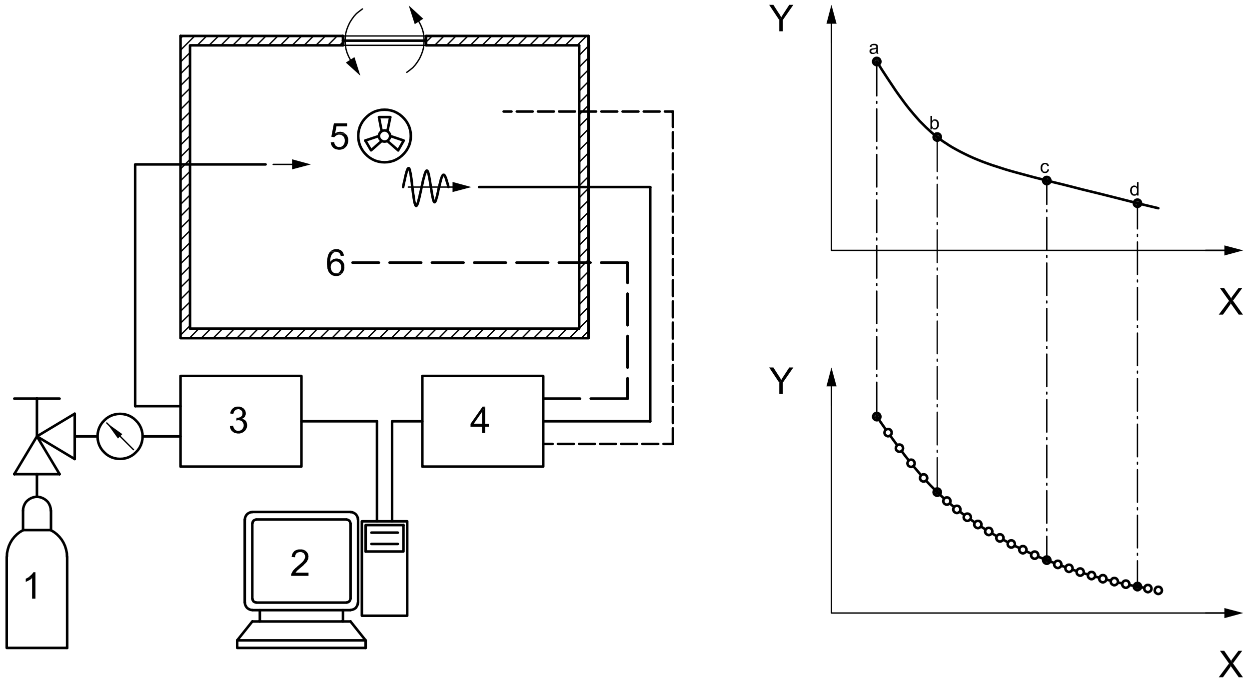
Step 2: Obtain first sample data of decaying samples.

Step 3: Obtain second sample data of the decaying process for 2-point method. At least one additional sample is required for multi-point method.

Step 4: Obtain the last sample of the decaying process to check the uniformity of concentration in the zone.

This test method is outlined in Figure 1. To make the initial concentration at step 1 that is close to the upper measurable limit of the gas concentration analyser, a sufficient and necessary amount of tracer gas is supplied into the zone. The tracer gas within the zone is then mixed. To confirm uniformity of the initial concentration, samples of air are taken from at least two points (three in total) away from the centre, in addition to the centre of the zone, and the sampling time is recorded. Air from the centre is then sampled two times and the sampling times are recorded.

The exhaust air from the measuring system must be placed to outside in order to avoid recirculation.



Key

1	tracer gas	a	step 1
2	data gathering, gas dose/air collection control	b	step 2
3	gas dose apparatus	c	step 3
4	gas concentration measuring instrument	d	step 4
5	mixing fan	X	elapsed time concentration measuring by sampling pouch, etc.
6	checking of spatial distribution	Y	concentration

Figure 1 — Overview of tracer gas decay method

4.3.3 Calculation of step-down exhaust concentration method and pulse method

In 4.3.3.1 and 4.3.3.2 the calculation of the step-down exhaust concentration method and the pulse method is described

4.3.3.1 Step-down exhaust concentration method

The specific airflow rate is calculated from Formula (21) from the uniform distributed concentration of point at start of measuring and the exhaust ventilation concentration data.

$$N = \frac{C\left(t_1\right)}{\int_{t_1}^{\infty} C_{\mathrm{E}}\left(t\right) dt} \tag{21}$$

$$\int_{t1}^{\infty} C_{\mathrm{E}}\left(t\right) dt \approx \int_{t1}^{t2} C_{\mathrm{E}}\left(t\right) dt + \frac{C_{\mathrm{E}}\left(t_2\right)}{a} \tag{22}$$

$$\log_{\mathrm{e}} C\left(t\right) = \log_{\mathrm{e}} C\left(t_2\right) - a\left(t - t_2\right) \tag{23}$$

where

N is specific airflow rate (1/h);

$C_E(t)$ is exhaust concentration at "t" (m^3/m^3);

$C(t_1)$ is the uniform distributed concentration at start point (m^3/m^3);

t_1 is start time of measuring (h);

t_2 is the end time of measurement (h);

a the estimated value related concentration decaying after t_2 (1/h).

To calculate the right denominator in Formula (21), the changes in concentration among the measurement time points is approximated by linear fit. Practically it is difficult to conduct measuring until the exhaust ventilation concentration has sufficiently lowered. Therefore, Formula (21) may be approximated by Formula (22). The estimated coefficient a of concentration decay is calculated by Formula (23) using the interpolation of semi-log curve fitting with the measured data that decays stably and linearly along time axis.

4.3.3.2 Pulse method

The ventilation rate is calculated from Formula (24) from the tracer gas volume dosed initially to the room and the exhaust ventilation concentration data.

$$Qv = \frac{V_{gas}\left(t_1\right)}{\int_{t_1}^{\infty} C_E\left(t\right) dt} \qquad (24)$$

where

t is time (h);

t_1 is point at start of measuring (h);

Qv is ventilation rate (m^3/h);

$V_{gas}(t_1)$ is tracer gas volume supplied to room at start of measuring (m^3/h);

$C_E(t)$ is exhaust ventilation concentration (m^3/m^3).

To calculate the denominator in Formula (24), the changes in concentration among the measured points are approximated using linear fit. When it is difficult to conduct measuring until the exhaust ventilation concentration has sufficiently lowered, and the changes in concentration after time t_2 are regarded to be approximated in Formula (22) as per the step-down method at exhaust concentration method, then the denominator in Formula (24) may be calculated from Formula (23).

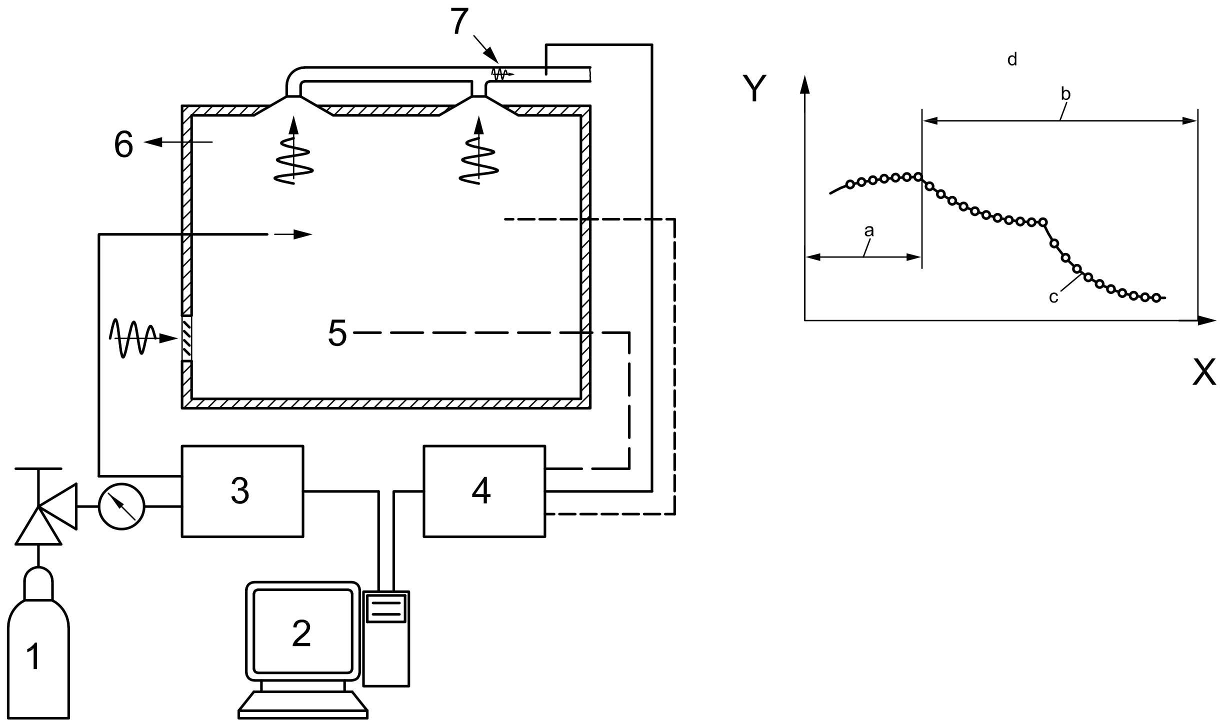
4.3.4 Procedure of the step-down exhaust concentration method and pulse method

For the step-down discharge method, after the initial concentration is increased high, measure the decaying process of concentration continuously for a long time until the concentration becomes almost the same as the atmosphere. For the pulse method, just before the gas is dosed into the zone in a transient time, start measuring the accurate amount of injected gas, increased concentration by dosing, and discharged amount of the gas over the decaying process continuously for a long time until the concentration is deemed to be the same as atmosphere. Each method requires continuous time integration of the change in concentration. In the event that discrete gas concentration can only be measured, the time interval of the measurement must be good enough, e.g. one minute.

Both of these are restricted in application to zones with mechanical exhaust equipment, so for measuring ventilation, the exhaust concentration needs to be measured continuously over a long period. Figures 2 and 3 outline the measuring methods. Conditions in which the ventilation rate does not change over a long period of time are also needed. If there are multiple exhaust outlets, the airflow weighted mean exhaust concentration for these must be calculated. Airflow at each outlet is unknown, so to enable measurement of this airflow weighted mean exhaust concentration, it is sometimes possible to measure the concentration after a mixing point where these multiple exhaust outlets have merged into one exhaust duct.

These measurement methods require uniformity of room concentration at the initial stage. Here, instances in which the mean exhaust concentration is measurable without making the room concentration uniform are those in which mechanical ventilation is performed using an exhaust fan, and the internal room pressure becomes negative in relation to the pressure outside. Thus leakages may be ignored, or instances in which the mechanical exhaust volume is known beforehand are to be considerably greater than the exfiltration rate, and the effect of the leakage may be ignored.

However, caution should be exercised if artificial mixing is not performed. For example, if the exhaust outlet is in the upper part of the zone and the external air supply is in the lower part, causing a near displacement flow effect, the decay of the exhaust concentration may initially be slow and then become rapid from when the gas in the zone is replaced by fresh outside air. Therefore, major errors can occur if the decay from the initial effective period to thereafter is estimated without measuring the gas concentration over a sufficiently long period.



Key

1 tracer gas

2 data gathering, gas dose/air collection control

3 gas dose apparatus

4 gas concentration measuring instrument

5 check of uniformity of initial gas concentration distribution

6 other exhaust must not exist

7 Airflow weighted mean discharge concentration must be measured

X Elapsed time in the case of displacement ventilation, the decay curve may suddenly change

Y Concentration

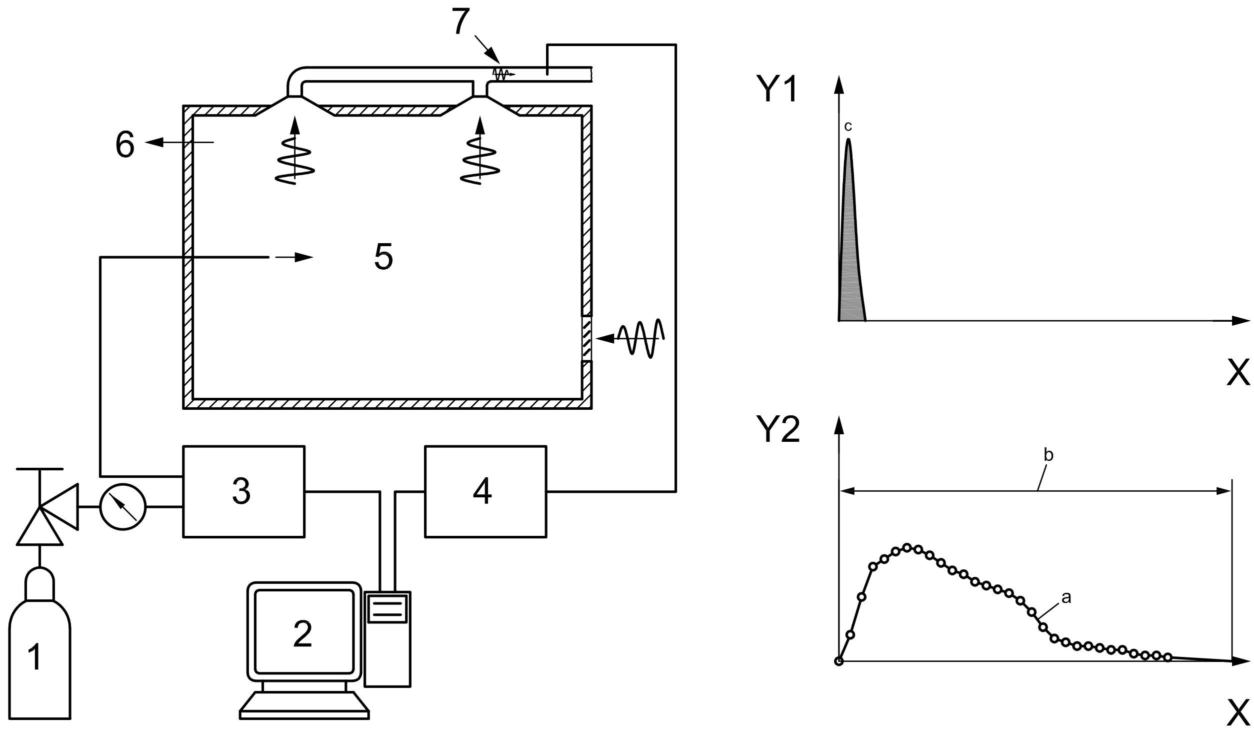
[a] Transition period.

[b] A long time is needed until the concentration has sufficiently attenuated.

[c] In the case of displacement ventilation, the decay curve may suddenly change.

[d] After confirmation of uniformity of room concentration distribution.

Figure 2 — Overview of step-down exhaust concentration method

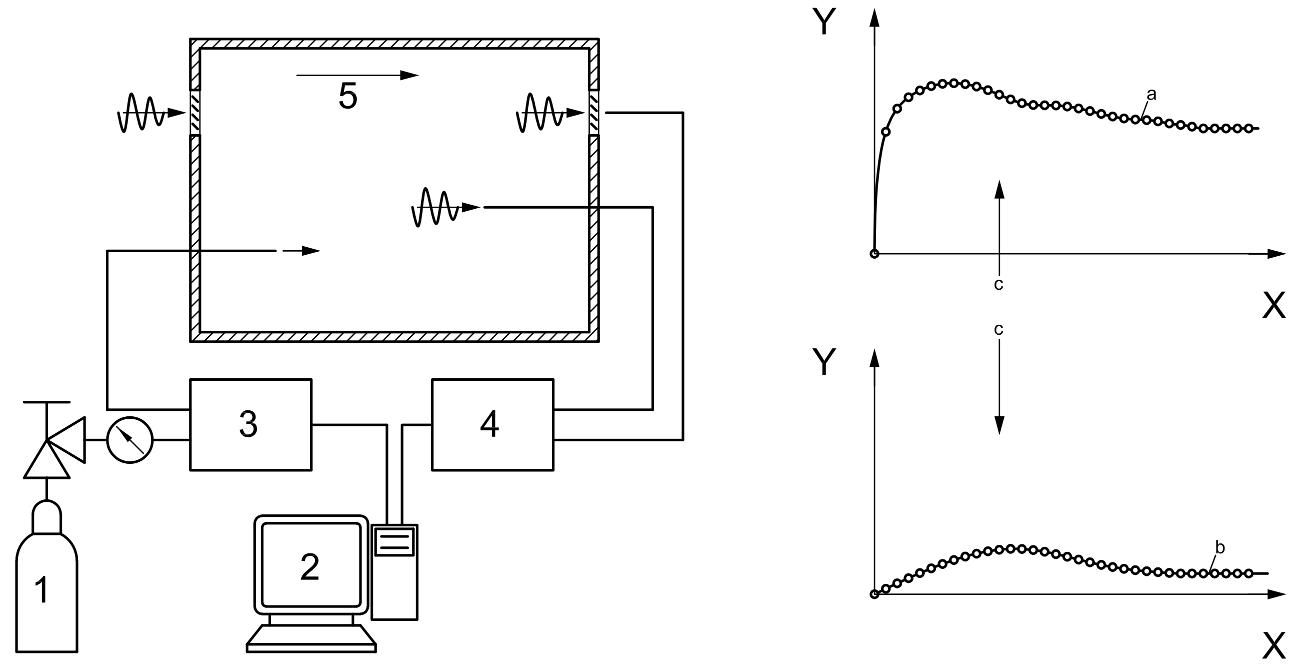


Key

1	Tracer gas	X	elapsed time
2	Data gathering, gas dose/air collection control	Y1	gas supply
3	Gas dose apparatus	Y2	concentration
4	Gas concentration measuring instrument	a	In the displacement ventilation, the concentration decay may rapidly change.
5	Can be applied only for mechanical exhaust	b	A long time is needed.
6	Other exhaust must not exist	c	Known quantity of gas is instantaneously released.
7	Airflow weighted mean exhaust concentration must be measured		

Figure 3 — Overview of pulse method

Even if, as per Figure 4, a short circuit flow occurs from the supply inlet to the exhaust outlet, a long enough measuring period must be exercised in order to provide whole characteristics of the decay curve. Because there is a risk this may lead to errors, namely because under actual conditions whereby the zone targeted for measuring has become a place of stagnant ventilation, leading to delays in the attenuation of exhaust concentration, and forcing the measurements to be cut off in a limited time, errors occur because attenuation thereafter is approximated using extrapolation, and also the zone is easily affected by disturbance fluctuations.



Key

1	Tracer gas	X	elapsed time
2	Data gathering, gas dose/air collection control	Y	concentration
3	Gas dose apparatus	a	Concentration at the representative point in the zone.
4	Gas concentration measuring instrument	b	Exhaust concentration.
5	Short circuit		

Figure 4 — Measuring error by short circuit flow

4.4 Continuous dose methods

4.4.1 Calculation of average of inverse concentration method

Through this method the average ventilation rate is obtained from the following equation, applying the volume of tracer gas dose from the start to the end of measurement, uniformly distributed room air concentration and effective mixing zone volume.

$$\bar{Q}v = \overline{\left[\frac{m}{C}\right]} + \frac{V_{\mathrm{emz}}}{t_2 - t_1} \log_{\mathrm{t}} \frac{C(t_1)}{C(t_2)} \qquad (25)$$

where

t_1 is the time at which measurement starts (h);

t_2 is the time at which measurement ends (h);

$\bar{Q}v$ is the mean time ventilation rate(m^3/h);

$$\overline{\left[\frac{m}{C}\right]} = \left[\frac{m_1}{C_1} + \ldots + \frac{m_{\mathrm{k}}}{C_{\mathrm{k}}} + \ldots + \frac{m_{\mathrm{n}}}{C_{\mathrm{n}}}\right] / n \;;$$

n is the number of measurements;

V_{efc} is the effective mixing zone volume (m^3);

C_k is the k_{th} measurement of room concentration (m^3/h);

m_k is the k_{th} volume of tracer gas dose (m^3/m^3);

$C(t_1)$ is the room concentration at "t_1" (m^3/h);

$C(t_2)$ is the room concentration at "t_2" (m^3/h).

Data from immediately after the start of tracer gas dosing must not be used. The acquisition of data must start from immediately after tracer gas dosing, and then the time-mean specific airflow rate in which t_1 changed calculated in trial bases, and the results of calculation of ventilation rate adopted from the time they had stabilized.

4.4.2 Procedure of average of inverse concentration method

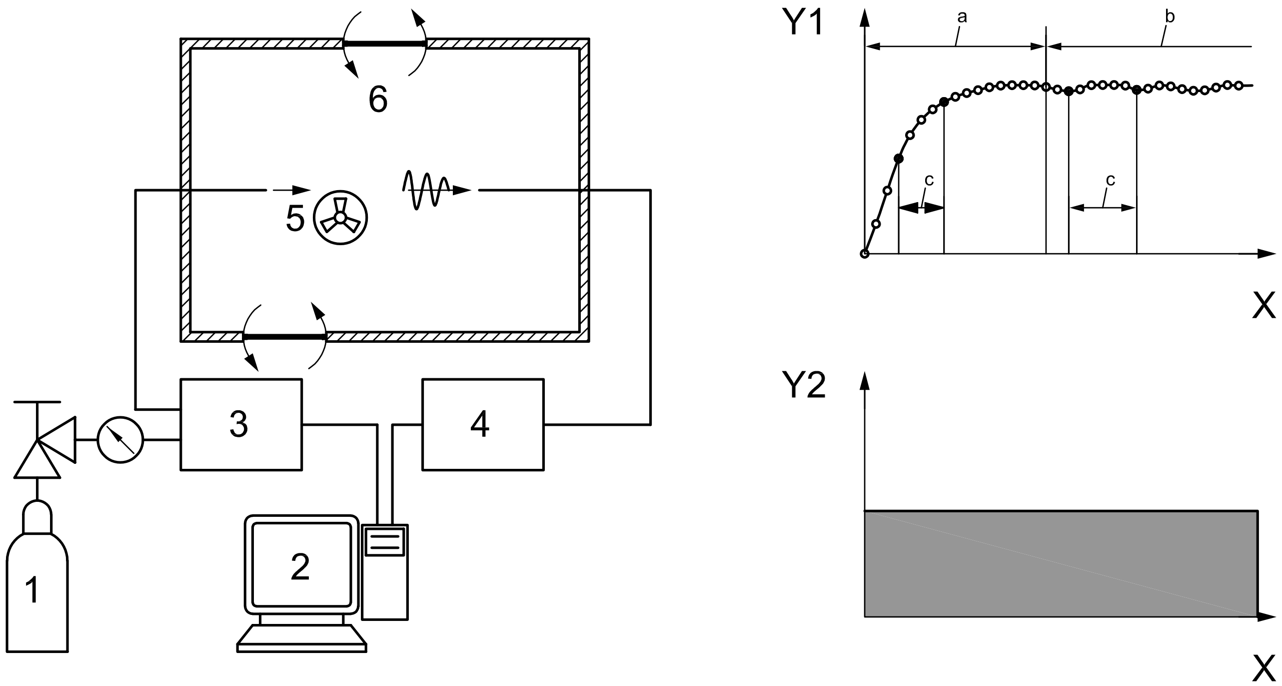
In this method, the tracer gas is supplied usually at a constant flow rate keeping uniform distribution in the zone while measuring the concentration of the gas in the zone. After gas concentration being stabilized, the mean time ventilation rate is obtained by the integrated ratio of tracer gas supply rate against gas concentration between the 2-points.

Therefore, it is preferable to measure both tracer gas supply rate and gas concentration continuously, however, when the measurement is carried out in discrete times, time intervals must be about one minute to minimize time differential error.

In order to verify transient ventilation rate over time, at least two ranges should be measured.

Figure 5 outlines this test method. So that the completion of the gas concentration elevation process can be confirmed, and because of gas concentration changes and the necessity of the integral value of a tracer gas supply rate, an apparatus is needed to enable continuous measuring and recording. Furthermore, a spatial multi-point measuring apparatus would be preferable for also confirming the uniformity of gas concentration in the zone. Typically, 30 min are appropriate for measurement intervals.

The tracer gas flow rate must be set so that errors are within 2 % of the target concentration, and so that concentration is within a detectable range for the gas analyser. The gas concentration within the zone should be mixed so that the gas concentration variation within the zone is less than 10 %.



Key

1 tracer gas
2 data gathering, gas dose/air collection control
3 gas dose apparatus
4 gas concentration measuring instrument
5 mixing fan
6 fluctuation in ventilation can be allowed

X elapsed time
Y1 concentration
Y2 gas supply
a Usable.
b Recommended.

Figure 5 — Overview of average of inverse concentration method

4.4.3 Calculation of average concentration method

The ventilation rate is calculated by inserting into Formula (26) the mean concentration from the measurement start point to the end point and instantaneous concentration at start and end point.

$$Qv = \frac{\bar{m}}{\bar{C}} - \frac{V_{\text{efc}}}{t_2 - t_1}\left[\frac{C(t_2) - C(t_1)}{\bar{C}}\right] \quad (26)$$

where

t_1 is the measurement start point (h);

t_2 is the measurement end point (h);

Qv is the ventilation rate (m^3/h);

$\bar{m}$ is the mean tracer gas supply rate $\left(\bar{m} = \frac{m_1 + \dots + m_k + \dots + m_n}{n}\right)$ (m^3/h);

$\bar{C}$ is the time-mean room concentration $\left(\bar{C} = \frac{C_1 + \dots + C_k + \dots + C_n}{n}\right)$ (m^3/m^3);

n is the number of concentration measurements;

V_{emz} is the effective mixing zone volume (m^3);

$C(t_1)$ is the room concentration at t_1 (m^3/m^3);

$C(t_2)$ is the room concentration at t_2 (m^3/m^3);

C_k is the k_{th} room concentration measured (m^3/m^3);

m_k is the tracer gas supply rate at k (m^3/h).

When using the average concentration method according to the passive method including the PFT method, $C(t_1)$ and $C(t_2)$ cannot be measured, so evaluation of the order should be performed for the right side of Formula (27) so that the second term on the right side of Formula (29) may be ignored. To meet this demand, a sufficiently long mean time is used or the measurement start time is set after room concentration is stabilized.

$$t_2 - t_1 >> \frac{\bar{C}}{\bar{m}} V_{efc}$$

$$t_2 - t_1 >> \frac{C(t_2) - C(t_1)}{\bar{m}} \cdot V_{emz} \qquad (27)$$

In this instance, Formula (28) is used to calculate the ventilation rate.

$$Q_v = \frac{\bar{m}}{\bar{C}} \qquad (28)$$

where

t_1 is the measurement start point (h);

t_2 is the measurement end point (h);

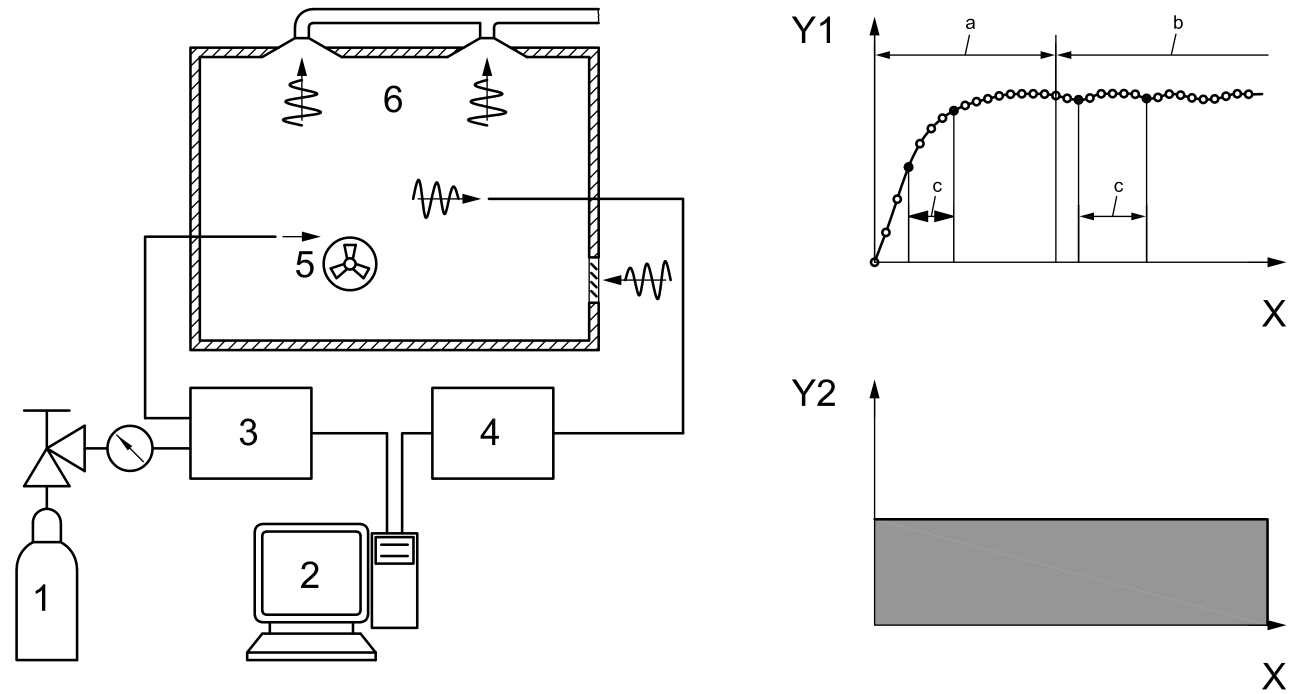
Qv is the ventilation rate (m^3/h);

$\bar{m}$ is the mean tracer gas supply rate $\left(\bar{m} = \frac{m_1 + \dots + m_k + \dots + m_n}{n}\right)$ (m^3/h);

$\bar{C}$ is the time-mean room concentration $\left(\bar{C} = \frac{C_1 + \dots + C_k + \dots + C_n}{n}\right)$ (m^3/m^3);

4.4.4 Procedure of average concentration method

Follows the procedure as the average concentration method (Figure 6). While the average of inverse concentration method bases ($\overline{(m/C)}$ m/C = average of (gas supply flow rate)/(gas concentration) in the Formula (12), the average concentration method relies on $(\bar{m}/\bar{C})$ (m/C) as seen from Formula (14), and averaging of gas supply rate and room concentration is made separately.



Key

1 tracer gas
2 data gathering, gas dose/air collection control
3 gas dose apparatus
4 gas concentration measuring instrument
5 mixing fan
6 only applicable in case of mechanical ventilation

X elapsed time
Y1 concentration
Y2 gas supply
a Usable.
b Recommended.

Figure 6 — Overview of average concentration method

4.4.5 Calculation of stationary concentration method

With the tracer gas supplied steadily to the room, this method is used to obtain the ventilation rate by using Formula (29), applied with the average exhaust concentration obtained after the room concentration has become stationary. If the exhaust concentration is measured several times, the average is applied to the equation.

$$Qv = \frac{m}{C_{\mathrm{E}}} \tag{29}$$

where

Qv is the ventilation rate (m^3/h);

m is the tracer gas supply rate (m^3/h);

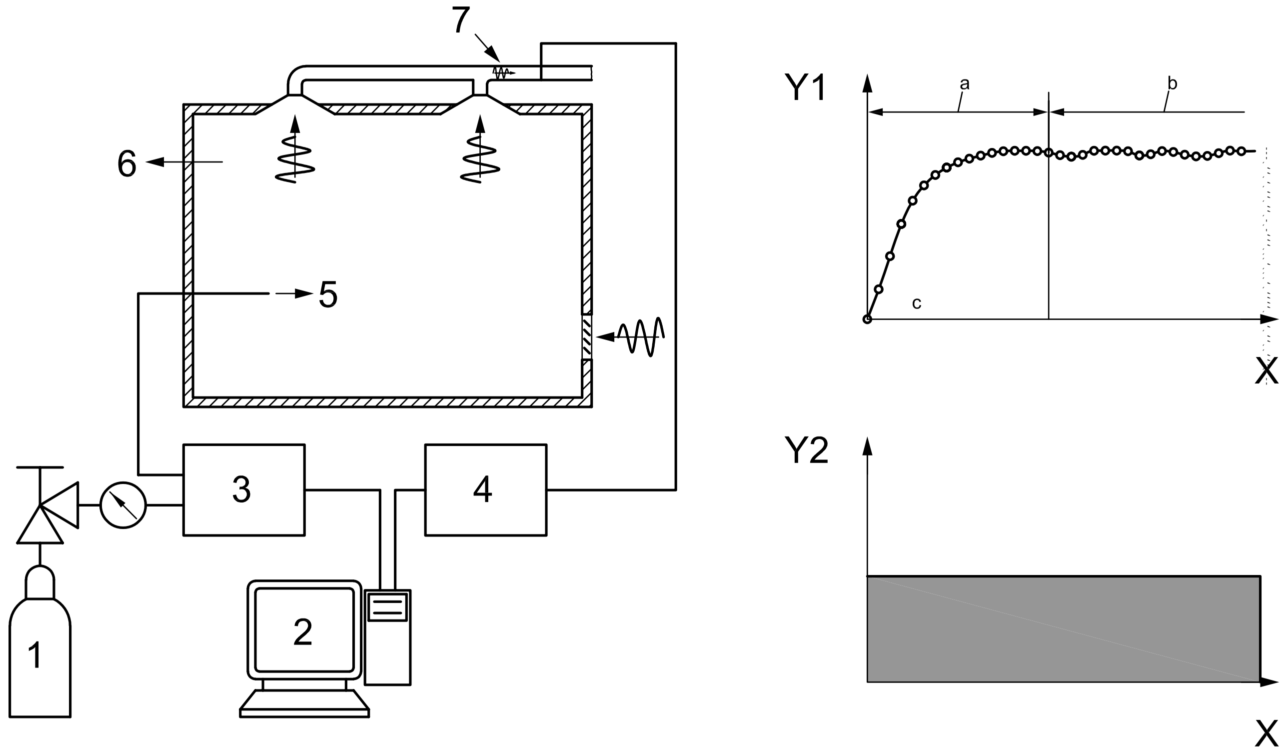
C_{E} is the stationary exhaust concentration (m^3/m^3).

4.4.6 Procedure of stationary concentration method

This method only applies to a zone where a mechanical ventilation system is installed. The tracer gas is supplied at a constant flow rate into the zone with the flow rate being measured. When a stationary state has reached, the gas supply rate and stationary exhaust concentration are measured.

An outline is shown in Figure 7. In order to measure stationary exhaust concentration accurately, the exhaust concentration must be measured continuously over the long term. Conditions are also needed to ensure that the ventilation rate does not change during this period. If there are multiple exhaust outlets, such airflow weighted mean exhaust concentrations must be measured. Although the airflow at each exhaust outlet is not known, it is possible to measure this airflow weighted mean exhaust concentration by setting the measurement point at a position downstream from a mixing point at which these multiple exhaust outlets have merged into one exhaust duct.

With this measurement method the room concentration does not need to be uniform. This method can be applied if the measured exhaust concentration represents more than 90 % of exhaust air concentration leaving from the zone. This situation is realized when exhaust only ventilation system or balanced ventilation system with larger airflow rate setting for exhaust fan is installed so that the room is kept negative pressure in relation to that of outside, or the zone is sufficiently airtight for negligible exfiltration flow rate to the outside.



Key

1 tracer gas
2 data acquisition, gas dose/air collection control
3 gas supply apparatus
4 gas concentration measuring instrument
5 negligibly small exfiltration flow rate
6 airflow weighted mean exhaust concentration must be measured

X elapsed time
Y1 concentration
Y2 gas supply
a transition state and not to be used
b can be used

Figure 7 — Overview of stationary concentration method

4.5 Constant concentration method

4.5.1 Calculation of constant concentration method

This method is used to obtain the transient ventilation rate using the following equation applied with the amount of tracer gas dose and uniformly distributed concentration, which is controlled at a constant value.

If the concentration in the zone consisting of spaces in building is kept at the same concentration, this method allows the determination of a combined airflow rate from multiple spaces that comprise the entire building.

$$Qv(t) = \frac{m(t)}{C(t)} \tag{30}$$

Refer to previous equations for the meaning of the symbols.

In order to calculate accurately the instantaneous ventilation rate it is necessary for the room concentration to be constantly kept in the vicinity of the target concentration thus $\frac{V_{\text{efc}}}{C_{\text{target}}} \cdot \frac{dC(t)}{dt} < Q(t)$

Formula (31) is used when the time-mean specific airflow rate is required.

$$\bar{Qv} = \frac{\bar{m}}{\bar{C}} \tag{31}$$

where

$\bar{Qv}$ is the time-mean specific airflow rate (m^3/h);

$\bar{m} = (m_1 + \ldots + m_\text{k} + \ldots + m_\text{n})/n$ (m^3/h);

$\bar{C} = (C_1 + \ldots + C_\text{k} + \ldots + C_\text{n})/n$ (m^3/m^3);

n is the number of concentration and tracer gas dose [-];

C_k is the k_th room concentration measured (m^3/h);

m_k is the k_th tracer gas dose measured (m^3/h).

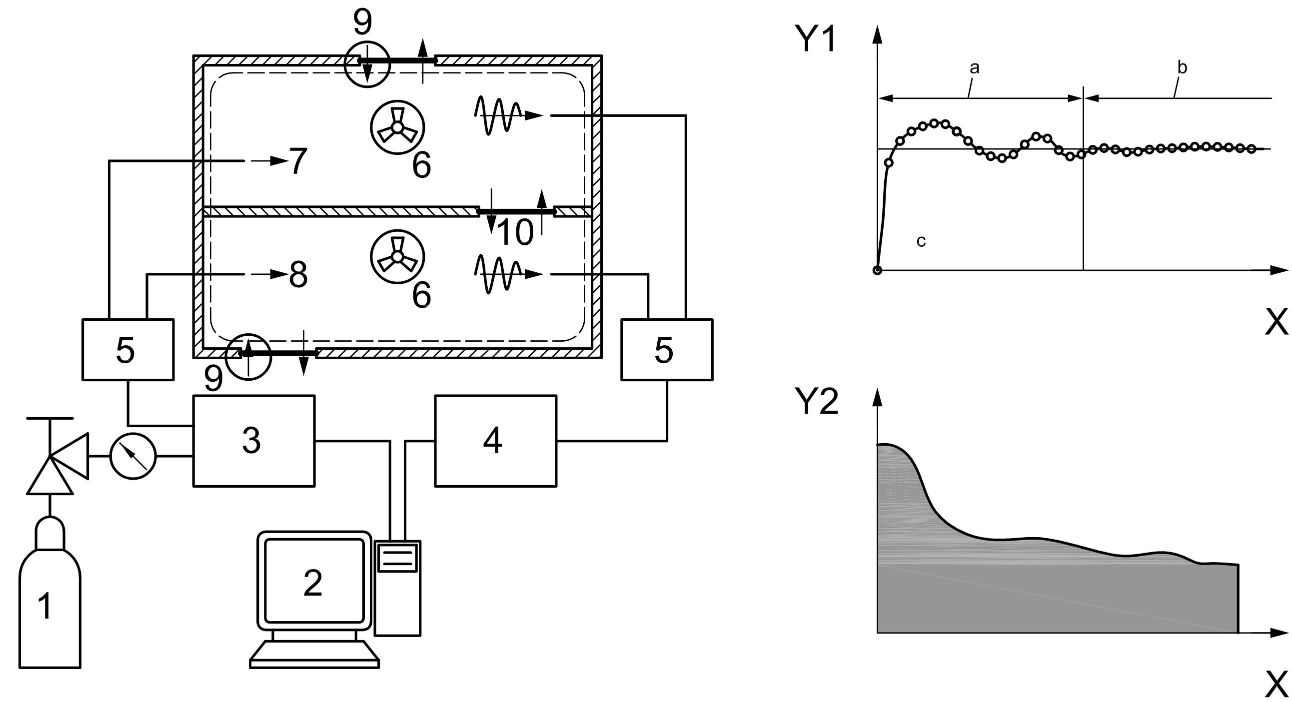
4.5.2 Procedure of constant concentration method

Generally, the amount of the tracer gas is controlled for injection to a zone consisting of two or more spaces in such a way that the concentration at each space becomes constant and uniformly distributed, and the amount of gas dosed is measured. The tracer gas is mixed to keep the concentration uniform so that the distribution in each zone does not become more than 10 %. The difference between zones should not be more than 5 %. The amount of air flowing from outside directly to a zone without passing through the connecting zone(s) can be obtained by the amount of gas supplied and constant concentration measured.

Figure 8 outlines this test method. It is important that the measured concentration value that can be used for calculating the ventilation rate must be virtually the target concentration and stable. In other words, a measured value transitional to this state must not be used. It is also necessary to continue measuring up until it can be confirmed that these concentrations become constant. When temporal discrete measurement is performed, it is necessary to conduct measurements every several minutes in each space.

When the constant concentration method is used for long-term measurements, the measurement period is broken down into short time periods, e.g. 30 min, and the results analysed for each of those short periods so that the trend over time of changing air change rate (or airflow rate) with weather or other parameters may be assessed.

When the gas concentration as a controlled variable and the gas dose flow rate as the operating variable are used for a feedback process, a control algorithm is needed to minimize deviations from the target concentration. To make the concentration constant, an adaptive control or proportional/integral/differential control may also be used.



Key

1 tracer gas
2 data gathering, gas dose/air collection control
3 gas dose apparatus
4 gas concentration measuring instrument
5 path switching
6 mixing fan
7 room A
8 room B
X elapsed time
Y1 concentration
Y2 gas supply
[a] Transition state.
[b] Usable measured value.
[c] Should not be used.

Figure 8 — Overview of constant concentration method

5 Accuracy

Based on the concentration of the tracer gas, the accuracy of the ventilation rate/specific airflow rate obtained from the equations in this clause are subject to the following factors:

— Dose procedure of the tracer gas and concentration distribution in a zone;

— Tracer gas sampling method and its storage method;

— Measurement instrument of the tracer gas concentration;

— Variation of wind, outdoor temperature, and the schedule of the HVAC system.

Errors occurring due to the above factors can be largely attributed to, a) errors in concentration measurement, and, b) errors in non-uniform concentration distribution due to inadequate mixing of tracer gas. The effect of errors in concentration measurement on the resulting ventilation rate/specific airflow rate differ depending on the measurement method However, if the standard deviation of the concentration error is known, the error in the ventilation rate/specific airflow rate could be estimated using the error propagation rule. It is also possible to conduct analysis on the confidence interval. Annex A shows the method for calculating the confidence interval for several measurement methods.

5.1 Tracer gas dose procedure and room concentration distribution

According to the measurement method shown in Table 1, the room concentration distribution caused by the tracer gas dose method and the airflow characteristics may provide errors in the estimated ventilation rate. In cases of the pulse method and continuous dose method, an error in tracer gas dose has a direct effect on ventilation rate so it is important to control the accuracy. Refer to Clause 4 for the effects of room concentration distribution on estimated ventilation rate.

5.2 Tracer gas sampling and storage method

Inappropriate positioning of the tracer gas sampling points can have a major effect on the concentration in a zone and the ventilation exhaust. Caution should also be exercised because concentration errors can sometimes occur due to adsorption depending on the collecting piping material and gas type and used concentration. Refer to 4.5 concerning collecting piping materials.

5.3 Tracer gas concentration measuring instruments

5.3.1 General

It is extremely important to control the accuracy of the tracer gas analyser for performing highly accurate concentration measurements. The tracer gas analyser should be determined based on attributes such as its resolution, accuracy, and drift, and in view of the relationship with the tracer gas concentration used. To maintain its accuracy it must also be calibrated when appropriate. The following discusses accuracy control of the tracer gas analyser.

5.3.2 Resolution

The minimum tracer gas concentration to be used should be decided based on the resolution of the tracer gas analyser. The minimum concentration to be used should be at least 20 times the resolution.

5.3.3 Tracer gas analyser drift

A tracer gas densitometer with minimal drift should be selected for long-term measuring. If there is a concern about the effects of drift, the standard gas (calibrated standard gas for which the concentration is known) concentration should be measured at any time and the measured data corrected. However, when the error rate of the read value exceeds 5 % of the standard gas, the measured value must not be corrected but the measuring instrument (zero and span adjustment) should be calibrated instead of correcting the measured value.

5.3.4 Accuracy of tracer gas analyser

It would be preferable to select a tracer gas analyser so that the difference in gas analyser output concentration and standard gas concentration when measuring the calibrated standard gas was no more than 5 % for the concentration of the used range.

5.3.5 Calibration of tracer gas analyser

The tracer gas analyser should be calibrated at least at two concentrations (2 types: zero gas and span gas) within the expected range of concentrations to be measured. If the analyser does not have the linear response or its response is not known, more than three concentrations are necessary for the calibration. Calibration should ideally be performed before conducting a series of measurements. When the constant concentration method is employed, calibration must be performed before and after measuring, and when other measuring methods are employed, calibration should also be performed after the completion of measuring if there is a concern about the effects of drift. The standard gas concentration is measured and the value checked to confirm the absence of a large drift. If drift is observed, the drift during the measuring should be estimated and the measured concentration corrected. However, if the error caused by drift exceeds 5 %, the preference would be to not perform correction but conduct measuring again after calibrating the analyser.

5.3.6 Standard gas concentration

The concentration of the standard gas used for calibration must be ± 3 % of the indicated concentration at a probability of 95 %.

As outlined, it is vital that concentration measuring should be highly accurate in order to measure ventilation rate with a high degree of accuracy. However, in view of the nature of error propagation, caution should be exercised to ensure highly accurate measuring, by investigating beforehand appropriate measuring conditions such as measurement time period and volume of gas generating rate.

5.4 Changes in outside wind and outside air temperature and schedule of air conditioning system

It is possible that the changes in ventilation rate may occur in response to changes in outside wind speed, outdoor air temperature, room temperature, and the schedule of the air conditioning system in the zone targeted. Corresponding to how ventilation is determined primarily by driving force (wind temperature difference between zones, and mechanical equipment), the ventilation rate changes may change differently. Even in mechanically ventilated rooms, depending on the type of air conditioning system, such as when it is a variable air volume system, it may also be affected by outside wind speed. Before measuring, ventilation rate variability should be investigated and if changes are anticipated, a measuring method that permits ventilation rate changes should be selected (see Table 1).

6 Test report

6.1 General

The report must include the following information:

a) Information about specific conditions where measurements were made, particularly focusing on building structure and its envelope;

b) Information about ventilation, the air conditioning system and openings for ventilation;

c) Description that the measurement was made as per the specifications set forth;

d) Measurement method and instruments employed;

e) Data collected and results of measurement;

f) Date of measurement.

The following shows examples of the content in the report for each of the above items.

6.2 All details necessary to identify the simulation tested

a) Use, dimensions, construction of walls, windows, doors, roof, foundation, overall heights of the enclosure and other important envelope features (including representative photographs);

b) Building information: name, address;

c) Site description: site plan sketch of structures, roads, terrain, major obstructions to wind flow, orientation of the enclosure, and the location of the meteorological station;

d) Zone description: a plan and section sketch of the zone, volume of zone.

6.3 Details of heating and ventilation systems

a) Heating, ventilation and air conditioning system: the type, capacity, and mode of ventilation;

b) Mechanical ventilation: the type, number, capacity, and locations of fans;

c) Natural ventilation: the type, dimensions, number and locations of doors, windows, openings, chimney flues, and other natural ventilation openings;

d) The type, number, size and location of exterior air inlet and outlet openings;

e) Leakage sites: any obvious sites or those that have been determined by such means as infrared thermography or infiltrometry.

6.4 Test conditions and apparatus

a) Purpose of the test;

b) Test method: concentration decay, continuous dose, or constant concentration;

c) Distribution of tracer gas: the type of gas, method of injection, volume of initial injection, injection locations, initial concentration, metering or volume measurement system, injection rate, target concentration, and method of distribution;

d) Sampling of tracer gas: location of sampling sites, method of spatial testing, sampling interval, initial sampling time, method of sampling, and method of testing from dilution or contamination in the zone and sampling system;

e) Gas analyser: type of analyser and the date, method, and results of its calibration;

f) Data acquisition and control: the format for obtaining and recording date; for the constant concentration test method, report the type of equipment and algorithm used to control the process;

g) Ancillary measurements: the method used for obtaining indoor and outdoor temperatures, wind speed and direction, and other meteorological observations; height and location of wind measurements; and means used for measuring other phenomena, such as door or damper positions.

6.5 Collected data and results

a) Record of tracer gas injection: the time, place, and amount;

b) Record of tracer gas concentration: the time, location, and concentration of specimens obtained for thefollowing tests: contamination, uniformity of concentration, equilibrium, and specific airflow;

c) Calculation of specific airflow: the type of calculation, time period for calculation, calculation of N or Qv from concentration and injection data;

NOTE When calculating the uncertainty, see Annex A.

d) Ancillary information: wind speed and direction, indoor and outdoor temperatures.

6.6 Date of the test

Test period with indoor and outdoor environmental conditions at start and finish.

Annex A
(normative)

Confidence intervals

A.1 General

This annex discusses the confidence levels and confidence intervals for the specific airflow rate determined by the multi-point decay method, which is a type of concentration decay method, the ventilation rate determined by the average concentration method, which is a type of continuous dose method, and the ventilation rate determined by the constant concentration method.

The accuracy of the ventilation rate obtained as a result is expressed using statistical procedures, i.e. ventilation rates are expressed within a range with a probability. The range is called the confidence interval and the probability is called the confidence level.

A.2 Multi-point decay method

The concentration resulting from ventilation may change with time, and the regression method is applied to analyse to what extent this can be explained by changes in time in the multi-point decay method. Using the following procedure, the level of confidence for the specific airflow rate N given as a constant value is expressed statistically. Details on the regression method are given in the literature [2].

The regression method applies each measured time t_i as an independent variable, and concentration C as an induced variable, resulting in the specific airflow rate N calculated from the regression coefficient for the independent variable t_i.

The predicted standard error E_N for the regression coefficient corresponding to the specific airflow rate N is then calculated. The standard error is the square root of the variance of the mean of the values calculated (sample mean), i.e. it is the standard deviation of the sample mean and shows the mean variance.

Assuming errors in the regression equation are normally distributed, the standard error of the regression coefficient corresponding to the specific airflow rate N is found from Formula (A.1).

$$E_N = \frac{s}{\sqrt{\sum_{i=1}^{k}\left(t_i - \bar{t}\right)^2}} \tag{A.1}$$

$$s^2 = \frac{\sum_{i=1}^{k}\left(Y_i - \hat{Y}_i\right)^2}{k-2} \tag{A.2}$$

where

Y_i is the measured value of lnC_i;

$\hat{Y}_i$ is the estimated value of lnC_i;

t_i is the measurement time for each sample, in seconds or hours;

$\bar{t}$ is the average value of the measurement times, in seconds or hours;

k is the number of samples.

s is a value adjusted by the degree of freedom $k - 2$ of the error in the regression equation for a population of measured sample, that is, the concentration error, when it is assumed to be normally distributed.

The variance in concentration for the population is not known beforehand, so it is substituted for that in which the variance in the measured values for the concentration, that is, the sample is divided by the degree of freedom $k - 2$. Two is subtracted because two degrees of freedom were used to calculate the two regression coefficients.

The confidence limit F_N for the specific airflow rate N for a level of confidence of $100(1 - \alpha)$ against the k units of the sample group is expressed as Formula (A.3) using a t-distribution table because the level of freedom of E_N is $k - 2$.

Here, the t-distribution table is used because the sample size is not that large and E_N is not a value directly calculated from the measured value.

$$F_N(t) = N \pm E_N \cdot t\left(k-2, 1-\alpha\right) \tag{A.3}$$

where

t	is the value obtained from a t-distribution table;
$1 - \alpha$	is the confidence level of N;
k	is the number of samples.

Table A.1 — t-distribution table

Freedom level	α				
	0,1	**0,05**	**0,025**	**0,01**	**0,005**
1	3,078	6,314	12,706	31,821	63,657
2	1,886	2,920	4,303	6,965	9,925
3	1,638	2,353	3,182	4,541	5,841
4	1,533	2,132	2,776	3,747	4,604
5	1,476	2,015	2,571	3,365	4,032
6	1,440	1,943	2,447	3,143	3,707
7	1,415	1,895	2,365	2,998	3,499
8	1,397	1,860	2,306	2,896	3,355
9	1,383	1,833	2,262	2,821	3,250
10	1,372	1,812	2,228	2,764	3,169
15	1,341	1,753	2,131	2,602	2,947
20	1,325	1,725 2	2,086	2,528	2,845

A.3 Average concentration method

The following procedure shows the statistical level of confidence in the calculated constant value for ventilation rate for sufficiently long measuring time. The predicted variance for concentration C is determined using Formula (A.4) as the estimate of the population variance, i.e. the unbiased variance.

Here, the second item in the numerator on the right is organized in the form of a fraction in which mean $\frac{1}{k}\sum_{i=1}^{k} C_i$ has been altered.

$$s^2 = \frac{k\sum_{i=1}^{k} C_i^2 - \left[\sum_{i=1}^{k} C_i\right]^2}{k(k-1)} \quad \text{(A.4)}$$

The confidence level is, for example, $\alpha = 0{,}05$ and $1 - \alpha = 0{,}95$. By t-distribution, the upper and lower limits of C in relation to the mean of C in $t(k - 1, 1 - \alpha)$ are calculated using Formulae (A.5) and (A.6).

$$C_{up} = \bar{C} + t(k-1, 1-\alpha) \cdot \frac{s}{\sqrt{k-1}} \quad \text{(A.5)}$$

$$C_{low} = \bar{C} - t(k-1, 1-\alpha) \cdot \frac{s}{\sqrt{k-1}} \quad \text{(A.6)}$$

where

$\bar{C}$ is the time-averaged value of the concentration, in m^3/m^3;

$1 - \alpha$ is the confidence level of $\bar{C}$.

If the equilibrium tracer gas concentration is known and it is assumed the variance for tracer gas dose m_a can be ignored, then the values corresponding to Q_v can be found using Formulae (A.5) and (A.6).

$$Q_{v,up} = \frac{m}{C_{up}} \quad \text{(A.7)}$$

$$Q_{v,low} = \frac{m}{C_{low}} \quad \text{(A.8)}$$

A.4 Constant concentration test method

This procedure has built-in indicators of bias and precision when performing calculations. C_{target} is sought, so this value may be compared with C to calculate bias. The precision of C may be estimated by calculating the estimate of variance using Formula (A.4).

Confidence levels at α and $1 - \alpha$ is 0,05 and 0,95, for example. Because the sample size is in general not that large, the mean value of C and the upper and lower limits for C in t $(k - 1, 1 - \alpha)$ should be calculated using Formulae (A.5) and (A.6), using t-distribution where the level of freedom is $k - 1$.

Analysis of the confidence interval for Q_v is performed in accordance with the algorithm that relates $C(t)$ to $m(t)$.

Annex B
(normative)

Method to estimate ventilation rate Q_V and effective mixed zone volume V_{emz} simultaneously [3,4]

B.1 General

This method is named the intermittent dose method but is sometimes called a system identification method from the mathematical point of view. In this method, the ventilation rate and effective mixed zone volume are estimated by the least square method from the measured values of tracer gas dose changes and gas concentration changes. The following explains under the condition that the ventilation flow rate Q_V and effective mixed zone volume V_{emz} are constant in certain periods.

B.2 Advantages and disadvantages of the intermittent dose method

a) Two parameters, ventilation rate and effective mixed zone volume, can be simultaneously estimated. When using a method employing an assumed effective mixed zone volume to estimate the ventilation rate, if the assumed value is completely wrong, then the ventilation rate may also be completely off the mark. The intermittent method therefore avoids this risk.

b) Universality: this method can be expanded easily to suit not only a single room model but also a multiple room one. By consistency of theory, the software used is the same thereby saving considerable resources.

c) This is a statistical method so it is robust to the ill effects of different types of error and the method can be rationally used to evaluate errors in estimated results. The principle relies on the least square method so it is robust to probable errors in value. The actual cause of the error is controlled by a difference between the actual phenomenon and the mathematical model as shown in Figure B.1, but this is also expressed as a residual error in the equation. The present method uses multiple regression analysis and a similar residual error analysis procedure, thereby enabling a proper evaluation by such error cause.

d) It is possible to also follow changes over time in ventilation rate etc. and to determine differences between the actual phenomenon and the model. A measuring period over several hours is required for obtaining an estimate for the ventilation rate etc., but shifting this period gradually would enable the determination of the changes over time in the same way as when the moving average is calculated. If there is a large difference between the estimated effective mixed zone volume and the geometrical room capacity, then it could be assumed that problems have arisen, such as insufficient gas mixing and rapid time changes in the ventilation rate.

e) Comparatively elaborate equipment is required for gas supply control and concentration measurements. Equipment is required for gas intermittent dose and supply flow measuring, and continuous concentration measuring.

f) Comparatively intricate measured data analysis is required. Measured data analysis that works out simultaneous equations and inverse matrices is required.

B.3 Basic equation model

The basic equation model arises from the following equation reproduced from Formula (9). The exhaust concentration C_E in this equation is generally unclear due to exfiltration, etc. Assuming the mean concentration C of the target zone is $C_E = C$, Formula (B.1) is established.

$$\frac{dV_{gas}(t)}{dt} = m(t) - C_E(t) Q_V(t)$$ (Reproduced from Formula (9) in the present text)

$$V_{emz} \cdot \frac{dC}{dt} = Q_V(C_0 - C) + m \quad \text{(B.1)}$$

where

C_0	is the tracer gas concentration in the outside air;
V_{efc}	is the effective mixed zone volume;
Q_V	is the ventilation rate;
m	is the tracer gas dose.

B.4 Formulation of multiple regression analysis

Formulation should be conducted to enable the use of an existing multiple regression analysis program. Assuming the V_{emz} and Q_V parameters are not known and the tracer gas dose m is known, the tracer gas dose is moved to the left, and the unknown member for calculation is moved to the right.

$$-m = -V_{efc} \cdot \frac{dC}{dt} + Q_V \cdot (C_0 - C) \quad \text{(B.2)}$$

The regression equation in the multiple regression analysis corresponding to this is described by a commonly used symbol. With the so-called target variable defined as y and the two explained variables expressed as x_1 and x_2, the regression coefficients related to these are defined as a_1 and a_2. Normally, the constant member a_0 introduced may be regarded as 0.

$$y = a_1 \cdot x_1 + a_2 \cdot x_2 \quad \text{(B.3)}$$

The above Formulae (B.2) and (B.3) are compared. $-m$ corresponds to y, $-V_{emz}$ corresponds to a_1, and Q_V corresponds to a_2. $-dC/dt$ corresponds to the explained variable x_1, but $(C_0 - C)$ corresponds to x_2. In the multiple regression analysis, it is necessary to obtain many of the explained variables and the target variable sets that correspond to them as measured or observed values under various conditions.

B.5 Method of calculating multiple regression model variables

Obtaining many explained variables in the multiple regression model and their corresponding target variable sets can be achieved by continuous measuring over a long period along the time axis. This long period T is divided by the Δt short time interval, and the explained variables and corresponding target variable sets are created from each Δt interval. In order to obtain explained variables with big changes and their corresponding target variables, the tracer gas dose is changed to create a change in the gas concentration.

However, using a derivative term with each passing moment, a negative influence is apt to occur as a result of errors in the measuring instruments and minute changes, so an integrated form is used. Formula (B.2) is integrated from temporal spatial (k – 1)Δt to Δt to obtain Formula (B.4).

$$-\int_{(k-1)\Delta t}^{k\Delta t} m dt = -V_{\text{emz}} \int_{(k-1)\Delta t}^{k\Delta t} \frac{dC}{dt} dt + Q_V \int_{(k-1)\Delta t}^{k\Delta t} \left(C_0 - C\right) dt \tag{B.4}$$

The integral of the first item in the right member is an increment of the concentration from (k – 1)Δt to $k\Delta t$. The integrals of the other two items calculate the area within the interval of Δt. About one minute is used for Δt in a large number of measurements. Most of the time the temporal changes during this period may approximate a linear interpolation. In contrast, it is necessary to work out the time gaps to the extent that errors are not exacerbated even with linear interpolation. The approximate integrals from linear interpolation in each item in Formula (B.4) are defined by ${}_{\text{s}}m_{\text{k}}$, ${}_{\text{b}}C_{\text{k}}$, and ${}_{\text{s}}C_{\text{k}}$.

$${}_{\text{s}}m_{\text{k}} = \int_{(k-1)\Delta t}^{k\Delta t} m dt \cong \frac{\Delta t}{2} \cdot \left\{ m\left(k\Delta t\right) + m\left[\left(k-1\right)\Delta t\right] \right\} \tag{B.5}$$

$${}_{\text{b}}C_{\text{k}} = \int_{(k-1)\Delta t}^{k\Delta t} dc = C\left(k\Delta t\right) - C\left[\left(k-1\right)\Delta t\right] \tag{B.6}$$

$${}_{\text{s}}C_{\text{k}} = \int_{(k-1)\Delta t}^{k\Delta t} (C_0 - C) dt \cong \frac{\Delta t}{2}\left[C_0(k\Delta t) - C(k\Delta t)\right] + \left[C_0(k-1)\Delta t\right] - C\left[(k-1)\Delta t\right] \tag{B.7}$$

From this, Formula (B.4) can be re-written into the following equation.

$$-{}_{\text{s}}m_{\text{k}} = V_{\text{efc}} \cdot \left(-{}_{\text{b}}C_{\text{k}}\right) + Q \cdot \left({}_{\text{s}}C_{\text{k}}\right) \tag{B.8}$$

If this Formula (B.8) is compared to the multiple regression equation of Formula (B.3), the method for calculating each variable in order to apply the existing multiple regression analysis program becomes evident.

B.6 Method using an existing multiple regression analysis calculation program

For Formula (B.8) mentioned above, if a combination of n_t units of measured data from temporal spatial k = 1 to nt is obtained and arranged in a matrix row, the following equation results.

$$\begin{bmatrix} -{}_{\text{s}}m_1 \\ -{}_{\text{s}}m_2 \\ -{}_{\text{s}}m_3 \\ \cdot \\ \cdot \\ \cdot \\ -{}_{\text{s}}m_{\text{nt}} \end{bmatrix} = \begin{bmatrix} \left(-{}_{\text{b}}C_1\right), & \left({}_{\text{s}}C_1\right) \\ \left(-{}_{\text{b}}C_2\right), & \left({}_{\text{s}}C_2\right) \\ \left(-{}_{\text{b}}C_3\right), & \left({}_{\text{s}}C_3\right) \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \\ \left(-{}_{\text{b}}C_{\text{nt}}\right), & \left({}_{\text{s}}C_{\text{nt}}\right) \end{bmatrix} \cdot \begin{bmatrix} V_{\text{emz}} \\ Q_V \end{bmatrix} \tag{B.9}$$

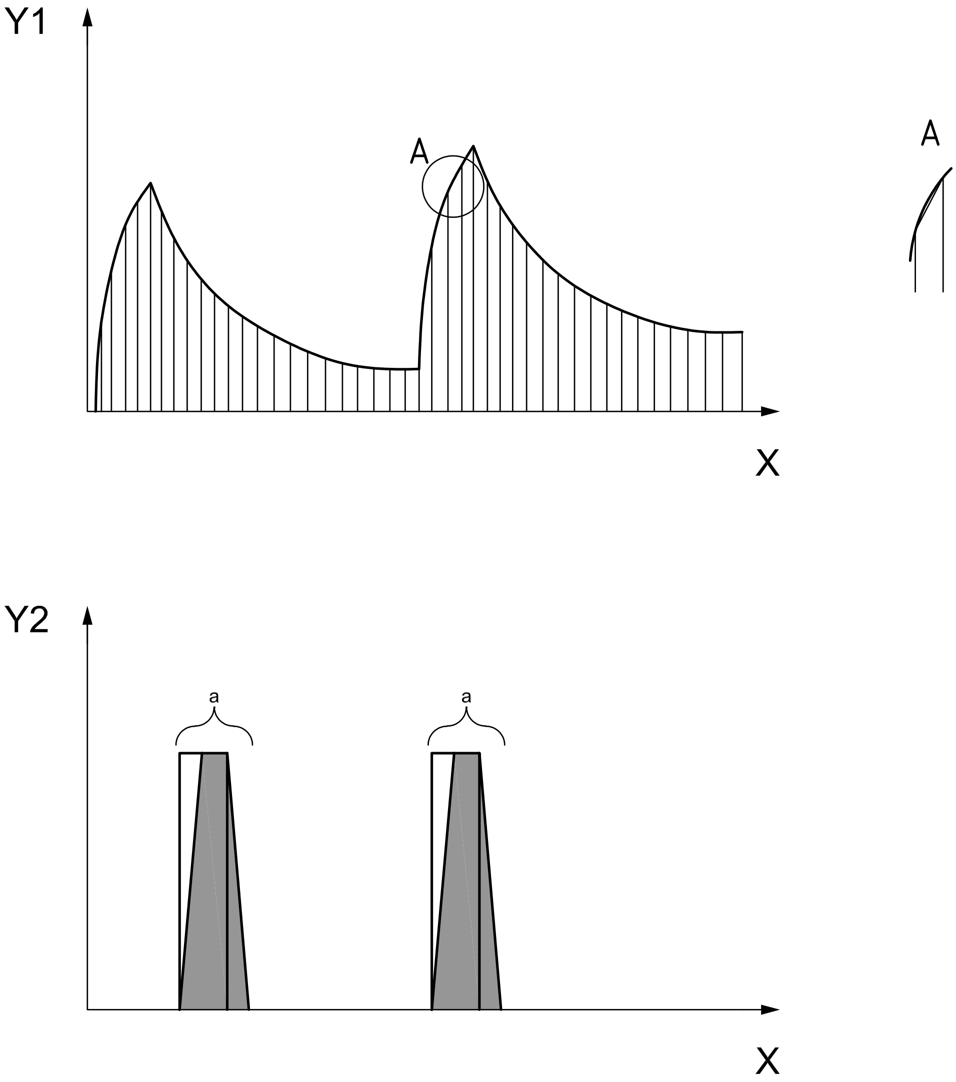
By notation in a normal multiple regression analysis, this equation is expressed as follows:

$$\text{Y} = \text{X} \cdot \text{A} \tag{B.10}$$

Here, the content of A in particular is ${}^t\,[V_{\text{emz}}, Q_V]$. Also, the working equation of parameter A becomes the following:

$$A = \begin{bmatrix} V_{\text{efc}} \\ Q_V \end{bmatrix} = \left({}^t X \cdot X\right)^{-1} \cdot \left({}^t X \cdot Y\right) \tag{B.11}$$

A special calculation program does not need to be created for this calculation and error analysis because the existing multiple regression analysis program is performed. However, it is necessary to prepare each variable calculated by Formulae (B.5) to (B.7) using a spread sheet, for example. Also, as shown in Figure B.2, accuracy can be estimated using equation residual analysis that is calculated using Formula (B.1) from the estimated V_{emz} and Q_V.



Key

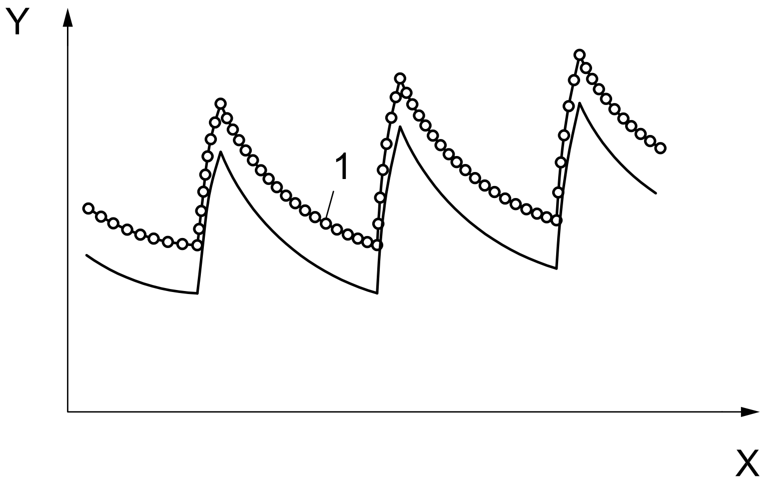
X elapsed time

Y1 concentration

Y2 gas infusion flow rate

a The areas of the original rectangle and approximated trapezium are the same.

Figure B.1 — Time interval segmentation for obtaining multiple regression analysis variables



Key

X elapsed time

Y concentration

1 residual error

Figure B.2 — Gas concentration changes and their residual errors

Annex C
(informative)

Considerations when measuring the ventilation rate of large spaces

When the ventilation rate of large spaces is measured using the step down method, it is important to make the concentration within the space uniform from the start. The following are some effective methods to make concentration uniform:

a) Conduct the step up method beforehand;

b) Distribute gas when only the recirculation air is circulated without intake of outdoor air;

c) Distribute the gas when the air conditioner is operated;

d) Distribute gas when the floor heater is operated;

e) Distribute a suitable amount of the gas from as many places as possible;

f) Establish as many ancillary fans as possible to circulate the gas.

Annex D
(informative)

Effects of internal and external temperature difference, temperature change, and outside air concentration change during the measurement period

D.1 When temperature and tracer gas concentration in a single zone are homogeneous

Temperature and tracer gas concentration in a single zone can be maintained homogeneous by the use of mixing fans, then the following Formula (D.1) for the conservation of the mass of tracer gas is applied.

NOTE Temperature in a zone is homogeneous, so the exhaust temperature is equal to the temperature in the zone.

$$\frac{d}{dt}\left({}^{\mathrm{t}}\rho_{\mathrm{i}} K V_{\mathrm{emz}} \right) = {}^{\mathrm{t}}\rho m' + {}^{\mathrm{t}}\rho_0 K_0 Q_{0\mathrm{i}} - {}^{\mathrm{t}}\rho_{\mathrm{i}} K Q_{\mathrm{i}0} \tag{D.1}$$

where

${}^{\mathrm{t}}\rho_{\mathrm{i}}$ is the density of tracer gas in the zone, (kg/m^3);

${}^{\mathrm{t}}\rho_0$ is the density of tracer gas in the outside air, (kg/m^3);

${}^{\mathrm{t}}\rho$ is the density of tracer gas during tracer gas injection, (kg/m^3);

K is the volume concentration of tracer gas in the zone, (m^3/m^3);

K_0 is the volume concentration of tracer gas at outside air, (m^3/m^3);

m' is the tracer gas dose, (m^3/h);

$Q_{0\mathrm{i}}$ is the ventilation rate from the outside to the zone, (m^3/h);

$Q_{\mathrm{i}0}$ is the ventilation rate from the zone to the outside, (m^3/h);

Formula (D.1) can be replaced by Formula (D.2) using ideal gas law for the tracer gas.

$$\frac{d}{dt}\left(\frac{K V_{\mathrm{emz}}}{T_{\mathrm{i}}} \right) = \frac{m'}{T} + \frac{K_0 Q_{0\mathrm{i}}}{T_0} - \frac{K Q_{\mathrm{i}0}}{T_{\mathrm{i}}} \tag{D.2}$$

where

T_{i} is the temperature in the zone, in Kelvin [K];

T_{o} is the outside temperature, in Kelvin [K];

T is the tracer gas supply temperature, in Kelvin [K].

The left hand side of Formula (D.2) can be expanded and results in Formula (D.3).

$$\frac{d}{dt}\left(\frac{KV_{\text{emz}}}{T_{\text{i}}}\right)=\frac{1}{T_{\text{i}}}\frac{dKV_{\text{emz}}}{dt}-\frac{KV_{\text{emz}}}{T_{\text{i}}^{2}}\frac{dT_{\text{i}}}{dt} \qquad \text{(D.3)}$$

The conservation equation of air mass of the zone is shown in Formula (D.4).

$$\frac{d}{dt}\left(\rho_{\text{i}}V_{\text{emz}}\right)=\rho_{0}Q_{0\text{i}}-\rho_{\text{i}}Q_{\text{i}0} \qquad \text{(D.4)}$$

where

ρ_{i} is the density of air in the zone, (kg/m3);

ρ_{0} is air density of air in the outside air, (kg/m3).

Using again ideal gas law assumption, Formula (D.4) can be replaced by Formula (D.5).

$$\frac{d}{dt}\left(\frac{V_{\text{emz}}}{T_{\text{i}}}\right)=\frac{Q_{0\text{i}}}{T_{0}}-\frac{Q_{\text{i}0}}{T_{\text{i}}} \qquad \text{(D.5)}$$

The left hand side of Formula (D.5) can be expanded and results in Formula (D.6).

$$\frac{d}{dt}\left(\frac{V_{\text{emz}}}{T_{\text{i}}}\right)=-\frac{V_{\text{emz}}}{T_{\text{i}}^{2}}\frac{dT_{\text{i}}}{dt} \qquad \text{(D.6)}$$

Combining Formulae (D.5) and (D.6), Formula (D.7) is obtained.

$$Q_{\text{i}0}=\frac{T_{\text{i}}}{T_{0}}Q_{0\text{i}}+\frac{V_{\text{emz}}}{T_{\text{i}}}\frac{dT_{\text{i}}}{dt} \qquad \text{(D.7)}$$

Formula (D.8) is obtained using Formulae (D.2), (D.3), and (D.7).

$$V_{\text{emz}}\frac{dK}{dt}=\frac{T_{\text{i}}}{T}m'-\left(K-K_{0}\right)\frac{T_{\text{i}}}{T_{0}}Q_{0\text{i}} \qquad \text{(D.8)}$$

Suppose *m*, *Q*, *C* and *dC* are defined in Formulae (D.9), (D.10), (D.11) and (D.12).

$$m=\frac{T_{\text{i}}}{T}m' \qquad \text{(D.9)}$$

$$Q=\frac{T_{\text{i}}}{T_{0}}Q_{0\text{i}} \qquad \text{(D.10)}$$

$$C=K-K_{0} \qquad \text{(D.11)}$$

$$dC=dK \qquad \text{(D.12)}$$

Then, Formula (D.8) can be expressed as (D.13):

$$V_{\text{emz}}\frac{dC}{dt}=m-CQ \qquad \text{(D.13)}$$

Formula (D.9) represents the zone temperature equivalent for the volume dose of tracer gas, and Formula (D.10) represents the zone temperature equivalent for the ventilation rate from the outside to the zone. Formula (D.13) corresponds to the main body in Formulae (9) and (17), and is equivalent to Formula (1) if m = 0.

Therefore, if temperature and tracer gas concentration in the zone are homogeneous, the ventilation rate measurement method for this condition can be applied using the above conversions, even when the temperature in the zone and the outside are changed during the period of measurement. The measured ventilation rate is the value in Formula (D.10) or the specific airflow rate based on the value in Formula (D.10).

The set up of Formula (D.12) is required to apply measurement methods, so the change of tracer gas concentration of outside air during the measurement period may need to be sufficiently low in respect of the change of tracer concentration in the zone.

D.2 When temperature and tracer gas concentration in a single zone are not homogeneous

The following shows the equation for the conservation of the mass of tracer gas when concentration and temperature in a zone are not homogenous.

$$\frac{d}{dt}\left(M_{gas}\right) = {}^{t}\rho m' + {}^{t}\rho_0 K_0 Q_{0i} - {}^{t}\rho_e K_e Q_{i0} \tag{D.14}$$

where

M_{gas}	is the mass of the tracer gas in the zone,(kg);
ρ_e	is the density of the tracer gas in the exhaust air, (kg/m^3);
K_e	is the volume concentration of tracer gas in the exhaust air, (m^3/m^3).

Formula (D.14) can be replaced by Formula (D.15) using ideal gas law assumption.

$$\frac{1}{\rho_e T_e}\frac{d}{dt}\left(M_{gas}\right) = \frac{m'}{T} + \frac{K_0 Q_{0i}}{T_0} - \frac{K_e Q_{i0}}{T_e} \tag{D.15}$$

where T_e is the absolute temperature of the exhaust air, in Kelvin [K].

If the temperature in the zone does not change during the measurement period, the equation for the conservation of mass of the room air is shown by Formula (D.16).

$$0 = \rho_0 Q_{0i} - \rho_e Q_{i0} \tag{D.16}$$

Using ideal gas assumption, Formula (D.16) can be replaced by Formula (D.17).

$$0 = \frac{Q_{0i}}{T_0} - \frac{Q_{i0}}{T_e} \tag{D.17}$$

If Formula (D.17) is substituted to Formula (D.15), Formula (D.18) is obtained.

$$\frac{d}{dt}\left(\frac{M_{gas}}{\rho_e}\right) = \frac{T_e}{T} m' - \left(K_e - K_0\right)\frac{T_e}{T_0} Q_{0i} \tag{D.18}$$

Suppose m, Q and C_E are defined in Formulae (D.19), (D.20), and (D.21).

$$m = \frac{T_e}{T} m' \tag{D.19}$$

$$Q = \frac{T_e}{T_0} Q_{0i} \tag{D.20}$$

$$C_E = K_e - K_0 \qquad \text{(D.21)}$$

Then, Formula (D.18) can be expressed as Formula (D.22).

$$\frac{d}{dt}\left(\frac{M_{gas}}{\rho_e}\right) = m - C_E Q \qquad \text{(D.22)}$$

The part in parentheses on the left side in Formula (D.22) is the volume of the tracer gas converted to the exhaust density. Formula (D.19) represents the exhaust air temperature equivalent of tracer gas volume dose, and Formula (D.20) is the temperature in the zone equivalent of ventilation rate from the outside to the zone. If such conversions are performed, Formula (D.22) corresponds to Formulae (9) and (17), and if $m = 0$, Formula (1).

Therefore, even if the temperature and concentration in the zone are not uniform, the ventilation rate measurement method for this condition can be applied if the temperature in the zone does not change over the period of measurement. The measured ventilation rate is the value in Formula (D.20) or the specific airflow rate based on the value in Formula (D.20).

It should be noted that the measured specific airflow rate using Formula (7) may not be the specific airflow rate converted into the exhaust temperature if the difference between the mean temperature of the zone and the temperature of the exhaust air T_e cannot be neglected. In such case, the specific airflow rate at mean temperature in the zone is measured.

As for the change in outside tracer gas concentration, Formula (D.21) may need to be as small as can be ignored once sufficient time has elapsed if the step-down exhaust concentration method and pulse method are used.

Annex E
(informative)

Estimation error minimizing method in 2-point and multi-point decay method

E.1 General

The specific airflow rate estimation error based on 2-point and multi-point decay method is not only dependent on the concentration measurement error, but also largely on the ventilation rate change in multi-point decay method, uneven concentrations within the zone and interaction with adjacent zones, i.e. the inappropriateness of the actual assumptions of the model itself. However, if the concentration measurement error alone is considered, the error propagation equation arising from the error variance and the specific airflow rate error can be defined.

By deducing the equation minimizing the specific airflow rate error, a curve representing the relation between the specific airflow rate, optimum decay time and the number of measurement points can be obtained. The optimum decay time is decided by referring to the curve.

E.2 Estimations of the specific airflow rate using the least squares method

The analytical solution from the concentration decay test process in the specific airflow rate measurements [2] uses the following equation under the constant airflow condition, taking the initial time $t_1 = 0$ and the time elapsed as t_j.

$$\log_e C(t_j) = -N \cdot t_j + \left\{ \log_e C(t_1) + N \cdot t_1 \right\} \tag{E.1}$$

Where N is the estimated specific airflow rate, while $C(t_j)$ indicates the measured gas concentration at time t_j. The equation error e_j is defined by the following equation. As in the next equation, y_j, Z_j and $\mathbf{a}$ represent the matrix notation to resolve the least squares solution.

$$\begin{aligned} e_j &= \log_e C(t_j) - \left[-N \cdot t_j + \left(\log_e C(t_1) + N \cdot t_1 \right) \right] \\ &= y_j - \begin{bmatrix} t_j & 1 \end{bmatrix} \cdot \begin{bmatrix} -N \\ \log_e C(t_1) + N \cdot t_1 \end{bmatrix} \\ &= y_j - \mathbf{Z}_j \cdot \mathbf{a} \end{aligned} \tag{E.2}$$

Vector $\mathbf{a}$, which includes the N and the logarithm of initial concentration, is calculated by the least squares using the following equation. Here, n_p is the number of measured elapsed points, when the value of j is 1 represents the initial concentration and n_p is more than two.

$$\mathbf{a} = \left(\sum_{j=1}^{np} {}^t\mathbf{Z}_j \cdot \mathbf{Z}_j \right)^{-1} \cdot \left(\sum_{j=1}^{np} {}^t\mathbf{Z}_j \cdot y_j \right) = \begin{bmatrix} \sum_{j=1}^{np} t_j^2 & \sum_{j=1}^{np} t_j \\ \sum_{j=1}^{np} t_j & np \end{bmatrix}^{-1} \cdot \begin{bmatrix} \sum_{j=1}^{np} t_j \cdot \log_e C(t_j) \\ \sum_{j=1}^{np} \log_e C(t) \end{bmatrix} \tag{E.3}$$

Calculation results on above equation gives the estimated specific airflow rate.

$$N = \frac{\left(\sum_{j=1}^{np} t_j \right) \cdot \sum_{j=1}^{np} \log_e C(t_j) - n_p \cdot \sum_{j=1}^{np} t_j \cdot \log_e C(t_j)}{n_p \cdot \sum_{j=1}^{np} t_j^2 - \left(\sum_{j=1}^{np} t_j \right)^2} \tag{E.4}$$

In many cases, t_j is measured at interval Δt then t_j is equal to $(j - 1)\Delta t$, and in this case, above equation can be rewritten relatively simple form. Here, T is defined as the complete decay period $(n_p - 1)\Delta t$.

$$N = \frac{12}{n_p \left(n_p + 1 \right) T} \left[\sum_{j=1}^{np} \left\{ \frac{\left(n_p - 1 \right)}{2} - \left(j - 1 \right) \right\} \log_e C \left\{ \left(\frac{j-1}{n_p - 1} \right) T \right\} \right] \tag{E.5}$$

E.3 Decay period to minimize the effects of concentration measurement errors

Gas concentration measurement error variance $\sigma^2{}_C$ is specific to the equipment used and so can be estimated more often than not. The equation of the propagation of measurement error variance to the estimated specific airflow rate variance ${}_m\sigma^2{}_N$ is as follows.

$$ {}_m\sigma_N^2 = \sigma_C^2 \sum_{j=1}^{np} \left(\frac{\partial N}{\partial C(t_j)} \right)^2 \tag{E.6} $$

Taking the differential of Formula (E.5) by $C(t_j)$, the following equation is obtained.

$$ \frac{\partial N}{\partial C(t_j)} = \frac{12}{\left(n_p - 1\right) n_p \left(n_p + 1\right) \Delta t} \left\{ \frac{\left(n_p - 1\right)}{2} - \left(j - 1\right) \right\} \frac{1}{C(t_j)} \tag{E.7} $$

The following equation is derived as this section assumes that there is no change in the structure of the decay model.

$$ C(t_j) = C(t_j) \cdot \exp\left(-\frac{(j-1)}{(n_p - 1)} N \cdot T \right) \tag{E.8} $$

Formula (E.6) becomes the following equation when using Formulae (E.7) and (E.8).

$$ {}_m\sigma_N^2 = \frac{12^2 \cdot \sigma_C^2}{n_p{}^2 \cdot (n_p + 1)^2 \cdot T^2 \cdot C(t_1)^2} \cdot \sum_{j=1}^{np} \left\{ \frac{(n_p - 1)}{2} - (j-1) \right\} \exp\left\{ \frac{2(j-1)}{n_p - 1)} N \cdot T \right\} \tag{E.9} $$

The objective of this section is to minimize the estimated error variance for the specific airflow rate with respect to decay period T. The differential of ${}_m\sigma_n{}^2$ by T is equated to 0 and next function is deduced.

$$ \begin{aligned} \frac{\partial\, {}_m\sigma_N^2}{\partial T} = -\frac{2 \cdot \sigma_C^2 \cdot 12^2}{n_p{}^2 (n_p + 1)^2 T^3 C(t_1)^2} \cdot \Bigg[& \sum_{j=1}^{np} \left\{ \frac{(n_p - 1)}{2} - (j-1) \right\}^2 \exp\left\{ \frac{2(j-1)}{(n_p - 1)} NT \right\} \\ & - NT \cdot \sum_{j=1}^{np} \frac{(j-1)}{(n_p - 1)} \left\{ \frac{(n_p - 1)}{2} - (j-1) \right\}^2 \exp\left\{ \frac{2(j-1)}{(n_p - 1)} NT \right\} \Bigg] = 0 \end{aligned} \tag{E.10} $$

This equation results in the following nonlinear equation for NT.

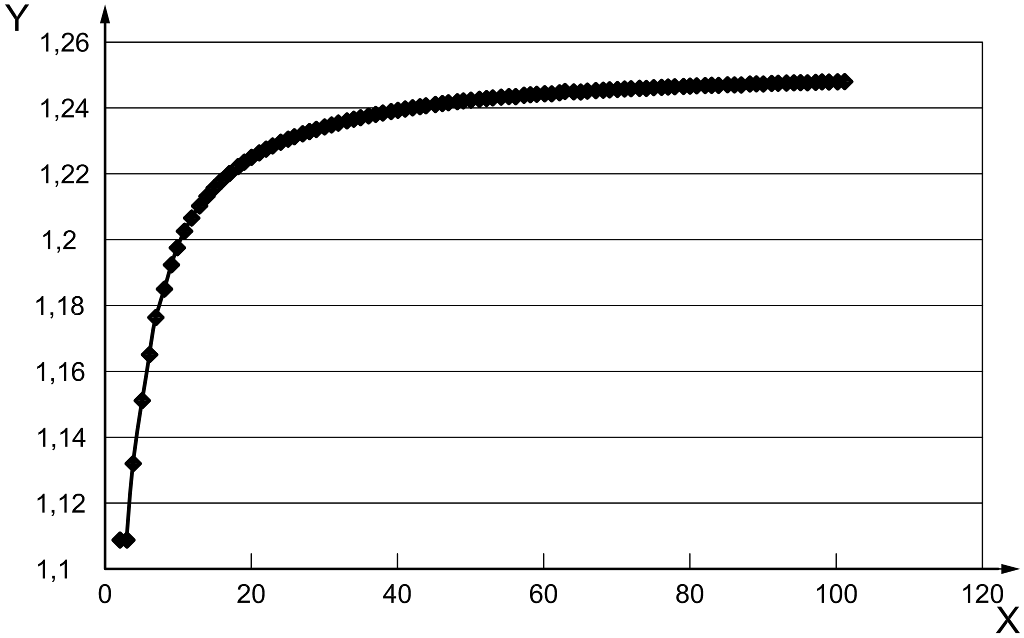
$$ \begin{aligned} f(NT) = & \sum_{j=1}^{np} \left\{ \frac{(n_p - 1)}{2} - (j-1) \right\}^2 \cdot \exp\left\{ \frac{2(j-1)}{(n_p - 1)} NT \right\} - NT \\ & \cdot \sum_{j=1}^{np} \frac{(j-1)}{(n_p - 1)} \left\{ \frac{(n_p - 1)}{2} - (j-1) \right\}^2 \exp\left\{ \frac{2(j-1)}{(n_p - 1)} NT \right\} = 0 \end{aligned} \tag{E.11} $$

This nonlinear equation for NT changes with the number of measured elapsed time points n_p. Subsequently, the optimum value for NT was determined beginning with two points up to approximately 100 points. The Newton method is used to solve the nonlinear equation, and as a result, the differential function for NT was used.

If the correctional value δNT is added to the assumed NT and the achieved the solution, the first term approximated Taylor series expansion is described as next equation. This becomes the recursive equation to approach the solution.

$$f(NT+\delta NT) \cong f(NT) + \frac{\partial f(NT)}{\partial NT} \cdot \partial NT = 0 \quad \text{(E.12)}$$

The initial value is only slightly larger than 1. The curve obtained for the optimum value of NT_m is shown in Figure E.1.



Key

X Total number of data points (n_p)

Y Error minimizing constant ($N \cdot T_m$)

Figure E.1 — Relationship between error minimizing constant $N \cdot T_m$ **and total number of measured points**

When using only two points, representing the initial and the final concentrations in particular, the optimum decay time T_m that minimizes the estimation error is the following value from the specific airflow rate N and the product NT_m

$$(NT_m)_{np=2} = 1{,}10885755288..... \quad \text{(E.13)}$$

The following procedure outlines how to use Figure E.1 to determine the optimum decay time.

— Assumes the optimum decay time T_m by estimating the specific airflow rate and setting $n_p = 2$.

— Measurements are carried out for 1,5 times the set optimum decay time T_m for safety reasons.

— The optimum decay time T_m is determined using the previously set specific airflow rate N. From the measured concentration data during this period, Formulae (E.4) or (E.5) are used to estimate the following specific airflow rate N.

— If the difference between estimated and previously set specific airflow rate falls below 5 % of the estimated specific airflow rate, the obtained results can be considered acceptable. If the difference is any greater than 5 %, the set specific airflow rate must be replaced with the estimated specific airflow rate and repeated from step 3 again. If acceptable results are not obtained after repeating several times, the measurements must be taken again as it can be deemed that one of the assumptions of the model is largely inappropriate.

Annex F
(informative)

Propagation of error analysis

NOTE This annex contains a summary of propagation of errors formulae that pertain to the 2-point decay method, average of inverse concentration method and constant concentration method.

F.1 2-point decay method

For nonsteady-state conditions, the variance s_N^2 of N should be calculated using Formula (F.1):

$$s_N^2 = \frac{1}{(t_2 - t_1)}\left[\frac{s_{C(t_2)}^2}{C(t_2)^2} + \frac{s_{C(t_1)}^2}{C(t_1)^2}\right] \quad \text{(F.1)}$$

where

$C(t_1)$ is the specimen concentration at time t_1;

$C(t_2)$ is the specimen concentration at time t_2;

t_1 is the time of the first sampling, in seconds or hours;

t_2 is the time of the last sampling, in seconds or hours.

For the multi-point decay method, use Formula (A.3).

F.2 Average of inverse concentration method

The error expression is:

$$\frac{s_{Q_V}^2}{Q_V^2} = \frac{s_m^2}{m^2} + \frac{s_C^2}{\bar{C}^2}\left[\alpha^2 + \frac{2_{Q_V}^2}{(t_2 - t_1)^2 Q_V^2}\right] \quad \text{(F.2)}$$

where

$$\alpha^2 = \frac{Var(1/C)}{\left[s_C(\bar{C}/C)_{av}\right]^2} \approx \frac{Var(1/C)}{s_C^2} \quad \text{(F.3)}$$

$$Var(f) = \frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2}\left[f(t) - \bar{f}\right]^2 dt \quad \text{(F.4)}$$

and

C is the spatially averaged tracer gas concentration;

$\bar{C}$ is the time-averaged tracer gas concentration divided by the spatially averaged tracer gas concentration at any given time;

$\bar{f}$ is a variable used to demonstrate the function Var(f).

For the constant ventilation rate, Formulae (A.7) and (A.8) should be used.

F.3 Constant concentration method

In general the error expression is:

$$\frac{s_{Q_V}^2}{Q_V^{\,2}} = \frac{s_m^2}{m^2} + \frac{s_C^2}{C^2}\left[\alpha^2 + \frac{2_{Q_V}^2}{\left(t_2 - t_1\right)^2 Q_V^{\,2}}\right] \tag{F.5}$$

where

$$\alpha^2 = \frac{\mathrm{Var}\left(1/C\right)}{\left[s_C\left(\bar{C}/C\right)_{tw t\mathrm{av}}\right]^2} \approx \frac{\mathrm{Var}_{twt}\left(1/C\right)}{s_C^{\,2}} \tag{F.6}$$

$$Var_{twt}(f) = \frac{1}{m\left(t_2 - t_1\right)} \int_{t_1}^{t_2} \left[f(t) - \bar{f}\right]^2 m(t)dt \tag{F.7}$$

$$m\left(t_2, t_1\right) = \int_{t_1}^{t_2} m(t)dt \tag{F.8}$$

and

C	is the spatially averaged tracer gas concentration;
$\bar{C}/C$	is the time-averaged tracer gas concentration divided by the spatially averaged tracer gas concentration at any given time;
f	is a variable used to demonstrate the function Var(f);
$m(t_2,t_1)$	is the volume of the tracer gas injected between times t_1 and t_2;
twt	indicates variables weighted according to tracer gas dose.

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ICS 91.120.10

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