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Thermal performance of buildings — Determination of air change in buildings — Tracer gas dilution method

Performances thermiques des bâtiments — Détermination du renouvellement d'air dans les bâtiments — Méthode de dilution de gaz traceurs

Reference number
ISO 12569:2000(E)

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Contents

Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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

Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights other than those identified above. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 12569 was prepared by Technical Committee ISO/TC 163, *Thermal insulation*, Subcommittee SC 1, *Test and measurement methods*.

Annexes A to G of this International Standard are for information only.

Introduction

Air change often accounts for a significant portion of the heating or air-conditioning load of a building. It also affects the moisture and contaminant levels in the building. Moisture-laden air passing through cracks in the building envelope under the influence of air pressure differences and through structural elements under the influence of vapour pressure differences can condense and cause material degradation. Air flow and air change rates depend on the size and distribution of air leakage sites, pressure differences induced by wind and temperature, mechanical system operation, and occupant behaviour. An appropriate level of ventilation is also required in all buildings for hygiene reasons.

This International Standard presents three test methods that use the measurement of tracer gas concentrations to determine air change in a building or other enclosure that can be characterized as a single zone. The measurement of tracer gas concentration, and sometimes the volume rate of flow at which the tracer gas is injected into the zone, allows calculation of the volume rate of air flow leaving the zone. The volume rate of incoming air flow can be inferred from this. The three test methods presented are:

a) tracer gas decay (5.4), which tracks the decay rate of tracer gas concentration after an initial injection of tracer gas,

b) constant injection (5.5), which tracks the tracer gas concentration resulting from a known, constant injection rate of tracer gas, and

c) constant concentration (5.6), which tracks the amount of tracer gas required to maintain it at a constant concentration at a constant level.

Each test method employs specific tracer gas injection and sampling strategies. Other techniques exist, but are beyond the scope of these test methods.

Because air change depends on such variable conditions as building operation, wind speed, and indoor-outdoor temperatures, this International Standard does not provide information about building airtightness directly. ISO 9972 should be used to measure airtightness.

Thermal performance of buildings — Determination of air change in buildings — Tracer gas dilution method

1 Scope

This International Standard describes the use of tracer gas dilution for determining the air change in a single zone as induced by weather conditions or mechanical ventilation. The procedures for tracer gas dilution include concentration decay, constant injection and constant concentration. Tracer gas concentration is determined by a gas analyser. Air change rate is directly calculated from the rate of change of tracer gas concentration by the tracer gas decay method. Air flow rate is calculated directly from the tracer gas flow rate by the constant injection or constant concentration method.

These test methods are restricted to any single tracer gas. The associated data analysis assumes that the tracer gas concentration can be characterized within the zone with a single value.

NOTE The constant concentration test method given in 5.6 is usually used for multiple zones and allows the measurement of the air flow rate from the outside to each zone, if the residential zones are kept at the same concentration.

2 Normative reference

The following normative document contains provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent edition of the normative document indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 7345, *Thermal insulation — Physical quantities and definitions.*

3 Terms and definitions

For the purposes of this International Standard, the terms and definitions given in ISO 7345 and the following apply.

3.1
air flow rate
$\dot{V}$
total volume of air passing through the zone to and from the outdoors per unit of time

NOTE It is expressed in cubic metres per second or per hour (m^3/s, m^3/h).

3.2
air change rate
n
ratio of the total volume of air passing through the zone to and from the outdoors per unit of time to the volume of the zone

NOTE It is expressed in reciprocal seconds or reciprocal hours (1/s, 1/h).

3.3

building envelope

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

3.4

single zone

space or set of spaces wherein the concentration of a tracer gas can be maintained uniformly throughout and that only exchanges air with the outside

3.5

tracer gas

gas that can be mixed with air and measured in very small concentrations in order to study air change

NOTE The tracer gas is not used to study air movement. Rather it is used to assess air transfer, exchange or infiltration. Types of tracer gas, measuring apparatus, limits of measurement, allowable concentration and specific gravity of the tracer gases are given in annex F. A gas at a temperature extremely different from that of the room should not be used for the tracer gas dilution method.

4 Apparatus

The apparatus includes means for distributing the tracer gas, means for obtaining air specimens, a gas analyser to measure tracer gas concentration in the air specimens, and other measurement devices, as follows.

4.1 Tracer gas concentration standard

Use a source of air with a known concentration of tracer gas.

Use the tracer gas within safe limits for concentration. Avoid conditions where the amount of tracer gas that may be absorbed onto surfaces and into subordinate enclosures is significant, compared with the amount of tracer gas in the zone. Avoid conditions where the added amount of tracer gas is small, compared to the atmospheric background level of that gas. The use of radioactive tracer gases should be avoided.

4.2 Tracer gas injection and distribution apparatus

Choose an apparatus from one or more of the following, as appropriate to the test method.

4.2.1 Graduated syringe, or other container of known volume with a means for controlled release of its content.

4.2.2 Compressed tracer gas supply, with a critical orifice, a critical orifice metering valve, an electronic mass flow controller, or other tracer gas flow rate measurement and control device.

4.3 Tracer gas distribution devices

Choose an apparatus from one or more of the following, as appropriate to the test method.

4.3.1 Fans that permit good mixing within the zone of manually-injected tracer gases.

These fans are required so as not to give any influence on the air change rate.

4.3.2 Tubing networks that dispense tracer gas via manifold or switches.

All parts of the tubing network shall be clearly labelled "Tracer Gas Only" and keyed to the location that receives the tracer gas.

NOTE Leaks in tubing networks can release tracer gas at unwanted locations and in uncontrolled unwanted concentrations.

4.4 Tracer gas sampling apparatus

4.4.1 Materials for sampling apparatus

Materials used in tracer gas sampling systems shall be nonabsorbent, non-reactive, and non-diffusive to the tracer gas in use. Depending on the tracer gas, desirable materials may include glass, copper, and stainless steel. Metal foil may be appropriate for flexible containers. Other acceptable materials may include polypropylene, polyethylene, and polyamide. Materials that absorb tracer gas may cause major inaccuracies in the measurement.

NOTE Inappropriate materials may release substances that interfere with the tracer gas analyser. Depending on the tracer gas, materials to avoid include soft plastics.

4.4.2 Manual samplers, including syringes, flexible bottles, or air specimen bags with a capacity of at least three times the minimum specimen size of the gas analyser used.

Each shall have a label that may be keyed to a record of the time and location that it was used.

Manual samplers shall have an airtight seal to assure that the specimen is not diluted or contaminated. Avoid reusing sample containers without first confirming that they are not contaminated with tracer gas.

4.4.3 Sampling network for *in-situ* analysis

Label all parts "Sampling only".

The sampling network may include:

a) tubing that is keyed to the location sampled;

b) manifold that connects to individual legs of the network and receives air with mutual equal air flow rates, combines them and leads to the gas analyser;

c) selection switch that permits sampling of individual legs of the network going to the gas analyser;

d) pump that delivers air specimens through the network to the gas analyser at a rate that minimizes delays between the time air specimens leave the zone and the time they reach the gas analyser;

e) sampling device for laboratory analysis, including, for example, syringes or bag samplers or direct to the gas analyser that may be programmed to draw air specimens at defined time intervals.

NOTE Separate automatic samplers may be placed at different locations throughout the zone to be evaluated.

4.5 Gas analyser

The gas analyser shall be suitable for the tracer gas used and the concentrations applied to conform to the test procedure within the zone studied. It should be properly calibrated and have a measurement uncertainty of less than ± 5 % at the concentrations employed in the tracer gas study.

4.6 Data acquisition and control system

NOTE This equipment is optional for all but the constant concentration technique.

4.6.1 Data acquisition device, with appropriate interfaces to provide indoor and outdoor temperatures, wind speed, wind direction, and tracer gas concentration data to a computer or other machine-readable data storage unit.

4.6.2 Process controller, i.e. a computer that uses current tracer gas concentration information to control metering and switching equipment to deliver tracer gas to the appropriate parts of the network.

NOTE When a feedback process controls the gas concentrations based on gas concentration measurements, an algorithm that minimizes deviation from the target concentration is required. A digital optimal adaptive proportional control algorithm has been used effectively for constant concentration measurements.

4.7 Portable meteorological station (optional), i.e. a device that records wind speed and direction and outdoor temperature.

4.8 Temperature measurement sensor (optional), i.e. thermometer or recorder for the output of thermocouples, thermistors and resistance thermal devices.

4.9 Timing device (optional), i.e. device to provide a common standard for all events relating to the measurement procedure, including gas injection times, sampling times, and meteorological driving forces.

The time difference between events shall be determined within a 1 % uncertainty by the timing device.

5 Procedure

5.1 General

Choose the tracer gas decay method (5.4) to determine air change rate, n. To determine the air flow rate, V, choose either the constant injection (5.5) or the constant concentration (5.6) method. If the zone configuration makes maintaining a uniform concentration difficult for the decay (5.4) or constant injection (5.5) methods, then choose the constant concentration (5.6) method with automated networks for tracer gas injection and for air sampling.

5.2 Preparation of the building envelope

The preparation of the building envelope depends on the purpose of the determination of the air flow rate, as follows.

a) When measuring only the air flow rate by infiltration into a building as the result of a corresponding weather situation (e.g. in cases of energetic considerations), all internal doors should be opened, all windows and external doors should be closed and the ventilation equipment (if any) shall be switched off.

b) When measuring only the air flow rate by infiltration into a room (e.g. for hygienic considerations), the internal doors and those to the adjoining rooms should be closed (possibly sealed off) and the ventilation equipment (if any) shall be switched off if there is no leakage interference from adjoining rooms. All windows and external doors should be closed and the ventilation equipment (if any) shall be switched off.

c) When assessing of the natural ventilation of a building (e.g. tilted windows), the corresponding boundary conditions shall be watched.

It should be emphasized that there is no general method of envelope preparation, because the purpose of air flow rate measurements can have different reasons. In the case where the internal doors are closed, the constant concentration method may be applied for air change measurement.

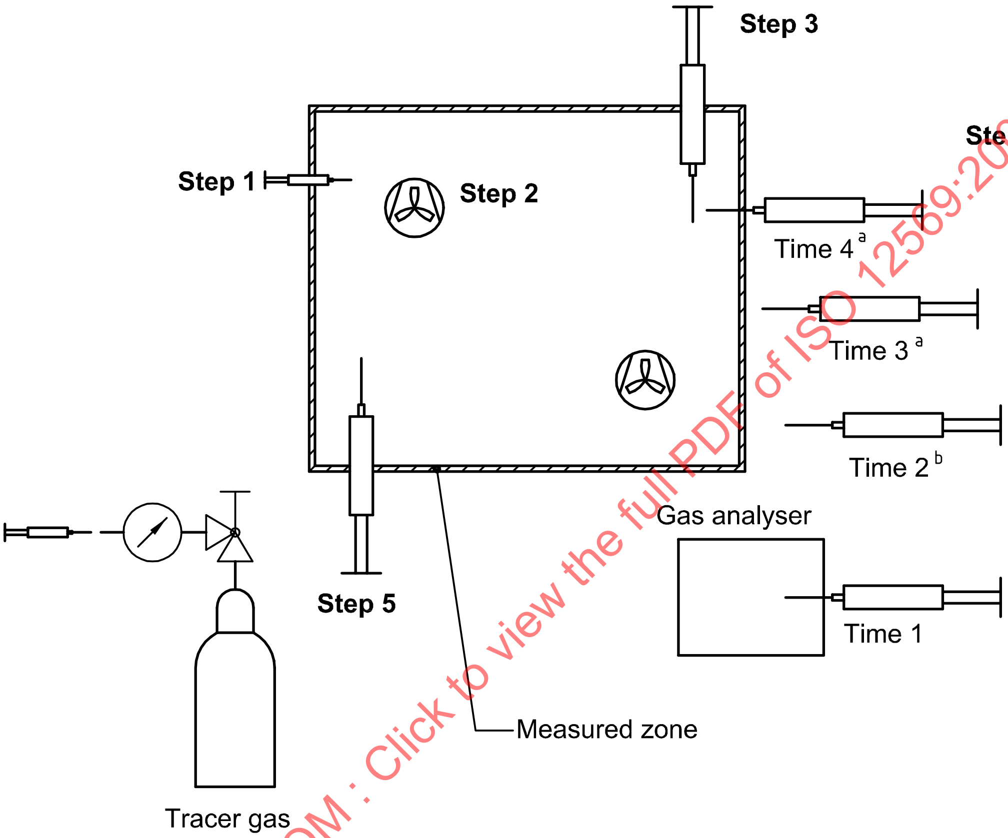
5.3 Ancillary measurements

Determine and record the indoor temperatures throughout the building zone. Obtain outdoor temperature, wind speed and wind direction from a nearby meteorological station or a portable meteorology station. Determine the status of building ventilation systems and envelope openings. Determine the volume of the zone, as required.

5.4 Tracer gas decay method

Introduce a small volume of tracer gas uniformly into the zone, sufficient to cause a concentration at the high end of the detection limits of the gas analyser. Mix the tracer gas in the zone, so that its concentration varies by less than 10 % from the mean value within the zone. Confirm a uniform initial concentration with simultaneous air specimens taken at least at two different places in the zone. Sample the air in the zone a minimum of two known times. As a recommended option, obtain additional air specimens at two different times to test the hypothesis that the air change rate was constant during the test. At the end of the sampling period, again confirm that the tracer gas concentration varies throughout the zone by less than 10 % with simultaneous air specimens. Analyse the tracer gas concentrations of the specimens. Figure 1 gives an overview of this test method.

NOTE The use of more than two samples permits determination of whether the air change rate was constant during the period or allows the choice of a period when the air change rate was constant.



NOTE For each step, perform the corresponding action in Table 1. The gas storage vessel should be stored outside the building at all times during the test.

[a] Recommended

[b] Minimum

Figure 1 — Overview of the tracer gas decay method

Table 1 — Summary procedure for the tracer gas decay method

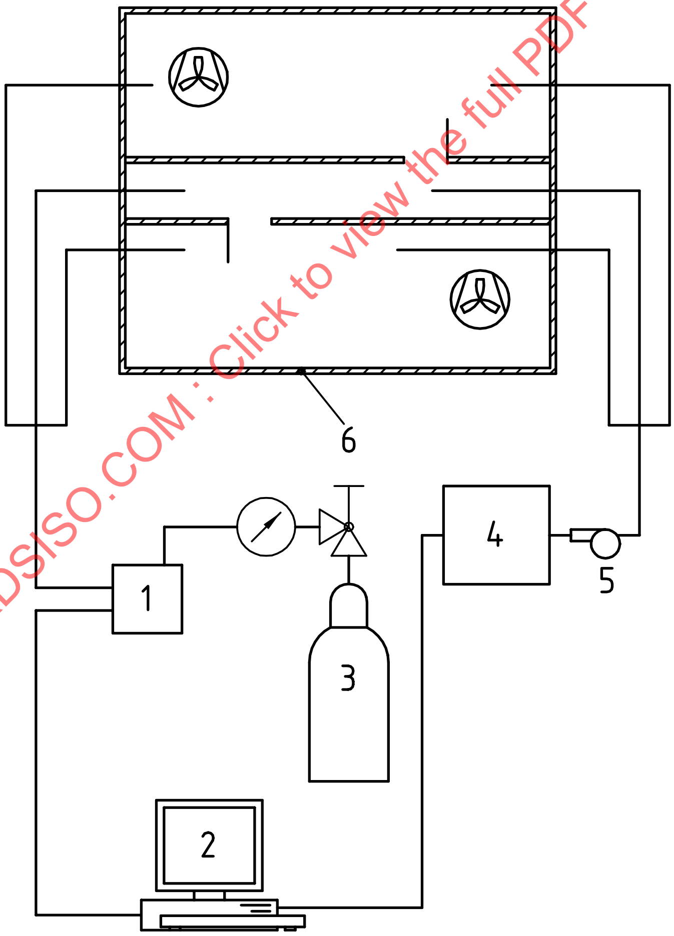
Step	Action
1	Measure and inject tracer gas.
2	Mix tracer gas uniformly.
3	Obtain spatial samples.
4	Obtain samples a minimum of two times.
5	Obtain spatial samples.

5.5 Constant injection method

Inject the tracer gas uniformly into the zone at a constant rate of flow, that is known within 2 % and is sufficient to cause a concentration within the detection limits of the gas analyser. Mix the tracer gas in the zone, so that its concentration varies by less than 10 % within the zone. Confirm a uniform concentration with simultaneous air samplings at diverse locations in the zone. Before the concentration measurement samples are taken, it is essential that the concentration of tracer gas in the zone has approached equilibrium for the prevailing weather conditions, not just an even distribution within the zone. Sample the air in the zone a minimum of two known times. As a recommended option, obtain additional air specimens at two different times to test the hypothesis that the air change rate was constant during the test. With the end of the sampling period, again confirm that the tracer gas concentration varies throughout the zone by less than 10 % by collecting simultaneously air specimens at the diverse locations with simultaneous air specimens. Analyse the tracer gas concentrations of the specimens. Determine that the concentration remains within ± 20 % of the average concentration during the measurement period. Determine the zone volume to within 15 % of the true value. Figure 2 gives an overview of this test method.

NOTE 1 The use of more than two samples permits determination of whether the air change rate was constant during the period or allows the choice of a period when the air change rate was constant.

NOTE 2 When the constant injection method is used for long-term measurements, the checks on how constant the concentration remains during the measurement period are irrelevant. For long-term tests the measurement period is broken down into short time periods (of say 30 min) and the results analysed for each of those short periods so that the trend over time of changing air change rate (or air flow rate) with weather or other parameters may be assessed.



Key

1	Gas	4	Gas analyser
2	Data aquisition	5	Pump
3	Tracer gas	6	Measured zone

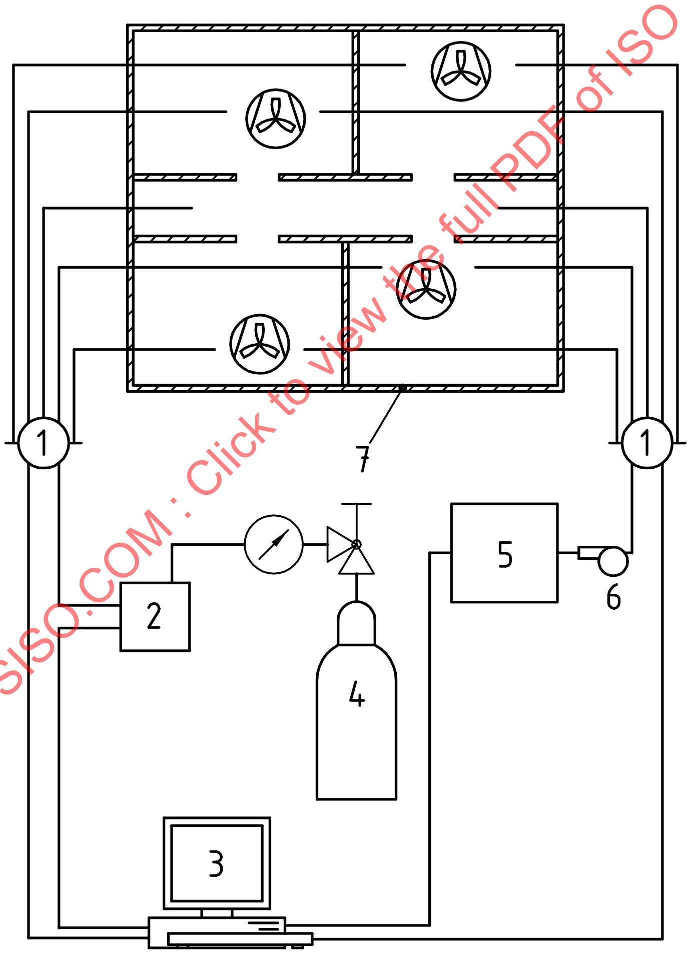
Figure 2 — Overview of the constant injection method

5.6 Constant concentration method

Inject tracer gas uniformly into the zone at a known rate that causes a constant concentration near a target concentration C_{targ} that is within the detection limits of the gas analyser. Mix the tracer gas in the zone, so that its concentration varies by less than 10 % within the zone. Confirm a uniform concentration with simultaneous air samplings at diverse locations in the zone. Before concentration measurement samples are taken, it is essential that the concentration of tracer gas in the zone has stabilized around the target concentration. Sample the air in the zone frequently enough to allow analysis of the tracer gas concentration and to control the rate of flow to maintain the constant concentration to within 5 % of the target concentration, based on the measurement of tracer gas concentration. It is assumed that the volume of the sampled air is negligible, compared to the air change rate. Figure 3 gives an overview of this test method.

NOTE 1 This method allows the determination of a combined air flow rate from multiple zones that comprise the entire building.

NOTE 2 When the constant concentration method is used for long-term measurements the measurement period is broken down into short time periods (of say 30 min) and the results analysed for each of those short periods so that the trend over time of changing air change rate (or air flow rate) with weather or other parameters may be assessed.



Key

1	Switch	5	Gas analyser
2	Gas controller	6	Pump
3	Data aquisition	7	Measured zone
4	Tracer gas		

Figure 3 — Overview of the constant concentration method

6 Expression of results

6.1 Calculation of air change rate

As a minimum, calculate the mean air change rate, n_{av}, determined by the tracer gas decay method, using equation (1):

$$n_{av} = \frac{\ln C(t_1) - \ln C(t_2)}{t_2 - t_1} \tag{1}$$

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.

NOTE Two points do not reveal whether n has changed over the sampling period due to environmental factors or experimental error.

6.2 Test for constant air change rate

As a recommended option, if concentrations were measured at times between the beginning and final specimens, plot ln $C(t)$ against t and perform a regression analysis, using equation (2) (see also C.1), of the logarithms of the tracer gas concentration measurements against time to test the hypothesis that the air change rate, n, was constant during the period:

$$\ln C(t) = -nt + \ln C(0) \tag{2}$$

where

$C(t)$	is the specimen concentration at time t;
t	is the time of sampling, in seconds or hours;
$C(0)$	is the specimen concentration at time zero.

6.3 Calculation of air flow rate from constant tracer gas flow

As a minimum, calculate the mean air flow rate, $\dot{V}_{av}$, determined by the constant injection method for the measurement period, using equation (3):

$$\dot{V}_{av} = \dot{V}_{tra}\left[\frac{1}{C}\right]_{av} - \frac{V_{zone}}{t_2 - t_1}\ln\left[\frac{\bar{C}_2}{\bar{C}_1}\right] \tag{3}$$

where

$\dot{V}_{tra}$	is the flow rate of the tracer gas, in cubic metres per second;

$$\left[\frac{1}{C}\right]_{av} = \left(\frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_k}\right)/k$$

$\left[\frac{1}{C}\right]_{\text{av}}$ is the the average of the inverse of the concentrations of k specimens obtained at different times;

$\overline{C}_1$ is the spatially averaged specimen concentration at the beginning of the measurement period;

$\overline{C}_2$ is the spatially averaged specimen concentration at the end of the measurement period;

t_1 is the time at the beginning of the measurement period, in seconds or hours;

t_2 is the time at the end of the measurement period, in seconds or hours;

k is the number of specimens;

V_{zone} is the volume of the zone, in cubic metres.

NOTE Two points do not reveal whether n has changed over the sampling period due to environmental factors or experimental error.

6.4 Test for constant air flow rate

As a recommended option, test the hypothesis that the air flow rate, $\dot{V}_{\text{air}}$, was constant during the period by performing a confidence interval calculation (see C.2) on $\dot{V}_{\text{air}}$, using individual values of C in equation (4):

$$\dot{V}_{\text{air}}(t) = \frac{\dot{V}_{\text{tra}}}{C(t)} \tag{4}$$

6.5 Calculation of air flow rate from constant tracer gas concentration

Confirm that the sample estimated standard deviation s of $C(t)$ for the measurement period is less than 10 % of the mean. Calculate the mean air flow rate, $\dot{V}_{\text{av}}(t)$, determined by the constant concentration method, using equation (5):

$$\dot{V}_{\text{av}}(t) = \frac{\sum_{t=t_1}^{t_2} \sum_{i=1}^{N} \dot{V}_{\text{tra}}(t,i)}{\sum_{t=t_1}^{t_2} C(t)} \tag{5}$$

where

$\dot{V}_{\text{tra}}(t,i)$ is the tracer gas flow rate at time t and location i, in cubic metres per second or per hour;

$C(t)$ is the spatially averaged concentration at time t;

i denotes the location of a sampling point;

t is the time of sampling, in seconds or hours;

N is the number of measurement points within one zone.

If the value of $C(t)$ remains within ± 2 % of the target concentration, C_{targ}, then calculate the mean air flow rate $\dot{V}_{\text{av}}(t)$ for the measurement period, using equation (6):

$$\dot{V}_{\text{av}}(t) = \frac{\sum_{i=1}^{N} \dot{V}_{\text{tra}}(i)}{C_{\text{targ}}} \tag{6}$$

7 Accuracy

If the procedures are followed and their requirements in these test methods are met, the air flow rate or air change rate within a zone can be determined within ± 10 % of its actual value. The precision and bias of these methods can be affected by

a) tracer gas injection and distribution procedures;

b) tracer gas sampling and storage;

c) changes in wind, temperature and zonal operation regimes; and

d) tracer gas concentration determination.

Annexes A to D give information about the accuracy of tracer gas analysers, the calibration of tracer gas analysers, confidence intervals for the test methods, and propagation of error analyses for the test methods.

8 Test report

The test report shall contain at least the following information:

a) all details necessary to identify the building tested, and the description of the zone tested;

b) a reference to this International Standard;

c) test conditions and apparatus used;

d) collected data and results;

e) date of the test.

Details for each item can be reported taking into consideration the information in annex G.

Annex A
(informative)

Tracer gas analyser accuracy

A.1 Bias at zero concentration

Most analysers have a threshold at which they cannot distinguish between zero tracer gas concentration and some positive concentration. This constitutes the bias at zero concentration, ε_0. All concentrations used in these test methods should be $C > 20 \cdot \varepsilon_0$.

A.2 Drift of concentration reading

The response of a gas analyser to a specimen with a known concentration of tracer gas may change over time. This effect should be checked during calibration. If it is found to be significant, a similar check and corresponding correction should be made during field measurements. For this purpose

— the time that will elapse for readings from a tracer gas standard or pure air to change by 5 % should be estimated,

— this should be used as the maximum interval for rechecking response to the tracer gas calibration standard, and

— all tracer gas concentration readings between checks should be corrected.

In these test methods no measurement should be used when the uncorrected drift of a concentration reading exceeds 5 %.

A.3 Deviate detector response

The response of a gas analyser to different concentrations of tracer gas is usually assumed to follow some empirical relationship, for example, linear or logarithmic, based on a limited number of discrete calibration gas concentrations. The extent to which the gas analyser's response differs from the empirical model is the detector bias, ε_{det}; this value is a function of concentration C. These test methods recommend $\varepsilon_{\text{det}} < 0{,}05\ C$ for all values of C in the range used.

A.4 Estimation of gas analyser precision error

The following should be performed for at least the maximum and minimum concentrations expected to be analysed. The standard deviation of at least $N = 10$ replicates of the same tracer gas concentration should be determined. Here, N is the number of tracer gas samples. The specimen standard deviation of C of the replicates, s_C, should be calculated. Their coefficients of variation ($v_{\text{C}} = s_C/C$) should be calculated. The largest becomes the gas analyser precision error, v_{GA}.

A.5 Determination of the number of replicates required

The number of replicate specimens N_{rep} should be determined to obtain a single concentration measurement with the gas analyser by using equation (A.1):

$$N_{\text{rep}} = \sqrt{\frac{t^2 \ (N - 1{,}95\,\%) \cdot v_{\text{GA}}^2}{d^2}} \qquad \text{(A.1)}$$

where

t is the volume obtained from a t-distribution table;

N is the number of samples;

v_{GA} is the gas analyser precision error.

In these test methods $d = 0{,}05$ should be used as a desired precision of the measurement. The value of N_{rep} in equation (A.1) should be rounded to the next higher integer.

Annex B
(informative)

Tracer gas analyser calibration

B.1 Applicability

Certain gas analysers, including many gas chromatographs, lend themselves to the techniques described in this annex. Other gas analysers may lend themselves to analogous techniques.

B.2 Summary of calibration technique

The gas analyser should be calibrated using at least three, and preferably more, tracer gas concentrations that are in the range anticipated in an actual test. For the concentration decay test method, the measurements need to be accurate only relative to each other. For the constant injection and constant concentration test methods, the measurements should be accurate relative to an absolute standard. Two levels of calibration are recommended here, laboratory and field.

B.3 Frequency of calibration

A field calibration should be performed every time the analyser is moved to a new site, before analysis of constant injection specimens, and at least before and after a constant concentration experiment. A laboratory calibration should be performed annually, after any servicing that might affect the calibration, or whenever a field calibration indicates a significant change.

B.4 Tracer gas concentration standards

Tracer gas standards should have a 95 % probability of having concentrations within a confidence interval that is ± 3 % of their stated concentrations.

B.5 Laboratory calibration

Two tracer gas concentration standards, one at the high end and one at the middle of the range of use, should be used. Ultrahigh-purity air should be used to dilute the standard. The background level of the tracer gas in that air should be tested. A minimum of five analyser readings should be obtained at each of the three following dilutions of each tracer gas standard: 1 part standard only, 1 part standard + 1 part air, and 1 part standard + 3 parts air. A regresssion analysis on the data should be performed in a manner in accordance with equation (2). The estimate of variance from the mean for all specimens that were drawn from the undiluted standard should be reported. Also the estimate of variance from the mean for those that were diluted to each level should be reported. The confidence limits of the calibration should be reported.

B.6 Field calibration

One tracer gas concentration standard at the high end of the range of use should be used. First the background level of the tracer gas in the air that will be used for diluting the standard should be tested. A minimum of three analyser readings should be obtained at each of the three following dilutions of the tracer gas standard: 1 part standard only, 1 part standard + 1 part air, and 1 part standard + 3 parts air. The readings obtained against the calibration curve supplied by the factory should be compared. A regression analysis on the data in a manner analogous to that used in equation (2) should be performed. If the published regression curve lies outside the 95 % confidence limits for this calibration, then a laboratory calibration should be performed.

Annex C
(informative)

Confidence intervals

C.1 Concentration decay test method

The following procedure statistically establishes the confidence in air change rate n as a constant value with the regression method. The estimated standard error E_n of n is found from equation (C.1):

$$E_n = \frac{s}{\sqrt{\sum_{i=1}^{k}(t_i - \bar{t})^2}} \qquad \text{(C.1)}$$

$$s^2 = \frac{\sum_{i=1}^{k}(Y_i - \hat{Y}_1)^2}{k-2} \qquad \text{(C.2)}$$

where

Y is the value of ln C_i;

$\hat{Y}$ is the predicted value of ln C_i;

t_i is a particular time, in seconds or hours;

$\bar{t}$ is the average value of the measurement times;

k is the number of samples.

The confidence limits F_n on n for k points in the grouping and a desired probability of 100 $(1-\alpha)$ % are calculated, using a t-distribution table, and equation (C.3):

$$F_n(t) = n \pm E_n \cdot t(k-2, 1-\alpha) \qquad \text{(C.3)}$$

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.

C.2 Constant injection test method

The following procedure can establish statistical confidence in the assumption of a constant value for $\dot{V}$. The estimate of variance C should be determined using equation (C.4):

$$s^2 = \frac{k \sum_{i=1}^{k} C_i^2 - \left(\sum_{i=1}^{k} C_i \right)^2}{k(k-1)} \tag{C.4}$$

Confidence levels at α and $1-\alpha$, for example 0,05 and 0,95, should be chosen. With $t(k-2, 1-\alpha)$ and the mean value of C, upper and lower limits for C should be calculated using equations (C.5) and (C.6):

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

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

where

$\bar{C}$ is the time-averaged value of the concentration;

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

If equilibrium tracer gas concentration and negligible variance of $\dot{V}_{\text{tra}}$ are assumed, the corresponding values found using equation (6) for $\dot{V}$ are:

$$\dot{V}_{\text{up}} = \frac{\dot{V}_{\text{tra}}}{C_{\text{up}}} \tag{C.7}$$

$$\dot{V}_{\text{low}} = \frac{\dot{V}_{\text{tra}}}{C_{\text{low}}} \tag{C.8}$$

C.3 Constant concentration test method

This procedure has built-in indicators of bias and precision of the calculation. Because C_{targ} is sought, this value may be compared with C to characterize bias. The precision of C may be estimated by calculating the estimate of variance of C using equation (C.4). Confidence levels at α and $(1-\alpha)$, for example 0,05 and 0,95, should be chosen. With $t(n-2, 1-\alpha)$ and the mean value of C, upper and lower limits for C should be calculated using equations (C.5) and (C.6). An analysis of the confidence intervals about $\dot{V}$ at any of the branches depends on the algorithm that relates $C(t)$ to $\dot{V}_{\text{tra}}$.

Annex D
(informative)

Propagation of error analysis

NOTE This annex contains a summary of propagation of errors formulae that pertain to each of the three methods presented in this International Standard.

D.1 Concentration decay test method

For nonsteady-state conditions, the variance s_n^2 of n should be calculated using equation (D.1):

$$s_n^2 = \frac{1}{(t_2 - t_1)}\left[\frac{s_{C(t_2)}^2}{C(t_2)^2} + \frac{s_{C(t_1)}^2}{C(t_1)^2}\right] \tag{D.1}$$

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 regression case, use equation (C.3).

D.2 Constant injection test method

The error expression is:

$$\frac{s_{\dot V}^2}{\dot V^2} = \frac{s_{\dot V \text{tra}}^2}{\dot V_{\text{tra}}^2} + \frac{s_C^2}{\bar C^2}\left[\alpha^2 + \frac{2\dot V^2}{(t_2 - t_1)^2 \dot V^2}\right] \tag{D.2}$$

where

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

$$\text{Var}(f) = \frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2}\left[f(t) - \bar f\right]^2 \,\mathrm{d}t \tag{D.4}$$

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 constant air flow rate, equations (C.7) and (C.8) should be used.

D.3 Constant concentration test method

In general the error expression is:

$$\frac{s_{\dot{V}}^2}{\dot{V}^2} = \frac{s_{\dot{V}\text{tra}}^2}{\dot{V}_{\text{tra}}^2} + \frac{s_C^2}{C^2}\left[\alpha^2 + \frac{2\dot{V}^2}{(t_2 - t_1)^2 \dot{V}^2}\right] \tag{D.5}$$

where

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

$$\text{Var}_{twt}(f) = \frac{1}{V_{\text{tra}}(t_2 - t_1)} \int_{t_1}^{t_2} \left[f(t) - \bar{f}\right]^2 V_{\text{tra}}(t)\,\text{d}t \tag{D.7}$$

$$V_{\text{tra}}(t_2, t_1) = \int_{t_1}^{t_2} V_{\text{tra}}(t)\ \text{d}t \tag{D.8}$$

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).

$V_{\text{tra}}(t_2, t_1)$ is the volume of the tracer gas injected between times t_1 and t_2.

twt indicates variables weighted according to tracer gas flow.

Annex E
(informative)

How to choose the test methods

The tracer gas decay method, constant injection method and constant concentration method are used for the measurement of air change in buildings. Guidance on the application of these test methods is as follows.

a) The decay method is a simple low-cost method of making a spot measurement of air change rate using relatively basic equipment.

b) The constant injection method and constant concentration method may be used for spot measurements (as indicated in 5.1) but are better suited to longer-term measurements (over several hours or days) where the variation of air change rate or air flow rate with time is of interest - such as variation due to the effect of weather. They are more expensive, particularly the constant concentration method, because they require more elaborate equipment than the decay method.