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Vacuum technology — Vacuum gauges — Specifications, calibration and measurement uncertainties for capacitance diaphragm gauges

Technique du vide — Manomètres à vide — Spécifications, étalonnage et incertitudes de mesure des manomètres capacitifs à membrane

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 112, *Vacuum technology*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

ISO 3567, *Calibration by direct comparison with a reference gauge*, and ISO 27893, *Evaluation of the uncertainties of results of calibrations by direct comparison with a reference gauge*, were published in 2011 and in 2009, respectively. Detailed guidance for a specific gauge is intended to be given in separate international standards or technical specifications for the calibration of special types of gauges.

This document complements ISO 3567 and ISO 27893 when characterizing, calibrating or using capacitance diaphragm gauges (CDGs) as reference gauges.

CDGs are widely used to measure pressures in the medium vacuum up to atmospheric pressure. For the dissemination of the pressure scale and measurement of low and medium vacuum pressures by this gauge, the relevant parameters, calibration guidelines and uncertainties are described in this document.

Vacuum technology — Vacuum gauges — Specifications, calibration and measurement uncertainties for capacitance diaphragm gauges

1 Scope

This document defines terms related to capacitance diaphragm gauges (CDGs), specifies which parameters have to be given for CDGs, details their calibration procedure and describes which measurement uncertainties have to be considered when operating these gauges.

This document complements ISO 3567 and ISO 27893 when calibrating CDGs and using them as reference standards.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3529-1, *Vacuum technology — Vocabulary — Part 1: General terms*

ISO 3529-3, *Vacuum technology — Vocabulary — Part 3: Total and partial pressure vacuum gauges*

ISO 3567, *Vacuum technology — Vacuum gauges — Calibration by direct comparison with a reference gauge*

ISO 27893, *Vacuum technology — Vacuum gauges — Evaluation of the uncertainties of results of calibrations by direct comparison with a reference gauge*

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

ISO/IEC Guide 99, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

3 Terms and definitions

For the purposes of this document the terms and definitions given in ISO 3529-1, ISO 3529-3, ISO 3567, ISO 27893, ISO/IEC Guide 98-3, ISO/IEC Guide 99 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1 Components

3.1.1
diaphragm
membrane
elastic element which deforms under differential pressure applied to it

3.1.2
measurement side
side of diaphragm on a CDG to which the pressure to be measured is applied

Note 1 to entry: Sometimes the measurement side is called the test side.

3.1.3
reference side
side of diaphragm on a CDG opposite the measurement side

3.1.4
absolute-type CDG
CDG where the reference side is permanently evacuated

3.1.5
differential-type CDG
CDG where the reference side is accessible from outside

3.1.6
measurement port
port connecting to the measurement side of a CDG

3.1.7
reference port
port connecting to the reference side of a CDG

Note 1 to entry: In absolute-type CDG, this port does not exist.

3.1.8
integrated type CDG
gauge in which the head and controller form one piece of equipment

3.2 Physical parameters

3.2.1
reproducibility
long-term instability
δ_t
relative quantity characterizing the typical change of measurement error near full scale (90% to 100% of full scale) of the CDG (nitrogen) after a specified period

Note 1 to entry: Reproducibility can be determined in two ways:

a) as the relative standard deviation of measurement error Δp_i obtained from at least three calibrations each being separated by the specified period

$$\delta_t = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{\Delta p_i}{p_i} - \overline{\left(\frac{\Delta p}{p}\right)}\right)^2} \quad (1)$$

where

n is the number of calibrations, i;

$$\overline{\left(\frac{\Delta p}{p}\right)} = \frac{1}{n}\sum_{i=1}^{n}\frac{\Delta p_i}{p_i}.$$

b) as the mean of absolute (non-negative) changes of measurement error Δp_i between recalibrations separated by the specified period

$$\delta_t = \frac{\sum_{i=1}^{n-1} \left| \frac{\Delta p_{i+1}}{p_{i+1}} - \frac{\Delta p_i}{p_i} \right|}{n-1} \tag{2}$$

and n as described above. Formula (1) is recommended when the measurement error does not show a significant drift but random variations, Formula (2) when the measurement error shows a systematic and monotonic drift. In both cases, δ_t shall be accompanied with the specified time period, for example δ_t per year or δ_t per two years.

Note 2 to entry: If the output signal of the gauge is not pressure (but e.g. voltage or current), this signal shall be converted to pressure according to specification, before the measurement error is calculated.

Note 3 to entry: Reproducibility can be determined by recalibrations with a more accurate gauge or a primary standard. This often requires a transport which itself can lead to an instability of the calibrated value. For this reason, it is not reasonable to assume a linear relationship of instability with time (e.g. δ_t for a period of two years is not two times δ_t for a period of one year).

Note 4 to entry: If not specified otherwise, it is recommended that δ_t is determined over a period of one year. This is usually a reasonable compromise between costs and influence of transport on the one hand and a possible drift and lowest possible measurement uncertainty on the other hand.

Note 5 to entry: Measurement error is defined in 3.3.3.

3.2.2
warm-up period
duration between the instant after which the power supply is energized and the instant when the measuring instrument is used to the expected measurement uncertainty as specified

Note 1 to entry: For a CDG with controlled temperature type gauge head, the time to achieve and stabilize the temperature of the gauge head shall be considered. For a gauge head without temperature control, the time to stabilize the temperature due to the heat generated from the electrical circuit equipped in the gauge head shall be considered.

Note 2 to entry: Warm-up period depends on, for example, the environment of the measurement or the equipment.

3.2.3
response time
time from a sudden change of an applied pressure until the corresponding change of an indication of the CDG has reached a specified fraction of its final value

Note 1 to entry: The amount of the change is specified. There are three variations of the corresponding change of the indication: 0 % to 90 %; 0 % to 63,2 %; 10 % to 90 %.

3.2.4
update interval
time interval at which an output of a CDG is updated

3.2.5
admissible pressure
maximum load pressure
maximum differential pressure that can be applied to the CDG while operating within its stated specifications

Note 1 to entry: When pressure above the admissible pressure is applied to a gauge head, the gauge head is required for recalibration.

3.2.6
disruption pressure
burst pressure
pressure applied to the gauge head above which a gauge head can fail

3.2.7
internal volume
volume of measurement (and reference side, if applicable) side in the gauge head up to the sealing plane of the measurement (and reference) port

3.3 Other parameters

3.3.1
measurement uncertainty
non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

Note 1 to entry: Measurement uncertainty includes components arising from systematic effects, such as components associated with corrections and the assigned quantity values of measurement standards, as well as the definitional uncertainty. Sometimes small estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated.

Note 2 to entry: The parameter can be, for example, a standard deviation called standard measurement uncertainty (or a specified multiple of it), or the half-width of an interval, with a stated coverage probability.

Note 3 to entry: Measurement uncertainty comprises, in general, many components. Some of these can be evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from a series of measurements and can be characterized by standard deviations. The other components, which can be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information.

Note 4 to entry: In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.

[SOURCE: ISO/IEC Guide 99:2007, 2.26]

3.3.2
measurement accuracy
closeness of agreement between a measured quantity value and a true quantity value of a measurand

Note 1 to entry: The concept 'measurement accuracy' is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error.

Note 2 to entry: The term “measurement accuracy” should not be used for measurement trueness and the term “measurement precision” should not be used for 'measurement accuracy', which, however, is related to both these concepts.

Note 3 to entry: 'Measurement accuracy' is sometimes understood as closeness of agreement between measured quantity values that are being attributed to the measurand.

Note 4 to entry: In the past and up to now, “accuracy of a CDG” is one of the important parameters given by manufacturers and has been published on the data sheets of many manufactures. Their definition of accuracy is a numerical value and included nonlinearity, repeatability, hysteresis and the difference in measurement error between a CDG and the reference standard used for calibration. It did not include the measurement uncertainty of the reference standard. For these reasons, this term is in contradiction to the above definition given in the VIM and should not be used.

[SOURCE: ISO/IEC Guide 99:2007, 2.13, modified — Note 4 to entry added.]

3.3.3
measurement error
measured quantity value minus a reference quantity value

Note 1 to entry: The concept of 'measurement error' can be used both a) when there is a single reference quantity value to refer to, which occurs if a calibration is made by means of a measurement standard with a measured quantity value of a negligible measurement uncertainty or if a conventional quantity value is given, in which case the measurement error is known, and b) if a measurand is supposed to be represented by a unique true quantity value or a set of true quantity values of negligible range, in which case the measurement error is not known.

Note 2 to entry: Measurement error should not be confused with production error or mistake.

[SOURCE: ISO/IEC Guide 99:2007, 2.16]

3.3.4
measurement precision
closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions

Note 1 to entry: Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement.

Note 2 to entry: The 'specified conditions' can be, for example, repeatability conditions of measurement, intermediate precision conditions of measurement, or reproducibility conditions of measurement (see ISO 5725-1:1994).

Note 3 to entry: Measurement precision is used to define measurement repeatability, intermediate measurement precision, and measurement reproducibility.

Note 4 to entry: Sometimes "measurement precision" is erroneously used to mean measurement accuracy.

[SOURCE: ISO/IEC Guide 99:2007, 2.15]

3.3.5
measurement repeatability
measurement precision under a set of repeatability conditions of measurement

[SOURCE: ISO/IEC Guide 99:2007, 2.21]

3.3.6
measurement reproducibility
measurement precision under reproducibility conditions of measurement

Note 1 to entry: Relevant statistical terms are given in ISO 5725-1:1994 and ISO 5725-2:1994.

[SOURCE: ISO/IEC Guide 99:2007, 2.25]

3.3.7
measurement trueness
closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value

Note 1 to entry: Measurement trueness is not a quantity and thus cannot be expressed numerically.

Note 2 to entry: Measurement trueness is inversely related to systematic measurement error, but is not related to random measurement error.

Note 3 to entry: "Measurement accuracy" should not be used for 'measurement trueness'.

[SOURCE: ISO/IEC Guide 99:2007, 2.14, modified — Note 1 to entry revised.]

4 Symbols and abbreviated terms

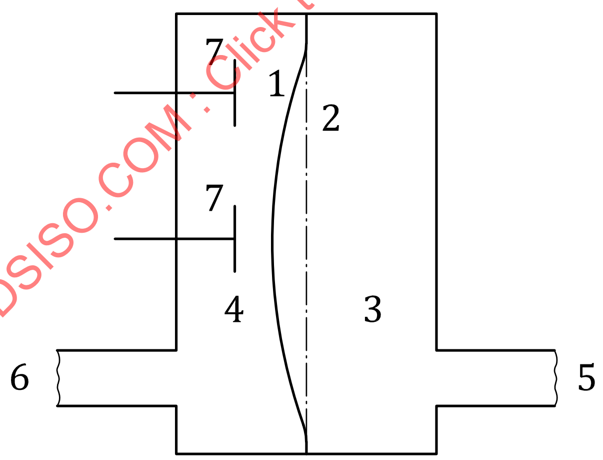
Abbreviation	Definition
CDG	capacitance diaphragm gauge
UUC	unit under calibration

5 Capacitance diaphragm gauge

5.1 Principle

A CDG is a device in which an elastic diaphragm deflects under the differential pressure across it (Figure 1). The size of the elastic deformation is proportional to the differential pressure between the measurement side and the reference side. The displacement of the elastic diaphragm is sensed by the change in the capacitance between the diaphragm and a fixed sensing counter electrode on the reference side. This set-up is preferable to avoid contamination and to ensure the use of a wide variety of measurable gas species. Materials from which the elastic diaphragm is composed include metal, ceramics and silicon. In an absolute-type CDG, the reference side is evacuated to a level that does not affect pressure measurements. In a differential-type CDG, both sides of the diaphragm are accessible from outside. Some types of CDGs are equipped with a self-heating system to maintain the gauge head at constant temperature to stabilize the offset value and make more accurate measurements or to protect the diaphragm from condensing gas species. The temperature difference between gauge head and gas inlet causes the sensitivity to become gas dependent in a certain pressure range. The underlying effect is the so-called thermal transpiration effect. Outside of this pressure range, the pressure indication is independent of the gas species.

Clause 6 and Clause 7 provide information for the user of this type of instrument on how to make reliable pressure measurements and how to estimate the measurement uncertainty and/or disseminate the pressure scale.



Key

1 diaphragm (pressurized)
2 diaphragm (unpressurized)
3 measurement side
4 reference side
5 measurement port
6 reference port
7 electrodes

Figure 1 — Typical CDG

6 Specifications for capacitance diaphragm gauge

6.1 Type of capacitance diaphragm gauge

The type of CDG, absolute-type or differential-type, shall be specified.

6.2 Temperature control of gauge head

The control ability of the temperature of a gauge head, such as temperature-controlled or no control, (room temperature) shall be specified.

For a temperature-controlled gauge head, the temperature(s) shall be specified. The type of temperature control, i.e. temperature-controlled, temperature-compensated or no control, shall be specified.

NOTE The temperature of the gauge head is one of the important parameters for the evaluation of the thermal transpiration effect and influences the uncertainty of measurements.

6.3 Display and measurement signal output unit

In the case of a control unit and an integrated type CDG, the display shall show the SI unit of pascals (Pa). Other additional units of pressure are also allowed.

If a gauge head or a control unit has a different measurement signal output than pressure, for example voltage, a clear assignment of this value to pressure shall be made by an equation, table or graph.

6.4 Measurement range of capacitance diaphragm gauge

The measurement range of a gauge head in which a specified expected measurement uncertainty is satisfied shall be specified. The pressure range shall be given in Pa. Other additional units are also allowed.

6.5 Expected measurement uncertainty

An expected measurement uncertainty of CDG shall be specified. This shall be given in Pa, "% of reading", "% full-scale" or their combinations. This includes the effect of fluctuation of the ambient temperature on the pressure readings. The measurement conditions (e.g. temperature, elevation or orientation) needed to obtain the expected measurement uncertainty should be specified.

The measurement uncertainty of type of device shall include the measurement error.

The calibration uncertainty of an individual gauge shall be given by a calibration certificate (see 7.13). The calibration uncertainty of an individual gauge can be significantly lower than the one for the same type of device, because the measurement error is corrected and excluded in the certificate.

6.6 Temperature coefficients of zero readings and span

The temperature coefficients of zero readings and span shall be specified.

6.7 Resolution

The resolution of a pressure readings and type of the resolution such as the resolution of a gauge head or the resolution of a displaying device shall be specified. The pressure shall be given in Pa. Other additional units are also allowed.

6.8 Response time of the gauge head

The response time of the gauge head shall be specified.

6.9 Warm-up period

The warm-up period shall be specified.

6.10 Admissible pressure (maximum load pressure)

The admissible pressure (maximum load pressure) (absolute pressure) shall be specified. The pressure shall be given in Pa. Other additional units are also allowed.

6.11 Disruption pressure (burst pressure)

CAUTION — This information is important for users' safety.

The disruption pressure (burst pressure) (absolute pressure) shall be specified. The pressure shall be given in Pa. Other additional units are also allowed.

6.12 Materials exposed to gas

Any materials of the gauge head exposed to an operating gas shall be specified.

6.13 Mounting orientation of the gauge head

The recommended mounting orientation of the gauge head shall be specified. For the calibration, it is recommended that the mounting orientation of the gauge head is the same as when operated. If the gauge head has no angle (orientation) dependence, it should be specified as "any".

6.14 Fitting to chamber

The fitting type and size shall be specified.

6.15 Internal volume

The internal volume of a gauge head accessible from outside shall be specified. For a differential-pressure-type gauge head, volumes of both side of the diaphragm should be mentioned.

6.16 Interface and pin connections

The protocol of communication with a computer shall be specified. The connector type and the function of the pin connections (pin-out) shall be specified.

6.17 Compatibility between a gauge head and a control unit

The type or model number of the control unit for the gauge head shall be specified. It shall be specified whether the gauge head and the control unit support one-to-one correspondence or not. The use of a gauge head and control unit as a fixed pair is recommended for precise measurement.

6.18 Dimension and weight of the gauge head and control unit

The dimensions of the gauge head and/or control unit with an outline drawing and their weight in SI units shall be specified. It may be expressed as width, depth and height (W*D*H). Other units (e.g. inches) can also be used.

6.19 Nominal operating (environmental) conditions

Temperature and relative humidity ranges in which the gauge head and/or control unit can be operated shall be specified.

6.20 Storage and transportation condition

Conditions of storage and transportation intended to avoid damage and harm to the gauge – for example temperature and relative humidity – shall be specified. The environment, cleanliness, vibration and shock conditions are optional.

NOTE The storage temperature is useful for determining the temperature for the system baking.

6.21 Input power and its requirements

The voltage (AC or DC), current, frequency and their requirements shall be specified.

7 Additional (optional) specifications for capacitance diaphragm gauge

7.1 Reproducibility (long-term instability)

Reproducibility (long-term instability) should be expressed in per cent of reading and/or per cent of full-scale for a specified period (e.g. one month, one year). For such measurements, stable or repeatable pressures shall be used and the gauge operated under its normal conditions. Typical values can be given by the manufacturer. Manufacturers decide to what extent this measurement is economically feasible considering the type of gauge and its intended field of application. If possible, such information should be gathered from customers. The measurement conditions of the reproducibility shall be specified.

NOTE Reproducibility (long-term stability) in particular is greatly influenced by the user and the field of application.

7.2 Tilting effect on zero readings

The effect of a gauge head tilting on both zero readings and its span shall be specified. For a gauge head whose span has the tilting effect, the tilting effect on the span shall be specified. The reference orientation of the tilting angle shall be specified as in 6.13.

7.3 Repeatability of zero

Repeatability of zero of gauge head shall be specified.

7.4 Durability of zero after the pressure of full scale

Durability of zero should be expressed in per cent of full scale for a specified cycle (e.g. 10 000 cycles, 1 million cycles).

The pressure applied to the test device shall be cycled lower than 1 % FS to about 100 % FS.

7.5 Durability of span after the pressure of full scale

Durability of span should be expressed in per cent of reading and/or per cent of full scale for a specified cycle (e.g. 10 000 cycles, 1 million cycles).

The pressure applied to the test device shall be cycled lower than 1 % FS to about 100 % FS.

7.6 Durability of zero after the admissible pressure

Durability of zero should be expressed in per cent of full scale for a specified cycle (e.g. 100 cycles, 10 000 cycles).

The pressure applied to the test device shall be cycled below its full scale to about the admissible pressure.

7.7 Durability of span after the admissible pressure

Durability of span should be expressed in per cent of reading and/or per cent of full scale for a specified cycle (e.g. 100 cycles, 10,000 cycles).

The pressure applied to the test device shall be cycled below its full scale to about the admissible pressure.

7.8 Update interval

The update interval of a gauge head and/or a controller unit shall be specified.

7.9 Inner diameter of connecting tube

An inner diameter of a connecting tube to the diaphragm shall be specified. The diameter shall be given in mm. Other additional units are also allowed.

NOTE The inner diameter of the connecting tube is used to calculate the effect of thermal transpiration.

7.10 Cable length

The cable length which is usually supplied shall be specified. The maximum cable length provided on demand should also be specified.

NOTE A longer cable is sensitive to electromagnetic interference.

7.11 Set point of pressure

It shall be specified whether set point(s) of pressures to control another unit are available or not.

7.12 Photographs

For clear outlook and details, computer graphics, a photograph or a drawing of an upright gauge head shall be given. Front and back panels (connector side) of both a gauge head and a control unit are recommended.

7.13 Inspection record and calibration certificate

An inspection record of a gauge head will increase the user's confidence in the readings of the gauge head and/or control unit. If a calibration certificate is available, it shall contain information on how it is traceable to a national standard of vacuum. It should be specified whether an inspection record and/or a calibration certificate will be issued or not.

8 Calibration

8.1 Calibration procedure

If the calibration is performed by direct comparison with a reference gauge, ISO 3567 applies. In the following subclauses, details for CDGs are given with reference to ISO 3567, if applicable.

If the calibration is performed by a primary standard, the user shall apply the following procedures correspondingly.

a) A mounting orientation of a gauge head is set as stated in 6.13 or otherwise agreed between the calibration laboratory and a user (see ISO 3567:2011, 6.2).

b) No strong airflow around a UUC and the reference gauge is required (see ISO 3567:2011, 6.2.3).

c) For calibrations with required low uncertainties, the warm-up period specified (see 6.9) cannot be sufficient. Suitable longer times (e.g. overnight) have to be chosen (see ISO 3567:2011, 6.6).

d) Relevant effects of the temperature are effects on zero reading, span and the thermal transpiration. The temperature effect is calculated when the temperature effect is significant compared with the expected calibration uncertainty or when it is significant for its later use. Details of how to correct this are given in Reference [1]. For the temperature-controlled type gauge head (e.g. 45 °C), there is a temperature difference between the gas in the reference gauge and the gas in the calibration chamber, and also between the gas in the UUC and the gas in the calibration chamber. In order to obtain reliable calibration results, these temperatures are considered.

   In the case of thermal transpiration, several compensation methods have been published (see Annex A). Note that the thermal transpiration effect depends on the gas species (see ISO 3567:2011, B.7).

e) Usually, the indication of the CDG is sensitive to vibration due to its principle (see ISO 3567:2011, B.6).

f) For some types of CDGs, it is strongly recommended that the admissible pressure (6.10) is not exceeded either during or after a calibration. In this case a valve in front of the inlet port shall be installed, which is closed, before the admissible pressure is reached. This reduces hysteresis effects and can improve long-term stability (see ISO 3567:2011, B.9).

8.2 Calibration uncertainty

Calibration uncertainty of a CDG is evaluated as stated in ISO 27893.

The following list gives an overview of contributions to the CDG uncertainty:

— uncertainty of the standard;

— resolution of signal output;

— short-term stability (repeatability);

— reproducibility of zero;

— change of ambient temperature;

— uncertainty of voltmeter (if used).

8.3 Calibration certificate

A calibration certificate of a CDG is prepared as specified in ISO 3567.

For the temperature-controlled type gauge head, it is recommended that the temperature of the gauge head is stated.

Mounting orientation of a gauge head at the calibration should be stated.

If the output signal of the CDG is not pressure, the mathematical model given by which the output signal (e.g. voltage, current) is converted to pressure should be repeated in the certificate.

9 Measurement uncertainty at use

Some measurement uncertainties are not important during a calibration but play a role later on, for example when used as a reference gauge.

The following list gives an overview of contributions to the measurement uncertainty in addition to those listed in 8.2:

— long-term instability;

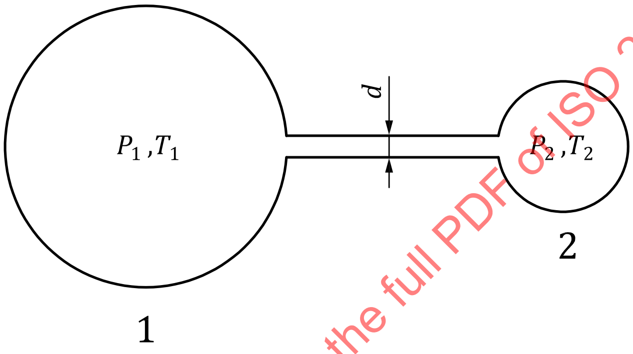
— nonlinearity;
— different ambient temperature than during calibration;
— drift of ambient temperature;
— cleanliness of gas which the gauge is exposed to and general gas composition;
— hysteresis;
— thermal transpiration (temperature and gas species).

Annex A
(informative)

Compensation of thermal transpiration effect

A.1 General

Several methods have been reported for the compensation of thermal transpiration effect. In this annex, three methods are introduced. A simple model is illustrated in Figure A.1 and the results are illustrated in Figure A.2. The parameters for A.2 are summarized in Table A.1.



Key

1 vacuum chamber

2 CDG

Figure A.1 — Expression of thermal transpiration

A.2 Takaishi-Sensui method[2] (including AVS recommendation[3]) and Setina's method[4]

$$\frac{p_1}{p_2} = \frac{Y + \sqrt{T_1 / T_2}}{Y + 1}$$

where

$T_1 < T_2$;

$Y = A \cdot X^2 + B \cdot X + C \cdot \sqrt{X}$;

$X = 7{,}5 d \cdot p_2$;

$A = a \cdot T^{-2}$;