Physikalisch-
Technische
Bundesanstalt

DKD

Guideline DKD-R 5-8

Calibration of hygrometers for the direct measurement of relative humidity

Edition 10/2019

https://doi.org/10.7795/550.20190214EN

Deutscher Kalibrierdienst (DKD) – German Calibration Service

Since its foundation in 1977, the DKD has brought together calibration laboratories of industrial enterprises, research institutes, technical authorities, inspection and testing institutes. On 3rd May 2011, the German Calibration Service was reestablished as a *technical body* of PTB and accredited laboratories.

This body is known as *Deutscher Kalibrierdienst* (DKD – German Calibration Service) and is under the direction of PTB. The guidelines and guides developed by DKD represent the state of the art in the respective areas of technical expertise and can be used by the *Deutsche Akkreditierungsstelle GmbH* (the German accreditation body – DAkkS) for the accreditation of calibration laboratories.

The accredited calibration laboratories are now accredited and supervised by DAkkS as legal successor to the DKD. They carry out calibrations of measuring instruments and measuring standards for the measurands and measuring ranges defined during accreditation. The calibration certificates issued by these laboratories prove the traceability to national standards as required by the family of standards DIN EN ISO 9000 and DIN EN ISO/IEC 17025.

Contact:
Physikalisch-Technische Bundesanstalt (PTB)
DKD Executive Office
Bundesallee 100 38116 Braunschweig, Germany
P.O. Box 33 45 38023 Braunschweig, Germany
Telephone: +49 531 592-8021
Internet: www.dkd.eu

Suggestion for the citation of sources:

Guideline DKD-R 5-8, Edition 02/2019, Revision 0, Calibration of hygrometers for direct measurements of relative humidity, Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin. DOI: https://doi.org/10.7795/550.20190214EN

Authors:

Hager, Helmut; G. Lufft Mess- und Regeltechnik GmbH / MBW Calibration GmbH, Fellbach
Deschermeier, Regina; Physikalisch-Technische Bundesanstalt (PTB), Braunschweig
Harke, Andreas; Vötsch Industrietechnik GmbH, Balingen
Hee, Willi; Vötsch Industrietechnik GmbH, Balingen
Jehnert, Diana; ZMK & ANALYTIK GmbH, Bitterfeld-Wolfen
Mitter, Helmut; BEV / E+E Elektronik Ges.m.b.H, Engerwitzdorf (Austria)
Reinshaus, Peter; Küssaberg
Sander, Eugen; Testo industrial services GmbH, Kirchzarten
Scheibe, Mario; CTS Clima Temperatur Systeme GmbH, Hechingen
Schnelle-Werner, Olaf; ZMK & ANALYTIK GmbH, Bitterfeld-Wolfen
Schüür, Jens; ELMTEC Ingenieurgesellschaft mbH, Königslutter
Waldera, Rudolf; Ahlborn Mess- und Regelungstechnik GmbH, Holzkirchen

Published by the Physikalisch-Technische Bundesanstalt (PTB) for the German Calibration Service (DKD) as result of the cooperation between PTB and the DKD Technical Committee *Temperature and Humidity*.

Foreword

DKD guidelines are application documents that meet the requirements of DIN EN ISO/IEC 17025. The guidelines contain a description of technical, process-related and organizational procedures used by accredited calibration laboratories as a model for defining internal processes and regulations. DKD guidelines may become an essential component of the quality management manuals of calibration laboratories. The implementation of the guidelines promotes equal treatment of the equipment to be calibrated in the various calibration laboratories and improves the continuity and verifiability of the work of the calibration laboratories.

The DKD guidelines should not impede the further development of calibration procedures and processes. Deviations from guidelines as well as new procedures are permitted in agreement with the accreditation body if there are technical reasons to support this action.

Calibrations by accredited laboratories provide the user with the security of reliable measuring results, increase the confidence of customers, enhance competitiveness in the national and international markets, and serve as metrological basis for the monitoring of measuring and test equipment within the framework of quality assurance measures.

This guideline has been drawn up by the DKD Technical Committee *Temperature and Humidity* and approved by the Board of the DKD.

Table of contents

1 Purpose and scope of application

The purpose of this guideline is to define minimum requirements for the reference standard, calibration equipment, calibration procedure and the estimation of the measurement uncertainty in the calibration of hygrometers. It applies to calibration devices with direct measurement of relative humidity by means of resistive, capacitive, resistive-electrolytic as well as mechanical sensor elements. In this guideline, the term gas humidity refers to gaseous substance systems consisting of the components water and carrier gas. The guideline applies to the carrier gases air and nitrogen. For other carrier gases, the application of the guideline still is to be assessed.
If the calibration of the gas temperature is desired in addition to the humidity calibration, the guidelines DKD-R 5-1 [1] or DKD-R 5-3 [2] apply to the temperature calibrations. The selection of the guideline depends on the sensor element.

2 Definitions

The terms and definitions used in this guideline are based on the guideline VDI/VDE 3514 Sheet 1 [3] / Sheet 2 [4]. A distinction can be made between pure substances (referred to as “pure” phase in VDI/VDE 3514 Sheet 1 [3]) consisting of one component (one-component system), e.g. water, and mixtures (mixed gas systems) consisting of several components (multi-component systems), e.g. humid air. The system can be a single-phase system, e.g. gaseous, or a multiphase one, e.g. gaseous and liquid.

Air humidity and gas humidity

Air humidity describes the water vapour content or the amount of water vapour in humid air. In practice, different humidity parameters are used depending on the application and requirements. A list of different calculation formulae for humidity parameters and their uncertainties can be found in the DKD guide DKD-L 5-1 [5]. In comparison to the term air humidity, the term gas humidity is used when referring to other carrier gases, e.g. nitrogen.

Ideal gas

A pure substance (one-component system) or a mixture consisting of several components (multi-component system) behaves like an ideal gas if each component behaves like an ideal gas. The individual components as well as the overall system (mixture) can be described by the ideal gas law.

Water vapour pressure

According to the guideline VDI/VDE 3514 Sheet 1 [3], the proportionate pressure (partial pressure) of the water in the gas phase as a component of the gas pressure p in the pure phase (one-component system, pure substance) or in an ideal gas or gas mixture is referred to as the water vapour pressure e.

Saturation vapour pressure in pure phase

The saturation vapour pressure in a pure phase describes the pressure occurring in a closed system with water ((e_w, Case a) in Figure 1) or with ice ((e_i, Case b) in Figure 1) at a given temperature t in a phase equilibrium in the absence of other components (one-component system, pure substance). In this case, the water vapour pressure e is equal to the saturation vapour pressure in the pure phase and equal to the gas pressure p. The saturation vapour pressure in the pure phase can be directly measured and only depends on the temperature t. The functional relationship between the saturation vapour pressure and the temperature is referred to as the vapour pressure equation.
At temperatures below 0.01 °C, both conditions are possible: saturation vapour pressure above ice or above water. At the same temperature, the saturation vapour pressure above water will be slightly higher than over ice.

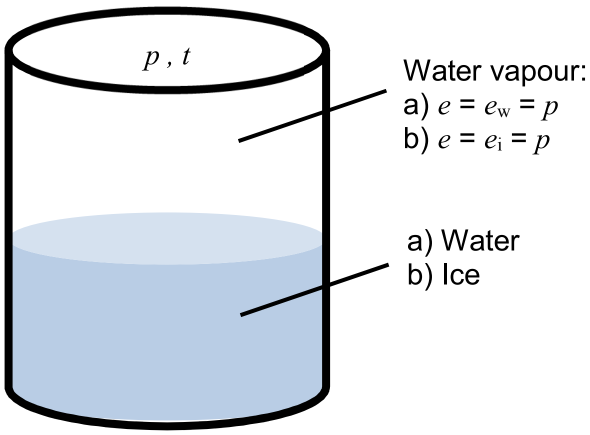

Figure 1: Schematic representation *saturation vapour pressure*

Real Gas

If, for example, a component in a pure phase (one-component system) or a mixture of several components do not behave like an ideal gas, e.g. due to different interactions between the components, deviations from the ideal gas behaviour occur. To indicate the deviation from the ideal behaviour, the symbols of the corresponding quantities in the real gas or gas mixtures are marked with an apostrophe (e.g. $e \rightarrow e'$).

Water vapour partial pressure

According to VDI/VDE 3514 [3], the water vapour partial pressure e' is the partial pressure of the water in the gas phase in a real gas or gas mixture.

Saturation vapour pressure in a mixture

Due to interactions between the individual components in a real gas mixture (e.g. humid air), there are differences compared to the behaviour of the component as a pure substance (e.g. water). These differences can be taken into account by using the so-called enhancement factor f. The enhancement factor is calculated from the gas temperature t, the gas pressure p and the saturation vapour pressure in pure phase, e_w or e_i. Thus, the saturation vapour pressure in the mixture above water e'_w and above ice e'_i is established by the following relations[1]:

$$e'_\mathrm{w}(p,t) = e_\mathrm{w}(t) \cdot f_\mathrm{w}(p,t) \qquad (1)$$

or

$$e'_\mathrm{i}(p,t) = e_\mathrm{i}(t) \cdot f_\mathrm{i}(p,t) \qquad (2)$$

Frost point temperature / Dew point temperature

Isobaric cooling of a humid gas mixture (e.g. humid air) at dew point temperature t_d results in liquid (dew) condensation, while at frost point temperature t_f solid (frost) condensation occurs. At this point the water vapour partial pressure is equal to the saturation vapour pressure. By means of the following equations, the water vapour partial pressure e' can be calculated from the dew point or frost point temperature, using the vapour pressure equation and the enhancement factor f:

$$e' = e'_\mathrm{w}(p,t_\mathrm{d}) = e_\mathrm{w}(t_\mathrm{d}) \cdot f_\mathrm{w}(p,t_\mathrm{d}) \qquad (3)$$

or

$$e' = e'_\mathrm{i}(p,t_\mathrm{f}) = e_\mathrm{i}(t_\mathrm{f}) \cdot f_\mathrm{i}(p,t_\mathrm{f}) \qquad (4)$$

Relative humidity

Relative humidity indicates the ratio of water vapour partial pressure e' to saturation vapour pressure e'_w as a percentage[2], e.g. U_w = 75 %.

Above 0 °C as well as according to definition by the WMO (World Meteorological Organization) also below 0 °C, relative humidity refers to the saturation above water e'_w:

$$U_\mathrm{w} = \frac{e'}{e'_\mathrm{w}(p,t)} \cdot 100\ \% \qquad (5)$$

In contrast, the technical definition of relative humidity at temperatures below 0 °C is related to the saturation above ice e'_i:

$$U_\mathrm{i} = \frac{e'}{e'_\mathrm{i}(p,t)} \cdot 100\ \% \qquad (6)$$

For calibrations below 0 °C, the definition of the relative humidity should be indicated according to the display of the calibration item (U_i, U_w). Alternatively, the information can be given in accordance with WMO (related to water), subject to other specifications by the customer.
If the saturation vapour pressure exceeds the gas pressure (e.g. at 1013.25 hPa and 99.974 °C), a relative humidity of 100 % can no longer be achieved. In this case, the relative

---

[1] When using concrete calculation formulae for the saturation vapour pressure in the pure phase as well as the enhancement factor, it must be ensured to use the correct unit for the input variable in the application of numerical value equations. It might be necessary to use kelvins instead of degrees Celsius (gas temperature T in K instead of gas temperature t in °C).

[2] Relative humidity is a dimensionless ratio with the variables U, U_i, U_w and $U_\mathrm{w,hyp}$. It is usually expressed as a percentage (%). Further prefixes or suffixes (e.g. % rh or % r.F.) are not mandatory but can be used for clarification.

humidity is indicated as ratio of the water vapour partial pressure, which cannot exceed the gas pressure, to a hypothetical system pressure at which saturation with water vapour would be possible (higher pressure than gas pressure). In the case of saturation, the humid gas mixture only consists of water vapour (saturation vapour pressure = gas pressure) and is thus single-phase (pure substance). Hence, a correction of the saturation vapour pressure is not required. Thus, the saturation vapour pressure in pure phase serves as reference quantity for the relative humidity. The relative humidity is given by the equation:

$$U_{\mathrm{w,hyp}} = \frac{e'}{e_{\mathrm{w}}(t)} \cdot 100\ \% \tag{7}$$

Due to the dependence of the relative humidity on the gas temperature t, the temperature and its thermal influences must be considered during calibration and in the calculation of the measurement uncertainty, analogous to the influences of the humidity.

If the relative humidity is not directly measured – as is the case with a capacitive polymer sensor, for example – but determined by applying the equations (5), (6), or (7), it must be borne in mind that the water vapour partial pressure e' cannot be measured directly. However, as described for example in Chapter 5.3 of this Directive, it can be measured indirectly by determining the dew point using a condensation (chilled mirror) hygrometer and determined by the following equations:

$$e' = e'_{\mathrm{w}}(p_{\mathrm{M}}, t_{\mathrm{d}}) = e_{\mathrm{w}}(t_{\mathrm{d}}) \cdot f_{\mathrm{w}}(p_{\mathrm{M}}, t_{\mathrm{d}}) \tag{8}$$

or

$$e' = e'_{\mathrm{i}}(p_{\mathrm{M}}, t_{\mathrm{f}}) = e_{\mathrm{i}}(t_{\mathrm{f}}) \cdot f_{\mathrm{i}}(p_{\mathrm{M}}, t_{\mathrm{f}}) \tag{9}$$

The water vapour partial pressure e' is equal to the saturation vapour pressure at the dew point temperature t_{d} (dew layer) or frost point temperature t_{f} (frost layer) measured with the dew point hygrometer and the pressure p_{M} prevailing at the mirror.

3 Symbols

3.1 Variables

Variable	Designation	Unit
e	Water vapour pressure	hPa
e'	Partial water vapour pressure	hPa
e_{i}	Saturation vapour pressure in pure phase above ice	hPa
e'_{i}	Saturation vapour pressure in mixture (e.g. moist air) above ice	hPa
e_{w}	Saturation vapour pressure in pure phase above water	hPa
e'_{w}	Saturation vapour pressure in mixture (e.g. moist air) above water	hPa
e'_{C}	Partial water vapour pressure in the calibration chamber	hPa
e'_{M}	Partial water vapour pressure above the mirror of the dew point hygrometer	hPa
f_{i}	Enhancement factor for ice	1
f_{w}	Enhancement factor for water	1
U	Relative humidity[3]	1 [4]

[3] The variable U of the relative humidity must not be confused with the variable U of the expanded measurement uncertainty. The meaning of the variables used must be checked in each individual case.

[4] The relative humidity is a dimensionless ratio which is usually given in percent (%).

U_i	Relative humidity in relation to ice	1 [4]
U_w	Relative humidity in relation to water	1 [4]
$U_{w,hyp}$	Relative humidity in relation to water and a hypothetical relative system pressure	1 [4]
T or t	Gas temperature	K or °C
T_d or t_d	Dew point temperature	K or °C
T_f or t_f	Frost point temperature	K or °C
T_i or t_i	Wet-bulb temperature of an icy surface	K or °C
T_w or t_w	Wet-bulb temperature of a moist surface	K or °C
T_C or t_C	Temperature of the calibration chamber	K or °C
T_S or t_S	Temperature of the saturator	K or °C
p	Gas pressure (absolute pressure)	hPa
p_C	Gas pressure (absolute pressure) in the calibration chamber	hPa
p_S	Gas pressure (absolute pressure) in the saturator	hPa
p_M	Gas pressure (absolute pressure) at the mirror of the dew point hygrometer	hPa
ε	Emissivity (see radiation influence)	1

Table 1: Overview of the variables used

3.2 Indices

Indices	Designation
′	(Apostrophe) indicates real gas or gas mixture
d	Dew point
f	Frost point
i	above ice
w	above water
hyp	Hypothetical state
C	Calibration chamber
M	Mirror of the dew point mirror hygrometer
S	Saturator

Table 2: Overview of the indices used

4 Aim of the calibration

The calibration of a hygrometer for the direct measurement of relative humidity serves to determine the measurement deviation of the relative gas humidity from the calibration value (target value) determined or represented by standards, with indication of the associated measurement uncertainty, the calibration condition and the calibration procedure. The results are documented in a calibration certificate.

5 Reference and working standards

All reference or working standards used must be directly or indirectly traceable to a national standard. The calibration is performed by directly comparing the measured values of the calibration item with the measured or displayed values of the reference or working standard.

Different methods are used to represent or determine the relative humidity (also see VDI/VDE 3514 Sheet 2 [4]).

The lowest uncertainties can be achieved by means of so-called primary methods. They are realized using two-pressure, two-temperature or two-pressure/two-temperature humidity generators. These generators generate a defined and known humid gas flow which is traced back to temperature and pressure measurements.

Dew point hygrometers and psychrometers are used as precise and long-term stable devices for measuring gas humidity. Gas temperature and gas pressure are required to calculate the relative humidity.

Capacitive polymer sensors or resistive-electrolytic sensors are used for the direct measurement of relative humidity. Compared to the previously mentioned methods, these sensors have a lower long-term stability and require intermediate tests.

All influencing variables must be recorded by means of calibrated reference or working standards. They are to be evaluated and considered in the measurement uncertainty budget.

In temperature measurements (e.g. gas temperature measurement, measurement of the temperature in a saturator, etc.), the influences of thermal coupling, self-heating and radiation must be particularly considered.

If the relative humidity is not directly measured but calculated from temperature and pressure values, as is the case for humidity generators, the validity and uncertainties of the calculation equations used must be taken into account (see DKD-L 5-1 [5]).

Due to the temperature dependence of the relative humidity, not only the hygrometric influences but also all thermal influences must be considered.

As to the reference and working standards used, records must be kept for the evaluation of their long-term behaviour.

5.1 Two-pressure / Two-temperature humidity generator

5.1.1 Operating principle

A carrier gas serves as starting point for calibration in the two-pressure/two-temperature humidity generator. This could be, for example, oil- and dust-free filtered compressed air from a compressor or nitrogen. A two-pressure/two-temperature humidity generator operated with compressed air is used to explain the mode of operation for saturation above water:
Compressed air, whose water content is usually below the desired dew point, is passed through heated water in a humidifier (also known as a pre-saturator). The air leaves the humidifier at the given temperature, having nearly reached the state of saturation. The humid air is then fed into the saturator (also called condenser). The saturator is a specially manufactured metal block with a large inner surface which, for example, has been inserted for temperature control into a precision thermostat. The saturator temperature is below the temperature of the humidifier. By cooling the humid air to the temperature of the saturator, the excess water is condensed from the air. At the output of the saturator we therefore find completely saturated air, as related to the temperature t_S and the pressure p_S of the saturator. The saturation vapour pressure $e_w(t_S)$ in pure phase is calculated using the vapour pressure equation (see DKD-L 5-1 [5]). The saturation vapour pressure of the humid air is obtained through multiplication by the enhancement factor $f_w(p_S,t_S)$. Usually, this humid air is now expanded to ambient pressure at a valve and fed into the calibration chamber. In the process, the water vapour partial pressure is reduced according to the quotient from calibration chamber pressure p_C and saturation pressure p_S. Based on the assumption that the vapour pressure equation is valid, the water vapour partial pressure and thus the absolute humidity can be traced back to the measurement of the saturator temperature as well as the saturator pressure and the gas pressure in the calibration chamber. A wide range can be set for the gas humidity by varying the parameters ‘saturator temperature’ and ‘saturator pressure’.

Apart from saturation above water, there may also be saturation above ice. In this case, a carrier gas with a water content below the value to be displayed is used. The carrier gas passes over a layer of ice in a specially manufactured saturator block. Thus, when leaving the saturator, a saturated state for the prevailing pressure and temperature in the saturator is restored. Here, as is the case for saturation above water, the water vapour partial pressure can be determined from the saturation vapour pressure $e_i(t_S)$ above ice and the corresponding enhancement factor $f_i(p_S,t_S)$.

To display the relative humidity, the object to be calibrated is placed in a calibration chamber which in turn is placed in a temperature chamber, e.g. for the purposes of temperature adjustment. The humid gas flow is passed through the temperature chamber by means of a specific construction. This is done to ensure that the gas flow reaches the measuring temperature (temperature t_C) before entering the calibration chamber. After the humid gas flow has adjusted to the measuring temperature in the calibration chamber, the value of the relative humidity is equalized. The relative humidity is calculated from the temperature and pressure conditions according to formula (10):

$$U_{\mathrm{i,w}} = \frac{e_{\mathrm{i,w}}(t_{\mathrm{S}}) \cdot f_{\mathrm{i,w}}(p_{\mathrm{S}}, t_{\mathrm{S}})}{e_{\mathrm{i,w}}(t_{\mathrm{C}}) \cdot f_{\mathrm{i,w}}(p_{\mathrm{C}}, t_{\mathrm{C}})} \cdot \frac{p_{\mathrm{C}}}{p_{\mathrm{S}}} \cdot 100\ \% \qquad (10)$$

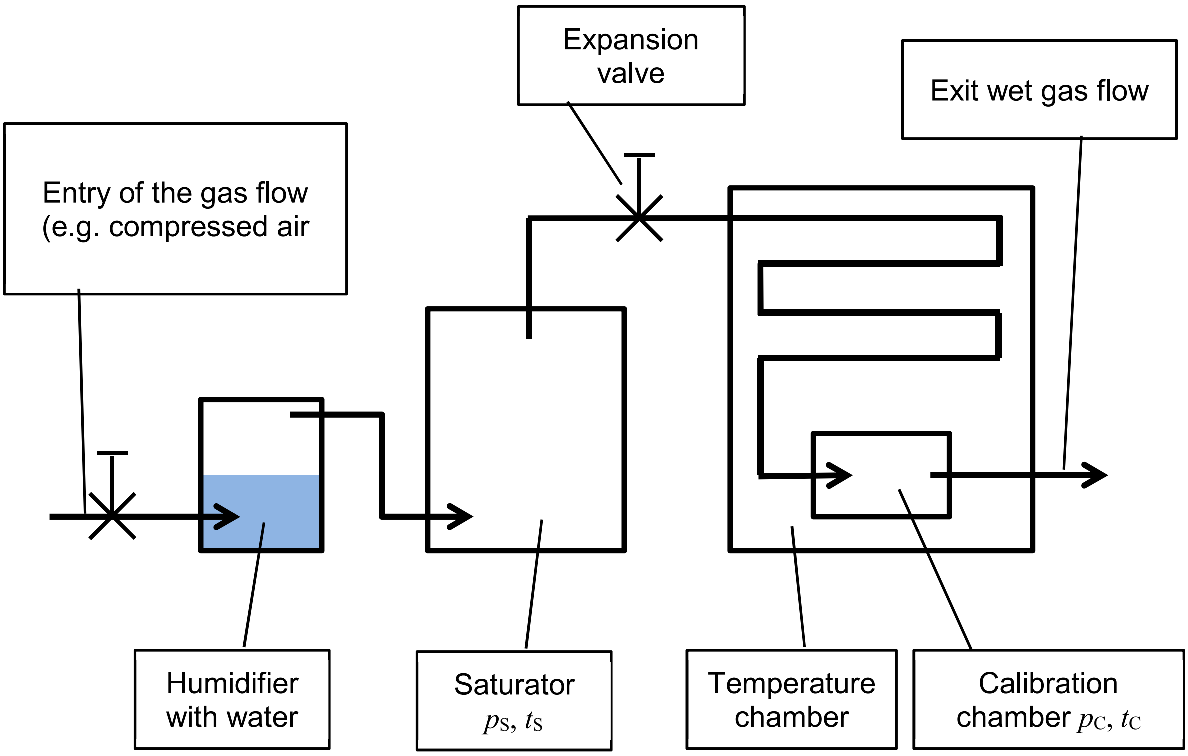

Figure 2: Schematic representation of a two-pressure/two-temperature humidity generator with saturation above water

5.1.2 Requirements

The saturator is the centrepiece of the generator. Its task is to saturate the wet gas flow at a rate of 100 % with water vapour. The reliable functioning of the saturator must be validated. To ensure a constant quality control, it is recommended to use an additional dew point hygrometer as transfer standard to be able to compare the frost or dew point calculated from the parameters of the generator with the indicated frost or dew point of the dew point hygrometer. Intervention criteria must be specified.

5.1.3 *Influence quantities*

In addition to the influence quantities of the calibration chamber (see Chapter 6.2), the temperature measurements (see Chapter 5.8) and the pressure measurement (see also DKD-R 6-1 [6]), the following influence quantities are to be determined and included in the uncertainty budget:

Calibration

The measurement uncertainty of the standards used to measure the pressure of saturator and calibration chamber as well as the temperature of both saturator and calibration chamber can be found in the current calibration certificate.
When calculating the calibration result, the measurement deviations need to be included. The calibration points of the respective standards must cover the entire range of application (pressure sensors in the respective pressure range of saturator and calibration chamber, temperature sensors in the respective temperature range of saturator and calibration chamber). Extrapolation is not permitted.

Mean value

The associated uncertainty of the mean value is to be calculated from the standard deviation and the number of measured values and must be included in the uncertainty budget.

Resolution

If the resolution that is used for the calculations differs from the resolution used for calibration in the calibration certificate, then it must be considered in the uncertainty budget.

Calculations

The uncertainty of the formulae used (e.g. vapour pressure equation, enhancement factor) must be included in the uncertainty budget (see also Chapter 5.9).

Non-linearity

Interpolation is permitted between the calibration points of the reference standards. A possible additional deviation or non-linearity must be considered in the uncertainty budget. Extrapolation is not permissible.

Long-term behaviour

The calibration history of the standards forms the basis to determine a possible drift which must be considered in the uncertainty budget.

Saturation behaviour

The saturation behaviour of the saturator must be examined and included in the uncertainty budget.

5.2 Two-pressure humidity generator

5.2.1 Operating principle

The two-pressure generator is a simplified version of the two-pressure/two-temperature generator. The temperature of the saturator and the calibration chamber are structurally the same. Thus, the relative humidity is calculated from the quotient of calibration chamber pressure p_C to saturator pressure p_S, taking account of the enhancement factors.

$$U_{i,w} = \frac{p_C}{p_S} \cdot \frac{f_{i,w}(p_S, t_S)}{f_{i,w}(p_C, t_C)} \cdot 100\ \% \tag{11}$$

For further simplification, humidifier and saturator can be combined in a single chamber.

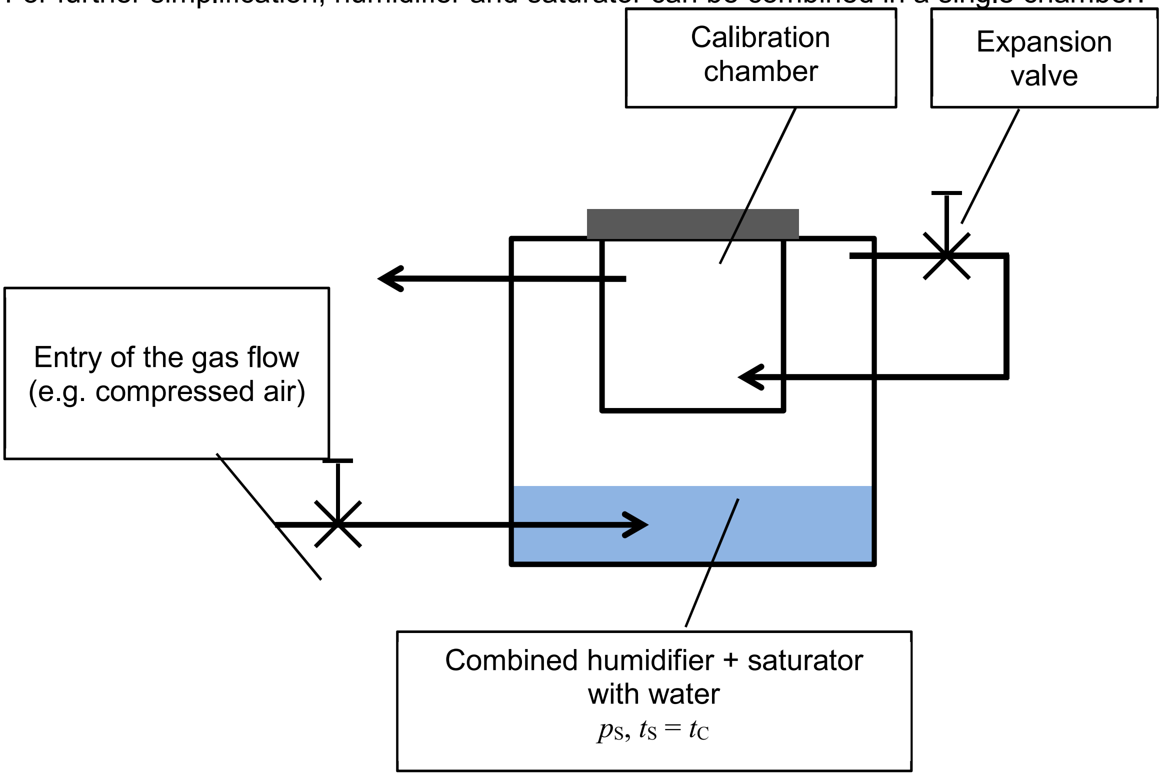

Figure 3: Schematic representation two-pressure humidity generator with combined humidification and saturation

5.2.2 Requirements

If the traceability is to be established via pressure and temperature measurements, the same requirements apply as for two-pressure/two-temperature generators (see Chapter 5.1.2). Alternatively, traceability can be established directly via calibration in relative humidity (e.g. by means of a dew point hygrometer and a temperature measuring instrument).

5.2.3 Influence quantities

The same influence quantities apply as for two-pressure/two-temperature generators (see Chapter 5.1.3).
If the traceability is established via calibration in relative humidity, the following influencing quantities must be taken into account in addition to the influencing variables of the calibration chamber (see Chapter 6.2) and the pressure measurement (see also DKD-R 6-1 [6]):

Calibration

The measurement uncertainty is stated in the current calibration certificate of the humidity generator. The measurement errors must be considered when determining the correct value, or in the uncertainty budget. The calibration points must cover the entire operating range of the relative humidity. If the humidity generator additionally contains a temperature control, the calibration must be carried out at several climate points, according to the designated range of application (recommendation: at least five humidity points, each for the lowest, medium and highest temperature). Extrapolation is not permitted.

Mean value

The attributed uncertainty of the mean value is to be calculated from the standard deviation and the number of measured values and must be considered in the uncertainty budget.

Non-linearity

Interpolation is permitted between the calibration points of the reference standard. A possible additional deviation or non-linearity must be considered in the uncertainty budget. Extrapolation is not permitted.

Resolution

If the resolution that is used for the calculations differs from the resolution used for calibration in the calibration certificate, then it must be considered in the uncertainty budget.

Long-term behaviour

The calibration history of the standards forms the basis to determine a possible drift which is to be considered in the uncertainty budget.

5.3 Dew point hygrometer

5.3.1 Operating principle

Dew point hygrometers operate according to the condensation principle. A surface (mirror) is cooled (by means of a Peltier element) until condensation occurs. The condensation, for example, is detected optically by means of photodiodes. The surface is regulated to the temperature at which dew or frost formation occurs (= dew point temperature or frost point temperature). A temperature sensor below the surface measures the mirror temperature and thus the dew point or frost point temperature.
In addition to the dew point temperature, it is also necessary to measure the gas temperature and the gas pressure on the dew point hygrometer to determine the relative humidity. The relative humidity is to be calculated from these parameters by means of the vapour pressure equation and considering the enhancement factors:

$$U_{\mathrm{i,w}} = \frac{e(t_{\mathrm{d,f}}) \cdot f_{\mathrm{i,w}}(p, t_{\mathrm{d,f}})}{e_{\mathrm{i,w}}(t) \cdot f_{\mathrm{i,w}}(p, t)} \cdot 100\ \% \tag{12}$$

5.3.2 Requirements

The calibration of dew point hygrometers must always be carried out for the measurement quantities dew or frost point and must cover the entire calibration range (example: if a dew point hygrometer is intended to be used for calibrations of relative humidity in the range of 5 % up to 95 % at temperatures of 5 °C up to 95 °C, then it must be calibrated from a frost point temperature of -29 °C to a dew point temperature of +94 °C). The calibration point interval should be adjusted to the desired measurement uncertainty and the measurement range (recommendation: maximum 15 K steps). The maximum recalibration interval for dew point mirror hygrometers serving as standards is 24 months. By establishing appropriate intermediate tests, the uncertainty contribution of a possible drift can be reduced.
Due to optical detection and condensation on the mirror, the mirror must be checked and cleaned on a regular basis. An adequate exchange of gas must be ensured. For this purpose, the manufacturer's specifications shall be taken into consideration. If the wet gas is led to the mirror via pipes, it has to be ensured that there is no dead volume in the pipe system. If dew points close to or above ambient temperature are to be measured, all pipe sections - including the measuring head of the dew point hygrometer - must be heated (e.g. at a temperature of 30 K above the dew point temperature). Only suitable materials that are neither hygroscopic nor exhibit absorption or desorption behaviour may be used for the piping system (e.g. polished, stainless steel pipes, Teflon hoses). A constant gas flow to the mirror must be ensured.
As to the requirements for measuring the gas temperature, see Chapter 5.8.

5.3.3 Influence quantities

The following influencing quantities shall be determined and taken into account in the measurement uncertainty budget. The influencing quantities of the gas temperature measurement are listed in Chapter 5.8.

Calibration

The measurement uncertainty is to be taken from the most recent calibration certificate. The measurement errors must be considered when determining the correct value or in the uncertainty budget. The calibration points must cover the entire application range of the frost and dew point temperature. Extrapolation is not permitted.

Mean value

The attributed uncertainty of the mean value is to be calculated from the standard deviation and the number of measured values and must be considered in the measurement uncertainty budget.

Resolution

If the resolution that is used for the calculations differs from the resolution used for calibration in the calibration certificate, then it must be considered in the uncertainty budget.

Calculations

The uncertainty of the formulae used (e.g. vapour pressure equation) or the fact of not paying attention to the enhancement factors must be considered in the uncertainty budget. (also see Chapter 5.9).

Distinction between dew and frost

At a mirror temperature between -36 °C and 0 °C, water (which means it is a dew point) **or** frost (which means it is a frost point) can form on the mirror. For further calculations (e.g. water vapour partial pressure), the corresponding calculation equation must be used - depending on the mirror coating (dew or frost). The use of the wrong formula leads to considerable calculation errors. The distinction between water and ice on the mirror must be ensured by a suitable procedure (e.g. by cooling the mirror to below -36 °C and ensuring that the temperature of the mirror does not exceed 0 °C afterwards). If this is not possible, the potential calculation error must be considered in the uncertainty budget.

Non-linearity

Interpolation is permitted between the calibration points of the reference standard. A possible additional deviation or non-linearity must be considered in the uncertainty budget. Extrapolation is not permitted.

Long-term behaviour

The calibration history of the standards forms the basis to determine a possible drift which is to be considered in the uncertainty budget.

Temperature dependence of the measuring head

Depending on the design of the measuring head (measuring unit with mirror), the measurement of the mirror temperature may depend on the ambient temperature. For models with external measuring head, it is usually installed in the calibration volume and exposed to different ambient temperatures. For instruments with an internal measuring unit, it can optionally be heated so that the measuring head can be operated at different temperatures. The temperature dependence must be investigated and included in the uncertainty budget.

Thermal feedback effects

For dew point mirror hygrometers with external measuring head, the measuring head is usually installed in the calibration volume to determine the dew point temperature. It should be noted that due to the heat dissipation of the measuring head (the cooling of the mirror e.g. by means of a Peltier element generates waste heat) a feedback effect on the calibration volume occurs, which can lead to temperature inhomogeneities, for example. The influence can be minimized. Considering the gas flow in the calibration chamber, the measuring head of the dew point mirror is placed in such a way that the waste heat from the sensor head does not flow through the measuring volume. The feedback effect is to be investigated and must be considered in the uncertainty budget.

Pressure loss

For dew-point mirror hygrometers with internal measuring head, the gas to be measured is to be conducted to the mirror via gas lines. The pressure loss occurring at the mirror is to be determined and the water vapour partial pressure calculated from the frost or dew point temperature is to be corrected according to formula (13).

$$e'_{\mathrm{C}} = e'_{\mathrm{M}} \cdot \frac{p_{\mathrm{C}}}{p_{\mathrm{M}}} \qquad (13)$$

The uncertainty component of the determination is to be considered in the uncertainty budget.

Absolute pressure

To correct the pressure loss as well as to calculate the enhancement factors, the absolute pressure must be measured by means of a calibrated barometer. It has to be considered in the uncertainty budget.

5.4 Psychrometer

5.4.1 Operating principle

A psychrometer consists of two thermometers. One of the thermometers (dry bulb) serves to detect the air temperature (t). The second thermometer (wet bulb) is wrapped in a wetted material (called wick), mostly moistened cotton, and serves to detect the humidity temperature (t_w or t_i). The drier the gas, the faster the water evaporates, producing more evaporative cooling, which in turn leads to a greater temperature difference between the two temperature sensors. A built-in fan ensures adequate flow around the wet bulb and prevents the already resulting water vapour from hindering evaporation. The air temperature, wet-bulb temperature, the psychrometer constant, which depends on type and flow velocity, as well as the absolute pressure serve to determine various humidity parameters. DKD-L 5-1 [5] is recommended as calculation basis.

5.4.2 Requirements

Accurate measurements are subject to certain prerequisites - the wet-bulb temperature sensor must always be adequately moistened; the air flow must be constant and the water that is used as well as the moistened wick must be free of impurities.
Due to the evaporation of water, the humidity of the air is increased which in turn can have a negative effect on the calibration medium.
The calibration of psychrometers can be carried out in the measurement quantities temperature (dry bulb thermometer as well as wet bulb thermometer) or relative humidity.
In the case of establishing traceability via temperature, calibration must be carried out over the entire range of application of the thermometers (Example: if a psychrometer is intended for calibrations of relative humidity in the range from 10 % to 95 % at temperatures from 10 °C to 50 °C, the dry bulb thermometer shall be calibrated at least in the range from 10 °C to 50 °C and the wet bulb thermometer, depending on the psychrometer constant, in the range from 1 °C to 50 °C). The requirements from Chapter 5.8 shall apply.
In addition, a validation of the psychrometer constant and other factors such as wick moistening, flow velocity and radiation influences affecting the measurement result is necessary. This investigation can be carried out, for example, by comparison measurements in relative humidity.
If a humidity calibration is favoured, the calibration must be carried out at several climate points according to the field of application (It is recommended to calibrate at least three humidity points each at lowest, medium and highest temperature).
The maximum recalibration interval for psychrometers used as standards is 24 months. In addition, the introduction of suitable intermediate tests (e.g. quarterly check of the thermometers at the ice point or water triple point) is necessary.

5.4.3 Influence quantities

In addition to the influence quantities of the temperature measurements (see Chapter 5.8), the following influence quantities are to be determined and included in the measurement uncertainty budget:

Calibration

The measurement uncertainty can be found in the current calibration certificate. The measurement deviations must be considered when determining the correct value or in the uncertainty budget. The calibration points must cover the entire range of application. Extrapolation is not permitted.

Mean value

The attributed uncertainty of the mean value is to be calculated from the standard deviation and the number of measured values and must be considered in the uncertainty budget.

Resolution

If the resolution that is used for the calculations differs from the resolution used for calibration in the calibration certificate, then it must be included in the uncertainty budget.

Calculations

The uncertainty of the formulae used (e.g. vapour pressure equation) or constants (e.g. psychrometer constant), as well as a neglect of the enhancement factors must be considered in the uncertainty budget (see also Chapter 5.9).

Non-linearity

Interpolation is performed between the calibration points of the reference standard. A possible additional deviation or non-linearity must be considered in the uncertainty budget (see also DKD-R 5-6, Table 6.2 [7]). Extrapolation is not permitted.

Gas pressure dependence

To be able to calculate the humidity parameters, the absolute pressure is required - in addition to the psychrometer constant and the dry and wet temperature. The absolute pressure must be measured with a calibrated barometer and the uncertainty of the pressure measurement must be considered in the uncertainty budget.

Long-term behaviour

The calibration history of the standards forms the basis to determine a possible drift which must be considered in the uncertainty budget.

Contamination of water or wick

Preferably, distilled or demineralized water should be used for moisturisation. Since contamination and impurities may lead to measurement deviations, the cleanliness of the water, thermometer and wick must be ensured. The uncertainty budget must take account of uncertainties resulting from contamination of the psychrometer wick or water which has been caused by measurement tasks.

Self-heating

The self-heating of the temperature sensors (probes) must be determined and considered in the uncertainty budget. The self-heating in air can be significantly higher than the self-heating in liquids. This is particularly important when calibrating thermometers in liquids.

Flow fluctuations in the psychrometer

Due to the direct dependence of the evaporation effect on the flow velocity, uncertainties due to flow fluctuations caused by the fan must be taken into account in the uncertainty budget.

5.5 Relative humidity sensor

5.5.1 Operating principle

Sensors belonging to that category measure the relative humidity directly. Capacitive polymer sensors or resistive-electrolytic sensors are used as sensor elements. The sensor signal is converted electronically into relative humidity. Other measuring principles as, for example, resistive solid-state sensors are not recommended as reference standards.

5.5.2 Requirements

When using relative humidity sensors as reference standards, at least two standards (diversity recommended) are to be employed. The difference between the two standards is to be considered in the measurement uncertainty.
The humidity sensors must be calibrated in the entire range of application (climatic range). The distance between the calibration points of the relative humidity should not exceed 20 % (depending on the desired measurement uncertainty). If the operating temperature of the standard differs by more than ±3 K from the temperature that is stated for the standard in the calibration certificate, the standard is to be calibrated at least at two temperatures that cover the whole application range and at several humidity points. If these two temperatures differ from each other by more than 10 K, calibration should be performed at several temperatures (depending on the desired measurement uncertainty).
The maximum recalibration interval for relative humidity sensors serving as standards is 12 months.
Measures should be taken to reduce the risk of additional drifts. This includes the prevention of harmful substances or gases. This in turn implies:

- cleanliness of the calibration device
- particularly thorough examination of the calibration items regarding contamination
- usage of appropriate cleaning agents in the laboratory
- storage of the sensors in suitable containers or material
- temporary removal of the standards during conversion work or renovations in the laboratory area, if necessary

Moreover, it is necessary to introduce suitable intermediate tests. Otherwise, a drift of least 2 % must be considered as rectangular distribution in the uncertainty budget at a recalibration interval of 12 months. The intermediate test interval should not exceed 1 month. Suitable measures with an adequately small uncertainty are, for example:

- testing by means of a more accurate reference (e.g. humidity generator)
- testing by using non-concentrated (unsaturated) salt solutions
- comparison with a humidity sensor which is not used for the calibration

The intermediate tests are to be documented and the specified limit values must be considered in the measurement uncertainty. If the limit values are exceeded, suitable measures shall be taken.

5.5.3 Influence quantities

The following influence quantities are to be determined and must be considered in the uncertainty budget:

Calibration

The measurement uncertainties can be found in the current calibration certificate. The measurement deviations must be taken into account when determining the correct value or in the uncertainty budget. The calibration points must cover the entire range of application (climatic range). Extrapolation is not permitted.

Mean value

The associated uncertainty of the mean value is to be calculated from the standard deviation and the number of measured values and must be considered in the uncertainty budget.

Resolution

If the resolution that is used for the calculations differs from the resolution used for calibration in the calibration certificate, then it must be included in the measurement uncertainty budget.

Non-linearity

Interpolation between the calibration points of the relative humidity of the reference standards is permitted. A possible additional deviation or non-linearity must be considered in the uncertainty budget. Depending on the distance between the calibration points of the relative humidity, a higher or lower uncertainty contribution is to be assumed. Extrapolation is not permitted.

Temperature dependence

If the standards for calibration of the relative humidity are used at different temperatures, the calibration must be carried out accordingly, i.e. at several temperatures. A possible deviation between the calibration points of the relative humidity at different temperatures must be considered in the uncertainty budget. Depending on the difference between the calibration temperatures, a higher or lower uncertainty contribution is to be assumed.

Long-term behaviour

The calibration history of the standards forms the basis to determine a possible drift which must be considered in the uncertainty budget.

Repeatability / Short-term stability

Depending on the calibrated humidity values, their sequence and history, the measurement values may change. The estimation must be considered in the uncertainty budget.

Self-heating

The self-heating is to be determined and considered in the uncertainty budget. The determination can be carried out, for example, during calibration according to Chapter 7.4.3.

Thermal coupling

Measurement errors due to missing thermal coupling (as, for example, heat dissipation) are to be avoided by appropriate mounting into the calibration device. They are to be investigated and must be considered in the uncertainty budget. The heat dissipations can be investigated by installing, for example, 1 m of a sensor cable in the calibration device and then pulling it out piece by piece.

Hysteresis

Consideration of the hysteresis is imperative when using relative humidity sensors as standards (e.g. calibration according to Chapter 9.3.1 – Sequence A1). If the hysteresis is not determined, at least 3 % relative humidity (rectangular distribution) are to be assumed.

5.6 Mechanical hygrometers

Mechanical hygrometers for the direct measurement of relative humidity are not recommended as reference or working standards for calibrations.

5.7 Salt solutions

Within this guideline, the use of salt solutions as reference material or certified reference material is not considered suitable to establish traceability of the relative humidity. However, if properly and carefully applied, they can be used for intermediate tests.

5.8 Gas temperature

When calibrating relative humidity, the gas temperature (air temperature) must always be determined with a reasonable degree of accuracy. By using resistance thermometers, smallest measurement uncertainties can be achieved.

5.8.1 Requirements

As far as the measurement of gas or air temperature is concerned, the requirements of the guideline DKD-R 5-1 [1] shall apply. The calibration points of the temperature must cover the entire range of application.
During measurements, special attention should be paid to self-heating, thermal coupling (heat dissipation) and radiation influences. For example, self-heating in air can be significantly higher than in liquids. If a characteristic curve is to be determined, reference is made to guideline DKD-R 5-6 [7]. The introduction of suitable intermediate tests is recommended, e.g. regular inspection at the ice point and measurement of the insulation resistance.

5.8.2 Influence quantities

When using resistance thermometers to measure the gas temperature, the following influencing factors must at least be considered (see DKD-R 5-1 [1]):

Calibration

The measurement uncertainty can be found in the current calibration certificate. The measurement deviations must be taken into account when determining the correct value by means of correction, or in the uncertainty budget. The calibration points must cover the entire range of application. Extrapolation is not permitted.

Mean value

The associated uncertainty of the mean value is to be calculated from the standard deviation and the number of measurement values and must be considered in the uncertainty budget.

Resolution

If the resolution that is used for the calculations differs from the resolution used for calibration in the calibration certificate, then it must be included in the uncertainty budget.

Non-linearity

Interpolation is performed between the calibration points of the reference standard. Extrapolation is not permitted. A possible additional deviation or non-linearity must be considered in the uncertainty budget. The same is valid for determining a characteristic curve (also see DKD-R 5-6, Table 6.2 [7]).

Long-term behaviour

The calibration history of the standards forms the basis to determine a possible drift which must be considered in the uncertainty budget.

Thermal coupling

Inadequate thermal coupling or an inadequate installation depth during calibration may result in considerable measurement deviations.
To avoid heat dissipation, for example, the complete reference standard including connecting cable (if available at least 1 m) should be installed – if possible – in the calibration device and exposed to the calibration temperature. Otherwise, investigations are to be carried out; the results on thermal coupling obtained by these investigations will have to be included in the measurement uncertainty.

Electrical measuring procedure

The measurement of the electrical resistance of the sensor element requires the selection of a suitable measuring instrument and measuring method. The selection depends on the desired measurement uncertainty. The characteristics must be considered in the uncertainty budget.

Connection technology

To measure the electrical resistance of the sensor element, a choice can be made between 2-, 3- and 4-wire circuits. When using low-impedance sensors (e.g. Pt100), a 4-wire circuit should be preferred. For high-impedance sensor elements (e.g. NTC), a 2-wire circuit should prove adequate. A possible deviation which can be caused by line resistances must then be investigated and considered in the uncertainty budget.

Parasitic thermoelectric voltages

Possible influences due to parasitic thermoelectric voltages in the measuring circuit of the reference standard must be considered in the uncertainty budget.

Self-heating

The measuring current used to determine the electrical resistance of the sensor element causes it to heat up. This self-heating not only depends on the strength of the measuring current, but also on the measuring medium. For example, an increased self-heating is to be expected in air, whereas in a liquid there is lower self-heating.
Besides the self-heating, sensor or device heating might occur, caused by integrated electronics and their power dissipation.
The self-heating as well as the device heating of the employed reference standards must be investigated and considered in the uncertainty budget.

Insulation resistance

A regular check of the insulation resistance as part of the intermediate tests (e.g. with Pt100 according to DIN EN 60751, IEC 60751) is recommended, since there is, for example, the risk of absorption of water vapour by the sensor structure at high humidity which may lead to a parallel resistance to the measuring element and thus to a possible measurement deviation.

Hysteresis

Hysteresis effects of the reference standards used are to be investigated and must be considered in the uncertainty budget.

5.9 Calculation equations

If the relative humidity is not measured directly but calculated from the measured values of a dew point hygrometer or primarily generated by a two-pressure/two-temperature humidity generator, then preferably the formulas according to DKD-L 5-1 [5] are to be used. The uncertainties of the calculation equations as well as of the calculation solutions must be considered in the uncertainty budget. It should be noted that these uncertainties can vary considerably - depending on the measuring principle and the calculation equation and the respective humidity range. When selecting the calculation equations, the reference to the saturation over water or ice, or to the dew point or frost point, must be known and considered accordingly. If a differentiation is not possible, or if calculations such as enhancement factor or pressure loss correction are not performed, the possible resulting errors must be fully considered in the uncertainty budget.

5.10 Analogue signals

A multimeter is required for the calibration of calibration items with analogue output signals (e.g. voltage signal with 0 V to 10 V, or current signal with 4 mA to 20 mA). The multimeter must be calibrated for the entire range of application. The influencing factors of the employed multimeter and of the measurement set-up must be taken into account in the uncertainty budget. Such factors include, among others: the measurement uncertainty from the calibration certificate of the multimeter, long-term behaviour, non-linearity, thermoelectric voltages, shunt resistances and their temperature dependencies.

6 Calibration device

For the calibration of hygrometers, a calibration device is required to generate defined climatic conditions (temperature and humidity). An extensive validation of the calibration device is necessary since it can have a significant influence on the measurement uncertainty.

6.1 Equipment groups

There are different types of devices for the generation of climatic conditions; they can be classified into the following categories.

6.1.1 Pressure / Temperature humidity generator

These humidity generators generate a defined gas flow with known humidity which is fed into a calibration chamber. They often work according to the 2-pressure principle. Further versions are two-temperature or two- pressure/two-temperature humidity generators. The reference value is determined by measuring pressure and temperature.

6.1.2 Climatic chamber

Climatic chambers (e.g. volumes of more than 100 l) have a built-in temperature and humidity sensor or a special psychrometer for adjusting the parameters. To reduce the measurement uncertainties, for example, only part of the chamber can be defined as the calibration volume. Standards that are independent of the climatic chamber should be used to determine the reference value. They are placed within the calibration volume, together with the object to be calibrated.

6.1.3 Mixed flow generator

As opposed to climatic chambers, mixed flow generators (often also called humidity calibrators) have small calibration chambers (e.g. 1 l to 20 l) which are specifically designed for calibrating hygrometers. For adjustment purposes, a humidity sensor or dew-point mirror hygrometer with a temperature sensor is installed. The internal control sensors can be used to determine the reference value, provided they have been traceably calibrated. Here, the requirements according to Chapter 5 must be considered.

6.1.4 Salt solution

Salt solutions can be used to generate humidity; however, this requires the use of separate reference measuring devices. To obtain stable humidity values, a high temperature stability as well as tightness and cleanliness of the set-up must be ensured. It is necessary to ensure that the equilibrium in the calibration volume has been established above the solution and that no salt aerosols damage the reference standard or the object to be calibrated. Due to the lack of air circulation, a long adjustment time is to be expected.

6.2 Influence quantities

The characteristics and influence quantities of the calibration device must be quantitatively determined and taken into account when determining the measurement uncertainty. First, the calibration volume must be defined. This is usually the entire chamber or, in the case of climatic chambers, only a part of it. A measuring point must be defined at each corner point and in the centre of the room. The centre should be defined as reference measuring point. The distance between two adjacent measuring points must not exceed 50 cm, otherwise the number of measuring points must be increased. These measuring points serve to characterize the calibration volume.
The measurements described below can be applied to the various measuring quantities, such as temperature and humidity.
By directly measuring the relative humidity, inhomogeneities of the water vapour partial pressure and the temperature are already considered in the measurement result since the relative humidity depends on the gas temperature. However, there is no information as to which input quantity influences the distribution. Therefore, it is advisable to always measure and evaluate the gas temperature as well, since the temperature often has a dominant influence on spatial inhomogeneities. By converting the relative humidity to an absolute value (e.g. water vapour partial pressure or dew point), or by direct measurement (e.g. dew point temperature), it is possible to separate the influencing quantities into temperature and absolute humidity.

6.2.1 Spatial inhomogeneity

The spatial inhomogeneity is determined as the maximum deviation of the relative humidity of a measuring point from the reference measuring point. On the one hand, this can be caused by the distribution of the water vapour (absolute humidity) and on the other hand by the distribution of the temperature since the relative humidity depends on the temperature. In calibration chambers with an adequate air circulation, the spatial distribution of the absolute humidity can be homogeneous. However, there might be inhomogeneities caused by loadings, leakages on door seals or feedthroughs as well as by the humidification or dehumidification system. The number of the required measuring points (temperature and humidity) to determine the inhomogeneities depends on the planned range of application and the design of the calibration chamber. It is recommended to perform measurements at low and high humidity over the entire temperature range in 20 K increments and to again measure some of the points to determine the repeatability.
The measurement of the spatial inhomogeneities[5] can be performed either by the simultaneous placement of sensors (identical type recommended) at each measuring point and at the reference measuring point, or by using two sensors. In the latter case, the first sensor is fixed at the reference measuring point and the second sensor passes the measuring points one after the other. At the beginning and at the end, both sensors are closely compared to each other at the reference measuring point. The maximum deviation of the relative humidity (or separate according to temperature and absolute humidity) of a measuring point from the reference measuring point must be considered in the uncertainty budget. Depending on the calibration set-up, the distribution type (e.g. rectangle) must be classified.

[5] For larger calibration chambers (e.g. climate chambers) it is recommended to always use several standard thermometers at the same time to determine the spatial temperature distribution during each calibration. The same applies to the determination of the radiation influence.

6.2.2 Temporal instability

The temporal instability for the humidity is determined from the registration of the temporal course of the relative humidity – or separately according to temperature and absolute humidity – over a period of at least 30 min after having reached the steady state. The steady state is reached when no more systematic changes can be detected. To measure the temporal instability, at least 30 measuring values with nearly constant time intervals must be recorded in 30 min. The temporal instability must be considered in the uncertainty budget. The maximum occurring variation (amplitude) in relation to the mean value is recommended.

6.2.3 Radiation influence

As result of the heat exchange caused by radiation, bodies can assume a temperature different from the gas temperature. This includes the reference or working standards as well as the objects to be calibrated. The radiation influence depends on the gas temperature, the emissivity ε and the temperature of the heat source or heat sink, the humidity sensor and its surfaces, the geometrical arrangement as well as the gas velocity.
Typical sources of radiation influences are:

- surface temperature of the chamber deviating from the gas temperature (wall insulation, pane)
- heated panes or door seals
- loading (e.g. devices with waste heat inside the calibration chamber)
- chamber lighting
- heating or cooling elements
- feedthroughs

The radiation influence increases with increasing temperature difference, increasing surface and increasing emissivity. In addition, this influence increases disproportionately with the absolute temperature. The radiation influence can be determined by measuring the temperature in the centre of the calibration volume with a thermometer with the largest possible emissivity (i.e. $\varepsilon > 0.6$) and a thermometer with the smallest possible emissivity (i.e. $\varepsilon < 0.15$). A possible recommendation is to use a thermometer with a gold-plated surface (low emissivity) and a thermometer with a Teflon or blackened surface (high emissivity). The emissivity of both thermometer surfaces must be known with an adequate degree of accuracy, especially in the infrared wavelength range. Especially for the realization of the low emissivity, oxidation and roughness of the surface must be avoided. The thermometer with a low emissivity will then display the approximate gas temperature. The gas temperature is obtained by extrapolation to the emissivity $\varepsilon = 0$. The difference between the two thermometers represents a measure of the radiation influence.
The gas temperature can also be measured by means of a thermometer (low emissivity recommended) which is shielded against radiation by a radiation shield (also low emissivity recommended). This radiation shield must be either ventilated, or its structural shape and placement must be such to ensure adequate flow around the thermometer. The gas temperature is measured approximately by means of a thermometer with a radiation shield. It can then be compared with the temperature measured by means of another thermometer with high emissivity and without radiation shield to determine the radiation influence.
The total radiation influence must be considered completely as rectangular distribution in the measurement uncertainty.

6.2.4 Pressure differences

Pressure differences in the calibration device which might occur, for example, in separate flow chambers, in the piping system of humidity generators or due to a different placement of reference standard and calibration item, lead to changes in the humidity. Therefore, these differences are to be determined and, wherever possible, corrected and taken into account in the measurement uncertainty.

6.2.5 Flow conditions

In the calibration volume, the flow direction of the air is to be determined. If possible, the reference or working standards should be placed parallel to the flow direction and the calibration item to minimise mutual interference from waste heat caused by power dissipation. Alternatively, the reference sensor can be placed upstream in front of the calibration item if the waste heat has been determined and is negligible. The flow velocity or the air exchange rate acting on the calibration item ought to be stated in the calibration certificate. Therefore, at least one of the two parameters must be determined

6.2.6 Feedback effects

When using devices with self-heating or heat dissipation (e.g. dew-point hygrometer with external measuring head), the effect on the reference system (e.g. temperature homogeneity) must be considered. Mutual interference between reference or working standards and calibration items should be avoided. The same applies to devices that influence the humidity (e.g. evaporation in psychrometers). The feedback effects on reference or working standards, calibration device and calibration item shall be avoided and taken into account in the calibration set-up and, if applicable, in the determination of measurement uncertainty.

7 Electronic calibration items

7.1 Types of equipment

This calibration guideline is applicable to the calibration of electronic hygrometers which are used to directly measure the relative gas humidity. It does not apply to instruments which calculate the relative humidity by using other measured variables, as is the case with dew point hygrometers or psychrometers.

7.1.1 Sensor element

The following sensor types are used in hygrometers for directly measuring the relative gas humidity:

- resistive solid-state sensors
- capacitive polymer sensors
- resistive-electrolytic sensors

7.1.2 Measurement conversion

The humidity-sensitive sensor signal is converted into a corresponding measured value by an electronic unit and can be displayed in various forms:

- as display value on a display or monitor
- as digital value which is transmitted via interface (e.g. RS232)
- as measured value via a secure radio connection
- as measured value in the memory of a data logger
- as assignment to an analogue output (e.g. 4 mA to 20 mA)

7.2 Calibration capability

All hygrometers that comply with the general rules of technology and the manufacturer's specifications can be calibrated. The manufacturer’s specification should be available. The suitability of the hygrometers for calibration must be determined by checking their condition as well as by means of an operational check. Observations, abnormalities and relevant instrument parameters (e.g. adjustment data) must be documented. In the event of irregularities, consultation with the customer must be held.

7.2.1 Functional test

In addition to an extensive visual inspection for completeness and damage, the legibility of the inscriptions must also be checked. Especially the area around the protective cap and the measuring element must be thoroughly inspected for damage, contamination and cleanliness. As to multi-channel devices, the exact assignment of the sensor or probe to the device channels must be existent or specified (except for sensors with digital transmission). The object to be calibrated must be free from contamination and must not emit any substances which could influence or damage the calibration device and reference systems.
Before calibration, the operating instructions of the calibration item should be carefully studied to make sure the functioning and handling of the instrument are known. The technical data of the calibration item must be at hand to make sure that information regarding power supply, measured value display or measurement conversion are available. Special attention should be paid to power consumption or power dissipation to identify a possible self-heating. Special care should be taken when using sensors with integrated heating. In this case, the mode of operation must be precisely known and considered during calibration. For calibration objects with measurement value storage (e.g. data logger), the measurement rate, the type of storage and possibly the averaging process must be known. If the instrument requires the input of calibration data or sensor coefficients before putting it into operation, this must be taken into

account. A functional test must be performed on the calibration item; if necessary, including an additional test of the operating elements and interface.

7.2.2 Preparatory treatment

A special ageing process is not necessary. As a pre-treatment, the device should be stored for at least 24 h under ambient conditions. For this purpose, the device must be removed from its packaging. For on-site calibrations, the operating conditions must be taken into account.

7.3 Packaging

When using packaging materials, foams, containers or transport boxes, care must be taken to ensure that these do not cause drift or destruction of the humidity sensor through outgassing of pollutants. Unsuitable materials must not be used. The manufacturer's packaging should preferably be used.

7.4 Influence quantities

The respective influence quantities strongly depend on the sensor and instrument type and must therefore be determined individually for each calibration item.

7.4.1 Mean value

The associated uncertainty of the mean value is to be calculated from the standard deviation and the number of measured values and must be considered in the uncertainty budget.

7.4.2 Resolution

The resolution of the measurement value is to be considered in the uncertainty budget. The resolution cannot be higher than the display/reading resolution.

7.4.3 Self-heating

A conditional determination of the self-heating is possible. The humidity analyser is not switched on until the calibration chamber has been adjusted and the object to be calibrated has been completely adjusted to the humidity content. The minimum settling times according to the manufacturer's specifications must be respected. The self-heating can be estimated from the change in the measured value caused by an increase in temperature. This estimation is based on the difference between two measured values - on the one hand, the measured value taken immediately after switch-on and, on the other hand, the measured value taken after an adjustment time of at least 30 min.
The self-heating can also be determined by measurements at vastly different flow velocities (e.g. in the climatic chamber at 3 m/s flow velocity - low self-heating and in the humidity generator at almost 0 m/s - high self-heating).
The self-heating must be considered in the measurement uncertainty or stated as a value in the calibration certificate.
If feasible, the customer's demands on flow velocity shall be taken into account during calibration.

7.4.4 Thermal coupling

Inadequate thermal coupling or an inadequate installation depth during calibration may lead to considerable measurement errors.
To avoid for instance heat dissipation, the entire calibration item, including connecting cable (if available, at least 1 m), should be installed in the calibration device and exposed to the calibration temperature. Otherwise, tests are to be carried out. This can be done in two different ways:

1. by gradually “pulling out” by e.g. 10 % of the immersion depth to determine the heat dissipation;
2. comparison measurement by means of a reference system “without heat dissipation”.

The heat dissipation can be in the order of 10 % of the difference between calibration temperature and ambient temperature and must be included in the measurement uncertainty.

7.4.5 Hysteresis

The evaluation of a possible hysteresis depends on the selected calibration procedure. The calibration sequences A1 and A2 are used for examination and consideration (see Chapters 9.3.1 and 9.3.2, respectively). For calibration procedure D (see Chapter 9.3.7), the respective customer requirement applies. All other procedures do not include a possible hysteresis.

7.4.6 Influences from ambient conditions

If existent, the effects of ambient conditions are to be considered.

7.4.7 Analogue signals

If the measured value of the relative humidity of the object to be calibrated is displayed in the form of an analogue signal (e.g. 4 mA to 20 mA), this must be measured by a calibrated multimeter (see Chapter 5.10) and converted into relative humidity by means of the scaling. It is recommended to specify both values, the analogue signal and the relative humidity calculated from it, as well as to state the scaling in the calibration certificate.

8 Mechanical calibration items

8.1 Types of equipment

Apart from the electronic calibration items described in Chapter 7, this calibration guideline does also apply to the calibration of mechanical hygrometers that measure the relative gas humidity directly. However, it is not applicable to devices that calculate the relative gas humidity by means of other measurement quantities as is the case, for example, with psychrometers.

8.1.1 Measuring element

The measurement principle is based on a change in length of a piece of material. Threads of hair, fibres made of cotton, plastic or non-woven material are used as measuring elements. The length of the measuring element increases with increasing relative humidity. The change in length is transmitted to a pointer. In the case of hygrographs, the measurement data are transmitted to a writing lever; a pen at the end of the lever records the measured values as measurement curves on diagram paper fastened to a revolving cylinder, or on continuous paper.

8.2 Calibration capability

All hygrometers that comply with the general rules of technology and the manufacturer's specifications can be calibrated. The manufacturer’s specification should be at hand. The suitability for calibration is to be determined by checking the condition and function of the hygrometer. Observations, abnormalities and relevant instrument data (e.g. diagram paper type) must be documented. In the event of irregularities, consultation with the customer must be held.

8.2.1 Functional test

Before calibration, the instrument's operating instructions should be carefully studied to ensure that the operation of the instrument is known. Hygrometers must be calibrated in the intended position, normally vertical. The calibration item must be free from contamination and must not release any substances that may affect or damage the calibration device and reference systems.
The proper functioning of the drum or strip chart recorder is to be checked. During calibration, it must be ensured that the prescribed chart paper and the matching pens in their original form are used. The paper must rest on the lower edge of the drum. Rapid changes of humidity might cause the chart paper to move vertically on the drum. The writing lever should only slightly contact the paper. This can often be adjusted by means of an adjustment screw.

8.2.2 Preparatory treatment

As an initial pre-treatment, the device should be stored for at least 24 h under room conditions. For this purpose, the device must be removed from its packaging. For on-site calibrations, the operating conditions must be taken into account.
If the customer asks for a regeneration of the measuring element (e.g. in the case of measuring elements made of hair by moistening with water), an initial calibration (calibration after receipt of the instrument) must first be performed. The regeneration should be carried out according to the manufacturer's instructions. Afterwards, a new calibration is necessary.

8.3 Influence quantities

The respective influence quantities depend on the sensor and instrument type and must therefore be determined individually for each calibration item

8.3.1 Mean value

The associated uncertainty of the mean value is to be calculated from the standard deviation and the number of measured values and must be considered in the uncertainty budget.

8.3.2 Scale intervals

The readability of the display is determined by the ratio of the pointer width to the centre distance of two adjacent graduation lines (scale division value). The recommended ratio is half the value of two adjacent graduation lines (see also DIN 43790).

8.3.3 Thermal coupling

See Chapter 7.4.4.

8.3.4 Hysteresis

See Chapter 7.4.5.

8.3.5 Repeatability

Due to the limited repeatability of mechanical hygrometers, the repeatability should be tested. Otherwise, an uncertainty contribution of at least 1 % is to be included in the measurement uncertainty budget as normal distribution (k = 1).

9 Calibration method

The following chapters explain the calibration procedure, starting with the preparation and installation into the calibration device and showing a total of seven different calibration procedures.

9.1 Preparation

First, a functional test is to be carried out (see Chapter 7.2 or 8.2). Pre-treatment must either be ensured in accordance with Chapter 7.2.2 or 8.2.2, or carried out in accordance with the customer's requirements. In the latter case, the pre-treatment process is to be described in the calibration certificate.

9.2 Installation into the calibration device

The decision on how to install the calibration item into the calibration device is based on the design of the object to be calibrated or on the customer's requirements (e.g. complete device or only external sensor). In case of doubt, the customer has to be contacted. If an appropriate measurement set-up is not possible, the calibration cannot be carried out. If possible, the installation should be in line with the customer's application. All parts to be installed in the calibration device must be approved for the planned calibration points (for example, the handles of external sensors have a limited temperature range). The thermal installation depth, which includes all parts of the calibration item that are exposed to the calibration temperature, must be documented and indicated in the calibration certificate (examples can be found in Annex A Measurement uncertainty budgets).

9.3 Calibration sequence

When calibrating the relative humidity, care must be taken to ensure an adequate hygrometric **and** thermal stability. Likewise, compliance with the adjustment time must be ensured. When setting the desired calibration points, it must be ensured that the reference standard and calibration item are not exposed to condensation, i.e. the temperature of the instruments must always be higher than the dew point temperature in the calibration device. This is equally the case when ending the calibration and when removing the reference standard or calibration item. If necessary, a defined climate must be set at the end to prevent condensation or drying out of the sensors.

The calibration points consist of humidity calibration points at one or more gas temperatures. For each gas temperature it is recommended to perform the calibration at least at 3 humidity calibration points which cover the customer's range of application. In the case of humidity sensors with separate gas temperature indication, other gas temperatures without humidity calibration points can also be calibrated if requested by the customer. In general, the selected calibration points should be adapted to the customer's application range.

As to the sequence, the following recommendations apply when calibrating the calibration points at more than one gas temperature:

- It is recommended to start with the highest gas temperature; the calibration should preferably be carried out in descending order of the gas temperatures. This serves to minimize a possible drift of the calibration item during calibration.
- At first, all isothermal humidity calibration points must be calibrated before proceeding to the next gas temperature.

In the case of further calibration points without humidity calibration points (only gas temperature), the following additional recommendations apply:

- The calibration of these additional calibration points for the gas temperature should be carried out prior to the calibration of the humidity calibration points to avoid the calibration to relative humidity being influenced by a subsequent temperature calibration.
- If the temperature range of the temperature calibration exceeds the temperature range of the humidity calibration, it is highly recommended to contact the customer since at high temperatures, outgassing of the calibration item can lead to changes in the characteristic curve.

For calibrations at high temperatures (above 40 °C), it is generally recommended to start with a calibration of the relative humidity at room temperature (23 °C ± 3 K) in order to document possible changes of the sensor at high temperatures (also see 2nd sample calibration certificate: Calibration according to method B2, Appendix B Sample calibration certificates (excerpts)

Below, seven different calibration sequences [6] are defined for the sequence of the humidity calibration points at only one gas temperature (isothermal).

[6] Depending on the requirements and intended use, the calibration is usually carried out according to sequence B2. For high demands on measuring task and precision, sequence A1 or A2 should be selected.

9.3.1 Sequence A1

The humidity calibration points are first calibrated in ascending order, then in descending order (see Figure 4). Excluding the upper calibration point (N4), this shall serve to investigate a possible hysteresis of the calibration item.
The first calibration value (N1a) must be approached from low humidity (S0) (at least 5 % lower; care must be taken to ensure an adequate adjustment time). Should this not be possible, sequence A2 according to Chapter 9.3.2 is recommended. For example, this would be the case at a humidity of 0 % or when the lower limiting value of the calibration device has already been reached with the calibration value N1a.
In the calibration certificate, all calibration values must be stated individually. The measurement uncertainty is to be calculated separately for each value without taking account of a possible hysteresis of the calibration item. Alternatively, the results can be summarized by arithmetic averaging (N1a and N1b); (N2a and N2b); (N3a and N3b) – except the upper calibration point (N4). When averaging, the hysteresis of the calibration points (N1a and N1b), (N2a and N2b) and (N3a and N3b) of the calibration item must be included in the uncertainty budget as a rectangular distribution (half-width of the difference between the measurement deviations a and b).

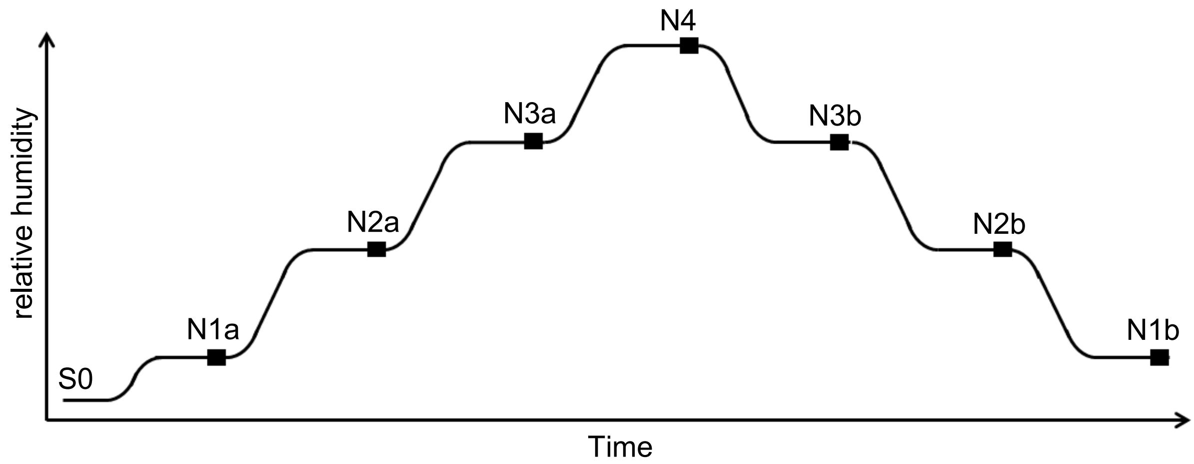

Figure 4: Visualisation calibration sequence A1: Relative humidity value of the calibration device (reference value) as a function of time

- ■ : Recording of measurement values for the calibration result
- S0: Starting point: defined relative humidity (e.g. 10 %)
- N1a: Calibration value no. 1: 1. Calibration point ascending (e.g. 20 %)
- N2a: Calibration value no. 2: 2. Calibration point ascending (e.g. 50 %)
- N3a: Calibration value no. 3: 3. Calibration point ascending (e.g. 80 %)
- N4: Calibration value no. 4: 4. Calibration point ascending (e.g. 90 %)
- N3b: Calibration value no. 5: 3. Calibration point descending (e.g. 80 %)
- N2b: Calibration value no. 6: 2. Calibration point descending (e.g. 50 %)
- N1b: Calibration value no. 7: 1. Calibration point descending (e.g. 20 %)

9.3.2 Sequence A2

Here, the humidity calibration points are first calibrated in ascending order within the calibration range, then in descending order (see Figure 5), in which case the first calibration value (N1a) is approached from above (SR) (e.g. from room humidity). This shall serve to investigate the repeatability between calibration points N1a and N1b and the hysteresis of the calibration item between calibration points N2a and N2b as well as between N3a and N3b. Calibration point N4 is only measured once in ascending order.

In the calibration certificate, all calibration values must be stated individually. The measurement uncertainty is to be calculated separately for each value without considering a possible repeatability or hysteresis of the calibration item. Alternatively, the results can be summarized by arithmetic averaging (N1a and N1b); (N2a and N2b); (N3a and N3b) – except for the upper calibration point (N4). When averaging, the repeatability of the calibration points (N1a and N1b) as well as the hysteresis of the calibration points (N2a and N2b) and (N3a and N3b) of the calibration item are to be included in the uncertainty budget as a rectangular distribution (half-width of the difference between the measurement deviations a and b).

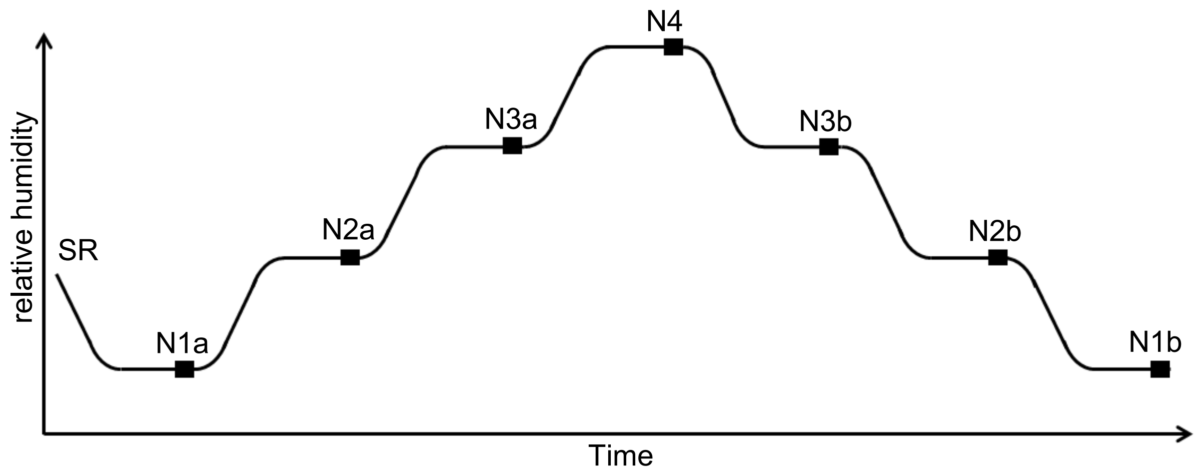

Figure 5: Visualisation calibration sequence A2: Relative humidity value of the calibration device (reference value) as a function of time

- ■ : Recording of measurement values for the calibration result
- SR: Starting value: relative humidity (e.g. room conditions at 50 %)
- N1a: Calibration value no. 1: 1. Calibration point descending (e.g. 20 %)
- N2a: Calibration value no. 2: 2. Calibration point ascending (e.g. 50 %)
- N3a: Calibration value no. 3: 3. Calibration point ascending (e.g. 80 %)
- N4: Calibration value no. 4: 4. Calibration point ascending (e.g. 90 %)
- N3b: Calibration value no. 5: 3. Calibration point descending (e.g. 80 %)
- N2b: Calibration value no. 6: 2. Calibration point descending (e.g. 50 %)
- N1b: Calibration value no. 7: 1. Calibration point descending (e.g. 20 %)

9.3.3 Sequence B1

The humidity calibration points are calibrated in ascending order (see Figure 6). The first point (N1) must be approached from low humidity (S0). This condition is fulfilled if the value is at least 5 % lower than the first calibration point N1. An adequate adaptation time is to be ensured. Should this not be possible, sequence B2 according to Chapter 9.3.4 is recommended. For example, this would be the case at a humidity of 0 % or when the lower limiting value of the calibration device has already been reached with the calibration value N1a.

A possible hysteresis of the calibration item is not investigated when using this procedure.

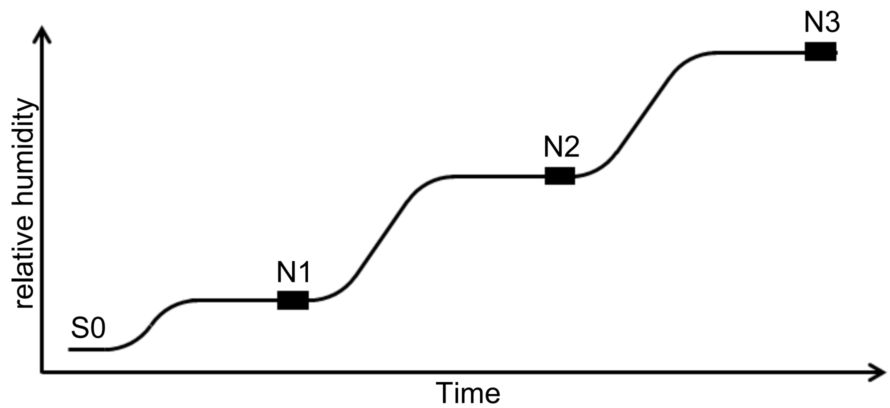

Figure 6: Visualisation calibration sequence B1: Relative humidity value of the calibration device (reference value) as a function of time

- ■ : Recording of measurement values for the calibration result
- S0: Starting point: defined relative humidity (e.g. 10 %)
- N1: Calibration point no. 1 ascending (e.g. 20 %)
- N2: Calibration point no. 2 ascending (e.g. 50 %)
- N3: Calibration point no. 3 ascending (e.g. 80 %)

9.3.4 Sequence B2

Here, the humidity calibration points are calibrated in ascending order within the calibration range (see Figure 7), in which case the first calibration point N1 is approached from above (SR) (e.g. room humidity).
A possible hysteresis of the calibration item is not investigated when using this procedure.

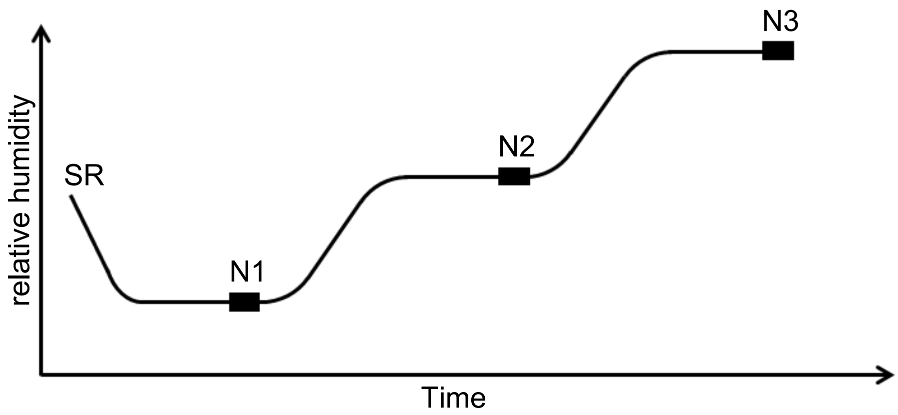

Figure 7: Visualisation calibration sequence B2: Relative humidity value of the calibration device (reference value) as a function of time

- ■ : Recording of measurement values for the calibration result
- SR: Starting point: relative humidity (e.g. room condition at 50 %)
- N1: Calibration point no. 1 descending (e.g. 20 %)
- N2: Calibration point no. 2 ascending (e.g. 50 %)
- N3: Calibration point no. 3 ascending (e.g. 80 %)

9.3.5 Sequence C1

The humidity calibration points are calibrated in descending order (see Figure 8). The first point (N1) must be approached from higher humidity (S0)[7]. This condition is fulfilled if the value is at least 5 % higher than at the first calibration point N1. An adequate adaptation time is to be ensured. Should this not be possible, sequence C2 according to Chapter 9.3.6 is recommended. For example, this would be the case at a humidity of 98 % or when the upper limiting value of the calibration device has already been reached with calibration value N1a. A possible hysteresis of the calibration item is not investigated when using this procedure.

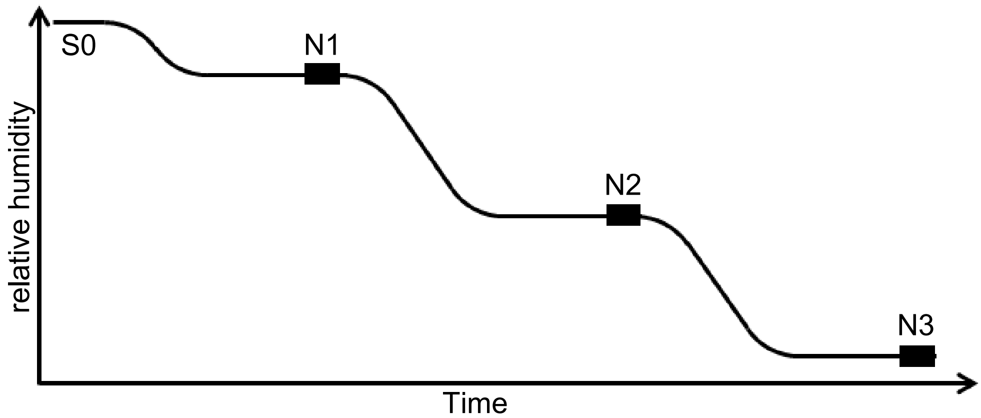

Figure 8: Visualisation calibration sequence C1: Relative humidity value of the calibration device (reference value) as a function of time

- ■ : Recording of measurement values for the calibration result
- S0: Starting point: defined relative humidity (e.g. 90 %)
- N1: Calibration point No. 1 ascending (e.g. 80 %)
- N2: Calibration point No. 2 descending (e.g. 50 %)
- N3: Calibration point No. 3 descending (e.g. 20 %)

[7] At a relative humidity of more than 80 %, humidity sensors might show temporary changes in the characteristic curve; it should therefore be examined whether to choose a higher humidity (S0) as starting point. Alternatively, sequence C2 can be selected according to Chapter 9.3.6.

9.3.6 Sequence C2

Here, the humidity calibration points are calibrated in descending order within the calibration range (see Figure 9), in which case the first calibration point N1 is approached from below (SR) (e.g. room humidity).
A possible hysteresis of the calibration item is not investigated when using this procedure.

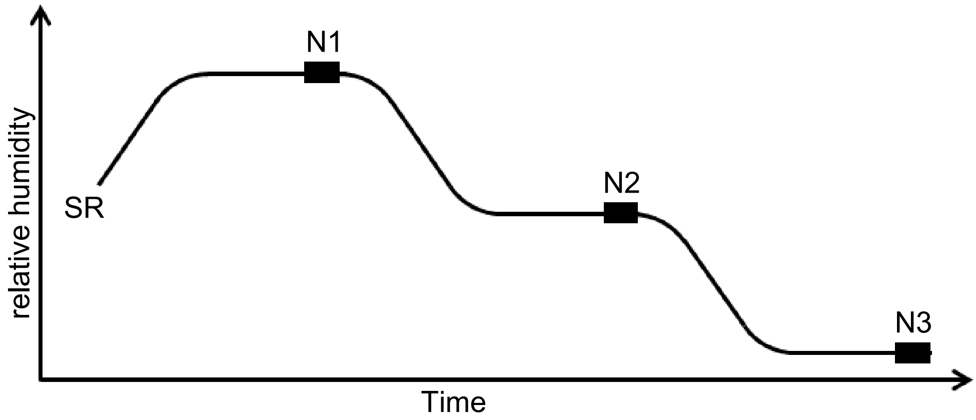

Figure 9: Visualisation calibration sequence C2: Relative humidity value of the calibration device (reference value) as a function of time

- ■ : Recording of measurement values for the calibration result
- SR: Starting point: relative humidity (e.g. room condition at 50 %)
- N1: Calibration point No. 1 ascending (e.g. 80 %)
- N2: Calibration point No. 2 descending (e.g. 50 %)
- N3: Calibration point No. 3 descending (e.g. 20 %)

9.3.7 Sequence D

The sequence of the calibration points is set according to the customer's requirements. The procedure must be described in the calibration certificate.

9.4 Stabilisation time

An adequate stabilisation time must be observed and documented. The stabilisation or equilibrium time is generally understood to be the time from reaching an adequate approximation of the reference value of the calibration device to the target value before the recording of the measurement values is started. It is used for the calibration result.
A procedure for determining the stabilisation time is proposed below. This procedure includes the minimum requirements. Alternative procedures are permitted. In general, it should be noted that the stabilisation time depends on the calibration point (humidity and temperature). Depending on the gas flow in the calibration device and the design of the calibration item, a stabilisation time of at least 3 h may be required. With a lower flow rate, the stabilisation time may also be noticeably longer (also see notes in Appendix D).

9.4.1 Proposed procedure for determining the stabilisation time

The prerequisite for the procedure described below is an adequate thermal coupling of the calibration object to the calibration device.
Within the framework of the proposed procedure, an adequate stabilisation time is maintained if the systematic change of the measured value within 20 min is less than 20 % of the desired measurement uncertainty. This evaluation must be based on at least 10 measured values.
The implementation of the process is graphically illustrated in Figure 10.

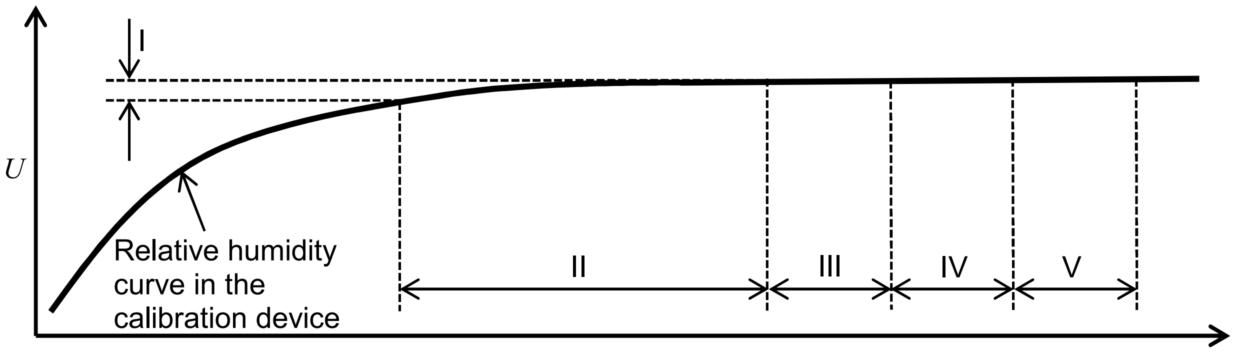

Figure 10: Visualisation of stabilisation time of the relative humidity

I) Criterion for the start of the waiting time: deviation from the desired value less than 2 % and 0.2 K
II) Waiting time, at least 30 min
III) Recording of the measurement value, at least 10 min as well as 10 measured values
IV) Waiting time, at least 10 min
V) Recording of the measurement value, at least 10 min as well as 10 measured values

The desired calibration point is set on the calibration device. The first waiting time starts from the time at which the reference value of the calibration device has come sufficiently close to the desired value, here this is set to an approximation of the reference value to 0.2 K (temperature) and 2 % (relative humidity) of the desired value. After a waiting time of 30 min (time segment II), an initial measurement of 10 min with at least 10 measurement values (time segment III) is carried out. After a waiting time of another 10 min (time segment IV), another measurement (time segment V) is started. If the systematic change in the measurement deviation of the calibration item between time segments III and V is less than 20 % of the desired measurement uncertainty, an adequate stabilisation time has been observed. The measurement deviation of the temperatures between time segments III and V must also be included as a further criterion to ensure thermal coupling.
The recording of the measurement values from time segment V is the calibration result. The stabilisation time is calculated as the sum of the times from time segments II, III and IV.
If the criteria for the end of the stabilisation time are not fulfilled, then time segment V is followed by another measurement recording and the criteria are checked again as described above. The stabilisation time is extended accordingly.
The times given above are minimum requirements. For detailed investigations it is recommended to extend the time segment IV in Figure 10 to at least 30 min, see also Appendix D .

10 Ambient conditions

The calibration should preferably be performed at a stable ambient temperature. The permissible temperature range shall be defined bearing in mind the specifications of the reference equipment used. The permissible temperature range must also be documented. If the indoor climate is the initial value for a calibration, the temperature and relative humidity must be documented.

If the absolute pressure is required for calculations (e.g. for psychrometers or enhancement factors), the air pressure must also be documented.

The ambient conditions shall be measured using traceable measuring equipment.

11 Calibration certificate

The calibration certificate must meet the requirements of the currently applicable standard (DIN EN ISO/IEC 17025) as well as the additional requirements of the respective accreditation body or regional metrology organisations. Moreover, the following points shall be indicated:

- pre-treatment process, if different from Chapters 7.2.2 or 8.2.2
- calibration method according to this guideline
- calibration sequence (A1, A2, B1, B2, C1, C2, D)
- order of calibration
- Mounting depth (see Chapter 9.2)
- reference to consider the hysteresis or repeatability in the measurement uncertainty
- ambient temperature
- ambient humidity, if relevant
- calibration results including indication of temperature
- indication of the relative humidity including reference to saturation above ice (U_i) or water (U_w)

11.1 Calibration result – Example

Calibration results relative humidity

Reference values		**Calibration item**		
Gas temperature t in °C	Relative humidity U_w in %	Indicated value U in %	Measurement error ΔU in %	Measurement uncertainty U in %
20	20.1	19.7	-0.4	0.4
20	50.0	49.9	-0.1	0.6
20	80.0	80.3	+0.3	0.8

The measurement results are shown in order of the calibration.

Table 3: Example for the indication of calibration results

12 Bibliography

[1] DKD, Richtlinie DKD-R 5-1: Kalibrierung von Widerstandsthermometer, Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Edition 09/2018, Revision 0.

[2] DKD, Richtlinie DKD-R 5-3: Kalibrierung von Thermoelementen, Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Edition 09/2018, Revision 0.

[3] VDI/VDE 3514, Blatt 1: Gasfeuchtemessung; Kenngrößen und Formelzeichen, Verein Deutscher Ingenieure e.V., 2016.

[4] VDI/VDE 3514, Blatt 2: Gasfeuchtemessung; Messverfahren, Verein Deutscher Ingenieure e.V., 2013.

[5] DKD, Leitfaden DKD-L 5-1: Feuchtekenngrößen und Berechnungsgleichungen, Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, (in preparation).

[6] DKD, Richtlinie DKD-R 6-1: Kalibrierung von Druckmessgeräten, Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Edition 03/2014, Revision 2.

[7] DKD, Richtlinie DKD-R 5-6: Bestimmung von Thermometerkennlinien, Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Edition 09/2018, Revision 0.

[8] EA-4/02 M: 2013, Ermittlung der Messunsicherheit bei Kalibrierungen (German translation), DAkkS, Translation as of 06.11.2018.

Appendix A Measurement uncertainty budgets – Examples

Calibration in a Climatic Chamber

Calibration of a hygrometer as calibration item (CI) with capacitive polymer sensor as measuring element in a climatic chamber at 80 % relative humidity and a gas temperature of 20 °C.
A standard thermometer (TM), a standard dew point hygrometer (DPM) with internal measuring head, which extracts the measuring gas from the chamber via a pipeline, and an absolute pressure measuring instrument (APM) serve as reference standards (RS). The calibration was carried out according to sequence B2 (see Chapter 9.3.4). After a stabilisation time of 3 h, the arithmetic mean value was calculated from 60 individual values over a period of 10 min. The set-up is divided into 4 steps.

1. Determination of the gas temperature in the climatic chamber including the associated uncertainty.
2. Determination of the dew point temperature in the climatic chamber including the associated uncertainty.
3. Calculation of the relative humidity from the gas and dew point temperature including the associated uncertainty.
4. Determination of the relative humidity of the calibration item and its measurement error as well as of the associated uncertainty.

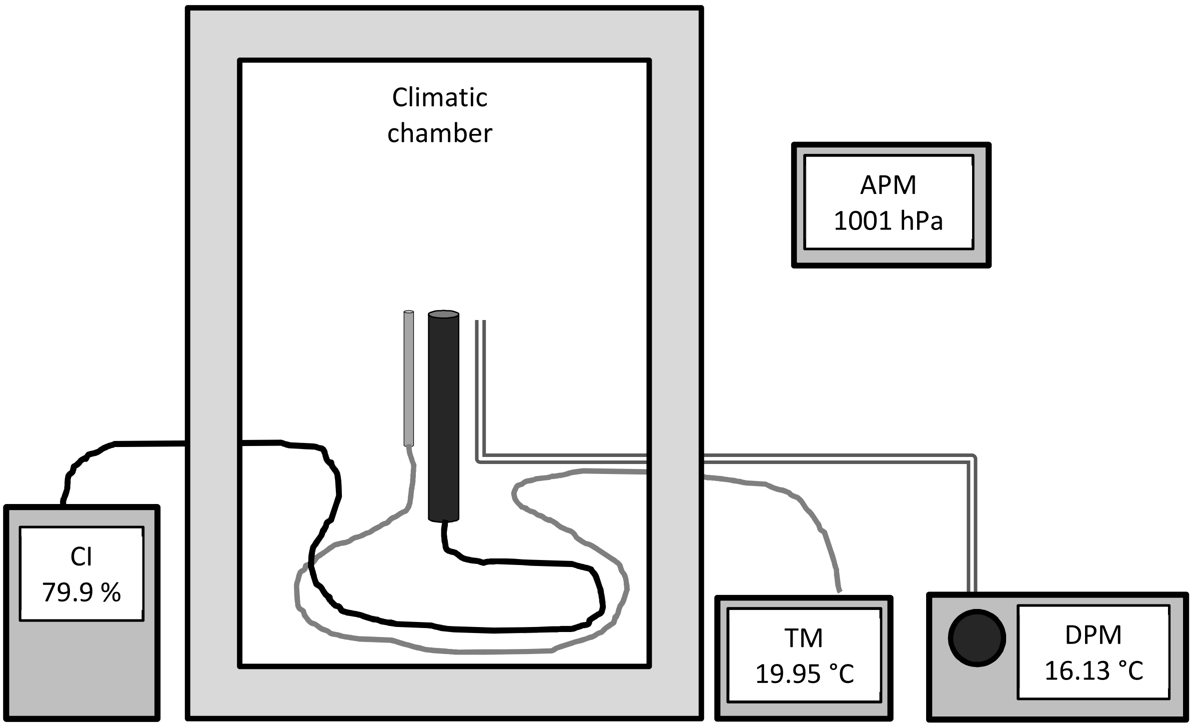

Figure 11: Schematic representation of the calibration set-up

Mounting depth

The external sensor of the calibration item has been completely installed, including 1 m of its connecting cable, in the climatic chamber (measured from the inner wall of the chamber).

Step 1: Gas temperature

Uncertainty budget of the gas temperature containing the contributions of the reference standard and the climatic chamber.

Model equation:

$$T_{\mathrm{S}} = T_{\mathrm{i,s}} + \delta T_{\mathrm{cal}} + \delta T_{\mathrm{res}} + \delta T_{\mathrm{int}} + \delta T_{\mathrm{dri}} + \delta T_{\mathrm{con}} + \delta T_{\mathrm{thv}} + \delta T_{\mathrm{htd}} + \delta T_{\mathrm{sht}} + \delta T_{\mathrm{hys}} + \delta T_{\mathrm{inho}} + \delta T_{\mathrm{rad}} + \delta T_{\mathrm{insta}} \quad (14)$$

Set out below are the contributions for the individual components of the model equation:

$T_{\mathrm{i,S}}$:

Temperature measured by using the standard thermometer (60 measured values). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the standard thermometer. If the number of readings is small (≤ 10), a factor corresponding to the t-distribution may have to be added here to take account of the low degree of freedom (see EA-4/02 M [8]). The example shows a mean value of 19.95 °C and 10 mK for the standard deviation of the mean value.

δT_{cal}:

Unknown measurement error of the standard thermometer due to calibration. A Pt100 with corresponding measuring instrument serves as standard measuring device for temperature. A correction of the standard thermometer of -0.01 K was determined during calibration. This is taken into account in the evaluation.

The uncertainty U of the temperature deviation is taken from the calibration certificate (U = 20 mK; normally distributed, k = 2). Thus, the assigned standard uncertainty is 10 mK.

δT_{res}:

Unknown measurement error due to the resolution of the standard thermometer. The resolution of the air temperature display is 10 mK. Therefore, a rectangular distributed contribution with a half width of 5 mK is assumed. Hence, the assigned standard uncertainty is 2.9 mK.

δT_{int}:

Unknown measurement error of the temperature of the standard thermometer due to interpolation between the calibration points. A rectangular contribution with a half width of 20 mK is assumed. Hence, the assigned standard uncertainty is 12 mK (see also DKD-R 5-6, Table 6.2 [7]).

δT_{dri}:

Unknown measurement error of the temperature of the standard thermometer due to the drift since the last calibration. The last calibrations of the standard revealed a maximum drift of 10 mK per year. Therefore, a rectangular distribution contribution with a half width of 10 mK is used. Hence, the assigned standard uncertainty is 6 mK.

δT_{con}:
Unknown measurement error of the temperature of the standard thermometer due to the connection technology of the standard thermometer. The Pt100 of the standard thermometer is connected to the corresponding measuring instrument via 4-wire technology.
Thus, the contributions of the connection are smaller than 1 mK. Therefore, a rectangular distribution contribution with the half width of 1 mK is used. Hence, the assigned standard uncertainty is 0.6 mK.

δT_{thv} :
Unknown measurement error of the temperature of the standard thermometer due to parasitic thermoelectric voltages in the measuring circuit of the standard thermometer. The accompanying measuring instrument measures the resistance of the Pt100 standard thermometer by means of alternating direct current and determines the average over several pole changing intervals. Possible parasitic thermoelectric voltages in the measuring circuit are thus compensated.
This means the remaining uncertainty due to thermoelectric voltages is smaller than 1 mK. Therefore, a rectangular distribution contribution of_1 mK is assumed. Hence, the assigned standard uncertainty is 0.6 mK.

δT_{htd} :
Unknown measurement error due to heat dissipation of the standard thermometer. Since the air temperature sensor of the standard is completely immersed, and a part of the cable also runs inside the climatic chamber, this contribution can be neglected. Therefore, a rectangular contribution with the half-width of the distribution of 0 mK is assumed. The assigned standard uncertainty is then 0 mK.

δT_{sht} :
Unknown measurement error due to self-heating of the standard thermometer. Based on investigations with different measuring currents for the flow rate of the air temperature sensor, a maximum uncertainty contribution of 30 mK is estimated. Therefore, a rectangular contribution with the half-width of 30 mK is used. Hence, the assigned standard uncertainty amounts to 17 mK

δT_{hys} :
Unknown measurement error due to the hysteresis of the standard thermometer. Based on investigations with ascending and descending temperatures, a maximum uncertainty contribution of 10 mK is estimated. Therefore, a rectangular contribution with the half-width of 10 mK is assumed. Hence, the assigned standard uncertainty is 6 mK.

δT_{inho} :
Unknown measurement error due to the spatial inhomogeneity of the temperature in the climatic chamber. The examination of the calibration volume according to Chapter 6.2.1 showed a maximum deviation of 0.2 K between the temperature at the measuring points and the temperature at the centre of the useful volume. Therefore, a rectangular contribution with the half-width of 200 mK is assumed. The assigned standard uncertainty is 115 mK.

δT_{rad} :
Unknown measurement error due to the radiation influence on the measurement of the temperature in the climatic chamber. The investigation was performed with two thermometers with different emissivity according to Chapter 6.2.3. The maximum temperature deviation between the two thermometers was 0.05 K. Therefore, a rectangular distributed contribution with the half width of 50 mK is used. The assigned standard uncertainty is 29 mK.

δT_{insta} :
Unknown measurement error due to temporal instability of the temperature in the climate chamber. The examination of the calibration volume in Chapter 6.2.2 showed a maximum deviation of ±0.1 K of the temperature from the mean value over 30 min. Therefore, a rectangular distribution with a half-width of 100 mK is used. The assigned standard uncertainty is 58 mK.

These contributions are summarized in Table 4.

Qauntity X_i	Description X_i	Estimated value x_i	Unknown measurement error δx_i	Standard measurement uncertainty $u(x_i)$	Distribution	Divisor	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$T_{i,S}$	Measured value reference standard thermometer	19.95 °C	0.010 K	0.010 K	normal	1	1.00	0.010 K
δT_{cal}	Correction reference standard from calibration	-0.010 K	0.020 K	0.010 K	normal	2	1.00	0.010 K
δT_{res}	Resolution reference standard	0.000 K	0.005 K	0.003 K	rectangular	√3	1.00	0.003 K
δT_{int}	Interpolation between the calibration points	0.000 K	0.020 K	0.012 K	rectangular	√3	1.00	0.012 K
δT_{dri}	Drift reference standard	0.000 K	0.010 K	0.006 K	rectangular	√3	1.00	0.006 K
δT_{con}	Connection technology reference standard	0.000 K	0.001 K	0.001 K	rectangular	√3	1.00	0.001 K
δT_{thv}	Parasitic thermoelectric voltages reference standard	0.000 K	0.001 K	0.001 K	rectangular	√3	1.00	0.001 K
δT_{htd}	Heat dissipation reference standard	0.000 K	0.000 K	0.000 K	rectangular	√3	1.00	0.000 K
δT_{sht}	Self-heating reference standard	0.000 K	0.030 K	0.017 K	rectangular	√3	1.00	0.017 K
δT_{hys}	Hysteresis reference standard	0.000 K	0.010 K	0.006 K	rectangular	√3	1.00	0.006 K
δT_{inho}	Spatial inhomogeneity climatic chamber	0.000 K	0.200 K	0.115 K	rectangular	√3	1.00	0.115 K
δT_{rad}	Radiation influences	0.000 K	0.050 K	0.029 K	rectangular	√3	1.00	0.029 K
δT_{insta}	Temporal instability climatic chamber	0.000 K	0.100 K	0.058 K	rectangular	√3	1.00	0.058 K
T_S	**Temperature in the climatic chamber**	**19.940 °C**					u =	**0.135 K**

Table 4: Measurement uncertainty budget for the temperature in the climatic chamber

Step 2: Dew point temperature

Uncertainty budget of the dew point temperature containing the contributions of the reference standard as well as of the climatic chamber.

Model equation:

$$T_{\mathrm{d,S}} = T_{\mathrm{d,i,s}} + \delta T_{\mathrm{d,cal}} + \delta T_{\mathrm{d,res}} + \delta T_{\mathrm{d,int}} + \delta T_{\mathrm{d,dri}} + \delta T_{\mathrm{d,rep}} - c_{\mathrm{Td}} \cdot \delta T_{\mathrm{d,Tdep}} + c_{\mathrm{p}} \cdot \delta p_{\mathrm{C-M}} + \delta T_{\mathrm{d,inho}} + \delta T_{\mathrm{d,inst}} \tag{15}$$

Set out below are the contributions for the individual components of the model equation:

$T_{\mathrm{d,i,S}}$:

Dew point measured by means of the standard dew point hygrometer (60 measured values). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the standard dew point mirror hygrometer. If the number of readings is small (≤ 10), a factor corresponding to the t-distribution may have to be added here to take account of the low degree of freedom (see EA-4/02 M [8]). The example shows a mean value of 16.19 °C and the standard deviation of the mean value is 10 mK.

$\delta T_{\mathrm{d,cal}}$:

Unknown measurement error of the standard dew point hygrometer due to calibration. During calibration, a correction of the standard dew point hygrometer of -0.02 K was observed. This is corrected during evaluation.

The uncertainty U of the dew point deviation is taken from the calibration certificate (U = 50 mK; normal distribution, k = 2). Thus, the assigned standard uncertainty is 25 mK.

$\delta T_{\mathrm{d,res}}$:

Unknown measurement error due to the resolution of the standard dew point hygrometer. The resolution of the dew point display is 10 mK. Therefore, a rectangular distribution with a half-width of 5 mK is assumed. The assigned standard uncertainty is then 2.9 mK.

$\delta T_{\mathrm{d,int}}$:

Unknown measurement deviation of the dew point of the standard dew point hygrometer due to interpolation between the calibration points. A rectangular distribution with a half-width of 20 mK is assumed. The assigned standard uncertainty is then 12 mK.

$\delta T_{\mathrm{d,dri}}$:

Unknown measurement deviation of the dew point of the standard dew point hygrometer due to the drift since the last recalibration. The last calibrations of the standard revealed a maximum drift of 50 mK per year. Therefore, a rectangular distribution with a half-width of 50 mK is assumed. The assigned standard uncertainty is 29 mK.

$\delta T_{\mathrm{d,rep}}$:
Unknown measurement error due to repeatability of the standard dew point hygrometer. Investigations with stable dew point and repeated adjustment of the standard dew point hygrometer have shown that the repeatability can be up to 50 mK. Therefore, a rectangular contribution with a half-width of 50 mK is assumed. The assigned standard uncertainty is 29 mK.

$\delta T_{\mathrm{d,Tdep}}$:
Unknown measurement error due to the dependence of the measurement of the standard dew point hygrometer on the ambient temperature. From investigations with a fixed dew point at different ambient temperatures it is known that the standard dew point hygrometer has an ambient temperature dependence of the dew point of 5 mK / K ($c_{\mathrm{Td}} = 5\,\mathrm{mK/K}$). The standard dew point hygrometer is calibrated in steps of 10 K at different ambient temperatures. Each of these calibrations therefore covers an ambient temperature range of ± 5 K. Therefore, a rectangular distribution with a half-width of 5 K is assumed. The assigned standard uncertainty is 2.9 K and the standard uncertainty contribution to the dew point amounts to 14 mK.

$\delta p_{\mathrm{C\text{-}M}}$:
Unknown measurement error due to a pressure loss in the measuring line to the standard dew point hygrometer. It is known from investigations that the pressure loss at the given gas flow will not exceed 5 mbar, with an uncertainty of 1 mbar.
At a dew point temperature of 16 °C, the sensitivity coefficient for the dew point as a function of the pressure at the mirror is $c_{\mathrm{p}} = 15.6\ \mathrm{mK/mbar}$. When evaluating the dew point temperature, the pressure loss of 5 mbar is corrected by +0.078 K.
The uncertainty contribution of 1 mbar is calculated as rectangular contribution. The assigned standard uncertainty is then 0.6 mbar and the standard uncertainty contribution to the dew point amounts to 9 mK.

$\delta T_{\mathrm{d,inho}}$:
Unknown measurement error due to the spatial inhomogeneity of the dew point in the climate chamber. A climatic chamber with air circulation is used. The dew point is therefore spatially homogeneous. From investigations with the standard dew point hygrometer it is known that the dew point does not deviate locally by more than 50 mK from the value in the centre of the useful volume. Therefore, a rectangular distribution with a half width of 50 mK is assumed. The assigned standard uncertainty is then 29 mK.

$\delta T_{\mathrm{d,inst}}$:
Unknown measurement error due to the instability of the dew point in the climate chamber. The examination of the calibration volume by means of the standard dew point hygrometer showed a maximum deviation of ±0.1 K from the mean value over 30 min. Therefore, a rectangular distribution with a half-width of 100 mK is assumed. The assigned standard uncertainty is then 58 mK.

These contributions are summarized in Table 5.

Quantity X_i	Descrition X_i	Estimated value x_i	Unknown measurement error δx_i	Standard measurement uncertainty $u(x_i)$	Distribution	Divisor	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$T_{d,i,S}$	Measured value reference standard dew point	16.19 °C	0.010 K	0.010 K	normal	1	1.00	0.010 K
$\delta T_{d,cal}$	Correction dew point mirror from calibration	-0.020 K	0.050 K	0.025 K	normal	2	1.00	0.025 K
$\delta T_{d,res}$	Resolution measured values reference standard	0.000 K	0.005 K	0.003 K	rectangular	√3	1.00	0.003 K
$\delta T_{d,int}$	Interpolation between the calibration points	0.000 K	0.020 K	0.012 K	rectangular	√3	1.00	0.012 K
$\delta T_{d,dri}$	Drift reference standard	0.000 K	0.050 K	0.029 K	rectangular	√3	1.00	0.029 K
$\delta T_{d,rep}$	Repeatability dew point measurement	0.000 K	0.050 K	0.029 K	rectangular	√3	1.00	0.029 K
$\delta T_{d,Tdep}$	Temperature dependence measuring head dew point mirror	0.000 K	5.000 K	2.887 K	rectangular	√3	0.005 K/K	0.014 K
$\delta p_{C\text{-}M}$	Pressure loss in the measuring line	0.078 K	1.000 mbar	0.58 mbar	rectangular	√3	0.0156 K/mbar	0.009 K
$\delta T_{d,inho}$	Spatial inhomogeneity climatic chamber	0.000 K	0.050 K	0.029 K	rectangular	√3	1.00	0.029 K
$\delta T_{d,inst}$	Temporal instability climatic chamber	0.000 K	0.100 K	0.058 K	rectangular	√3	1.00	0.058 K
$T_{d,S}$	**Dew point temperature in the climatic chamber**	**16.248 K**					u =	**0.084 K**

Table 5: Measurement uncertainty budget dew point temperature in the climatic chamber[8]

[8] The measurement uncertainty of the dew point may also be expressed in °C instead of K, if necessary. This does not change its numerical value. It is preferable to use the unit K for measurement uncertainties of temperatures and dew or frost points.

Step 3: Calculation relative humidity

The relative humidity in the climatic chamber is calculated by means of the following equation (16) using the gas and dew point temperatures from Tables 4 and 5 and the absolute pressure of the APM (absolute pressure measuring device):

$$U_{\mathrm{w}} = \frac{e(T_{\mathrm{d,S}}) \cdot f_{\mathrm{w}}(T_{\mathrm{d,S}}, p_{\mathrm{S}})}{e_w(T_{\mathrm{S}}) \cdot f_{\mathrm{w}}(T_{\mathrm{S}}, p_{\mathrm{C}})} \cdot 100\ \% \qquad (16)$$

The unknown deviation $\delta U_{\mathrm{w,S}}$ of the calculated relative humidity is represented by the following model equation:

$$\delta U_{\mathrm{w,S}} = c_{\mathrm{T}} \cdot \delta T_{\mathrm{S}} + c_{\mathrm{Td}} \cdot \delta T_{\mathrm{d,S}} + c_{\mathrm{p1}} \cdot \delta p_{\mathrm{C}} + c_{\mathrm{p2}} \cdot \delta p_{\mathrm{S}} + \delta U_{\mathrm{S,A}} \qquad (17)$$

Set out below are the contributions for the individual components of the model equation:

δT_{S}:
Gas temperature measured with the standard thermometer. The uncertainty of the gas temperature is the result of the corresponding sub-balance according to Table 4. The contribution has a normal distribution and the associated standard uncertainty is 0.135 K. The associated sensitivity coefficient at 20 °C and 79.3 % is $c_{\mathrm{T}} = 4.92\,\%/\mathrm{K}$.

$\delta T_{\mathrm{d,S}}$:
Dew point measured with the standard dew point hygrometer. The uncertainty of the dew point is the result of the corresponding sub-balance according to Table 5. The contribution has a normal distribution and the associated standard uncertainty is 0.084 K. The associated sensitivity coefficient at 20 °C and 79.3 % is $c_{\mathrm{Td}} = 5.06\,\%/\mathrm{K}$.

δp_{C} ; δp_{S} :
The absolute pressure is only included in the enhancement factors. The corresponding sensitivity coefficients are very small, which means that these contributions can be neglected.

$\delta U_{\mathrm{S,A}}$:
Calculation of the relative humidity from gas and dew point temperature. The uncertainty of the vapour pressure equation used for the saturation vapour pressure (calculated from the gas temperature) or for the water vapour partial pressure (calculated from the dew point temperature) is 0.02 % (see DKD-L 5-1 [5]) and is thus significantly smaller than the resolution of the calculation result of 0.1 %. Therefore, a rectangular contribution with a half-width of 0.1 % is assumed. The associated standard uncertainty is 0.06 %.

These contributions are summarized in Table 6.

Quantity X_i	Description X_i	Estimated value x_i	Unknown measurement error δx_i	Standard measurement uncertainty $u(x_i)$	Distribution	Divisor	Sensitivity coefficient c_i	Ucertainty contribution $u_i(y)$
δT_S	Temperature in the climatic chamber	19.940 °C	0.135 K	0.135 K	normal	1	4.92 %/K	0.66 %
$\delta T_{d,S}$	Dew point temperature in the climatic chamber	16.248 °C	0.084 K	0.084 K	normal	1	5.06 %/K	0.42 %
$\delta U_{S,A}$	Formula error / rounding calculated relative humidity	0.00 %	0.10 %	0.058 %	rectangular	√3	1.00	0.06 %
$U_{w,S}$	**Relative humidity in the calibration chamber**	**79.28 %**					u =	**0.79 %**

Table 6: Measurement uncertainty budget for the calculated relative humidity in the climatic chamber

Step 4: Calibration result

The deviation of the relative humidity displayed by the calibration item from the reference humidity measured in the climatic chamber represents the calibration result.
The uncertainty of the reference humidity and the uncertainty contributions of the calibration item are assigned to the calibration result.
The expanded measurement uncertainty U is obtained by assuming a standard distribution and multiplying the standard measurement uncertainty by the coverage factor k = 2.
As to the calibration result (deviation of the calibration item), the following model equation applies:

$$\Delta U_X = U_{i,X} - U_{w,S} + \delta U_{res,X} + c_T \cdot (\delta T_{htd,X} + \delta T_{sht,X}) + \delta U_{hys,X} + \delta U_{w,S} \quad (18)$$

Set out below are the contributions for the individual components of the model equation:

$U_{W,S}$; $\delta U_{W,S}$:
Uncertainty of the humidity reference value (measured with the standard thermometer and standard dew point hygrometer in the climate chamber). The uncertainty of the reference humidity is the result of the corresponding sub-balance according to Table 6. The contribution is assumed to be normally distributed and the associated standard uncertainty is 0.79 %.

$U_{i,X}$:
Relative humidity measured with the calibration item (capacitive humidity sensor) (60 measured values). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the capacitive humidity sensor. If the number of readings is small (≤ 10), a factor corresponding to the t-distribution may need to be added here to take account of the low degree of freedom (see EA-4/02 M [8]). The example shows a mean value of 79.9 % and 0.04 % for the mean value's standard deviation.

$\delta U_{res,X}$:
Unknown measurement error due to the resolution of the calibration item. The resolution of the relative humidity display is 0.1 %. Therefore, a rectangular contribution with a half-width of 0.05 % is assumed. The assigned standard uncertainty is 0.03 %.

$\delta T_{htd,X}$:
Unknown measurement error due to heat dissipation of the calibration item. Since the sensor of the calibration item is completely installed, including 1 m of its connecting cable, this contribution is neglected and estimated to be 0.0 K. The sensor of the calibration item is not

included in the calibration. Therefore, a rectangular distribution with a half-width of 0.0 K is assumed. The assigned standard uncertainty is then 0.0 K. The associated sensitivity coefficient at 20 °C and 79.3 % has a value of $c_T = 4.92\ \%/K$.

$\delta T_{sht,X}$:
Unknown measurement error due to self-heating of the calibration item. The self-heating is investigated in accordance with Chapter 7.4.3 and estimated to a maximum of 0.1 K. Therefore, a rectangular contribution with a half-width of 0.1 K is assumed. The assigned standard uncertainty is then 0.06 K. The associated sensitivity coefficient at 20 °C and 79.3 % has a value of $c_T = 4.92\ \%/K$.

$\delta U_{hys,X}$:
Unknown measurement error due to hysteresis of the calibration item. Calibration was carried out according to sequence B2. This sequence does not comprise the examination of a possible hysteresis. Therefore, a rectangular contribution with a half-width of 0.0 % is assumed. The assigned standard uncertainty is 0.0 %.

These contributions are summarized in Table 7.

Quantity X_i	Description X_i	Estimated value x_i	Unknown measurement error δx_i	Standard measurement uncertainty $u(x_i)$	Distribution	Divisor	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$U_{i,X}$	Humidity display calibration item	79.9 %	0.04 %	0.04 %	normal	1	1.00	0.04 %
$\delta U_{res,X}$	Resolution humidity display calibration item	0.0 %	0.05 %	0.03 %	rectangular	√3	1.00	0.03 %
$\delta T_{htd,X}$	Heat dissipation calibration item	0.0 %	0.00 K	0.00 K	rectangular	√3	4.92 %/K	0.00 %
$\delta T_{sht,X}$	Self-heating calibration item	0.0 %	0.10 K	0.06 K	rectangular	√3	4.92 %/K	0.28 %
$\delta U_{hys,X}$	Hysteresis calibration item	0.0 %	0.00 %	0.00 %	rectangular	√3	1.00	0.00 %
$U_{w,S}$	Relative humidity in the calibration chamber	79.28 %	0.79 %	0.79 %	normal	1	1.00	0.79 %
ΔU_X	**Display deviation calibration item**	**0.6 %**	U =	**1.7 %**	**(k = 2)**		u =	**0.84 %**

Table 7: Measurement uncertainty budget relative humidity calibration result

At 20 °C and 79.9 %, the display deviation of the hygrometer is +0.6 %, with an expanded measurement uncertainty[9] U (based on the assumption of a normal distribution and the coverage factor k = 2) of 1.7 %.[10]

[9] The variable U of the relative humidity must not be confused with the variable U of the expanded measurement uncertainty. The meaning of the variable used must be checked in each individual case.
[10] Alternatively, the display correction can be used instead of the display deviation. They only differ with respect to the algebraic sign. In the above example, the calibration result would be as follows:
"The hygrometer has a correction of 0.6 % at 20 °C and 79.9 %, with an expanded measurement uncertainty U (based on the assumption of a normal distribution and the coverage factor k = 2) of 1.7 %."
The use of the display correction offers the user of the hygrometer the advantage that the best estimate for the measured humidity can be determined by adding the correction to the displayed humidity of the hygrometer.

Calibration in a mixed gas generator

Calibration of a hygrometer with capacitive polymer sensor as measuring element in a mixed gas generator at a relative humidity of 50 % and a gas temperature of 23 °C.
A resistive-electrolytic sensor (WS1) and a capacitive polymer sensor (WS2) serve as working standards (WS). The calibration was carried out according to sequence B1 (see Chapter 9.3.3). After a stabilisation time of 2 h, the arithmetic mean value was formed from 60 individual values, over a period of 10 min. The set-up is divided into 2 steps.

1. Determination of the relative humidity in the chamber of the mixed gas generator.
2. Determination of the relative humidity of the calibration item and its measurement deviation as well as the associated expanded measurement uncertainty.

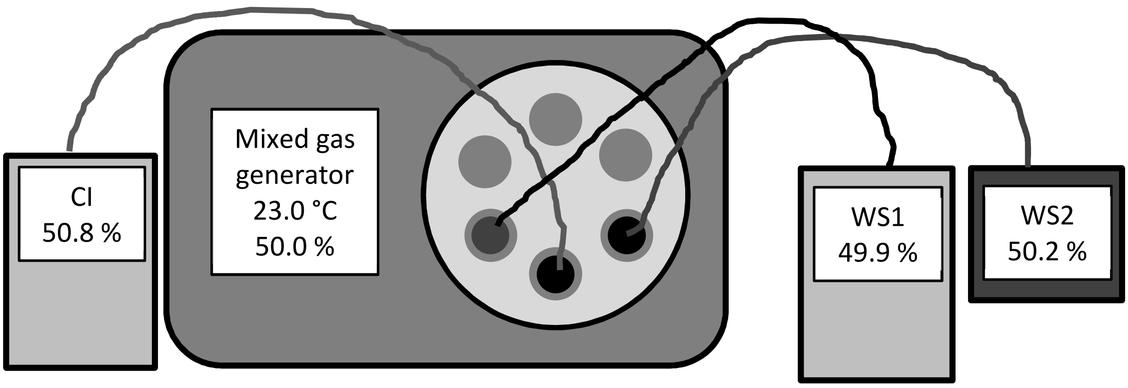

Figure 12: Schematic representation calibration set-up

Mounting depth

The installation depth of the external sensor of the calibration object is 15 cm (measured from the inner edge of the lid of the mixed gas generator).

Step 1: Humidity reference value in the mixed gas generator

Determination of the humidity reference value in the calibration chamber of the mixed gas generator, measured by using the working standards.

Model equation:

$$\begin{aligned} U_{\mathrm{w,S}} = \tfrac{1}{2}\cdot\left(U_{\mathrm{i,S1}} + U_{\mathrm{i,S2}}\right) \\ + c_{\mathrm{S1}}\cdot\delta U_{\mathrm{cal,S1}} + c_{\mathrm{S1}}\cdot\delta U_{\mathrm{res,S1}} + c_{\mathrm{S1}}\cdot\delta U_{\mathrm{int,S1}} + c_{\mathrm{S1}}\cdot\delta U_{\mathrm{dri,S1}} + c_{\mathrm{S1}}\cdot\delta U_{\mathrm{hys,S1}} \\ + c_{\mathrm{S2}}\cdot\delta U_{\mathrm{cal,S2}} + c_{\mathrm{S2}}\cdot\delta U_{\mathrm{res,S2}} + c_{\mathrm{S2}}\cdot\delta U_{\mathrm{int,S2}} + c_{\mathrm{S2}}\cdot\delta U_{\mathrm{dri,S2}} + c_{\mathrm{S2}}\cdot\delta U_{\mathrm{hys,S2}} \\ + \delta U_{\mathrm{i,S1-2}} + \delta U_{\mathrm{Tdep}} + c_{\mathrm{T}}\cdot\left(\delta T_{\mathrm{htd}} + \delta T_{\mathrm{sht}} + \delta T_{\mathrm{inho}} + \delta T_{\mathrm{rad}}\right) + \delta U_{\mathrm{inst}} \end{aligned} \qquad (19)$$

The sensitivity coefficients c_{S1} und c_{S2} are derived using the following equations:

$$c_{\mathrm{S1}} = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{cal,S1}}}\right) = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{res,S1}}}\right) = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{int,S1}}}\right) = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{dri,S1}}}\right) = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{hys,S1}}}\right) = \frac{1}{2} \qquad (20)$$

$$c_{\mathrm{S2}} = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{cal,S2}}}\right) = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{res,S2}}}\right) = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{int,S2}}}\right) = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{dri,S2}}}\right) = \left(\frac{\partial U_{\mathrm{w,S}}}{\partial U_{\mathrm{hys,S2}}}\right) = \frac{1}{2} \qquad (21)$$

This model equation applies in the case that the contributions (calibration, resolution, interpolation, drift and hysteresis) of the two standard hygrometers can be assumed to be uncorrelated from each other.
This is approximately fulfilled, for example, if both standard hygrometers have not been calibrated at the same time by the same calibration laboratory using the same standards. Ideally, the calibration dates of both standards are such that they are time-shifted by half the calibration period.
Especially when using working standards whose measuring methods are different (e.g. capacitive and resistive-electrolytic) or when using humidity sensors produced by different manufacturers, drift and hysteresis are not correlated, or only to a small degree.
Another option would be to avoid the constant use of both standards in calibrations to ensure that they are not constantly exposed to identical influences.[11]
For the contributions of both standards, which are considered correlated due to the non-fulfilment of these conditions, the corresponding sensitivity coefficients for each standard are not to be set at 0.5 but at $\frac{1}{\sqrt{2}} = 0.71$! (also see EA-4/02 M: 2013 Annex D [8]).

Set out below are the contributions for the individual components of the model equation:

$U_{\mathrm{i,S}}$:
Mean value which is determined by using the corresponding display corrections of the corrected relative humidity displays of the two reference standards from all individual measurements of the standard hygrometers (60 measured values each). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the standard hygrometer. If the number of readings is small (≤ 10), a factor corresponding to the t-distribution may have to be added to take account of the low degree of

[11] Therefore, it is recommended:

- to hold available more than 2 standard hygrometers (diversity recommended)
- to take another combination of standard hygrometers from the pool for each new calibration
- to have all standard hygrometers recalibrated individually (if required, also at different laboratories)

freedom (see EA-4/02 M [8]). In the example, the mean value is 50.1 % and the standard deviation of the mean value is 0.04 %.

$\delta U_{\mathrm{cal,S1}}$, $\delta U_{\mathrm{cal,S2}}$:
Unknown measurement error of the standard hygrometers due their calibration. The hygrometers serving as standards are resistive-electrolytic or capacitive humidity sensors including the respective measuring device. The display of each standard hygrometer is corrected by means of the display correction of the corresponding calibration certificate before calculating the mean value of both hygrometers. The uncertainty U of the relative humidity deviation is taken from the calibration certificate (U = 0.6 %; normally distributed, k = 2). Thus, the assigned standard uncertainty is 0.3 %.

$\delta U_{\mathrm{res,S1}}$, $\delta U_{\mathrm{res,S2}}$:
Unknown measurement error due to the resolution of the standard hygrometers. The resolution of the relative humidity display is 0.1 %. Therefore, a rectangular distribution with a half-width of 0.05 % is assumed. Hence, the assigned standard uncertainty is 0.03 %.

$\delta U_{\mathrm{int,S1}}$, $\delta U_{\mathrm{int,S2}}$:
Unknown measurement error of the relative humidity display of the standard hygrometers due to interpolation between the calibration points.
A rectangular distribution with a half-width of 0.25 % is assumed. Hence, the assigned standard uncertainty is 0.14 %.

$\delta U_{\mathrm{dri,S1}}$, $\delta U_{\mathrm{dri,S2}}$:
Unknown measurement error of the averaged relative humidity of the standard hygrometers due to the drift since the last recalibration. The last calibrations of the standards showed a maximum drift of the standard hygrometers of 2.0 % per year. For each standard, this drift represents a rectangularly distributed contribution with a half-width of 2.0 %. Hence, the assigned standard uncertainty is 1.2 %.

$\delta U_{\mathrm{hys,S1}}$, $\delta U_{\mathrm{hys,S2}}$:
Unknown measurement error of the relative humidity display of the standard hygrometers due to a possible hysteresis. An examination according to calibration sequence A1 showed only minor hysteresis effects for both standard hygrometers. Due to the selection of calibration sequence B1, each calibration point is approached only with increasing relative humidity. Based on the investigations, the hysteresis is in this case corrected accordingly (but may have to be considered for other processes).
A rectangular distribution with a half-width of 0.0 % is assumed. Hence, the assigned standard uncertainty is 0.0 %.

$\delta U_{\mathrm{i,S1\text{-}2}}$:
Unknown measurement error of the standard hygrometers due to the difference of the displays of both standard hygrometers. The difference of the measured relative humidity observed between the two standard hygrometers shall not be greater than ±0.42 % ($\widehat{=}\ 0.7 \cdot U_{\mathrm{cal,S}}$). If the difference is not within these limits, the observations must be repeated and/or the reasons for the large differences that have been identified must be investigated in more detail.
With respect to the indicated values, both hygrometers show a difference of 0.3 %. Thus, the criterion has been satisfied and the mean value of the indication is used as reference value.
If the difference between the readings of both standard hygrometers is clearly smaller than the uncertainty of the calibration of the standard hygrometers, no additional uncertainty

contribution has to be assumed for the mean value. Therefore, a rectangular distribution with a half-width of 0.0 % is assumed. Hence, the assigned standard uncertainty is 0.0 %.[12]

δU_{Tdep} :
Unknown measurement error due to the dependence of the humidity measurement of the standard hygrometers on the gas temperature. The relative humidity of the standard hygrometers has been calibrated at several points at a temperature of 15 °C and 25 °C. In between an interpolation is carried out. Due to the interpolation, a rectangular distribution with a half-width of 0.35 % is assumed. Hence, the assigned standard uncertainty is 0.20 %.[13]

δT_{htd} :
Unknown measurement error due to heat dissipation of the standard hygrometers. Since the sensors of the standard are not completely immersed, a rectangular distributed contribution with a half-width of 0.1 K is assumed. Hence, the assigned standard uncertainty is 0.06 K. The associated sensitivity coefficient at 23 °C and 50.1 % has a value of $c_T = 3.03\,\%/\mathrm{K}$.

δT_{sht} :
Unknown measurement error due to self-heating of the standard hygrometers. Based on investigations regarding the inflow velocities of the standard hygrometers, a maximum uncertainty contribution of 0.1 K is estimated. Therefore, a rectangular distribution with a half-width of 0.1 K is assumed. The assigned standard uncertainty is 0.06 K. The associated sensitivity coefficient at 23 °C and 50.1 % has a value of $c_T = 3.03\,\%/\mathrm{K}$.

δT_{inho} :
Unknown measurement error due to the spatial inhomogeneity of the relative humidity in the calibration chamber. The examination of the calibration volume was carried out according to Chapter 6.2.1 in the measurement quantities temperature and dew point temperature (= absolute humidity). The maximum deviation of the temperature at the temperature measuring points at the centre of the useful volume was ± 0.2 K. A spatial inhomogeneity of the dew point temperature between the measuring points has not been determined. Therefore, the spatial inhomogeneity of the relative humidity is only considered for the measurement quantity ‘temperature’. A rectangular distribution with a half-width of 200 mK is assumed. Hence, the associated standard uncertainty is 115 mK. The associated sensitivity coefficient at 23 °C and 50.1 % has a value of $c_T = 3.03\,\%/\mathrm{K}$.

δT_{rad} :
Unknown measurement error due to the radiation influence on the temperature measurement in the calibration chamber. The investigation was carried out according to Chapter 6.2.3, using two thermometers with different emissivity. The maximum temperature deviation between the two thermometers was 0.05 K. Therefore, a rectangular distribution with a half-width of 50 mK is assumed. Hence, the assigned standard uncertainty is 29 mK. The associated sensitivity coefficient has a value of $c_T = 3.03\,\%/\mathrm{K}$ at 23 °C and 50.1 %.

δU_{inst} :
Unknown measurement error due to the instability of the relative humidity in the calibration chamber. The examination of the calibration volume according to Chapter 6.2.2 showed a

[12] If the deviation of the indications of both standards is greater than 0.7 times the expanded calibration uncertainty of the standards and if there is no investigation regarding the causes and the measurements are not repeated, then the difference of the indications of both standards is to be assumed as half the width of the rectangular distribution $\delta U_{\mathrm{i,S1\text{-}2}}$.

[13] If the normal hygrometers differ in type, a non-correlated behaviour can also be assumed here (see contributions to calibration, drift, ...).

maximum deviation of ±0.3 % of the relative humidity from the mean value over 30 min. Therefore, a rectangular distribution with a half width of 0.3 % is assumed. Hence, the assigned standard uncertainty is 0.17 %.

These contributions are summarized in Table 8.

Quantity X_i	Description X_i	Estimated value x_i	Unknown measurement error δx_i	Standard measurement uncertainty $u(x_i)$	Distribution	Divisor	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$U_{i,S}$	Mean value of the corrected readings of the standards	50.1 %	0.04 %	0.04 %	normal	1	1.00	0.04 %
$\delta U_{cal,S1}$	Calibration standard 1	0.0 %	0.60 %	0.30 %	normal	2	0.50	0.15 %
$\delta U_{cal,S2}$	Calibration standard 2	0.0 %	0.60 %	0.30 %	normal	2	0.50	0.15 %
$\delta U_{res,S1}$	Resolution measured values standard 1	0.0 %	0.05 %	0.03 %	rectangular	√3	0.50	0.01 %
$\delta U_{res,S2}$	Resolution measured values standard 2	0.0 %	0.05 %	0.03 %	rectangular	√3	0.50	0.01 %
$\delta U_{int,S1}$	Interpolation between the calibration points standard 1	0.0 %	0.25 %	0.14 %	rectangular	√3	0.50	0.07 %
$\delta U_{int,S2}$	Interpolation between the calibration points standard 2	0.0 %	0.25 %	0.14 %	rectangular	√3	0.50	0.07 %
$\delta U_{dri,S1}$	Drift of standard 1	0.0 %	2.00 %	1.15 %	rectangular	√3	0.50	0.58 %
$\delta U_{dri,S2}$	Drift of standard 2	0.0 %	2.00 %	1.15 %	rectangular	√3	0.50	0.58 %
$\delta U_{hys,S1}$	Hysteresis standard 1	0.0 %	0.00 %	0.00 %	rectangular	√3	0.50	0.00 %
$\delta U_{hys,S2}$	Hysteresis standard 2	0.0 %	0.00 %	0.00 %	rectangular	√3	0.50	0.00 %
$\delta U_{i,S1-2}$	Difference between the two standards	0.0 %	0.00 %	0.00 %	rectangular	√3	1.00	0.00 %
δU_{Tdep}	Temperature dependence humidity measurement	0.0 %	0.35 %	0.20 %	rectangular	√3	1.00	0.20 %
δT_{htd}	Heat dissipation	0.0 %	0.10 K	0.06 K	rectangular	√3	3.03 %/K	0.17 %
δT_{sht}	Self-heating	0.0 %	0.10 K	0.06 K	rectangular	√3	3.03 %/K	0.17 %
δT_{inho}	Spatial inhomogeneity calibration chamber	0.0 %	0.20 K	0.12 K	rectangular	√3	3.03 %/K	0.35 %
δT_{rad}	Radiation influences	0.0 %	0.05 K	0.03 K	rectangular	√3	3.03 %/K	0.09 %
δU_{inst}	Temporal instability calibration chamber	0.0 %	0.30 %	0.17 %	rectangular	√3	1.00	0.17 %
$U_{w,S}$	**Relative humidity in the calibration chamber**	**50.1 %**					u =	**0.99 %**

Table 8: Measurement uncertainty budget of the relative humidity in the mixed gas generator (measured by means of the standard hygrometers)

Step 2: Calibration result

The deviation of the relative humidity displayed by the calibration item from the reference humidity measured in the mixed gas generator represents the calibration result.
The uncertainty of the reference humidity and the uncertainty contributions of the calibration item are assigned to the calibration result.
The expanded measurement uncertainty U is obtained by assuming a standard distribution and multiplying the standard measurement uncertainty by the coverage factor k = 2.
The following model equation determines the calibration result:

$$\Delta U_{\mathrm{X}} = U_{\mathrm{i,X}} - U_{\mathrm{w,S}} + \delta U_{\mathrm{res,X}} + c_{\mathrm{T}} \cdot \left(\delta T_{\mathrm{htd,X}} + \delta T_{\mathrm{sht,X}}\right) + \delta U_{\mathrm{hys,X}} + \delta U_{\mathrm{w,S}} \quad (22)$$

Set out below are the contributions for the individual components of the model equation:

$U_{\mathrm{w,S}}$:
Uncertainty of the humidity reference value measured in the calibration chamber by means of the standard hygrometers. The uncertainty of the reference humidity is the result of the corresponding sub-balance according to Table 8. The contribution is assumed to have a rectangular distribution and the associated standard uncertainty is 1.0 %.

$U_{\mathrm{i,X}}$:
Relative humidity measured by means of the calibration item (capacitive humidity sensor) (60 measured values). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the capacitive humidity sensor. If the number of readings is small (≤ 10), a factor corresponding to the t-distribution may have to be added to account for the low degree of freedom (see EA-4/02 M [8]). The example shows a mean value of 50.8 % and 0.04 % for the mean value's standard deviation.

$\delta U_{\mathrm{res,X}}$:
Unknown measurement error due to the resolution of the calibration item. The resolution of the relative humidity display is 0.1 %. Therefore, a rectangular contribution with a half-width of 0.05 % is assumed. Hence, the associated standard uncertainty is 0.03 %.

$\delta T_{\mathrm{htd,X}}$:
Unknown measurement error due to heat dissipation of the calibration item. Since the sensor of the calibration item is only partially immersed (at 15 cm) and not completely, this contribution is estimated to a maximum of 0.1 K, based on investigations A rectangular distribution with a half-width of 0.1 K is assumed. The assigned standard uncertainty then amounts to 0.06 K. The associated sensitivity coefficient at 23 °C and 50 % has a value of $c_T = 3.03\,\%/\mathrm{K}$.

$\delta T_{\mathrm{sht,X}}$:
Unknown measurement error due to self-heating of the calibration item. The self-heating is investigated in accordance with Chapter 7.4.3 and estimated to a maximum of 0.1 K. Therefore, a rectangular distribution with a half-width of 0.1 K is assumed. The assigned standard uncertainty then amounts to 0.06 K. The associated sensitivity coefficient at 23 °C and 50 % has a value of $c_T = 3.03\,\%/\mathrm{K}$.

$\delta U_{\mathrm{hys,X}}$:
Unknown measurement error due to the hysteresis of the calibration item. The calibration has been carried out according to sequence B1 without considering a possible hysteresis. Therefore, a rectangular distribution with a half-width of 0.0 % is assumed. Hence, the associated standard uncertainty is 0.0 %.

These contributions are summarized in Table 9.

Quantity X_i	Description X_i	Estimated value x_i	Unknown measurement error δx_i	Standard measurement uncertainty $u(x_i)$	Distribution	Divisor	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$U_{\mathrm{i,X}}$	Humidity display calibration item	50.8 %	0.04 %	0.04 %	normal	1	1.00	0.04 %
$\delta U_{\mathrm{res,X}}$	Resolution humidity display calibration item	0.0 %	0.05 %	0.03 %	rectangular	√3	1.00	0.03 %
$\delta T_{\mathrm{htd,X}}$	Heat dissipation calibration item	0.0 %	0.10 K	0.06 K	rectangular	√3	3.03 %/K	0.17 %
$\delta T_{\mathrm{sht,X}}$	Self-heating calibration item	0.0 %	0.10 K	0.06 K	rectangular	√3	3.03 %/K	0.17 %
$\delta U_{\mathrm{hys,X}}$	Hysteresis calibration item	0.0 %	0.00 %	0.00 %	rectangular	√3	1.00	0.00 %
$U_{\mathrm{w,S}}$	Relative humidity in the calibration chamber	50.1 %	0.99 %	0.99 %	normal	1	1.00	0.99 %
ΔU_{X}	**Display deviation calibration item**	**0.7 %**	U = **2.0 %**		**(k = 2)**		u = **1.02 %**	

Table 9: Measurement uncertainty budget calibration result

At 23 °C and 50.8 %, the hygrometer shows a deviation of +0.7 %, with an expanded measurement uncertainty U (based on the assumption of a normal distribution and with coverage factor k = 2) of 2.1 %.[14]

[14] Instead of using the display deviation, it is also possible to use the display correction. They only differ with respect to the algebraic sign. In the above example, the calibration result would be as follows:
"At 23 °C and 50.8 %, the hygrometer has a correction of –0.7 %, with an expanded measurement uncertainty U (based on the assumption of a normal distribution and with the coverage factor k = 2) of 2.1 %."

Calibration in a two-pressure humidity generator

Calibration of a hygrometer with capacitive polymer sensor as measuring element in a two-pressure humidity generator at 75 % relative humidity and 22 °C gas temperature. The humidity generator has been calibrated in relation to the display deviation of the measured variable 'relative humidity'. The display serves as a reference standard (RS). The calibration was carried out according to sequence A1 (see Chapter 9.3.1). The calibration was carried out first in ascending and then in descending order. After an adjustment time of 2 h, the arithmetic mean value was formed from 60 individual values over a period of 10 min. The set-up is divided into 2 steps.

1. Determination of the relative humidity in the chamber of the humidity generator
2. Determination of the relative humidity of the calibration item and its measurement deviation as well as the associated expanded measurement uncertainty.

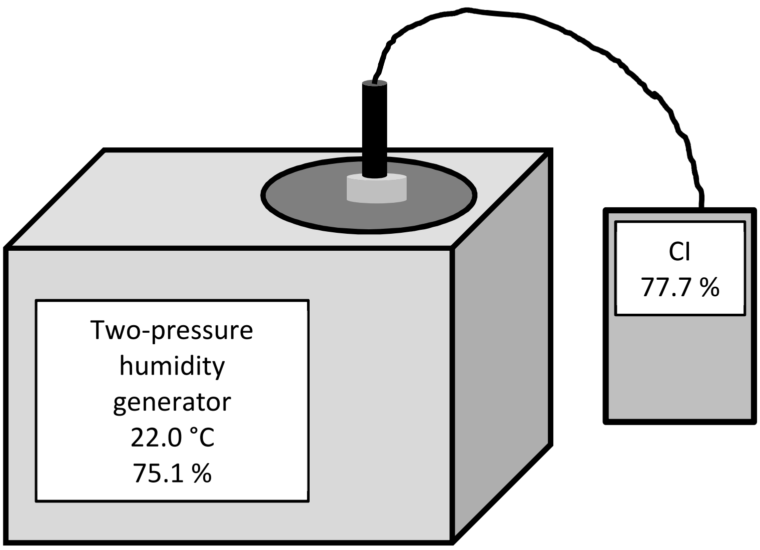

Figure 13: Schematic representation calibration set-up

Mounting depth

The installation depth of the external sensor of the calibration object is 5 cm (measured from the inner edge of the lid of the humidity generator).

Step 1: Reference standard

Model equation:

$$U_{\mathrm{W,S}} = U_{\mathrm{i,s}} + \delta U_{\mathrm{cal}} + \delta U_{\mathrm{res}} + \delta U_{\mathrm{int}} + \delta U_{\mathrm{dri}} + c_{\mathrm{t}} \cdot (\delta t_{\mathrm{inho}} + \delta t_{\mathrm{rad}}) + \delta U_{\mathrm{inst}} \quad (23)$$

Set out below are the contributions for the individual components of the model equation:

$U_{\mathrm{i,S}}$:

Mean value of the relative humidity displayed by the humidity generator (60 measured values). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the capacitive humidity sensor. If the number of readings is small (≤ 10), a factor corresponding to the t-distribution may have to be added to account for the low degree of freedom (see EA-4/02 M [8]). The example shows a mean value of 75.1 % and 0.02 % for the mean value's standard deviation.

δU_{cal} :

Unknown measurement error of the humidity generator due to calibration. During calibration, the humidity generator showed an average correction of 0.01 %. The uncertainty U of the relative humidity deviation is taken from the calibration certificate (U = 0.6 %; normally distributed, k = 2). Thus, the associated standard uncertainty is 0.3 %.

δU_{res} :

Unknown measurement error due to the resolution of the humidity generator. The resolution of the relative humidity display is 0.1 %. Therefore, a rectangular contribution with a half-width of 0.05 % is assumed. Hence, the associated standard uncertainty is 0.03 %.

δU_{int} :

Unknown measurement error of the relative humidity display of the humidity generator due to interpolation between the calibration points. A rectangular distribution with a half-width of 0.05 % is assumed. The associated standard uncertainty is 0.03 %.

δU_{dri} :

Unknown measurement error of the relative humidity of the humidity generator due to the drift since the last recalibration. The last calibrations of the generator showed a maximum drift of 0.2 % per year. Therefore, a rectangular contribution with a half-width of 0.2 % is assumed. The associated standard uncertainty is then 0.12%.

δt_{inho} :

Unknown measurement error due to the spatial inhomogeneity of the temperature in the calibration chamber of the humidity generator. The examination of the calibration volume according to Chapter 6.2.1 resulted in a maximum deviation of 0.05 °C between the temperature at the measuring points and the temperature at the centre of the useful volume. A spatial inhomogeneity of the dew point temperature between the measuring locations was not determined. Hence, the spatial inhomogeneity of the relative humidity is only considered for the measured quantity 'temperature'. A rectangular contribution with a half-width of 0.05 °C is assumed. The assigned standard uncertainty is 0.029 °C. The associated sensitivity coefficient at 22 °C and 75 % has a value of $c_t = 4.58\,\%/°\mathrm{C}$.

δt_{rad} :
Unknown measurement error due to the radiation influence on the temperature measurement in the calibration chamber of the humidity generator. The measurement was performed with two thermometers with different emissivity in accordance with Chapter 6.2.3. It showed a maximum temperature deviation of 0.03 °C between both thermometers. A rectangular contribution with a half-width of 0.03 °C is assumed. The assigned standard uncertainty is 0.017 °C. At 22 °C and 75 %, the associated sensitivity coefficient has a value of $c_t = 4.58\,\%/°\mathrm{C}$.

δU_{inst} :
Unknown measurement error due to the instability of the relative humidity in the calibration chamber. The examination of the calibration volume according to Chapter 6.2.2 showed a maximum deviation of the relative humidity of ±0.1 % form the mean value over a period of 30 min. Therefore, a rectangular distribution with a half-width of 0.1 % is assumed. The assigned standard uncertainty is 0.06 %.

These contributions are summarized in Table 10.

Quantity X_i	Description X_i	Estimated value x_i	Unknown measurement error δx_i	Standard measurement uncertainty $u(x_i)$	Distribution	Divisor	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$U_{i,S}$	Display reference standard humidity generator	75.1 %	0.02 %	0.02 %	normal	1	1.00	0.02 %
δU_{cal}	Calibration reference standard	0.1 %	0.60 %	0.30 %	normal	2	1.00	0.30 %
δU_{res}	Resolution reference standard	0.0 %	0.05 %	0.03 %	rectangular	√3	1.00	0.03 %
δU_{int}	Interpolation between the calibration points	0.0 %	0.05 %	0.03 %	rectangular	√3	1.00	0.03 %
δU_{dri}	Drift reference standard	0.0 %	0.20 %	0.12 %	rectangular	√3	1.00	0.12 %
δt_{inho}	Spatial inhomogeneity calibration chamber	0.0 %	0.05 °C	0.03 °C	rectangular	√3	4.58 %/°C	0.13 %
δt_{rad}	Radiation influences	0.0 %	0.03 °C	0.02 °C	rectangular	√3	4.58 %/°C	0.08 %
δU_{inst}	Temporal instability calibration chamber	0.0 %	0.10 %	0.06 %	rectangular	√3	1.00	0.06 %
$U_{w,S}$	**Relative humidity in the calibration chamber**	**75.2 %**					u =	**0.36 %**

Table 10: Measurement uncertainty budget relative humidity

Step 2: Calibration result

The deviation of the relative humidity displayed by the calibration item from the reference humidity displayed by the humidity generator represents the calibration result.
The uncertainty of the reference humidity and the uncertainty contributions of the calibration item are assigned to the calibration result.
The assumption of a normal distribution and the multiplication of the standard uncertainty by the coverage factor k = 2 yields the expanded measurement uncertainty U.

The following model equation is used for the calibration result:

$$\Delta U_{\mathrm{X}} = U_{\mathrm{i,X}} - U_{\mathrm{w,S}} + \delta U_{\mathrm{res,X}} + c_{\mathrm{T}} \cdot \left(\delta T_{\mathrm{htd,X}} + \delta T_{\mathrm{sht,X}}\right) + \delta U_{\mathrm{hys,X}} + \delta U_{\mathrm{w,S}} \tag{24}$$

Set out below are the contributions for the individual components of the model equation:

$U_{\mathrm{w,S}}$:
Uncertainty of the humidity reference value displayed by the humidity generator. The uncertainty of the reference humidity of 75.2 % is the result of the corresponding sub-balance according to Table 10. The contribution is assumed to have a normal distribution and the associated standard uncertainty is 0.37 %.

$U_{\mathrm{i,X}}$:
Relative humidity measured by the calibration item (capacitive humidity sensor) (60 measured values). The type A uncertainty contribution is determined from the standard deviation of the mean value for the multiple readings of the capacitive humidity sensor. If the number of readings is small (≤ 10), a factor corresponding to the t-distribution may have to be added to account for the low degree of freedom (see EA-4/02 M [8]). The example shows a mean value of 77.7 % and 0.04 % for the standard deviation of the mean value.

$\delta U_{\mathrm{res,X}}$:
Unknown measurement error due to the resolution of the calibration item. The resolution of the relative humidity display is 0.1 %. Therefore, a rectangular distribution with a half-width of 0.05 % is assumed. The associated standard uncertainty is 0.03 %.

$\delta t_{\mathrm{htd,X}}$:
Unknown measurement error due to heat dissipation of the calibration item. Since the immersion depth of the sensor is only 5 cm, this contribution is estimated to be 0.1 °C, based on investigations. Therefore, a rectangular distribution with a half-width of 0.1 °C is assumed. The assigned standard uncertainty is 0.06 °C. At 22 °C and 75 %, the associated sensitivity coefficient has a value of $c_t = 4.71\ \%/°\mathrm{C}$.

$\delta t_{\mathrm{sht,X}}$:
Unknown measurement error due to self-heating of the calibration item. The self-heating is examined according to Chapter 7.4.3 and estimated at a maximum of 0.1 °C. Therefore, a rectangular distribution with a half-width of 0.1 °C is assumed. The assigned standard uncertainty is 0.06 °C. At 22 °C and 75 %, the associated sensitivity coefficient has a value of $c_t = 4.71\ \%/°\mathrm{C}$.

$\delta U_{\mathrm{hys,X}}$:
Unknown measurement error due to the hysteresis of the calibration item. The hysteresis was determined from a measurement series with ascending and descending humidity in accordance with Chapter 9.3.1. The hysteresis difference is 1.6 %. The mean value of the ascending and descending measurement series is used for the display of the calibration item. Therefore, a rectangular distribution with a half-width of 0.8 % is assumed. The assigned standard uncertainty is 0.46 %.

These contributions are summarized in Table 11.

Quantity X_i	Description X_i	Estimated value x_i	Unknown measurement error δx_i	Standard measurement uncertainty $u(x_i)$	Distribution	Divisor	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$U_{\mathrm{i,X}}$	Humidity display calibration item	77.7 %	0.04 %	0.04 %	normal	1	1.00	0.04 %
$\delta U_{\mathrm{res,X}}$	Resolution humidity display calibration item	0.0 %	0.05 %	0.03 %	rectangular	√3	1.00	0.03 %
$\delta T_{\mathrm{htd,X}}$	Heat dissipation calibration item	0.0 %	0.10 °C	0.06 °C	rectangular	√3	4.58 %/°C	0.26 %
$\delta T_{\mathrm{sht,X}}$	Self-heating calibration item	0.0 %	0.10 °C	0.06 °C	rectangular	√3	4.58 %/°C	0.26 %
$\delta U_{\mathrm{hys,X}}$	Hysteresis calibration item	0.0 %	0.80 %	0.46 %	rectangular	√3	1.00	0.46 %
$U_{\mathrm{w,S}}$	Relative humidity in the calibration chamber	75.2 %	0.36 %	0.36 %	normal	1	1.00	0.36 %
ΔU_{X}	**Display deviation calibration item**	**2.5 %**	U =	**1.4 %**	**(k = 2)**		u =	**0.70 %**

Table 11: Uncertainty budget calibration result

At 22 °C and 77.7 %, the hygrometer shows a display deviation of +2.5 %, with an expanded uncertainty U of 1.4 %[15] (based on the assumption of a rectangular distribution and the coverage factor k = 2).

[15] Instead of using the display deviation, it is also possible to use the display correction. They only differ with respect to the algebraic sign. In the above example, the calibration result would be as follows:
"At 22 °C and 77.7 %, the hygrometer shows a correction -2.5 %, at an expanded uncertainty of U of 2.5 % (based on the assumption of a normal distribution and the coverage factor k = 2)."

Appendix B Sample calibration certificates (excerpts)

Calibration method
The humidity calibration was carried out according to the DKD guideline DKD-R 5-8 "Calibration of hygrometers for the direct measurement of relative humidity", Edition 10/2019, in accordance with sequence A2 (upward/downward).

Measurement conditions
The calibration was carried out in a climatic chamber at a flow velocity of approximately 2 m/s.
The external sensor of the calibration item was positioned in the climatic chamber, including 1 m of its connecting cable. The display unit was exposed to room conditions outside the measuring chamber during calibration. The adjustment time for each calibration point was at least 150 min.
The starting value for the calibration was the specified environmental condition.
The value of the hysteresis is not considered in the measurement uncertainty.
The reference value of the relative humidity was calculated from the measured values of the air temperature and dew point temperature of the reference standards.

Ambient conditions

Temperature	23.0	°C	±1 K
Relative humidity	45	%	±10 %

Calibration results of the relative humidity

Reference values		Calibration item		
Gas temperature t in °C	Relative humidity U_w in %	Displayed value U in %	Measurement error ΔU in %	Measurement uncertainty U in %
20	20.1	19.7	-0.4	0.6
20	50.0	49.9	-0.1	0.8
20	80.0	80.3	+0.3	1.0
20	90.1	91.2	+1.1	1.1
20	80.1	81.3	+1.2	1.0
20	50.0	50.6	+0.6	0.8
20	20.0	19.7	-0.3	0.6

The measurement results are stated in order of their calibration.

Measurement uncertainty
The uncertainty stated here is the expanded uncertainty which results from the standard uncertainty multiplied by the coverage factor k = 2. It was determined in accordance with EA-4/02 M: 2013. In case of a normal distribution, the value of the measurement quantity lies within the assigned fixed value interval with a probability of 95 %.

Calibration method
The humidity calibration was carried out according to the DKD guideline DKD-R 5-8 “Calibration of hygrometers for the direct measurement of relative humidity”, Edition 10/2019, in accordance with sequence B2 (upward).

Measurement conditions
The calibration was carried out in a humidity generator at an air change rate of approximately 10 / min. Traceability is established by means of temperature and pressure measurements.
The calibration item was completely built into the calibration device. The adjustment time for each calibration point was at least 120 min.
The starting value for the calibration was the specified environmental condition.
A possible hysteresis of the calibration object is not considered in the measurement uncertainty.

Ambient conditions

Temperature	22.5	°C	±1 K
Relative humidity	56	%	±10 %

Calibration results of the relative humidity

Reference values		Calibration item		
Gas temperature t in °C	Relative humidity U_w in %	Displayed value U in %	Measurement error ΔU in %	Measurement uncertainty U in %
25	10.0	10.3	+0.3	0.3
25	40.0	40.3	+0.3	0.4
25	70.0	69.4	-0.6	0.6
70	10.1	10.5	+0.4	0.3
70	40.0	40.8	+0.8	0.4
70	69.9	71.2	+1.3	0.6
-10	10.0	11.0	+1.0	0.4
-10	40.1	40.5	+0.4	0.5
-10	70.1	68.9	-1.2	0.7
25	10.0	9.9	-0.1	0.3
25	40.0	40.2	+0.2	0.4
25	70.0	69.8	-0.2	0.6

The measurement results are stated in order of their calibration.
Even at a gas temperature of -10 °C, the relative humidity refers to the saturation above water.

Measurement uncertainty
The uncertainty stated here is the expanded uncertainty which results from the standard uncertainty multiplied by the coverage factor k = 2. It was determined in accordance with EA-4/02 M: 2013. In case of a normal distribution, the value of the measurement quantity lies within the assigned fixed value interval with a probability of 95 %.

Calibration method
The humidity calibration was carried out according to the DKD guideline DKD-R 5-8 "Calibration of hygrometers for the direct measurement of relative humidity", Edition 10/2019, in accordance with sequence C1 (downward).

Measurement conditions
The calibration was carried out in a climatic chamber at a flow velocity of approximately 1 m/s.
The external sensor of the calibration item was immersed at a depth of 10 cm in the calibration device. The adjustment time for each calibration point was at least 120 min.
The starting values for calibration were 75 % relative humidity at 23 °C gas temperature.
A possible hysteresis of the calibration item is not included in the measurement uncertainty.

Ambient conditions

Temperature	21.7	°C	±1 K
Relative humidity	34	%	±10 %

Calibration results of the relative humidity

Reference values		Calibration item		
Gas temperature t in °C	Relative humidity U_w in %	Displayed value U in %	Measurement error ΔU in %	Measurement uncertainty U in %
23	65.1	66.3	+1.2	1.5
23	40.0	40.9	+0.9	1.3
23	15.0	15.4	+0.4	1.2

The measurement results are stated in order of their calibration.

Measurement uncertainty
The uncertainty stated here is the expanded uncertainty which results from the standard uncertainty multiplied by the coverage factor k = 2. It was determined in accordance with EA-4/02 M: 2013. In case of a normal distribution, the value of the measurement quantity lies within the assigned fixed value interval with a probability of 95 %.

Appendix C Notes on thermal coupling

Notes on thermal coupling
As the relative humidity depends on the temperature, complete thermal coupling of the sensor to the gas or air temperature is required when measuring the humidity by means of a sensor for relative humidity. Otherwise, considerable measurement errors can occur due to self-heating, heat dissipation, radiation influence or insufficient waiting times.
In the following, the change of the relative humidity, which results from a heating of the humidity sensor by 1 K in relation to the air temperature of 20°C, is shown as a function of the relative humidity at a temperature of 20 °C.

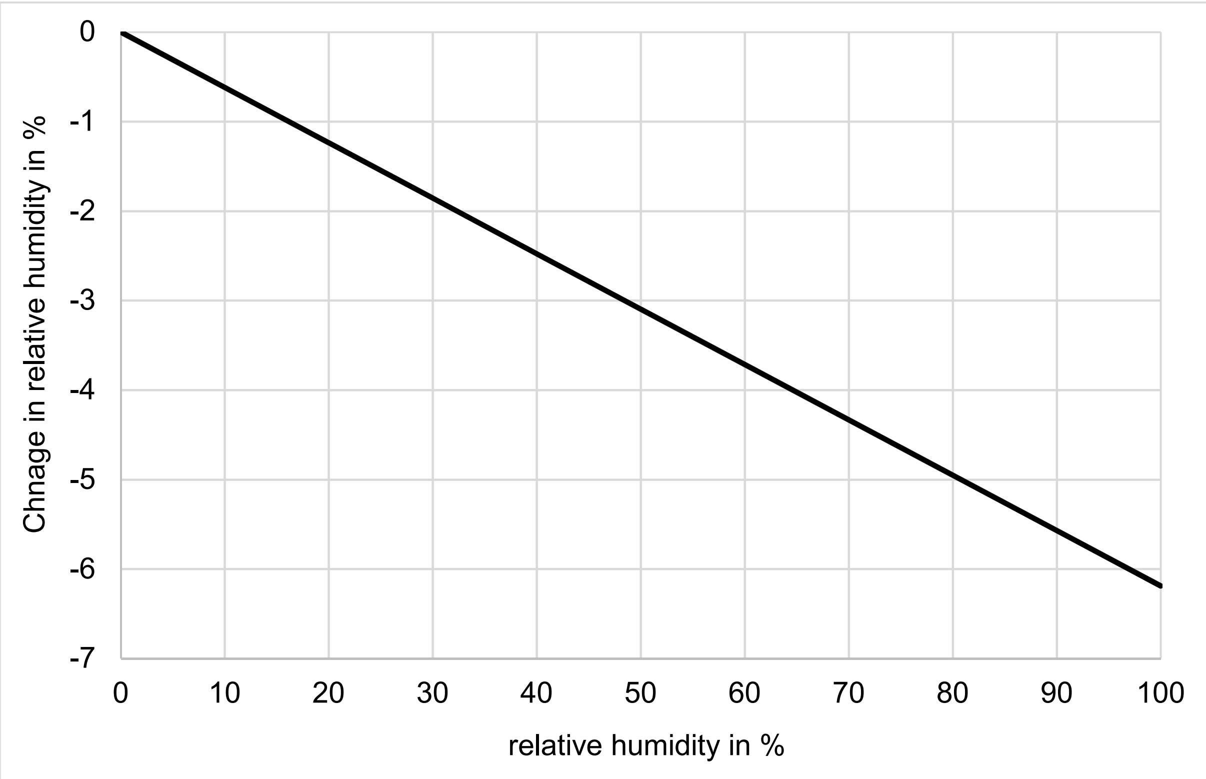

Figure 14: Change in relative humidity as a function of relative humidity at a temperature of 1 K in relation to an air temperature of 20 °C.

This results in a decrease of the relative humidity, while the sensitivity increases with increasing relative humidity.

On the other hand, if the humidity sensor dissipates heat, i.e. the temperature of the sensor is lower than the air temperature, the relative humidity increases.
Moreover, at high humidity there is also the risk of condensation.

Appendix D Information on electronic humidity sensors

Details regarding hysteresis and adjustment behaviour of electronic humidity sensors

To facilitate the classification of the hysteresis and the adjustment behaviour, the following figure graphically represents the calibration results of 3 different capacitive humidity sensors (Sensor 1, Sensor 2, Sensor 3).

Calibration sequence

The calibration was carried out according to sequence A1 (upward / downward) at a flow velocity of 0.08 m/s and an air temperature of 20 °C, with the following relative humidity:

S0: 40 %; N1a: 65 % - upward; N2: 90 % - upward; N1b: 65 % - downward

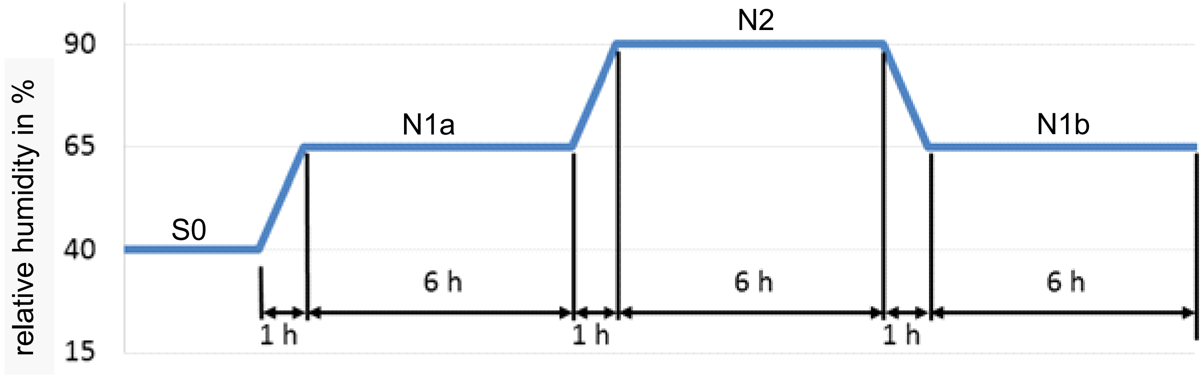

Figure 15: Graphic representation of the calibration sequence (Sequence A1)

Each calibration point was held for 6 h. The change to the next point was carried out slowly over a period of 1 h.

The calibration was carried out in a two-pressure humidity generator. A dew point mirror and four Pt100 resistance thermometers, read out via a temperature measuring bridge, were used as reference standards.

Calibration results N1a and N1b

The measurement deviations of the humidity sensors at the calibration points N1a (upward) and N1b (downward) are shown below. For better comparability, the mean value of the measurement deviations at 6 h of N1a and N1b was set to zero to show only the temporal course of the hysteresis:

$$\frac{\Delta U_{\mathrm{N1a}}(6{:}00) + \Delta U_{\mathrm{N1b}}(6{:}00)}{2} \triangleq 0\,\% \qquad (25)$$

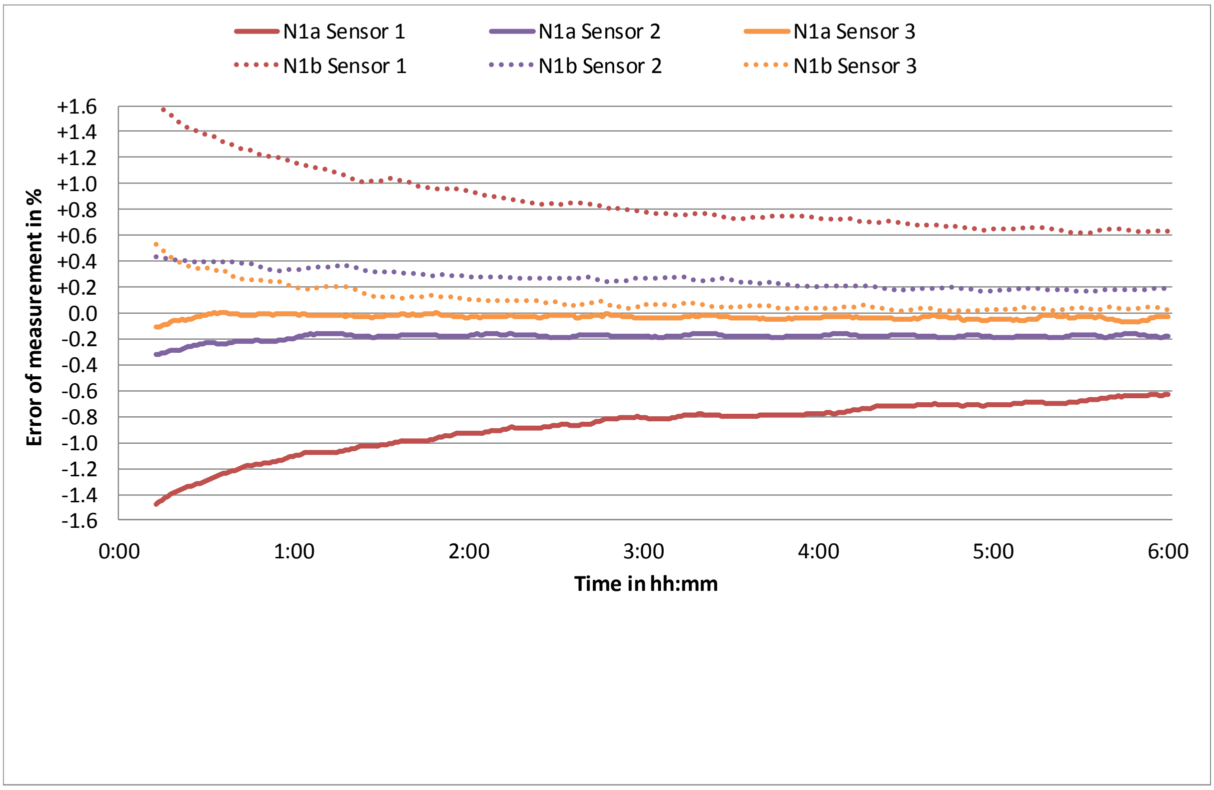

Figure 16: Measurement deviations of the relative humidity of 3 humidity sensors as a function of time at points N1a and N1b

Result

The three humidity sensors show a different adjustment behaviour, e.g. sensor 1 and 2 are adjusted faster than sensor 3. Sensor 3 also shows a more pronounced hysteresis behaviour than sensor 1 and 2. In addition, the hysteresis is asymmetrical with short equalisation times (hysteresis rising is smaller than hysteresis falling).

Calibration results N2

The measurement deviations of the humidity sensors at calibration point N2 (upward) are shown below. For better comparability, the measurement deviations were set to zero at 6 h to show only the temporal course of the adjustment behaviour:

$$\Delta U_{\mathrm{N2}}(6{:}00) \triangleq 0\ \% \tag{26}$$

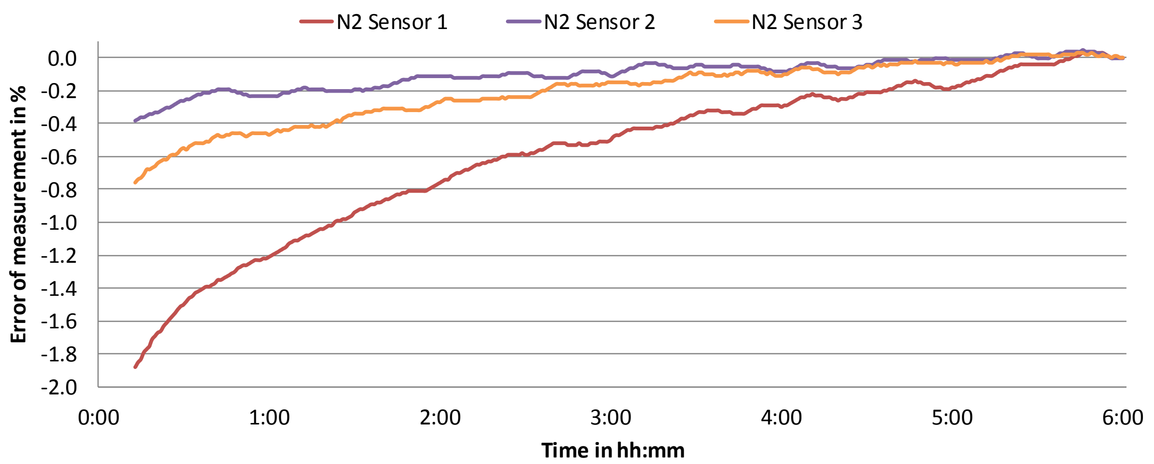

Figure 17: Measurement deviations of the relative humidity of 3 humidity sensors as a function of time at calibration point N2

Result

The humidity sensors show a different adjustment behaviour. Especially with high relative humidity (over 80 %), the measured value can increase continuously.

Summary

The behaviour regarding the hysteresis as well as the adjustment behaviour depend on several factors. These include: structure of the humidity measuring instrument (installation of the sensor element in the measuring instrument), filter or protective cap, adaptation time, flow velocity, electronic or mathematical corrections, manufacturer, as well as temperature and humidity.

In case of high demands on measuring task and precision, an investigation into hysteresis and adjustment behaviour is recommended.

Published by:

Physikalisch-Technische Bundesanstalt
Deutscher Kalibrierdienst
Bundesallee 100
38116 Braunschweig

www.dkd.eu
www.ptb.de