Int J Thermophys (2008) 29:1632–1643
DOI 10.1007/s10765-008-0432-y

# Miniaturized Two-Pressure Generator for Relative Humidity

**Helmut Mitter**

Published online: 23 April 2008
© Springer Science+Business Media, LLC 2008

**Abstract** The concept and design of a miniaturized two-pressure humidity generator are presented. The generator is suitable for achieving relative humidity ranging from 10% to 95% with uncertainties of under 1% at ambient temperature and can be used for the calibration of relative humidity instruments in the laboratory and on site. By virtue of the concept, the relative humidity achieved is traced to only two pressure measurements. Further references are not necessary. A special adjustment algorithm enables standard industrial pressure sensors to be used. The two pressure sensors are synchronized by aligning their readings at ambient pressure. The resulting correlation of the uncertainties leads to very small systematic errors in the humidity display. Each humidity generator can still be individually adjusted through comparison with a chilled-mirror hygrometer, the total uncertainty of the generator being largely determined by the uncertainty of this hygrometer. Any drift of the pressure sensors that occurs can be compensated at any time by performing an alignment at ambient pressure without changing the individual adjustment of the generator. It can be demonstrated that the uncertainty of the displayed humidity remains practically unchanged over the course of a year by virtue of this alignment process.

**Keywords** Humidity generator · Miniaturized · Relative humidity · Traceable · Two-pressure generator

## 1 Introduction

With the market for humidity meters for industrial and semi-industrial applications expanding rapidly, it is becoming increasingly useful to have calibration equipment

H. Mitter (✉)
E+E Elektronik Ges.m.b.H, Langwiesen 7, Engerwitzdorf 4209, Austria
e-mail: helmut.mitter@epluse.at

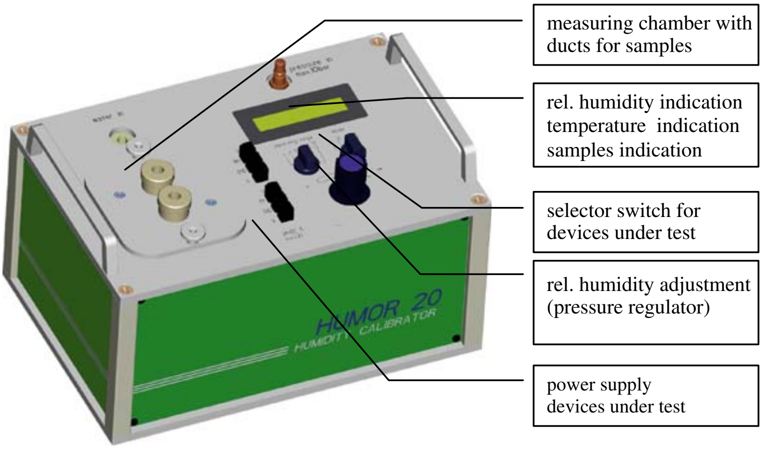


**Fig. 1** Miniaturized two-pressure generator “HUMOR 20” (E+E Elektronik, Austria)

that enables the measurand “relative humidity” to be traceable to international units. Various commercially available humidity generators are, in principle, suitable to provide this type of proof. However, such systems are generally very complex and expensive and only suitable for stationary operation, rendering them unsuited to in-house quality control departments catering to a broad market. Saturated, and also unsaturated, salt solutions are still used for relative humidity calibration. In this case, however, it is very difficult, if not impossible, to demonstrate complete traceability to international units. Various miniaturized humidity generators are now available on the market. In most cases, these work on the principle of a mixed-gas generator with an internal reference, with either a dedicated chilled mirror hygrometer or a capacitive polymer sensor serving as the internal reference. In the first case, high system costs must be considered. The second case provides a reference that to all intents and purposes exhibits the same stability and measuring uncertainty as most of the devices to be tested.

A transportable, user-friendly humidity generator (Fig. 1) employing the same working principle as a two-pressure generator will be presented. Basically, this device displays humidity using a fundamental technique analogous to, for instance, the reference humidity generator of NIST [1]. The traceability of the device is ensured by periodic calibration against a traceable chilled-mirror hygrometer. Between the periodic calibrations, the device operates with high stability due to its fundamental basis. The generator works at ambient temperature and therefore displays the relative humidity at a slightly elevated ambient temperature. The only operating resources required are a power supply and compressed, oil-free air at 1.1 MPa.

The aim of the paper is not to give a full uncertainty evaluation of the generator but to demonstrate how to minimize the influence of pressure sensor tolerance and drift on the performance of the generator by means of different adjustment procedures.

## 2 Generator Concept and Setup

Compressed oil-free air at a pressure of 1.1 MPa is fed via a pressure regulator into the saturator chamber where it becomes completely saturated with water vapor. The pressure regulator allows the pressure inside the saturator chamber to vary, depending on the requested relative humidity. By varying the pressure in the saturation chamber between approximately 1 MPa and 105 kPa at an ambient pressure of $p_a = 100\,\text{kPa}$, the relative humidity in the measuring chamber can be varied from 10% to 95%. Then, the compressed and saturated gas is fed to a second pressure reduction unit via a heated line. The pressure of the gas is first regulated to 15 kPa above ambient pressure and then throttled to ambient pressure $p_a$ via a heated needle valve. The needle valve is used to set a gas flow of $3\,\text{L} \cdot \text{min}^{-1}$. This is largely independent of the pressure in the saturation chamber [2,3], as the admission pressure of the needle valve is always held stable at $p_a + 15\,\text{kPa}$. Finally, the humid gas is fed into a measuring chamber where the required relative humidity is achieved (Fig. 2), and ultimately released into the open air via an exhaust line. The displayed relative humidity $U_w$ in the measuring chamber is derived from the saturation vapor pressure in the saturator $e'_w(t_1, p_1)$ [4] at temperature $t_1$ and pressure $p_1$, the relationship between the pressures in the saturator and the measuring chamber, and the associated saturation vapor pressure in the measuring chamber at temperature $t_2$, according to

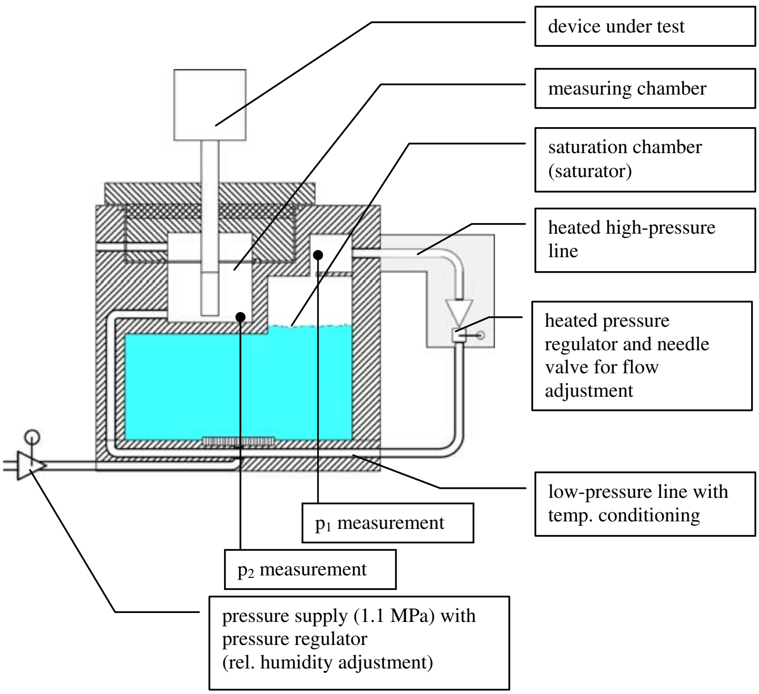


**Fig. 2** Principle scheme of the miniaturized two-pressure generator

$$U_w = \frac{e'_w(t_1, p_1)}{e'_w(t_2, p_2)} \frac{p_2}{p_1} \times 100 \tag{1}$$

$$e'_w(t, p) = e_w(t) f(t, p) \tag{2}$$

where $e_w(t)$ is the saturation vapor pressure in the pure phase with respect to water [5,6], $f_w(t, p)$ is the enhancement factor of air [7], and $e'_w(t, p)$ is the saturated vapor pressure of the actual system in the presence of air or nitrogen with respect to water [4].

The measuring chamber and saturation chamber are manufactured jointly from a solid, highly heat-conductive metal block (special aluminum alloy), the measuring chamber being positioned within the saturation chamber (Fig. 2). The generator has to be operated either with distilled water or deionized water, and the user is obliged to change the water each month for purity reasons. However, failing to change the water for several months resulted in no measurable contamination effects on the achieved relative humidity.

Before being discharged into the measuring chamber, the humid gas is also fed repeatedly through gas conduits inside the wall of the saturator which very effectively brings the temperature of the gas into equilibrium with that of the saturator. These design features ensure that the saturator temperature $t_1$ and measuring chamber temperature $t_2$ are practically the same and Eqs. 1 and 2 can therefore be simplified:

$$t = t_1 = t_2$$

$$U_w = \frac{e'_w(t, p_1)}{e'_w(t, p_2)} \frac{p_2}{p_1} \times 100 = \frac{e_w(t) f(t, p_1)}{e_w(t) f(t, p_2)} \frac{p_2}{p_1} \times 100 = \frac{p_2}{p_1} \frac{f(t, p_1)}{f(t, p_2)} \times 100 \tag{3a}$$

Equality of temperatures is ensured by the construction of the chambers as described in Sect. 2 and shown in Fig. 2. Also, the effects of changing environmental temperatures are shown in Fig. 7. Even if the ambient temperature differs by more than 10 K from the chamber temperature, the effect on the achieved relative humidity is very small. Nevertheless, the user has to operate the generator under normal laboratory conditions without heat radiation sources.

As the generator is operated in a restricted temperature range for an average temperature $t$, the relation $f(t, p_1)/f(t, p_2)$ can be numerically approximated with sufficient accuracy by a polynomial in $p_2/p_1$, $f(p_2/p_1)$

$$\frac{f(t, p_1)}{f(t, p_2)} \rightarrow f\left(\frac{p_2}{p_1}\right) \quad \text{(polynomial in } p_2/p_1\text{)} \tag{3b}$$

and the fundamental equation of a two-pressure humidity generator is obtained:

$$U_w = \frac{p_2}{p_1} f\left(\frac{p_2}{p_1}\right) \times 100 \quad [\%] \tag{3}$$

Apart from a small correction parameter that takes into account the real saturation behavior of air, the displayed humidity depends only on the pressure relationship between the measuring chamber and the saturation chamber. The pressure measurement and its measuring uncertainty are therefore crucially significant. Although other device-specific properties such as temperature homogeneity and saturation behavior play a role in calibrating a generator and can lead to either systematic display errors or increased uncertainty, this design means these properties will not change significantly over the course of time and can be corrected by adjusting the device.

## 3 Adjustment and Calibration Concept

A key objective in the development of the humidity generator was to keep system costs low. For the pressure measurement, industrial pressure transmitters with a specified uncertainty of 0.5% of the maximum readout are used. A simple estimate shows immediately that the pressure sensor specification leads to an uncertainty of up to 6% rh for the displayed relative humidity. In principle, this deviation could be corrected by adjusting the generator, e.g., with reference to a chilled-mirror hygrometer. However, similar problems are immediately encountered when looking at the long-term stability of the pressure sensors, which means that this procedure does not produce an acceptable result without employing additional measures. An adjustment concept is therefore implemented, in which the tolerances and drifts of the sensors are largely cancelled out by means of a software-based adjustment of the two pressure sensors for $p_1$ and $p_2$ at ambient pressure, thereby ensuring the humidity generator achieves a high degree of accuracy and stability. The individual steps in the adjustment concept

- Basic adjustment
- Adjustment
- Alignment

are presented in the sections that follow, and an uncertainty estimate is presented for the humidity generator, both in its new state and after one year. All steps of the adjustment concept can be repeated at any time, but usually for the user there is only the need to do step 3 (alignment).

### 3.1 Basic Adjustment

For pressure measurement, industrial sensors with a specified tolerance of 0.5% of the measuring range are used, the specification being interpreted as a rectangularly distributed uncertainty. The pressure sensors are described by the following model:

$$\begin{aligned}
&\text{Saturation chamber } p_1: \\
&\text{Measuring range} \quad 0\text{–}1\,\text{MPa} \\
&p_1 = a_0 + a_1 p_{1\text{w}} \qquad (4) \\
&a_0 = 0 \quad u(a_0) = 5.8\,\text{kPa} \qquad (k = 2) \\
&a_1 = 1 \quad u(a_1) = 5.8 \times 10^{-3} \quad (k = 2)
\end{aligned}$$

Measuring chamber $p_2$:

Measuring range 0–0.2 MPa

$$p_2 = b_0 + p_{2\text{w}} \tag{5}$$

$b_0 = 0 \quad u(b_0) = 1.15\,\text{kPa} \quad (k = 2)$

$p_2 = p_\text{a} \quad p_\text{a} \ldots$ ambient pressure

$p_{1\text{w}}, p_{2\text{w}}$ measured values in saturation chamber and measuring chamber, respectively

The uncertainties of the pressure measurement are derived from the models of the pressure sensors, Eqs. 4 and 5, using

$$u(p_1) = \left[u^2(a_0) + p_{1\text{w}}{}^2 u^2(a_1)\right]^{1/2} \tag{6}$$

$$u(p_2) = u(b_0) \tag{7}$$

As the aim of the paper is to point out the effects of pressure sensor tolerance and drift and how to eliminate them by a special adjustment procedure, here the measurement uncertainties of $p_{1\text{w}}$ and $p_{2\text{w}}$ are neglected. Besides, the contribution of the measurement uncertainties of $p_{1\text{w}}$ and $p_{2\text{w}}$ is very small compared with the effects of pressure sensor tolerance (~0.2% rh compared with 6% rh).

If the pressure sensors are used without any additional measures, the uncertainty of the displayed relative humidity can be determined as follows from Eq. 3:

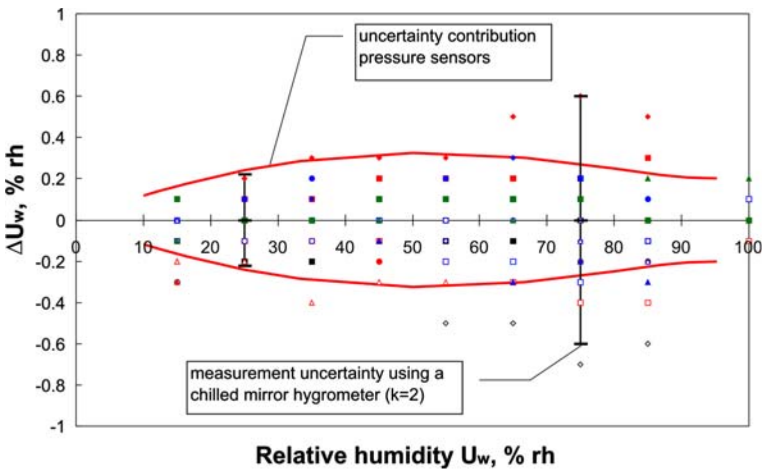


**Fig. 3** Deviation of indicated relative humidity of 30 generators from a certified chilled-mirror hygrometer after basic adjustment. Uncertainty contributions of the pressure sensors after basic adjustment, including the contribution of pressure measurement uncertainty and the measurement uncertainty using a chilled-mirror hygrometer of about 0.22% at 25% and 0.6% at 75%, respectively (all $k = 2$), are also indicated

$$u(U_{\mathrm{w}}) = \left[ \left( \frac{1}{p_1} u(p_2) \right)^2 + \left( \frac{-p_2}{p_1^2} u(p_1) \right)^2 \right]^{1/2} \tag{8}$$

which leads to the uncertainty mentioned above of ∼6% rh at 95% rh (the small correction made by the enhancement factors has been omitted here as it does not make any significant contribution to the total uncertainty). In the basic adjustment, the generator is depressurized, both pressure sensors are read at ambient pressure $p_{\mathrm{a}}$, and the difference $\Delta(p_{\mathrm{a}}) = p_1(p_{\mathrm{a}}) - p_2(p_{\mathrm{a}})$ calculated. Using the difference, a corrected value $p_{1k}$ is calculated for the saturator pressure and a revised model equation is obtained for the corrected pressure $p_{1k}$

$$p_{1k} = a_0 + a_1 p_{1\mathrm{w}} - \Delta(p_{\mathrm{a}}) = b_0 + a_1(p_{1\mathrm{w}} - p_{\mathrm{a}}) + p_{\mathrm{a}} \tag{9}$$

and the uncertainty of $p_{1k}$ is

$$u^2(p_{1k}) = u^2(b_0) + (p_{1\mathrm{w}} - p_{\mathrm{a}})^2 u^2(a_1) \tag{10}$$

Basically, the offset of the pressure measurement $p_1$ at ambient pressure $p_{\mathrm{a}}$ is corrected to the same value as $p_2$ and the two pressure measurements synchronized at ambient pressure. The readings from the two pressure sensors thereby become correlated, with total correlation at ambient pressure. The uncertainty of the displayed humidity, taking into account the correlation, is derived as follows from Eqs. 3, 5, and 9:

$$u^2(U_{\mathrm{w}}) = u^2(b_0) \left[ \frac{1}{{p_{1k}}^2} + \frac{{p_2}^2}{{p_{1k}}^4} - 2\frac{p_2}{{p_{1k}}^3} \right] + \frac{{p_2}^2}{{p_{1k}}^4} \left[ (p_{1k} - p_{\mathrm{a}})^2 u^2(a_1) \right] \tag{11}$$

It can easily be demonstrated that the uncertainty of the displayed relative humidity $u(U_{\mathrm{w}})$ for $p_{1k} = p_2 = p_{\mathrm{a}}$ ($\rightarrow U_{\mathrm{w}} = 100\%$) becomes exactly zero (total correlation). In practice, the uncertainty of the pressure measurements includes the standard deviation from random variations, the limited resolution of the electronics, and the sensor stability must also be taken into account, which results in a further small residual uncertainty of approximately 0.2% rh at the adjustment point. Figure 3 shows measurements of the displayed humidity compared to a certified chilled-mirror hygrometer after the basic adjustment. The uncertainty calculated per Eq. 11 resulting from the pressure sensor tolerance is also shown, including the contribution from the pressure measurement uncertainty of about 0.2%. Most measuring values lie within the uncertainty estimate of Eq. 11. However, if the measuring uncertainty of the chilled-mirror hygrometer is also taken into account, all measurements and the uncertainty estimate resulting from the pressure sensor contribution are compatible after the basic adjustment.

### 3.2 Adjustment of the Humidity Generator

After the basic adjustment, the humidity generator is checked against a certified chilled-mirror hygrometer and the deviations are stored as a correction table. Figure 4 shows

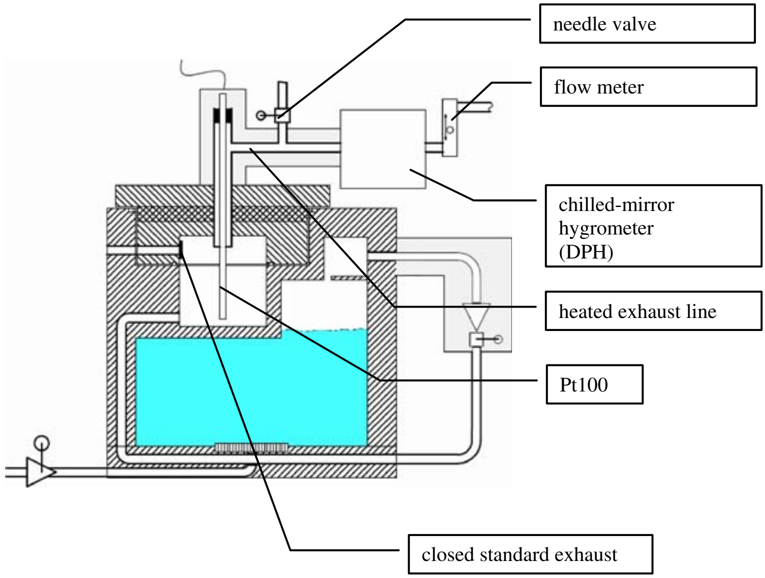


**Fig. 4** Setup for verifying a generator (principle scheme) using a chilled-mirror hygrometer

the setup for the calibration of the generator. The output of the gas stream into the measuring chamber is closed, and the gas stream is discharged via a special insulated pipe. A Pt100 reference thermometer is placed within the pipe. The gas stream is then routed via a heated line and split by a T-section, with one part (typically $0.5\,\mathrm{L}\cdot\mathrm{min}^{-1}$) being sent to the chilled-mirror hygrometer while the rest is released into the open air via a needle valve controlling the gas stream split. Located behind the chilled-mirror hygrometer is a flowmeter to control the gas stream through the chilled-mirror hygrometer (DPH). When calculating the relative humidity from temperature and dew-point temperature, the following key uncertainty contributions are taken into account:

– DPH calibration uncertainty
– Stability of DPH in the calibration interval
– Dew-point stability during the measurement
– Pressure loss in the measuring line
– Pt100 calibration uncertainty
– Pt100 self-heating
– Pt100 heat conduction
– Stability of the Pt100 in the calibration interval
– Temperature stability during calibration
– Spatial temperature inhomogeneity in the saturation and measurement chambers
– Resolution of the humidity generator

When adjusted in this way, the generator exhibits deviations from the chilled-mirror reference within the specified tolerance indicated in Fig. 5. The total uncertainty of the generator is calculated from the specification limits (rectangular distribution) and the uncertainty of the calibration using the chilled-mirror hygrometer. The spatial

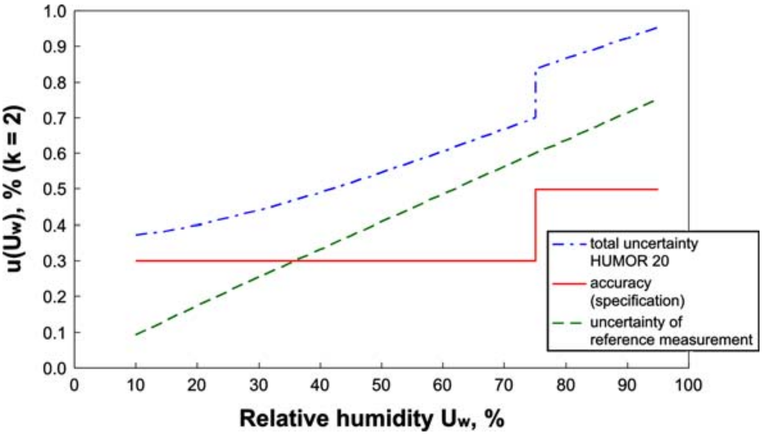


**Fig. 5** Specification, calibration uncertainty, and total uncertainty ($k = 2$) of a new generator

distribution of the relative humidity within the measuring chamber is largely determined by the temperature inhomogeneity of 0.1°C (difference between maximum and minimum values of a rectangular distribution) in the measuring chamber, varies from 0.03 to 0.33% rh depending on the displayed humidity, and is included in the uncertainty calculation.

### 3.3 Alignment

By means of the adjustment outlined in Sect. 3.2, all systematic deviations of the generator from an ideal generator were corrected, within the measuring uncertainty of a DPH. In particular, the systematic readout errors of the pressure sensors were also corrected. During operation, however, a generator drift must be reckoned with. This derives almost exclusively from drift of the pressure sensors. For the pressure sensors, the manufacturer specifies a maximum drift per year of 0.5 kPa ($p_2$) or 1 kPa ($p_1$). For the annual drift, the manufacturer's specifications (rectangular distribution) are doubled, resulting in the following models for the *additional* uncertainty of the pressure measurement after one year, based on Eqs. 4 and 5:

$$\begin{aligned} p_1 &= a_0{}' + a_1{}' p_{1\mathrm{w}} \\ a_0{}' &= 0 u(a_0{}') = 2.3\,\mathrm{kPa}(k = 2) \\ a_1{}' &= 1 u(a_1{}') = 2.3 \times 10^{-3} (k = 2) \end{aligned} \tag{12}$$

$$\begin{aligned} p_2 &= b_0{}' + p_\mathrm{a} \\ b_0{}' &= 0 \quad u(b_0{}') = 1.15\,\mathrm{kPa} \quad (k = 2) \end{aligned} \tag{13}$$

Exactly as with the basic adjustment in Sect. 3.1, here too the generator is depressurized and the pressure sensors are once again synchronized at ambient pressure. Unlike the basic adjustment, however, the generator correction values per Sect. 3.2

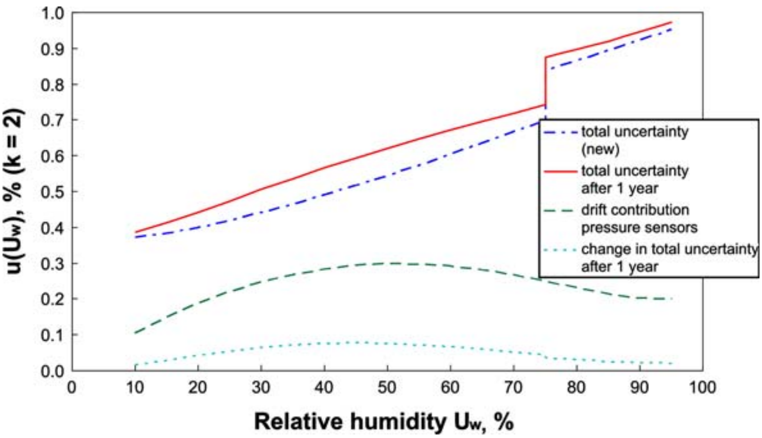


**Fig. 6** Total uncertainty of a new generator and after one year. Also, the drift contributions of the pressure sensors and the change in total uncertainty after one year are indicated ($k = 2$)

are retained in the alignment, i.e., only the change occurring within one year is examined. The additional uncertainty contribution after a year is then derived as follows, according to Eq. 11:

$$u^2(U_\mathrm{w}) = u^2(b_0{}') \left[ \frac{1}{p_{1k}{}^2} + \frac{p_2{}^2}{p_{1k}{}^4} - 2\frac{p_2}{p_{1k}{}^3} \right] + \frac{p_2{}^2}{p_{1k}{}^4} \left[ (p_{1k} - p_\mathrm{a})^2 u^2(a_1{}') \right] \tag{14}$$

Figure 6 shows the uncertainty contribution resulting from the drift after one year. An additional contribution resulting from the resolution of the electronics has also been taken into account. The total uncertainty when new and after one year, and the increase in uncertainty after one year, has also been entered.

The generator can be aligned by the user at any time and as often as required. An alignment is particularly recommended whenever the humidity readout deviates significantly, i.e., more than 0.3% rh —from 100% rh when the generator is depressurized.

## 4 Measurements

For a stable humidity display, the generator requires only a room with normal climatic conditions and no direct sources of thermal radiation. In order to demonstrate the stability of the humidity display with fluctuating temperatures, a generator was stabilized at 75% and exposed to changing temperature conditions in a temperature cabinet, while at the same time the displayed humidity was monitored with a chilled-mirror hygrometer (Fig. 7). At different ambient temperatures of 10, 25, and 40°C, the largest change in the achieved humidity is less than 0.2% rh. During the temperature change from 10 to 25°C and from 25 to 40°C, the humidity display is incorrect by less

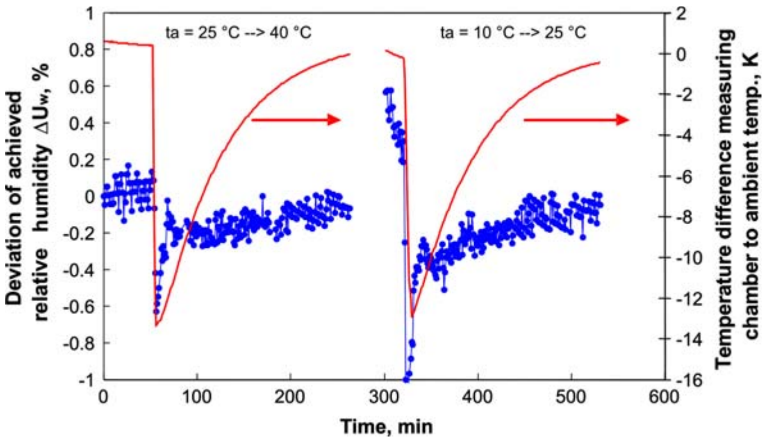


**Fig. 7** Influence of the ambient temperature $t_a$. Different ambient temperatures of 10, 25, and 40°C lead to a change in achieved relative humidity of less than 0.2%

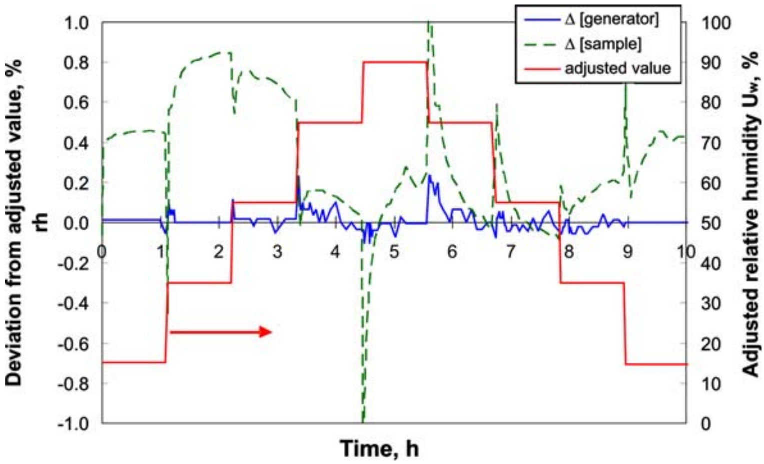


**Fig. 8** Response of generated humidity and of a device under test after selecting a new value

than 1%, even though there is a difference of up to 12°C between the temperature of the generator's measuring chamber and the ambient temperature.

Figure 8 shows the response of the humidity display over time, the deviation of a humidity meter awaiting calibration from the displayed humidity, and the deviation of the generator from the target humidity. The target humidity is stable to within 0.1% rh after a few minutes; the settling time is primarily determined by the speed at which a new target pressure can be set in the saturator. The settling response of the device under test is largely determined by its properties. The generator itself makes practically no contribution to the stabilization time.

The humidity generator can be traced to international units (SI units) by means of its calibration against a certified chilled-mirror hygrometer. Because of its high stability and small uncertainty, it is used as a humidity reference device in various

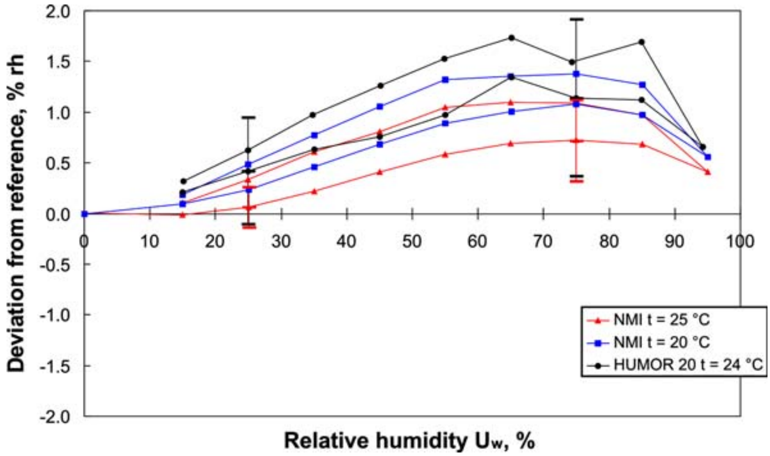


**Fig. 9** Comparison of calibration measurements using (1) the described miniaturized two-pressure generator (HUMOR 20) (2) the national Austrian reference generator (NMI). The uncertainties of each generator ($k = 2$) are indicated

calibration laboratories. Figure 9 compares the calibration of a humidity meter based on a capacitive polymer sensor carried out using the Austrian national standard generator at two temperatures (20 and 25°C) with a calibration using the described "HUMOR 20" miniaturized two-pressure generator as a reference device of the Austrian Calibration Service (ÖKD). The accredited uncertainties ($k = 2$) are shown for each case. Within the combined measuring uncertainties, no differences in the calibrations can be identified.

## References

1. S. Hasegawa, J.W. Little, J. Res. Nat. Bur. Stand. **81A**, 81 (1977)
2. Accorded patent, *US 6 299 147 B1*
3. Accorded patent, *EP 0 989 373 B1*
4. L.P. Harrison, in *Humidity and Moisture, Fundamentals and Standards*, vol. 3, ed. by A. Wexler, W.A. Wildhack (Reinhold Publishing, New York, 1965), pp. 3–69
5. A. Wexler, J. Res. Nat. Bur. Stand-A Phys. Chem. **80A**, 775 (1976)
6. D. Sonntag, Z. Meteorol. **70**, 340 (1990)
7. L. Greenspan, J. Res. Nat. Bur. Stand-A Phys. Chem. **80A**, 41 (1976)