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Calibration of hygrometers at non-static conditions

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Abstract

The current practice of calibrating humidity sensors at discrete measurement points under static conditions is time-consuming, i.e. expensive, due to the long stabilization times. In order to reduce the calibration time, we introduce a new calibration method based on humidity ramp measurements, i.e. measurements are performed at first while humidity is increased with constant speed and then decreasing with the same speed. A calibration system based on the mixing flow humidity generation principle was developed for generating linear humidity ramps inside a measurement chamber. Two different calibration approaches were investigated. In the first one, high accuracy was targeted with moderate ramp speeds (2 h to 12 h) and a large volume measurement chamber using a chilled mirror hygrometer as a reference. In the second approach, a shorter calibration time was achieved with fast ramp speeds (0.5 h to 2 h) and a small volume chamber using a fast capacitive humidity sensor as a reference. The developed calibration procedure was validated by comparing results of non-static and static calibrations to each other for five different capacitive humidity sensors from two manufacturers. The non-static calibration was found to provide equivalent results compared to the static calibration with a potential of reducing the overall calibration time by up to 50%. Preconditions of the non-static calibration related to the ramp speed and sensors response times are discussed, and an estimation of the calibration uncertainty is given. The main advantage of the developed non-static calibration method is that calibrations can be performed faster and more data on the sensor behaviour is obtained than with the conventional point-wise calibration without any significant increase in uncertainty.

Keywords: relative humidity, calibration, hygrometer

(Some figures may appear in colour only in the online journal)

1. Introduction

Humidity measurements are frequently performed in many meteorological applications, as well as in various fields of industry as part of environmental monitoring, manufacturing and process control. In many cases, humidity is the key parameter defining process efficiency and product quality and, in some cases, even requirements for measurement accuracy exists, e.g. pharmaceutics [1] and weather observations [2]. Consequently, sensors need to be traceably calibrated on a regular basis to ensure their performance.

The current practice of calibrating humidity sensors is time consuming and therefore costly; 'it can be estimated that by saving only 1.5 h of the calibration time for 1000 units, one man-year of costs can be cut' [3]. Calibrations are usually performed at discrete measurement points under static conditions [4, 5]. Due to the long stabilisation time required for each point, and potentially significant hysteresis of the sensor, a calibration at the accuracy level provided at National Metrology Institutes (NMI) might take several days and an industry level calibration up to one day.

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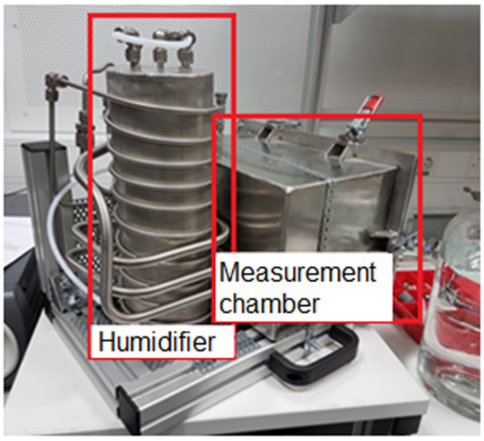

Figure 1. Calibration system comprising a mixed flow generator with a bubbler humidifier and a measurement chamber.

Figure 2. Calibration system fitted inside a climatic chamber.

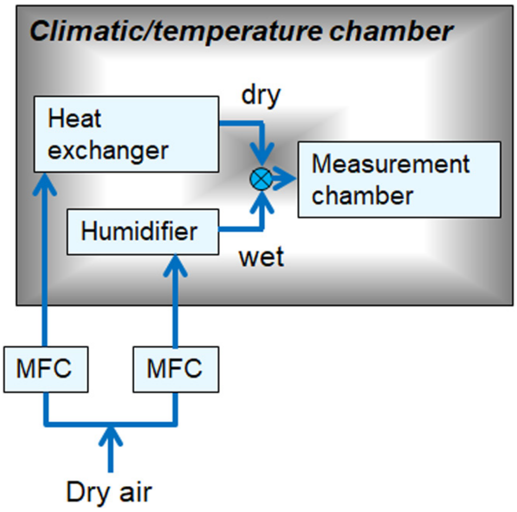

Figure 3. Schematic of the calibration system. MFC = Mass flow controller.

In order to reduce the calibration time, a calibration method based on incomplete stabilization was developed. Much research has been published on static calibration methods. However, there is very little published work on calibrations under changing humidity conditions. Test methods applied by manufacturers of humidity instruments also include response time tests, but methods or procedures for non-static calibrations, which provide SI traceability have not been developed. A method for calibrating humidity sensors at non-static conditions based on Laplace-domain studies and data fusion has recently been demonstrated [6]. The method is applicable to very fast humidity ramps where the transient behaviour of humidity sensors becomes relevant. However, the method involves mathematical modelling of sensor response, which inherently causes additional uncertainties.

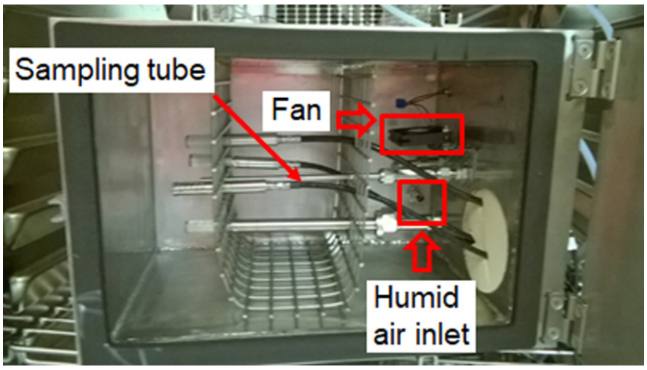

Figure 4. Humidity sensors fitted inside the large volume chamber.

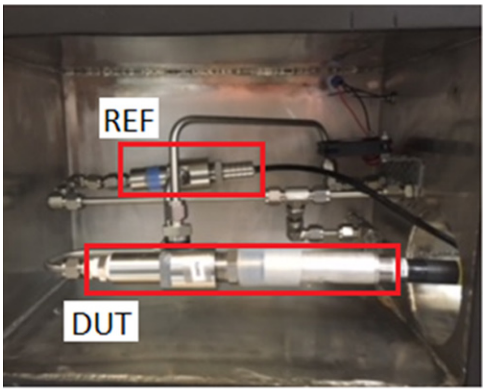

Figure 5. Humidity sensors fitted inside small chambers to enable fast humidity ramps.

In this study, we present a more practical approach for calibrating relative humidity sensors using moderate speed humidity ramps. The aim was to develop a calibration procedure that is less time consuming than the conventional method, but yet provides equivalent results without significantly increasing in uncertainty. This paper presents the developed calibration system and procedure including validation results and an estimation of the calibration uncertainty.

2. Non-static calibration

The basic idea is to generate linear humidity ramps in the desired calibration range by continuously changing, in a controlled way, the humidity inside a measurement chamber. The calibration is based on comparing the device under test (DUT) with a reference hygrometer acting as a secondary standard. Two different approaches were investigated, namely a large

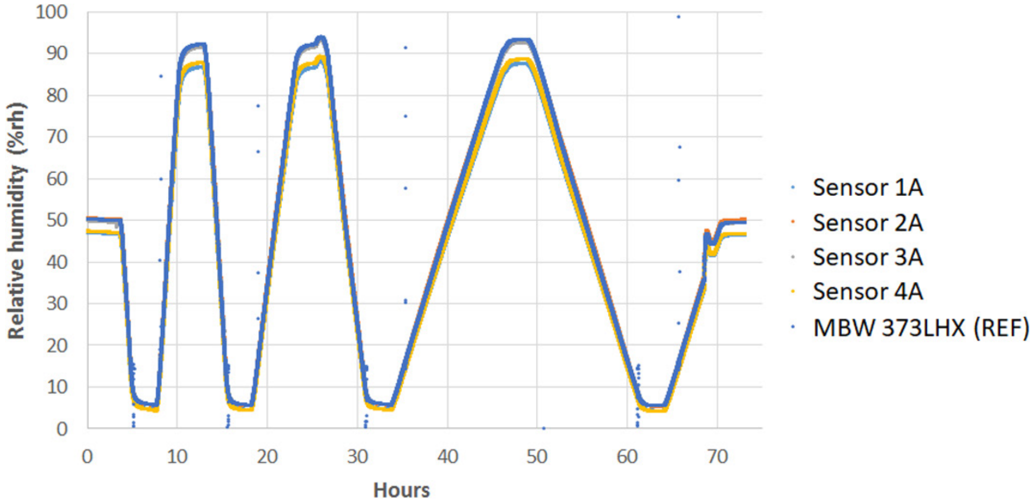

Figure 6. Example of humidity ramps for non-static calibrations with the large volume chamber at three different ramp speeds (rise times about 2 h, 4 h, 12 h for a humidity change from 10 %rh to 90 %rh).

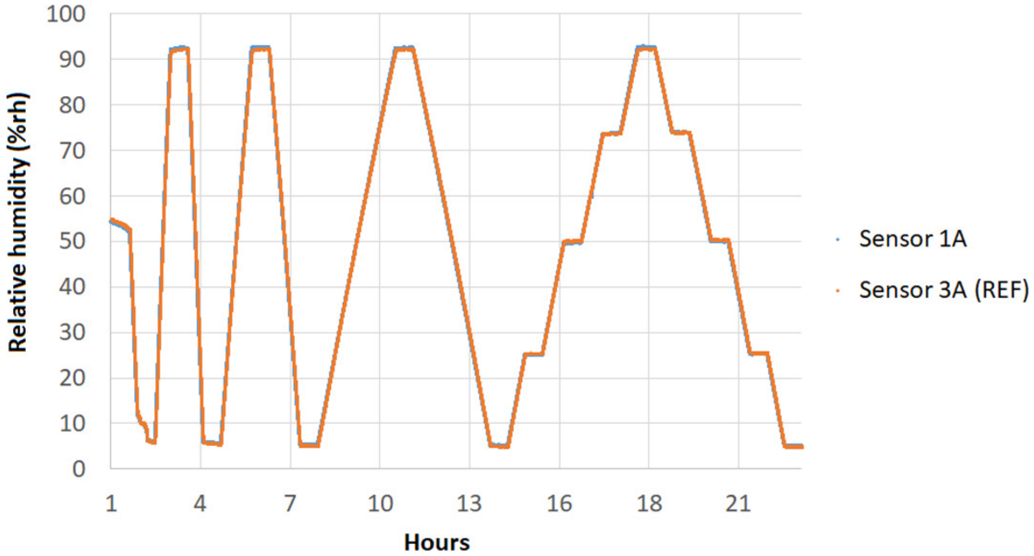

Figure 7. Example of humidity ramps for non-static calibrations with the small volume chambers at three different ramp speeds (rise times about 0.5 h, 1 h, 2 h for a humidity change from 10 %rh to 90 %rh).

volume chamber with a high-accuracy dew-point hygrometer as a reference, and a small volume chamber with a capacitive humidity sensor as a reference to enable fast humidity ramps.

2.1. Calibration system

The developed calibration system is based on a mixed flow humidity generator. It has a modular design, which comprises a humidifier and a measurement chamber (figure 1), and it can be easily installed in any commercial temperature test chamber with an inner volume of 200 dm^3 or larger (figure 2). The humidity is generated by mixing dry and humidified air using mass flow controllers located outside the temperature chamber (figure 3). The humidifier is based on the bubbler principle, in which air is humidified by passing it through a cylinder filled with water. To compensate for evaporative cooling, the heating of the water is applied. The generated humid air is thereafter mixed with dry air before entering the measurement chamber. A dedicated LabVIEW program was developed for controlling the calibration system and to enable automatic calibrations at non-static conditions.

2.2. Large volume chamber with a dew-point hygrometer reference

In the large volume chamber configuration, the DUT sensors are placed close to each other and next to the sampling tube connected to the reference dew point hygrometer MBW 373LHX (figure 4). A pt-100 temperature sensor is located inside the sampling tube. In this way, the conditions at the point of the sampling match as close as possible the conditions around the DUT. The flow rate of the humid air entering the chamber is rather low (1 l min^{-1}), and therefore a fan is placed inside the chamber close to the humid air inlet in order to properly mix the air inside the chamber. The reference hygrometer (REF) is connected to a pump and the flow rate is

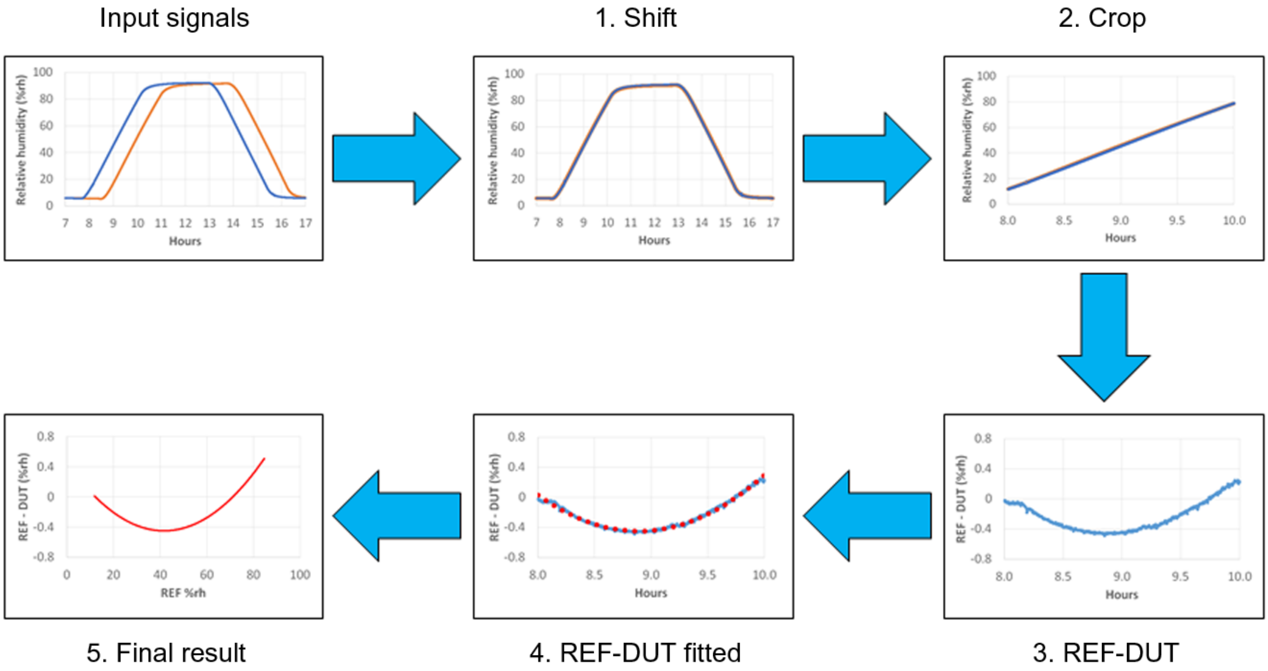

Figure 8. Signal processing scheme for calculating calibration correction (REF—DUT).

Table 1. Summary of experiments.

Chamber	Sequence	DUT[a]	REF	Results figure
Large volume	Ramp 5 %rh to 95 %rh: 2 h, 4 h, 12 h Static (5 %rh, 50 %rh, 95 %rh)	Sensor 1A Sensor 2A Sensor 3A Sensor 4A	MBW 373LHX	Figures 9 and 11 (25 °C)
Large volume	Ramp 5 %rh to 95 %rh: 2 h, 4 h, 12 h Static (5 %rh, 50 %rh, 95 %rh)	Sensor 1A Sensor 2AF Sensor 3AF Sensor 4A	MBW 373LHX	Figures 10 and 12 (40 °C)
Small volume	Ramp 5 %rh to 95 %rh: 0.5 h, 1 h, 2 h Static (5 %rh, 25 %rh, 50 %rh, 75 %rh, 95 %rh)	Sensor 2AF Sensor 1BF	Sensor 3A	Figure 13 (25 °C)

[a] A and B stands for sensor manufacturer and F indicates that a filter was applied.

adjusted to 0.5 l min^{-1} to ensure that there is a small overpressure inside the chamber; hence humid air is leaking out of the chamber from the sensor electric cord feed-through.

2.3. Small volume chamber with a capacitive humidity sensor as a reference

To enable one humidity ramp, another configuration was applied where the DUT sensor and the reference sensor were placed inside small chambers connected in series (figure 5). In this approach, a capacitive humidity sensor with a fast response time (no filter) was used as a reference instead of a dew point hygrometer. The flow rate of the humid air flowing through the chamber was fixed to 1 L/min. The flow rate was kept stable to maintain constant air velocity around the sensors. This minimizes potential errors due to flow induced changes in thermal and water vapour mass transfer.

2.4. Calibration procedure

The calibration procedure is based on ramping the humidity up and down by changing the ratio of air that passes through the humidifier (humid air) and heat exchanger (dry air). The calibration sequence applied for the large volume chamber is shown in figure 6 for three different ramp speeds. The ramp duration is limited to about 2 h due to the relatively large inner volume (12 dm^3) and the low flow rate (1 l min^{-1}) of the input humid air. Using the smaller chambers, faster humidity ramps (30 min) were generated (figure 7). In addition to the non-static calibration ramps, static measurements were performed

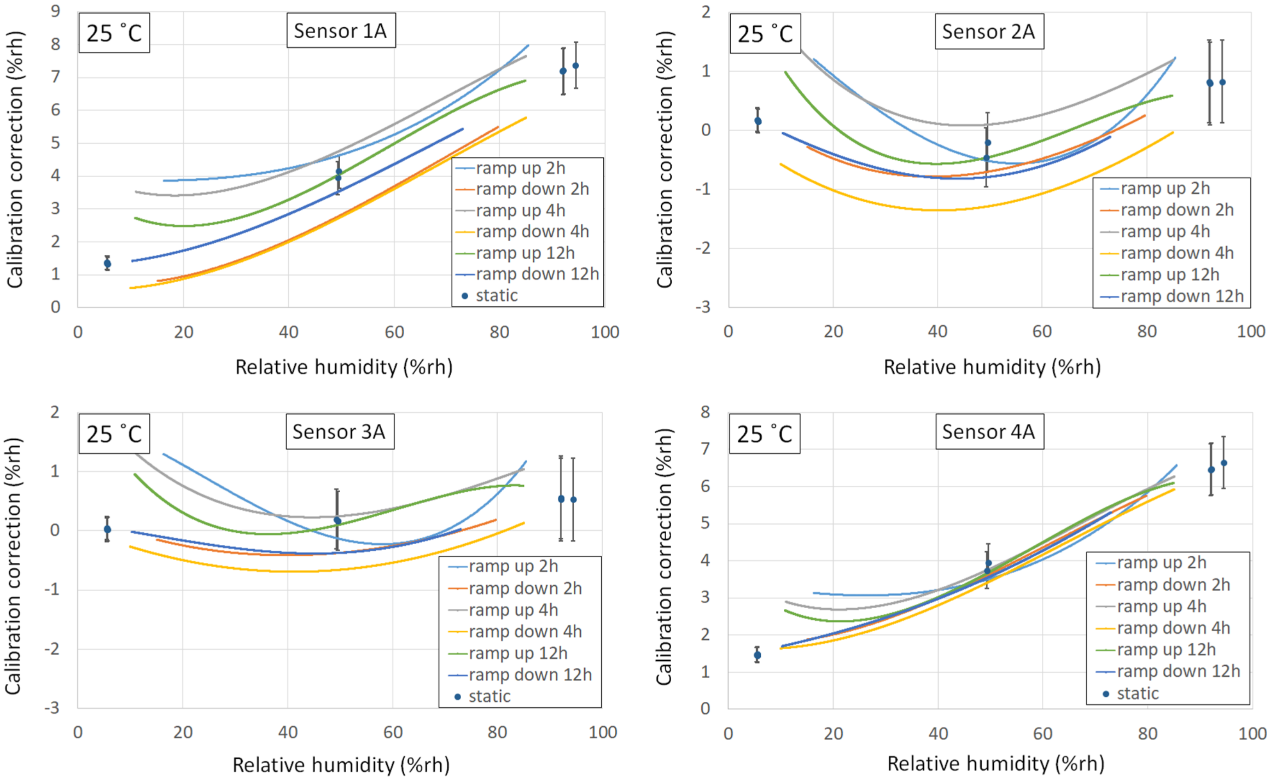

Figure 9. Calibration results obtained with the large volume chamber at 25 °C with three different ramp speeds (rise time of 2 h, 4 h and 12 h). Error bars show the measurement uncertainty ($k = 2$) of static calibration.

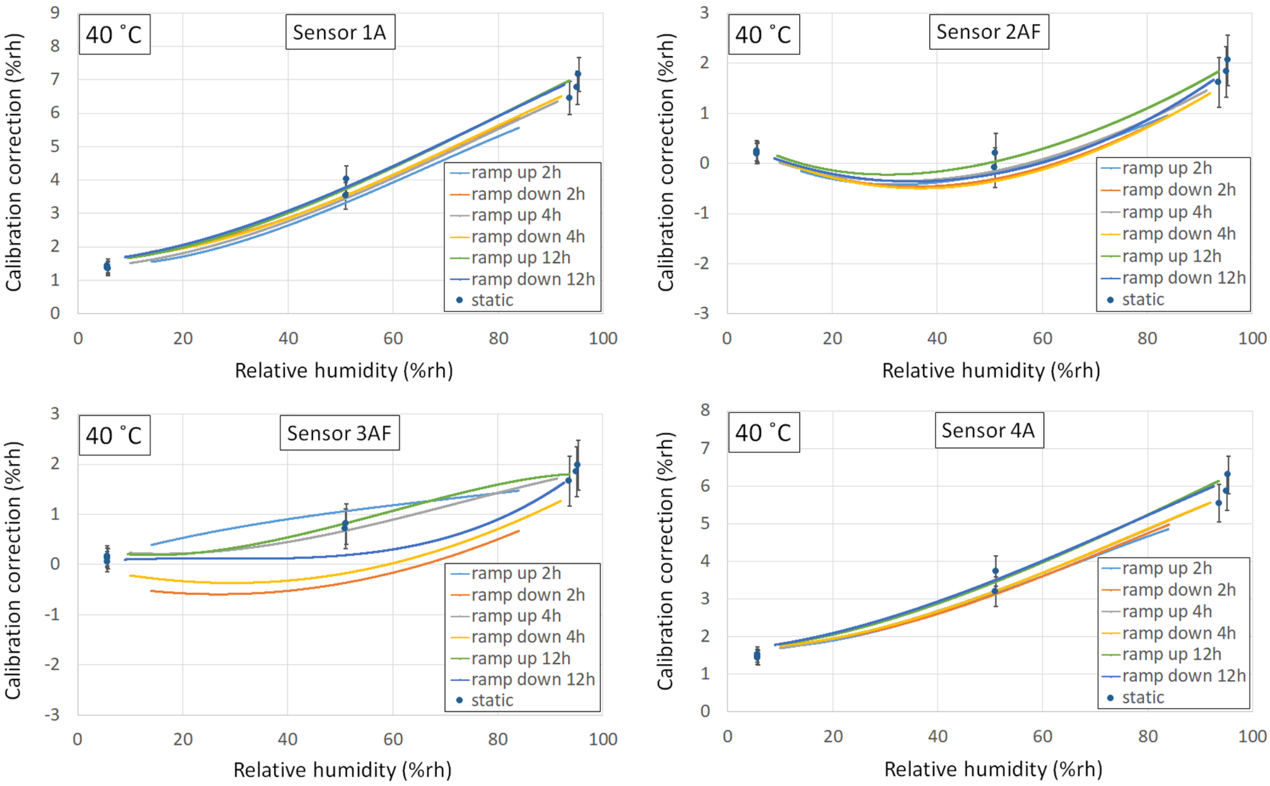

Figure 10. Calibration results obtained with the large volume chamber at 40 °C with three different ramp speeds (rise time of 2 h, 4 h and 12 h). Error bars show the measurement uncertainty ($k = 2$) of static calibration.

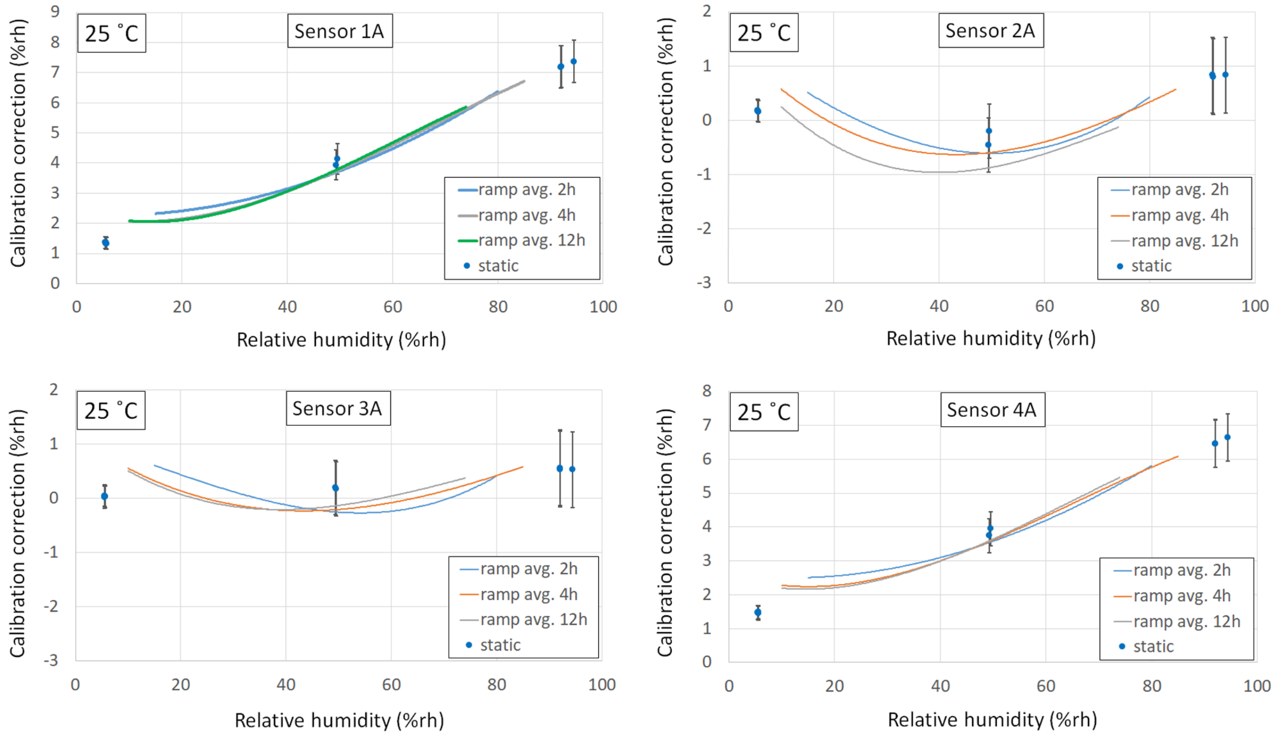

Figure 11. Average of increasing and decreasing ramp calibrations at 25 °C obtained with the large volume chamber at three different ramp speeds (rise time of 2 h, 4 h and 12 h). Error bars show the measurement uncertainty ($k = 2$) of static calibration.

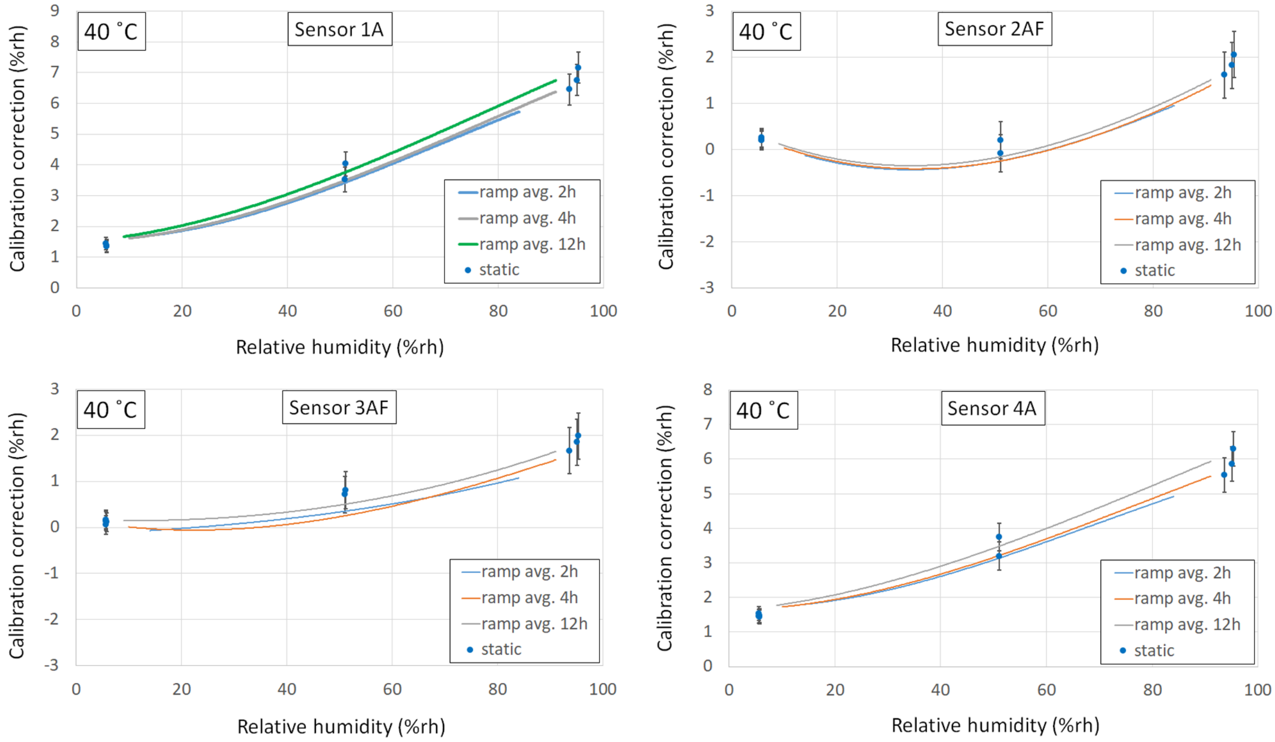

Figure 12. Average of increasing and decreasing ramp calibrations at 40 °C obtained with the large volume chamber at three different ramp speeds (rise time of 2 h, 4 h and 12 h). Error bars show the measurement uncertainty ($k = 2$) of static calibration.

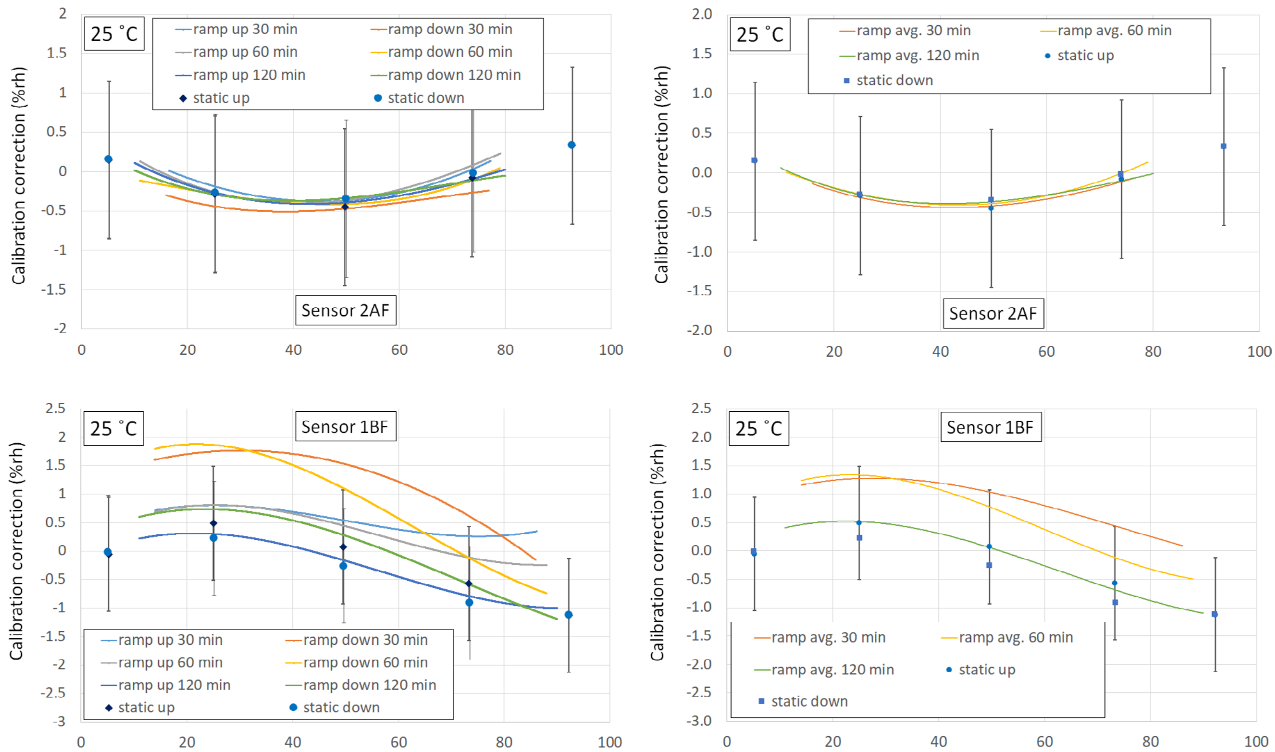

Figure 13. Calibration results at 25 °C for sensors 2AF and 1BF with the small volume chamber at three different ramp speeds (rise time of 0.5 h, 1 h and 2 h). Average of increasing and decreasing ramp calibrations are shown in figures to the right. Error bars indicate the accuracy specification of the sensors ($k = 2$).

at about 5 %rh and 90 %rh. Moreover, for validation purposes, static measurement were performed also at intermediate humidity values to enable a direct comparison of static and non-static calibration results.

2.5. Signal processing scheme

After completing the calibration cycle, some signal processing and data analysis is required for calculating the calibration correction for each sensor as a function of relative humidity of the REF sensor (figure 8). The data processing includes the following steps: 1. DUT signal is shifted in time to match the reference signal by cross-correlating signals. 2. The linear region of the signal ramp is cropped for further analysis. 3. The calibration correction is calculated by subtracting REF and DUT signals. 4. A polynomial fit is applied to the calibration correction. 5. The final result is presented as the sensor calibration correction is a function of relative humidity of the reference.

The REF and DUT sensors will respond differently to the ramping humidity, if the time constants of the DUT and REF sensor are different and long compared to the signal ramp speed. For a constant ramp speed, i.e. a linear change in humidity, different response times will show up as a delay of the sensor signal with a slower response time. An effort to compensate for this effect was made by shifting the signals. In most cases, however, the ramp speed was rather slow (30 min and more) compared to the response times of the sensors (less than 1 min), and therefore no delay in the signal response was observed.

Further analysis is performed for the linear region of the ramp, because in this region the sensors have adapted to the humidity change, i.e. the signals track the humidity change inside the measurement chamber. The calibration correction is presented as a calibration function instead of multiple single points. A polynomial fit is applied to the calibration correction curve and the final results are presented as the calibration correction as a function of relative humidity. The data analysis is performed in LabVIEW.

3. Experiments and results

3.1. Experiments

The validity of the developed calibration method was studied by performing non-static calibrations at different ramp speeds. Capacitive humidity sensors with different response times and characteristics were selected for the studies, including sensors from two manufacturers (denoted A and B) and options with a stainless steel sintered filter (denoted F). The aim was to demonstrate that the non-static calibration provides equivalent results compared to a static calibration, i.e. the ramp speed does not affect the calibration results. The different experiments and applied measurement configurations are summarized in table 1.

3.2. Results with the large volume chamber and dew-point hygrometer reference

The calibration results at different ramp speeds with the large volume chamber were found to be similar, in most cases within 1%, for all studied sensors at the calibration temperature of

Table 2. Example of uncertainty estimation for non-static humidity calibration results at 50 %rh and 25 °C using a chilled mirror hygrometer as a reference.

Source of uncertainty	Standard uncertainty	Sensitivity coefficient	Contribution to uncertainty
Reference dew-point temperature			
Stability of the hygrometer reading	0.010 °C	3.771 %rh °C^{-1}	0.038 %rh
Calibration of the hygrometer	0.045 °C	3.771 %rh °C^{-1}	0.170 %rh
Long-term stability of the hygrometer	0.017 °C	3.771 %rh °C^{-1}	0.065 %rh
Resolution of the hygrometer	0.003 °C	3.771 %rh °C^{-1}	0.011 %rh
Pressure difference (REF versus DUT)	0.011 °C	3.771 %rh °C^{-1}	0.042 %rh
Water vapour-pressure gradients	0.006 °C	3.771 %rh °C^{-1}	0.022 %rh
Reference air temperature			
Stability of the thermometer reading	0.020 °C	2.982 %rh °C^{-1}	0.060 %rh
Calibration of the thermometer	0.006 °C	2.982 %rh °C^{-1}	0.016 %rh
Long-term stability of the thermometer	0.014 °C	2.982 %rh °C^{-1}	0.043 %rh
Resolution of the thermometer	0.003 °C	2.982 %rh °C^{-1}	0.009 %rh
Temperature gradients	0.006 °C	2.982 %rh °C^{-1}	0.017 %rh
DUT			
Stability of the hygrometer reading	0.010 %rh	1	0.010 %rh
Resolution of the hygrometer	0.003 %rh	1	0.003 %rh
Uncertainties of non-static procedure			
Hysteresis of results	0.173 %rh	1	0.173 %rh
Sampling time of the hygrometer	0.058 %rh	1	0.058 %rh
Fitting of calibration results	0.115 %rh	1	0.115 %rh
Combined standard uncertainty of non-static calibration			0.30 %rh
Expanded uncertainty of non-static calibration ($k = 2$)			0.60 %rh

25 °C and 40 °C (figures 9 and 10, respectively). Moreover, the non-static results were found to correspond well to the static calibration results in most cases, demonstrating that the non-static calibration provides similar results compared to the static calibration.

A closer inspection, however, reveals that the ramp speed has a slight effect on the calibration results, such that a slower ramp speed results in a smaller hysteresis. This is reasonable, since the sensors have more time to adapt to the changing conditions at a slower ramp speed. Based on the results, it cannot be concluded to which extent the observed hysteresis is attributed to the chilled-mirror hygrometer or the capacitive sensor. It is well known that capacitive humidity sensors exhibit hysteresis due to the slower diffusion time of moisture sensitive films while dehumidifying [7]. On the other hand, dew-point hygrometers are known to have longer response times than capacitive sensors owing to their operating principle based on the equilibrium between water on a cooled surface and water vapour in the gas sample.

Another thing to notice is the inconsistent shape of the calibration correction for increasing humidity ramps at relative humidities around 20 %rh for calibrations performed at 25 °C (see e.g. figure 9 sensor 4A). This humidity corresponds to a dew point of 0 °C, which implies that in case of an increasing humidity ramp, the mirror of the dew-point hygrometer will be covered with ice. It is likely that the dew-point hygrometer will respond differently to humidity changes depending on the physical state (and phase transition) of the water layer on the mirror. For the decreasing humidity ramp, a similar behaviour was, however, not observed. This is probably because a phase transition has not yet been initiated, or that the phase transition from water to ice causes a different response. For calibrations at 40 °C, the water on the mirror is in a liquid is at all times, and therefore no such effect was observed.

The hysteresis in the calibration correction is larger at 25 °C than at 40 °C for sensor 1A and sensor 2A, while for sensors 3A and 4A the hysteresis behaviour is similar at 25 °C and 40 °C. The reason for the different behaviour of the sensors is unclear. Any influence of the filter on the response of sensor 2A and 3A at 40 °C was not found. It seems that the ramp speeds are much slower than the response times of the sensors even when equipped with filters.

To include hysteresis effects in the calibration results, the final results are given as an average of the calibration points in the increasing and decreasing direction. Despite the hysteresis effect, the averaged results of the increasing and decreasing ramps are, in most cases, equal within 0.5 %rh for different ramp speeds and within the uncertainties of the static calibration results (figures 11 and 12). It seems that although fast humidity ramps might introduce excess hysteresis to the results, the average calibration results are not significantly affected.

3.3. Results with the small volume chamber and capacitive humidity sensor reference

Measurements were also performed with the small volume chamber configuration in order to generate even faster humidity ramps. In these measurements, a capacitive humidity sensor (sensor 3A) was used as a reference to overcome the limitations in response time of the dew point hygrometer at subzero dew point temperatures. Similar to the results with the

Table 3. Example of uncertainty estimation for a non-static humidity calibration at 50 %rh and 25 °C using a capacitive humidity sensor as a reference.

Source of uncertainty	Standard uncertainty	Sensitivity coefficient	Contribution to uncertainty
Reference capacitive humidity sensor (REF)			
Stability of the hygrometer reading	0.010 %rh	1	0.010 %rh
Calibration of the hygrometer	0.400 %rh	1	0.400 %rh
Long-term stability of the hygrometer	0.289 %rh	1	0.289 %rh
Resolution of the hygrometer	0.003 %rh	1	0.003 %rh
Humidity gradients	0.058 %rh	1	0.058 %rh
DUT			
Stability of the hygrometer reading	0.010 %rh	1	0.010 %rh
Resolution of the hygrometer	0.003 %rh	1	0.003 %rh
Uncertainties of non-static procedure			
Hysteresis of results	0.058 %rh	1	0.058 %rh
Sampling time of the hygrometer	0.058 %rh	1	0.058 %rh
Fitting of calibration results	0.115 %rh	1	0.115 %rh
Combined standard uncertainty of non-static calibration			0.6 %rh
Expanded uncertainty of non-static calibration ($k = 2$)			1.2 %rh

large volume chamber, faster ramp speeds slightly increased the hysteresis for both sensors (figure 13). Again, the effect of ramp speed on the average calibration result was found negligible for manufacturer A sensors. However, for the manufacturer B sensor, the average calibration result was found to depend on the ramp speed. A good match with the static calibration results was only achieved with 2 h ramps. For faster ramp speeds, a systematic shift in the calibration correction compared to the static results was found. It seems that the sensor response time is not fast enough to track the humidity change, which can be seen from the raw data (not shown here) as a delay in the signal response compared to the reference sensor. An attempt to correct for the delay by cross-correlating signals was not successful. This indicates that the delay is not constant, but rather depends on the relative humidity and the direction of humidity change, i.e. increasing or decreasing humidity ramp. Therefore, a simple shift in the time domain is not sufficient to compensate for differences in the sensor response characteristics.

The large difference in the response of the tested sensors is probably caused by their different history, i.e. the sensor from manufacturer B has been used in laboratory work for many years and sensors from manufacturer A were newly acquired for the study. Any build-up of contamination on the sensor will slow down the response time, because it will take a longer time for water vapor to equilibrate in the sensor.

4. Uncertainty of non-static humidity calibration

An uncertainty analysis was carried out for both chamber and reference hygrometer configurations (examples shown in tables 2 and 3). In addition to the uncertainties relevant for a static humidity calibration [5], uncertainty components inherent to the non-static procedure need to be considered. Uncertainty sources related to the sampling rate and hysteresis of the sensors, as well as fitting of the results, were investigated more closely.

In the non-static calibration, the finite sampling rate of the sensors causes uncertainty related to temporally matching the output signals. For example, in this study the sensors were sampling at a 2 s sampling rate. This implies that the humidity changes by 0.1 %rh between two consecutive samples for the fastest humidity ramp (5 %rh to 95 %rh in 0.5 h). Thus, the uncertainty related to the limited sampling rate of the sensors will have a very small influence on the overall uncertainty in this case. For faster ramp speeds, however, the limited sampling rate may become significant.

The signal processing scheme of the non-static calibration procedure (figure 8) includes polynomial fitting of the calibrations results. Uncertainty of the fitting procedure is estimated based on the residuals of the fit. In this study, a second order polynomial was in most cases sufficient for fitting the calibration results. The standard uncertainty of fitting was around 0.1%, and thus it had only a small influence on the overall uncertainty. However, the fitting uncertainty depends on the non-linearity of the sensor response, and thus it may become significant for some other type of sensors.

Hysteresis of the results, i.e. the difference between ramp up and ramp down results, was found to be the most significant additional uncertainty source of the non-static calibration procedure. It was shown that hysteresis depends on the ramp speed, such that faster humidity ramps result in a larger hysteresis. Moreover, the hysteresis was found to vary between the sensors, ranging from 0.5 %rh up to 1.5 %rh. As the final calibration result is calculated as an average of the ramp up and down results, the standard uncertainty of hysteresis is less than 0.2 %rh for most cases in this study. In any case, hysteresis will introduce an additional uncertainty compared to the static calibration, especially in calibrations where a high accuracy dew-point hygrometer is used as a reference.

Temperature and humidity gradients inside the measurement chamber were also investigated for both chamber configurations. Very good temperature homogeneity was achieved with the chamber inside climatic chamber design together with a temperature-controlled evaporation unit. The maximum temperature gradients were only 0.02 °C and 0.04 °C for the large and small volume chambers, respectively. In addition, the humidity ramps of the non-static procedure did not influence the temperature gradients in the chamber.

The estimated expanded uncertainty ($k = 2$) of the non-static calibration at 50 %rh and 25 °C was 0.6 %rh and 1.2 %rh when using a chilled mirror hygrometer and a capacitive humidity sensor as a reference, respectively. This is at the same level as typically reported for reference hygrometer-based relative humidity calibration systems applying a static calibration procedure [8–14]. Tables 2 and 3 indicate an excess of 0.19 %rh and 0.03 %rh in expanded uncertainty due to the non-static procedure when using a chilled mirror hygrometer and a capacitive humidity sensor as a reference, respectively.

5. Discussion

The concept of calibrating sensors at non-static conditions is based on the assumption that the rate of change of the sensor reading reflects the rate of change of the humidity inside the measurement chamber. It takes some time for the sensors to adapt to the changing humidity after the ramp has been initiated. It is therefore important that the signal analysis is performed from the linear region of the humidity ramp. If the time constants of the sensors are different and long compared to the ramp speed, a delay between the signals will appear. This delay cannot be simply compensated by shifting the signals in the time domain (as attempted in this study), because the shape of the response function is unique for each sensor. In such cases, a more complex approach based on the modelling of the sensor response is needed [6]. This approach would, however, increase the uncertainty and add complexity of data processing. Thus, the developed non-static method is only applicable to calibrations with moderate ramp speeds, i.e. ramp speeds that are much longer than the sensor response times, and a linear region of the sensor output can be identified.

The main objective of the developed procedure is that it provides equivalent results with the static calibration. In this study, a good match between the static and non-static procedure was found for the studied sensors in cases where the ramp speeds are slow enough compared to the response times of the sensors. The small systematic difference of about 0.2 %rh between the static and non-static results (see e.g. figure 11) is most likely attributed to the non-conventional calibration scheme (figure 6) applied for the static points in the large volume chamber measurements. For a typical staircase calibration scheme (figure 7) as applied in the small volume chamber measurements, a good match between the static and non-static procedure was found for the same sensor (figure 13). The results of both the static and non-static calibration will always depend, to some extent, on the calibration scheme, and therefore it might not even be meaningful to assign an additional uncertainty for the non-static procedure. The essential question is what type of calibration procedure (static or non-static) is more representative of the actual measurement application. In many applications, the humidity is constantly changing and, in such cases, a non-static calibration would provide more reliable information on the sensor behaviour in actual measurement conditions than a static calibration.

The most significant additional uncertainty related to the non-static calibration is the larger hysteresis observed for the sensors compared to the static calibration. Faster humidity ramps result in a larger hysteresis. Although the average calibration result is not influenced by the ramp speed, the larger hysteresis will influence the calibration uncertainty. This is not necessarily a shortcoming of the method, but rather it provides a more realistic estimate of the sensor performance in conditions where the humidity is constantly changing.

The optimum ramp speed will depend on the response time of the sensors and the response of the measurement chamber, which in turn depends on the inner volume and inlet flow rate of the chamber. For the large volume chamber, the rather big internal volume (12 dm^3) and low flow rate (1 l min^{-1}) limits the applicable ramp speed. Despite this, the dynamic calibration is considerably faster than the static one. For example, a typical five-point static calibration, with 1 h stabilization time at each calibration point, will take up to 10 h (each point is measured twice) compared to a dynamic calibration of 7 h (three 1 h static points and two 2 h ramps). In case of more than five measurement points, the benefit will be even larger. Similarly, for the small volume chamber and a capacitive humidity sensor as a reference, a dynamic calibration can be performed in 2.5 h (three 0.5 h static points and two 0.5 h ramps), compared to a five-point static calibration that takes up to 5 h (five 0.5 h static points measured twice).

6. Conclusion

A calibration system and measurement procedure for calibrating hygrometers at non-static conditions was developed and validated. Two different approaches were investigated—one with a chilled mirror hygrometer as a high accuracy reference and another with a smaller measurement chamber and a capacitive humidity sensor as a reference to enable fast humidity ramps. The slow response time of the chilled mirror hygrometer at sub-zero dew point temperatures limits its use to higher temperatures and relative humidities, e.g. at a laboratory temperature of 20 °C, the applicable range is above 30 %rh. This limitation can be overcome by using a capacitive humidity sensor as a reference. Both methods were shown to provide equivalent calibration results compared to the conventional method based on calibrations at stable humidity points. It was shown that the non-static calibration method has the potential to reduce the calibration time by up to 50%, without a significant increase in the calibration uncertainty. In addition, more data on the sensor behaviour is obtained than with the conventional point-wise calibration.

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