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Calibration of hygrometers at fluctuating and transient conditions

Master's Thesis

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Table of Contents

1. INTRODUCTION

Humidity affects many aspects of life. In addition to climate, water vapour affects several properties of air and of materials in contact with air.

Many manufacturing, storage and testing processes are affected by humidity. Measuring humidity can be important in many cases, as in preventing condensation, corrosion, mould, warping or other spoilage. It is highly relevant for food, pharmaceutical, chemical, fuel, wood, paper, and other industries. So humidity measurements can be a critical aspect of business costs, product quality, health and safety [1, 2].

In order to make humidity measurements more accurate and reliable, thus more effective, measuring instruments for humidity – hygrometers – need to be calibrated. Calibration of hygrometers is not always done under stable conditions. Hygrometers are quite commonly calibrated in climatic chambers where conditions are not perfectly stable and humidity and temperature are fluctuating. Therefore it is necessary to assess how accurately hygrometers can be calibrated under fluctuating humidity conditions. This depends on the amplitude of fluctuation as well as on the time constants of the hygrometers. Slower probes are more susceptible to fluctuation and drift effects.

Additionally being able to calibrate hygrometers under transient conditions would save time and money and have a positive impact in several fields, from a range of industrial fields to test and calibration service providers. For example during an industrial drying procedure, it is necessary to measure humidity content and adapt the humidity levels continuously in order to achieve the desired drying result, which could reduce cost. Also it would be time saving if hygrometers could already be calibrated at slightly drifting humidity values before final stabilization [3].

The main goal of this work is to study how possible it is to calibrate hygrometers with low uncertainty under transient and fluctuating conditions. In order to achieve this, the following steps are taken:

i. Measurement of time constant values for three capacitive hygrometers,
ii. Covering two hygrometers with different covers in order to increase the time constant values and measuring time constant values for the two covered hygrometers,
iii. Calibrating the three uncovered hygrometers under stable conditions using the two-flow method and comparing the results obtained by this method to those obtained by the climatic chamber method,

iv. Calibrating the two covered hygrometers and one uncovered hygrometer at fluctuating relative humidity values in the climatic chamber in order to estimate the highest possible effect due to fluctuation,

v. Creating different relative humidity drift speeds in the climatic chamber and measuring relative lag errors of the two covered hygrometers with respect to the uncovered hygrometer,

vi. Estimating measurement uncertainty for different calibration procedures.

2. LITERATURE OVERVIEW

2.1. Humidity and its importance

Humidity is the presence of water vapour in air or other gases [4].

Water vapour affects many processes. On gases humidity has an impact on their thermal, electrical or optical properties. Also the moisture content of liquids and solids is affected by the humidity of their environment. Humidity can lead to change of physical properties of materials, deterioration of substances and organic matter, or corrosion. As a result humidity measurements are very important in many fields of industry, such as food, pharmaceutical, wood, paper and others [4].

Humidity also plays an important role on weather forecasting and climate studying, on conservation of art and antiquities and on human comfort and indoor air conditioning.

2.2. Humidity quantification

Humidity can be expressed in several different ways. One of the central humidity related quantities is water vapour pressure that is the partial pressure of water vapor in some gas mixture.

Saturated water- vapour pressure $\left(E_w(T)\right)$ is the maximum pressure of water vapour that can exist in a gas at a given temperature T. It is expressed in units of pressure.

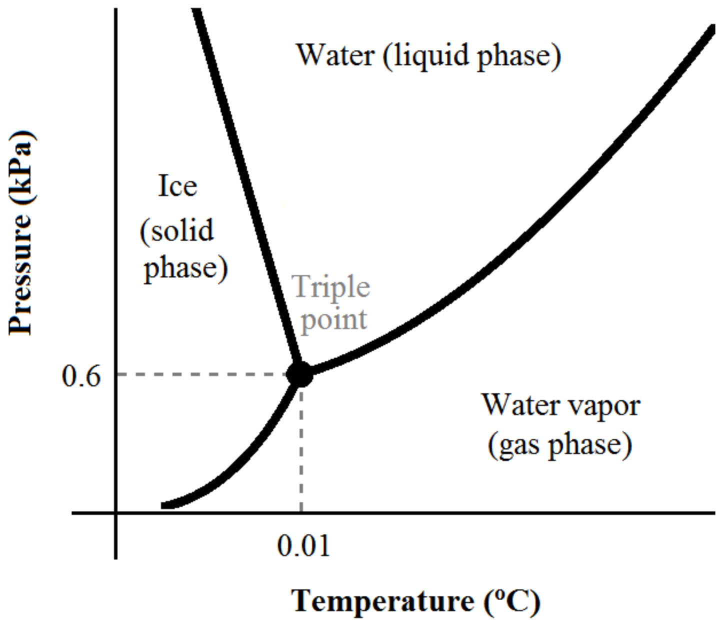

Figure 1. Water phase diagram.

On the water phase diagram seen in figure 1 the boundary layer between the liquid and the gaseous phase of water is the saturated water vapour pressure curve [5].
The theoretical formula for the saturated water-vapour pressure curve is the Clausius – Clapeyron equation [6].

$$E_w(T) = E_w(T_0)\, exp\left[-\frac{\Delta H_{vap}}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right] \qquad (2.1)$$

where ΔH_{vap} is the enthalpy of vapourisation, R is the universal gas constant and $E_w(T)$ and $E_w(T_0)$ is saturated water vapour pressure at temperatures T and T_0 respectively.

Clausius – Clapeyron equation can be used to calculate the water vapour pressure of a liquid at any given temperature but it is not a very accurate formula due to several assumptions in deriving it.

A gas is saturated of water vapour at a given temperature and pressure with respect to liquid water, if water vapour can coexist in equilibrium with liquid water at the same temperature and under the same pressure, when the surface of separation between the two phases is plane [7].

Dew point temperature is the temperature at which condensation (dew) occurs when a gas is cooled. The dew point temperature tells us in which temperature to keep a gas, to prevent condensation. Dew point temperature is expressed in temperature units. If the condensation would be ice (temperatures below 0 °C) then the term frost point temperature should be used instead.

Relative humidity is the ratio of the actual water vapour pressure to the saturation water vapour pressure and it expresses how saturated a gas is with water vapour. This is the most commonly used measure of humidity. Usually the unit of relative humidity is expressed as a percentage (%). The term relative humidity is commonly abbreviated to *RH*:

$$RH = \frac{e_w}{E_w(T,p)} = \frac{E_w(T_d,p)}{E_w(T,p)} \approx \frac{E_w(T_d)}{E_w(T)} \cdot 100\ \% \qquad (2.2)$$

where $e_w$is actual water vapour pressure, $E_w(T_d,p)$ is saturated water vapour pressure of moist air at dew point temperature, $E_w(T,p)$ is saturated water vapour pressure of moist air at air temperature, $E_w(T_d)$ is the saturated vapour pressure of pure water at dew point temperature and $E_w(T)$ is the saturated vapour pressure of pure water at air temperature.

Interaction of water vapour with materials is often proportional to relative humidity.

Mole fraction is the ratio of the amount (number of moles) of water vapour to the total amount of substance present. It is a unitless quantity.

Absolute humidity is the mass of water vapour present per unit volume of air. Its unit is grams per cubic meter $\left(\frac{\mathrm{g}}{\mathrm{m}^3}\right)$ [7, 8].

2.3. Different humidity generators and hygrometers used

2.3.1. Humidity generators

Saturators are used in order to get gas saturated with water vapour. Saturator units are immersed in a thermally controlled liquid bath. So the dew-point temperature of gas leaving the saturator is equal to the temperature inside the liquid bath. In case of condensation based saturators wet air is pumped through the saturator and excess water condenses out. For generating lower dew/frost-point temperatures, evaporation (sublimation) of water takes place in the saturator unit [9].

In case of two-pressure humidity generator air is saturated with respect to water or ice in the saturator unit at higher pressure and passes to the measurement chamber at lower pressure. Since air expands isothermally to a lower pressure, its relative humidity drops. Relative humidity can roughly be calculated as the ratio of the measurement chamber pressure to the saturator pressure provided that temperatures in the saturator and measurement chamber are almost equal. Different relative humidity or dew-point temperature values can be achieved by controlling the saturator and measurement chamber pressures. So two-pressure humidity generator can work as dew-point generator as well as relative humidity generator.

In case of two-temperature humidity generator the saturator and measurement chambers are maintained at almost equal pressures (usually atmospheric pressure). Gas is saturated with respect to water or ice in the saturator and passes to the measurement chamber, maintained at higher temperature. After gas passes to the measurement chamber, relative humidity drops and it can be calculated from the ratio of saturated water-vapor pressure at the saturation temperature to saturated water-vapor pressure at the measurement chamber temperature [9].
Two-temperature generators can be only relative humidity generators.

Two-flow method is based on mixing dry and moist air in controlled proportions, in order to achieve desirable values of humidity. This method produces rather stable humidity conditions.

Two-flow humidity generator can be either relative humidity generator as well as dew-point generator [10].

2.3.2. Most common hygrometers

The instruments used for measuring humidity are called hygrometers. The most common hygrometers are psychrometers, chilled mirror dew point hygrometers, and impedance hygrometers.

The working principle of impedance hygrometers is based on the change of electrical resistance or capacitance of a moisture absorbing material due to changing relative humidity.

Capacitive hygrometers absorb moisture in between the two capacitor plates. This changes the dielectric permittivity of a substance between the two capacitor plates causing a change in capacitance that can be measured. The relationship between relative humidity of air and change in capacitance is almost linear in a wide range of relative humidity values [11].

The working principle of a chilled mirror dew-point hygrometer is based on equilibrium between air passing the mirror and dew layer on the mirror. The mirror is cooled with a Peltier cooler and its temperature is measured by a small platinum resistance thermometer imbedded in the mirror. The constant thickness of dew or frost layer on the mirror is maintained by electro-optical feedback. [12, 13].

Typical accuracy for impedance hygrometers is between 2 % to 3 %, while for chilled mirror hygrometers, accuracy is 0.1 ^{o}C to 0.2 ^{o}C [14].

Chilled mirror hygrometers are often combined with climatic chambers for calibrating hygrometers. Climatic chamber is a facility which allows selectively specified temperature and relative humidity values to be set in a working range in a closed volume. Climatic chamber is insulated and air circulation is used, in order to minimize the inhomogeneity of temperature and relative humidity [15, 16].

Psychrometers consist of two thermometers, which are suspended side by side in the air. One of them is kept dry (dry-bulb) while the other's bulb is covered with a wet wick (wet-bulb). As moisture evaporates from the wet bulb, latent heat is removed from the bulb and thermometer's temperature falls. Moisture evaporation rate depends on air humidity. Psychrometers measure humidity by measuring the temperature difference between the two thermometers [17].

2.4. Time constant of a measuring instrument

Time constant is a feature of a measurement instrument, which characterizes how quickly it follows changes in the measured quantity. If the quantity changes according to a step function from an initial value MV_I to a final value MV_F, the instrument's reading approaches exponentially to the final value $MV(\tau_0)$ according to equation (2.3):

$$MV(\tau_0) = MV_F - \frac{(MV_F - MV_I)}{e} \quad (2.3)$$

where e is Euler's number.

For a capacitive hygrometer, its time constant depends on the time needed to change the moisture content of dielectric between the capacitor plates, which is the ability to absorb or emit moisture. This is related to the design (materials and geometry) of the probes. These characteristics define hygrometer's time constant τ_0 [18].

The higher the time constant is, the more resistive to humidity changes a hygrometer is. On the contrary, hygrometers with a low time constant quickly adapt humidity changes. According to equation (2.4) there is a linear relationship between time constant and lag error. For a certain humidity drift speed, the smaller the time constant of a hygrometer is, the smaller is the lag error in its measured values [18].

$$\text{Lag error} = \text{drift speed} \cdot \text{time constant} \quad (2.4)$$

2.5. Measurement uncertainty

Uncertainty is a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used [19, 20].

The outcome of a measurement depends on many factors. Measuring procedure, instruments used, skills of the person that is performing the measurement, environmental conditions, etc.

Because of the many factors that affect each measurement and the not ideal conditions under which a measurement is performed, every measurement result is accompanied by a doubt. Uncertainty is the value that quantifies this doubt.

The first step of every measurement is the establishment of a mathematical model which relates the measurand (Y) with the input quantities ($X_1, X_2, \ldots, X_n$).

$$Y = f(X_1, X_2, \ldots, X_n) \quad (2.5)$$

In order to evaluate each individual uncertainty component there are two approaches:

Type A evaluation of uncertainty is done by statistically treating data. This type of uncertainty is equal to the standard deviation of the mean $s(\overline{x_i})$ if measurements have been performed under repeatability conditions.

$$s(\overline{x_i}) = \sqrt{\frac{1}{N(N-1)}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad (2.6)$$

Type B evaluation of uncertainty is done by using any other information available. This could be knowledge from previous measurement data, calibration certificates, manufacturer's specifications, or any other possible source, even from common sense.

Every uncertainty component $\left(u(x_i)\right)$ is either an A-type or a B-type component. By calculating the standard uncertainties of all the uncertainty components and combining them we get the combined standard uncertainty, (u_C).

$$u_c^2(y) = \sum_{i=1}^{n}\left[\frac{\partial f}{\partial x_i}\right]^2 \cdot u^2(x_i) + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left[\frac{\partial f}{\partial x_i}\cdot\frac{\partial f}{\partial x_j}\right]\cdot u\left(x_i, x_j\right) \qquad (2.7)$$

where $u\left(x_i, x_j\right)$is the estimated covariance of correlated input quantities.

In order to define an interval about the measurement result within which the value of the measurand Y can be asserted to lie with a certain probability, expanded uncertainty (U) is used. Expanded uncertainty is obtained by multiplying the combined standard uncertainty by a coverage factor (k).

$$U = k \cdot u_C \qquad (2.8)$$

For k = 2 the probability of the result to lie in the interval $Y \pm U$ is 95 % provided that the values of the measurand are normally distributed. Results are presented as "$Y \pm U(k = 2)$" [21].

3. EXPERIMENTAL

3.1. Testing objects

The three Ahlborn FHA646-E1C hygrometers that were used in this work were capacitive hygrometers. These hygrometers have rather similar time constant values. In order to create hygrometers of different time constant values, two of them were during some experimental methods covered with 12 mm inner diameter copper pipe pieces. Two 4 mm diameter holes were drilled on the wall of the first cover, in order to resemble a very slow hygrometer. Six holes were drilled on the wall of the second, in order to make the hygrometer faster than the other covered one, but still slower than the uncovered hygrometer. In the following table it is given how the three hygrometers were used in every method.

Table 1. The use of differently covered hygrometers for different measurements.

<table>
<tr><th rowspan="2">Hygrometer no</th><th rowspan="2">Time constant measurement</th><th colspan="4">Calibration of hygrometers</th></tr>
<tr><th>Two-flow method</th><th>Climatic chamber method</th><th>Fluctuating conditions</th><th>Drifting conditions</th></tr>
<tr><td>1</td><td rowspan="2">Both covered and uncovered</td><td colspan="2" rowspan="2">Uncovered</td><td colspan="2">Covered with 6-hole cover</td></tr>
<tr><td>2</td><td colspan="2">Covered with 2-hole cover</td></tr>
<tr><td>3</td><td colspan="5">Uncovered</td></tr>
</table>

3.2. Determining time constants of hygrometers

In order to determine the time constants of three Ahlborn FHA646 E1C hygrometers, the hygrometers' probes were set inside the climatic chamber with a sudden move. Relative humidity in the climatic chamber was 80 % and air temperature was kept close to laboratory temperature. Relative humidity in the laboratory was between (20…30) % during the measurements. Relative humidity values of the probes that were quickly set inside the chamber, were saved to computer using Ahlborn data acquisition program. After one time constant τ_o, relative humidity $RH(\tau_0)$ can be found from the relation:

$$RH(\tau_0) = RH_F - \frac{(RH_F - RH_I)}{e} \quad (3.1)$$

where RH_F and RH_I are the relative humidity values inside the chamber (final value) and in the laboratory (initial value) respectively and e is Euler's number. After the readings of the probes were settled at about 80 % the probes were pulled out from the climatic chamber through the port as quickly as possible and the lowering humidity values were recorded to the computer once again until they settled at laboratory relative humidity value. Time constants for the lowering relative humidity values were calculated keeping in mind that in this case RH_F and RH_I are relative humidities in the laboratory and in the climatic chamber, respectively.

After calculating the corresponding relative humidity value to the time constant $RH(\tau_0)$, the next step is to calculate the time constant. This is done by measuring the time that is needed for the probe to reach this relative humidity value and it is described in detail in Appendix 1.

Time constants for the covered probes were determined in a similar way as described above.

Two time constant periods in Table 1 below are calculated by the following formula:

$$RH(2\tau_0) = RH_F - \frac{(RH_F - RH_I)}{e^2} \,. \qquad (3.2)$$

The time constant values as well as corresponding standard deviations of 4 repeated measurements for all the three hygrometers and the two different probe covers, are presented in Tables 2 and 3:

Table 2. Time constant values for uncovered probes

n τ_0	**Hygrometer no 1**			
	Increasing *RH*		Decreasing *RH*	
	value (s)	*s* (s)	value (s)	*s* (s)
n = 1	5.7	0.6	13.4	0.9
n = 2	19.5	4.5	28.9	3.2
	Hygrometer no 2			
	Increasing *RH*		Decreasing *RH*	
	value (s)	*s* (s)	value (s)	*s* (s)
n = 1	6.6	1.2	12.2	1.7
n = 2	22.2	7.5	27.0	1.0
	Hygrometer no 3			
	Increasing *RH*		Decreasing *RH*	
	value (s)	*s* (s)	value (s)	*s* (s)
n = 1	6.1	1.1	7.8	0.5
n = 2	17.0	3.8	29.2	2.1

When uncovered, all three hygrometers have similar time constant values. Both τ_0 and $2\tau_0$ are a few seconds higher when *RH* is decreasing, but this difference is not high enough to prevent us from calculating hygrometers’ time constants as the mean values of time constants for increasing and decreasing *RH*.

Table 3. Time constant values for covered probes

n τ_0	Hygrometer no 1			
	Increasing *RH*		Decreasing *RH*	
	value (s)	*s* (s)	value (s)	*s* (s)
n = 1	5.1	0.5	88	9
n = 2	20.8	3.9	208	18
	Hygrometer no 2			
	Increasing *RH*		Decreasing *RH*	
	value (s)	*s* (s)	value (s)	*s* (s)
n = 1	25.5	12.7	328	5
n = 2	156	61	742	21

For covered probes τ_0 for decreasing *RH* is more than 10 times higher, than τ_0 for increasing *RH.* In this case time constant cannot be calculated from the average of these two values. The same applies to $2\tau_0$.

In both cases (covered and uncovered probes) quotient of $2\tau_0$ over τ_0 is higher than 2, so we can conclude that relative humidity values of hygrometers’ probes do not increase or decrease exponentially described by a single time constant.

Nevertheless, it can be concluded that uncovered probes have the time constant of typical modern hygrometers, while the 6-hole covered probe is a bit slower and the 2-hole covered probe is the slowest and models old and slow relative humidity hygrometers and loggers.

3.3. Calibration of hygrometers under stable conditions.

During calibration measurements that are described in the following parts of this work, the chilled mirror dew-point hygrometer together with an external platinum resistance thermometer (PRT) was used as a reference instrument for measuring reference values of relative humidity. This instrument together with climatic chamber is an important part of Estonian reference standard of air humidity. Dew-point temperature measurement results are traceable to Finnish National humidity standard at VTT MIKES Metrology. Air temperature measurement results are traceable to Estonian National temperature standard at AS Metrosert.

3.3.1. Two-flow method

This method was chosen because it provides a stable humidity environment, contrary to the climatic chamber method where humidity levels are fluctuating at medium relative humidity values, especially around 50 %.

The three hygrometers were calibrated at room temperature for 5 different levels of relative humidity: 30 %, 40 %, 50 %, 60 % and 70 %.

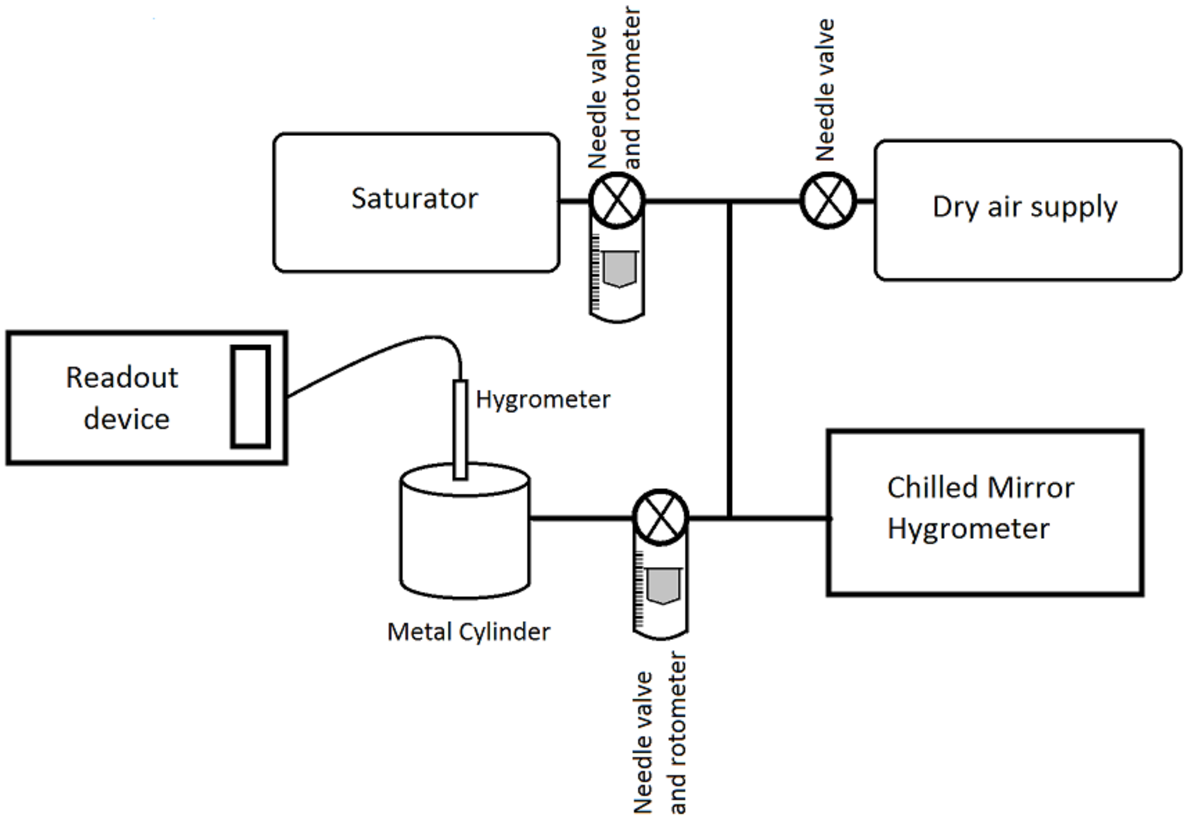

Figure 2. Two-flow method for calibrating hygrometers.

During this experimental method controlled quantities of saturated air and dry air are mixed in order to achieve the desired level of relative humidity. The air mixture is driven in a parallel connection of the measurement vessel (metal cylinder) where the hygrometer under calibration is placed and to the chilled mirror dew point hygrometer that serves as the reference standard. Gas flow is regulated by needle valves. Teflon tubes are used to connect the devices and measuring instruments. Dry air is provided by the compressed air supply of the building of the institute of chemistry, while saturated air is created by a saturator. The validation of this set-up is described in [22].

Hygrometers under calibration are placed in a metal cylinder which, regarding relative humidity, is isolated from the environment as much as possible.

Each time, after the measurements had taken place for a certain point, the dry and humid air mixture was altered in order to achieve the next desired point of humidity in the air flow and the system was let to be stabilized for an hour. Then 10 repeated readings of hygrometer's temperature and relative humidity values, as well as for chilled mirror hygrometer's dew point temperature values, were taken. The average values of these 10 points were used in calculations.

Corrections were calculated for different levels of relative humidity, from 30 % to 70 %, according to the formula:

$$RH_{corr} = RH_{ref} - RH_{meas} \quad (3.3)$$

where RH_{corr} is the relative humidity correction for the hygrometer under calibration, RH_{ref} is the reference value of the relative humidity, and RH_{meas} is the measured value of relative humidity by the hygrometers under calibration.

RH_{ref} is calculated using equation (2.2).

Dew point temperature is measured by the chilled mirror hygrometer and air temperature in the metal cylinder is measured by the hygrometer probe itself. The average of ten points for each quantity is used for the calculations.

In order to calculate the water vapour pressure, Sonntag formula is used [23]:

$$E_w(T) = A_0 \cdot \exp\left(\frac{A}{T} + B + C \cdot T + D \cdot T^2 + E \cdot ln(T)\right) \quad (3.4)$$

where A_0, A, B, C, D and E are the Sonntag coefficients that are presented in Table 4.

Table 4. Sonntag coefficients for calculating water vapour pressure.

Coefficient	Value	Unit
A₀	1	hPa
A	-6096.9385	K
B	16.635794	1
C	$-2.711193 \cdot 10^{-2}$	K^{-1}
D	$1.673952 \cdot 10^{-5}$	K^{-2}
E	2.433502	1

3.3.2. Climatic Chamber method

During this method, the three hygrometers were placed at the same time into the climatic chamber Weiss 111-340 of the Institute of Chemistry. The sensor unit of the chilled mirror hygrometer together with an external temperature probe (PRT) was also placed in the climatic chamber in order to measure both the corresponding dew point temperature and air temperature values in the chamber. The tip of the sampling tube of the chilled mirror hygrometer was set close to the three capacitive probes and the air thermometer.

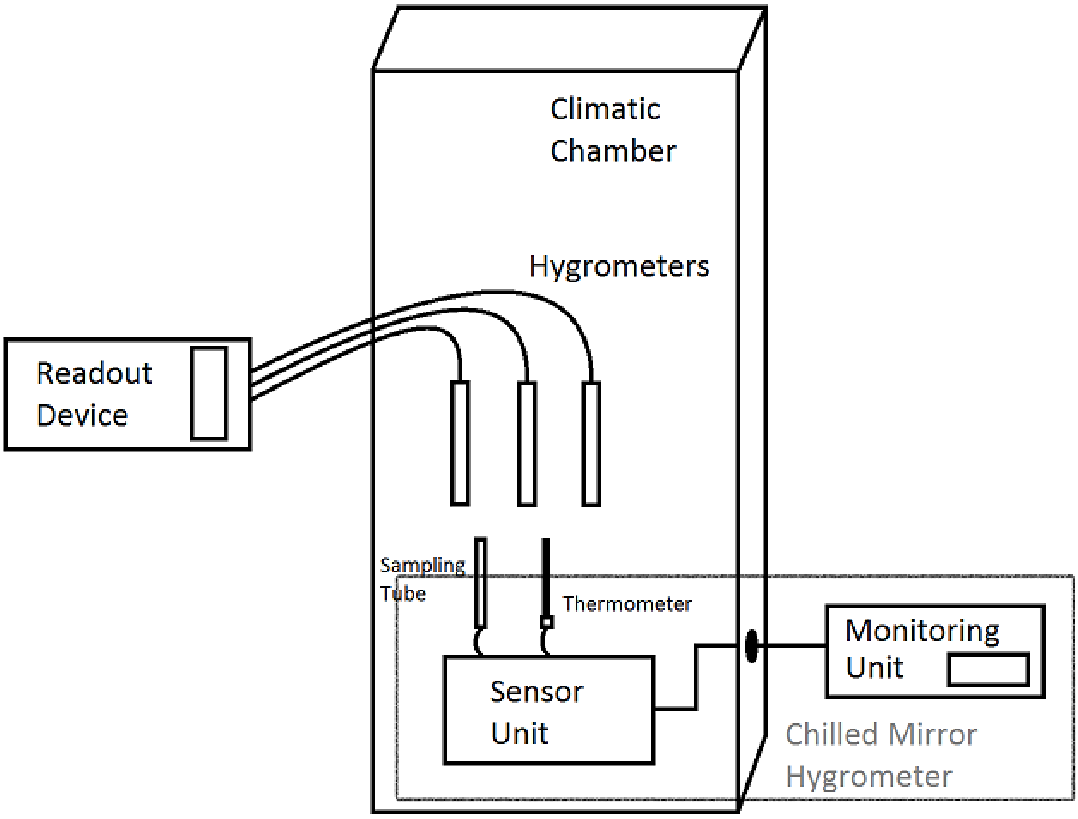

Figure 3. Calibration of hygrometers in the climatic chamber.

This method was used in order to compare the hygrometers' corrections in the climatic chamber with these of the more stable two-flow method described in 3.3.1. In addition, it was also used for calibrating hygrometers at the more stable levels of relative humidity, 20 %, 80 % and 90 %.

Initially the climatic chamber was set to reach a certain point of relative humidity and after it was left for an hour to get stabilised, 10 hygrometers' relative humidity readings, as well as for chilled mirror hygrometer's dew point temperature and air temperature readings, were written down. The average values of these 10 readings were used in calculations. Subsequently RH of the climatic chamber was set to the next calibration point and the procedure was repeated.

Corrections were calculated for different levels of relative humidity, from 20 % to 90 %, according to the formula (3.3), as described in section 3.3.1.

3.3.3 Estimation of measurement uncertainty

During the measurements and the calculation of the relative humidity corrections, there was a number of uncertainty sources that interfered. They were taken into account in order to calculate the expanded uncertainty of the results [20].

The uncertainty sources were:

- Measuring instruments' resolutions
- Instruments' uncertainties (according to calibration)
- Air temperature and dew-point temperature stability
- Air temperature and dew-point temperature inhomogeneity
- Hysteresis of hygrometer under calibration

For the calculation of standard uncertainty the following equation is used

$$u^2(RH_{corr}) = u^2(RH_{ref}) + u^2(RH_{meas}) \qquad (3.5)$$

where $u(RH_{ref})$ is the combined standard uncertainty of the reference value of relative humidity and $u(RH_{meas})$ is the combined standard uncertainty due to the hygrometers under calibration.

The latter is easier to calculate as it occurs out of three uncertainty sources: A-type uncertainty (of repeated readings), B-type uncertainty due to instrument resolution and B-type uncertainty due to hysteresis.

$$u(RH_{meas}) = \sqrt{u_A^2 + u_{B\ resolution}^2 + u_{B\ hysterisis}^2} \qquad (3.6)$$

In order to calculate $u(RH_{ref})$, standard uncertainty of temperature and dew point temperature measurements should be calculated at first. Uncertainty sources taken into account in this step are: A-type uncertainty due to the instability of dew-point temperature and air temperature readings, B-type uncertainty due to resolution of the instruments, B-type uncertainty provided from previous instruments' calibration certificates and B-type uncertainty due to temperature and dew-point temperature inhomogeneity.

$$u_{c\ (T\ or\ T_d)} = \sqrt{u^2_{A\ stability} + u^2_{B\ resolution} + u^2_{B\ instrument} + u^2_{Binhomogeneity}} \quad (3.7)$$

The next step is to insert the uncertainty of the temperature measurements to the water vapour pressure calculations, which are done using the Sonntag formula.

$$u_{C\ E_w(T)} = \frac{\partial E_w}{\partial T} \cdot u_{C\ (T)} \quad (3.8)$$

Equation (3.8) applies for T_d as well.

Finally $u(RH_{ref})$is calculated combining the water vapour pressure standard uncertainties for temperature and dew-point temperature.

$$\frac{u(RH_{ref})}{RH} = \sqrt{\left(\frac{u_{C\ E_w(T_d)}}{E_w(T_d)}\right)^2 + \left(\frac{u_{C\ E_w(T)}}{E_w(T)}\right)^2} \quad (3.9)$$

For calibration in the climatic chamber the correlation between the uncertainty because of dew point temperature instability and A-type uncertainty of the hygrometers' readings was taken into account during the uncertainty evaluation.

3.4. Calibration of hygrometers under fluctuating conditions

When calibrating hygrometers in the climatic chamber, usually it is not possible to achieve stable conditions of relative humidity, especially at medium values. This experimental method was chosen in order to study how big are the differences of the hygrometers' corrections between real (fluctuating) and ideal (stable) conditions.

During this experimental method the three hygrometers were placed in the climatic chamber at the same time. The chilled mirror dew-point hygrometer was also placed in the climatic chamber. Measurements took place for three different levels of *RH*, 30 %, 50 % and 70 %.

Two of the hygrometers were covered with different covers (the third one was kept uncovered), in order to achieve that each one of the three hygrometers will have a different time constant during the measurements (See Tables 2 and 3). That was made so for investigating how a bigger time constant affects calibration under fluctuating conditions.

10 measurements of the climatic chamber temperature and dew point temperature, along with the *RH* values of the hygrometers, were taken at the highest points of the fluctuation curve and 10 more at the lowest points. At some occasions especially at 30 % or 70 %, humidity in the chamber eventually was stabilized, so less than ten measurements for each peak were taken. The highest and the lowest points of the curve were seen in the climatic chamber touch panel where "*RH* to *time*" graph was displayed in real time.

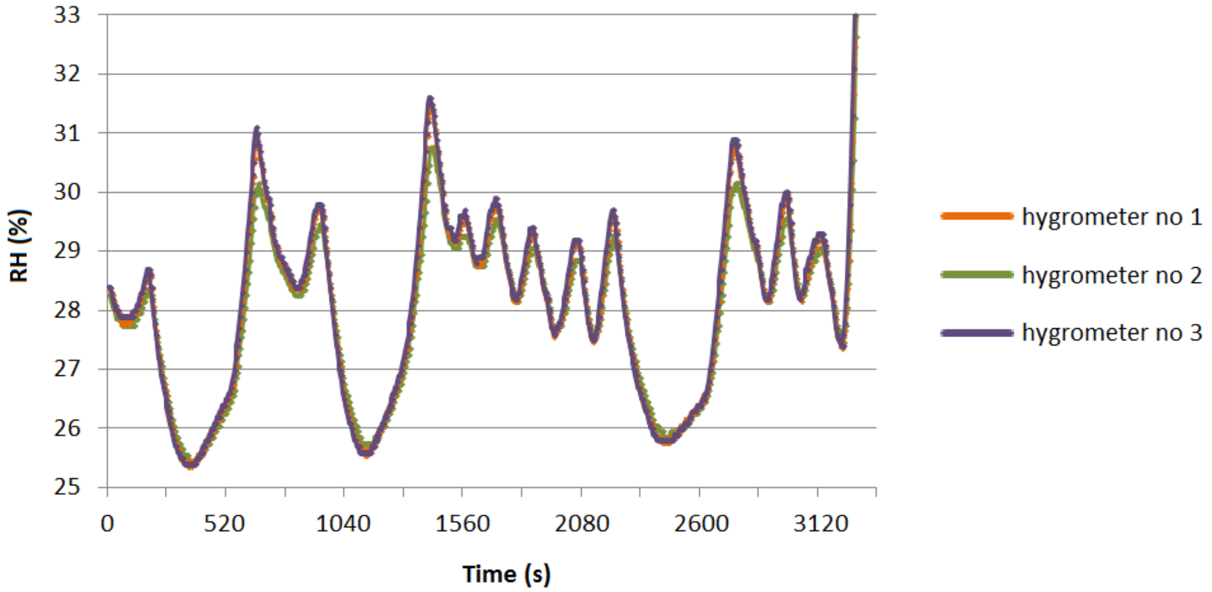

Figure 4. Relative humidity fluctuation curve in the climatic chamber at the 30 % level.

3.5. Calibration of hygrometers under drifting conditions

It is necessary at some applications to calibrate the hygrometers under transient conditions. This method was chosen in order to measure how the time constant values of the hygrometers affect their calibration under drifting values of relative humidity. During this method relative humidity values inside the climatic chamber were programmed to drift between 20 % and 80 % using the SIMPATI software of the climatic chamber, while air temperature and relative humidity readings of the three probes were saved in the computer using the Ahlborn data acquisition program. The three different drift speeds of relative humidity where measurements were done were 0.1 %/min, 0.5 %/min and 1 %/min.

In this case hygrometers had also three different time constants and this was achieved as previously, by covering two of them with different covers and keeping the third one uncovered. In order to calculate relative humidity corrections for increasing relative humidity values (upward drift curve), all the points on the upward drift curve were taken into account. Relative humidity corrections for the downward drift curve were calculated in a similar way.

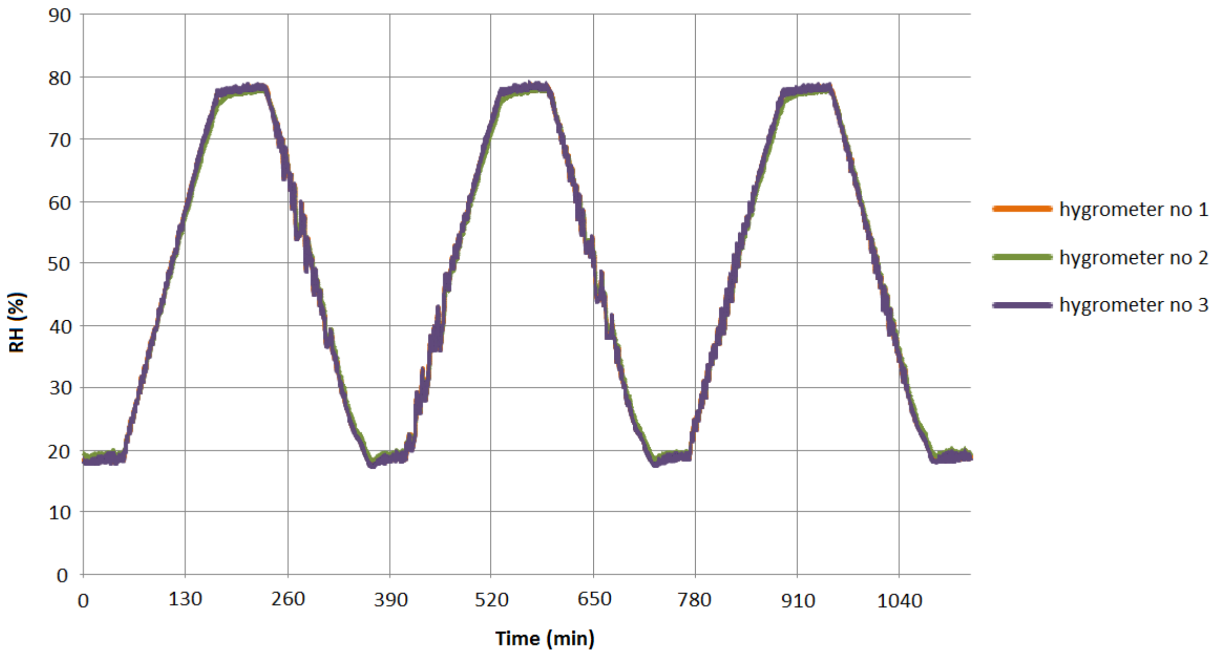

Figure 5. Relative humidity drift curves between 20 % and 80 %.

4. RESULTS AND DISCUSSION

4.1. Calibration under stable conditions

As mentioned in section 3.3.1 except from calculating relative humidity corrections by making measurements only in the climatic chamber, the two-flow method was also used as it could create a more stable humidity environment.

The results of both methods are presented and compared below. For two-flow method, relative humidity values over 70 % and below 30 % were not measured as for these measurement ranges *RH* in the climatic chamber is stable. Also, *RH* values over 70 % would not be possible to be created using the two-flow method, due to saturator limitations.

In Tables 5, 6 and 7 values of the corrections for the two methods are presented along with their corresponding expanded uncertainties for confidence level of 95 %. The differences of the results of the two methods' corrections are also presented.

For each method 4 different sets of measurements were done for each calibration point. Half of the calibration points were measured in the direction of increasing humidity and the other half were measured in the direction of decreasing humidity in order to take into account the correction due to hysteresis of the hygrometers.

Table 5. Relative humidity corrections for hygrometer no 1.

Relative Humidity	Two-flow method RH_{corr} (%)	*U* (k=2) (%)	Climatic chamber method RH_{corr} (%)	*U* (k=2) (%)	Difference (%)
90 %	-	-	0.0	1.2	-
80 %	-	-	0.4	1.1	-
70 %	1.4	1.1	1.3	1.0	-0.1
60 %	1.1	1.0	0.8	0.9	-0.3
50 %	0.7	1.0	0.3	0.9	-0.4
40 %	-0.1	0.9	-0.2	0.8	-0.1
30 %	-1.0	0.9	-1.0	0.7	0.0
20 %	-	-	-2.4	0.7	-

Table 6. Relative humidity corrections for hygrometer no 2.

Relative Humidity	Two-flow method RH_{corr} (%)	U (k=2) (%)	Climatic chamber method RH_{corr} (%)	U (k=2) (%)	Difference (%)
90 %	-	-	0.6	1.2	-
80 %	-	-	0.1	1.1	-
70 %	0.6	1.2	0.5	1.0	-0.1
60 %	0.2	1.0	-0.2	0.9	-0.4
50 %	-0.6	1.0	-1.0	0.9	-0.4
40 %	-1.3	0.8	-1.7	0.8	-0.4
30 %	-2.3	0.7	-2.5	0.7	-0.2
20 %	-	-	-3.7	0.7	-

Table 7. Relative humidity corrections for hygrometer no 3.

Relative Humidity	Two-flow method RH_{corr} (%)	U (k=2) (%)	Climatic chamber method RH_{corr} (%)	U (k=2) (%)	Difference (%)
90 %	-	-	-2.8	1.2	-
80 %	-	-	-2.4	1.1	-
70 %	-1.1	1.1	-1.1	1.0	0.0
60 %	-1.1	1.1	-1.2	0.9	-0.1
50 %	-1.3	1.1	-1.5	0.9	-0.2
40 %	-1.8	1.0	-1.8	0.8	0.0
30 %	-2.4	0.8	-2.3	0.7	0.1
20 %	-	-	-3.3	0.7	-

As can be seen from the tables above, the differences of RH_{corr} between the two methods are significantly lower than the expanded uncertainties of the two methods.

Expanded uncertainty U (k=2) of the results stands in the interval (0.7…1.2) %.

Such small differences of the corrections between the two calibration methods, show that climatic chamber is stable enough to calibrate modern hygrometers of low time constant values, even at medium relative humidity levels, where it fluctuates the most.

4.2. Calibration under fluctuating conditions

During this method, measurements were taken for fluctuating *RH* in 3 levels, 30 %, 50 % and 70 %. Also as mentioned in section 3.4, the three hygrometers had different time constants during this experiment. Four measurements were done for approaching each of the three *RH* levels from both higher humidity values and from lower humidity values. In each of these measurements 10 readings were taken for the high peaks and 10 for the low peaks of fluctuation curve. At some occasions it was not possible to get 10 readings at high peaks and 10 readings at low peaks. In any case not less than 15 readings in total were used every time (see Figure 6).

The first step in order to calculate the final corrections for hygrometers is to calculate the differences between corrections under fluctuating conditions and under stable conditions. This is done for all the three hygrometers, for both high and low peaks of fluctuation curve. The results are presented in Appendix 2.

In order to filter out the effect of the fluctuation on the RH_{corr} results, next calculation step was to correct the previously calculated differences of covered probes, with respect to these of the uncovered probe. The results are presented in Table 8.

Table 8. Net correction differences between stable state and fluctuating state calibration for two covered probes.

	Net high peak correction differences			
RH	**Hygrometer no 1** RH_{corr} (%)	*U* (k=2) (%)	**Hygrometer no 2** RH_{corr} (%)	*U* (k=2) (%)
70 %	0.3	1.2	0.8	1.3
50 %	0.2	1.1	0.7	1.2
30 %	0.1	0.8	0.2	0.9
	Net low peak correction differences			
RH	**Hygrometer no 1** RH_{corr} (%)	*U* (k=2) (%)	**Hygrometer no 2** RH_{corr} (%)	*U* (k=2) (%)
70 %	-0.2	1.2	0.0	1.3
50 %	0.0	0.9	-0.2	0.9
30 %	-0.1	0.5	-0.1	0.6

Calibration using only the high and the low peaks' points was chosen during this method, in order to take into account the highest possible fluctuation effect. In real life measurements though, calibration points are chosen randomly, which means that the possibility of all of them being on the fluctuation peaks is extremely low. Moreover, calibration usually takes about 15 minutes and there can be a maximum of 3 high or low humidity peaks during this time interval (see Figure 3). So it is evident that not all the 10 relative humidity calibration readings have maximum or minimum values during this interval. Thus we can conclude that in real life calibration, the difference of RH_{corr} results between stable and fluctuating conditions is going to be smaller than in this experiment, in which the maximum RH_{corr} calculated was 0.8 %.

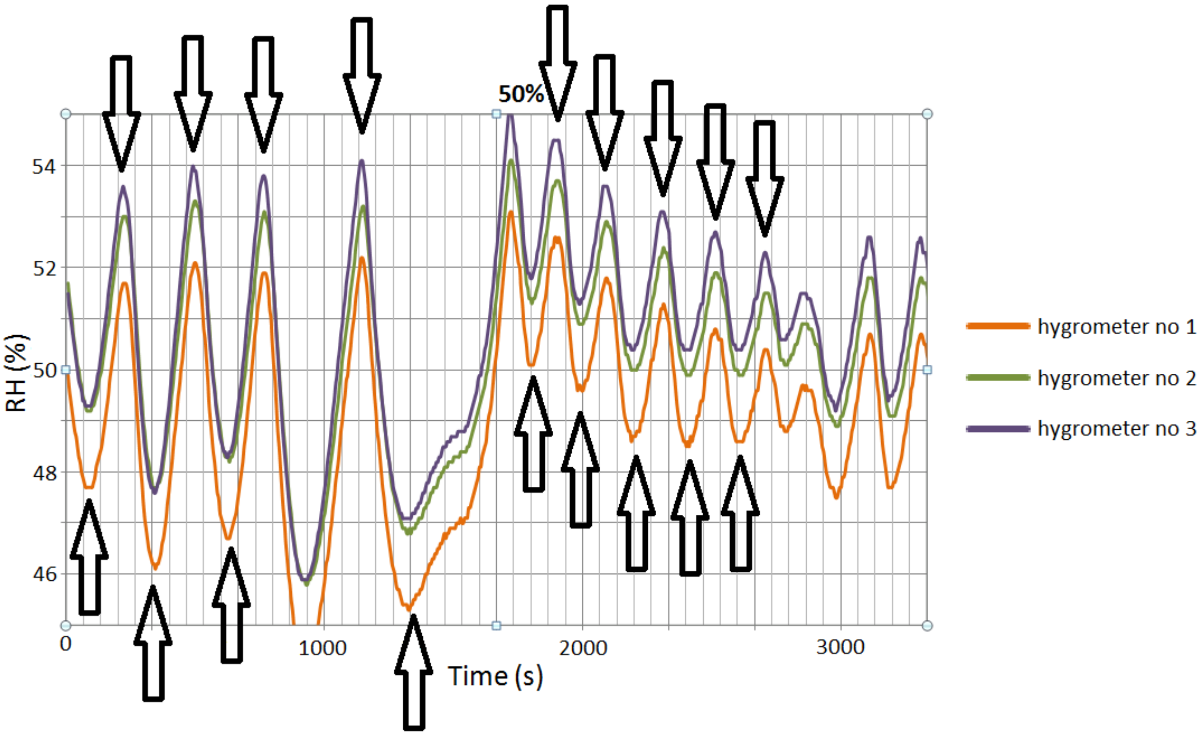

Figure 6. The typical choice of calibration points on the relative humidity fluctuation curve at 50 % level. Hygrometers' readings on the figure are not corrected.

4.3. Calibration under drifting conditions

During this method relative humidity in the climatic chamber was programmed to drift between 20 % and 80 %, while measurements of the three probes were saved in the computer. There were 3 different drift speeds measured, for *RH* changing 0.1 %/min, for 0.5 %/min and for 1 %/min.

In this case probes also had three different time constant values and this was achieved as previously, by covering two of them with different covers and keeping the third one uncovered.

For each drift speed 4 different cycles of measurements were done. For 1 %/min drift speed each cycle included 4 increasing and 4 decreasing slopes. For 0.5 %/min drift speed, each cycle included 3 increasing and 3 decreasing slopes. Finally for 0.1 %/min drift speed, each cycle included 1 increasing and 1 decreasing slope.

Table 9. Average *RHcorr* differences between covered probes and the uncovered probe (no 3).

Increasing drift				
Drift speed	**Hygrometer no 1**		**Hygrometer no 2**	
	RH_{corr} difference (%)	U (k=2) (%)	RH_{corr} difference (%)	U (k=2) (%)
1 %/min	-0.10	0.21…0.80	-1.26	0.31…0.83
0.5 %/min	-0.02	0.25…0.81	-0.92	0.25…0.81
0.1 %/min	0.40	0.22…0.80	-0.23	0.23…0.80
Decreasing drift				
Drift speed	**Hygrometer no 1**		**Hygrometer no 2**	
	RH_{corr} difference (%)	U (k=2) (%)	RH_{corr} difference (%)	U (k=2) (%)
1 %/min	0.34	0.20…0.80	1.35	0.21…0.80
0.5 %/min	0.26	0.20…0.80	0.75	0.21…0.80
0.1 %/min	0.39	0.20…0.80	0.12	0.21…0.80

In Table 9, RH_{corr} difference results are expected to have negative signs for increasing drift and positive signs for decreasing drift. This happens because the differences are calculated with respect to the uncovered probe, which is the fastest. When relative humidity increases, the slower probes follow this increase with a delay, so these are expected to show lower results than the uncovered hygrometer. The opposite happens when relative humidity decreases.

Time constants of hygrometers with covered probes were measured significantly higher when *RH* was decreasing than when it was increasing (table 3). Regarding that fact it would be expected for the RH_{corr} to be higher when the *RH* drift was in a decreasing order, something that is not clearly concluded from the results (values and expanded uncertainties) of Table 9.

Lag error for the uncovered hygrometer (no 3) can be calculated from (2.4) and it is very small. Even for the highest drift speed the biggest lag error for this hygrometer is: 7.8 s × 1 %/min = 0.13 %.

From RH_{corr} differences of the Table 9, the average relative lag error is estimated according to the following formula:

$$LE_{rel} = \frac{RH_{corr}(D) - RH_{corr}(I)}{2} \quad (4.1)$$

where LE_{rel} is the relative lag error of the slower hygrometers, $RH_{corr}(D)$ is the relative humidity correction difference for decreasing drift and $RH_{corr}(I)$ is the relative humidity correction difference for increasing drift. This formula is used in order to cancel out possible errors in the lag error measurement for increasing and decreasing drifts. For example in Table 9 it can be seen that for hygrometer no 1 lag errors are 0.40 % and 0.39 % for increasing and decreasing drifts respectively, although it would be expected that these lag errors would have different signs and be more close to 0. The average relative lag error estimation results are presented in table 10:

Table 10. Estimation of relative lag error after calibration under drifting relative humidity values.

Drift speed	**Hygrometer no 1**		**Hygrometer no 2**	
	Relative lag error (%)	U (k=2) (%)	Relative lag error (%)	U (k=2) (%)
1 %/min	0,22	0,29…1,1	1.31	0,37…1,2
0.5 %/min	0,14	0,32…1,1	0.84	0,33…1.1
0.1 %/min	-0,01	0.30…1.1	0.18	0.31…1.1

From the relative lag error results (table 10) it can be concluded that 1 %/min drift speed is too high to calibrate a very slow hygrometer, but doesn’t affect significantly the quicker ones, even if they are not the quickest possible. The relative lag error for this drift speed and for the slowest hygrometer (no 2) is 1.31 %, while for hygrometer no 1 it is 0.22 %. The relative lag errors for 0.5 %/min drift speed are 0.84 % and 0.14 % respectively for these two hygrometers. On the other hand 0.1 %/min drift speed is suitable to calibrate even the very slow hygrometers, as for this drift speed the relative lag error is very low, even for the slowest hygrometer (0.18 %). The results agree with the general understanding that the accuracy of calibration of hygrometers under drifting conditions depends on two parameters:

- Drift speed,
- Time constant of the hygrometer.

Expanded uncertainties are given as a range of values in Tables 9 and 10 because for every different relative humidity point of the drift, the uncertainty is different. The highest uncertainty value appears for 80 % relative humidity, while the lowest for 20 % relative humidity.

5. SUMMARY

Humidity measurements play an important role in many aspects of our life. In addition to the climate, were humidity is one of the main parameters, it affects many other aspects, from manufacturing and storage, to testing processes.

To make humidity measurements more accurate, hygrometers should be calibrated. Ideally calibration should take place under stable conditions, but in reality this is not always the case. In the climatic chamber, where hygrometers are usually calibrated, relative humidity can fluctuate, especially at medium levels. Part of this work was to measure how much this fluctuation affects the calibration results.

In the beginning of this work, time constants of the hygrometers were measured. In order to create slower probes, two of the three capacitive hygrometers were covered with different covers made of copper pipe and their time constants were measured again.

In order to calibrate the uncovered hygrometers under stable relative humidity conditions, two-flow method was used. Using this method calibration was done for 5 different levels of relative humidity, from 30 % to 70 %.

Next, calibration was carried out in the climatic chamber for relative humidity range from 20 % to 90 %. Comparison of the two methods showed that climatic chamber method is suitable for calibrating modern hygrometers even at medium strongly fluctuating relative humidity values, as the differences of the relative humidity corrections between the two methods were small compared to corresponding expanded uncertainties.

Calibration of different time constant hygrometers under fluctuating conditions was carried out in the climatic chamber for three levels of relative humidity, 30 %, 50 % and 70 %. During this experimental method calibration points were taken only on the high and low peaks of the fluctuation curves. This was chosen so, in order to measure the highest possible fluctuation effect. In reality, if a hygrometer is calibrated under fluctuating conditions, calibration points are taken randomly throughout the curve. This means that in reality the fluctuation effect in calibration is significantly smaller than 0.8 % that was found to be the maximum value of the effect. So it is possible to calibrate even slowest hygrometers under fluctuating conditions in the climatic chamber without significantly increasing measurement uncertainty.

For calibration of hygrometers under drifting conditions, drift effect to the uncovered probes was not directly measured. It can be calculated theoretically from the lag error formula (2.4). It was calculated 0.13 % for the uncovered hygrometer no 3 in case of drift speed 1 %/min. The relative lag errors for the two covered hygrometers were measured for 0.1 %/min, 0.5 %/min and 1 %/min drift speeds generated by the climatic chamber. In general the lag error of hygrometers under drifting conditions depends on two parameters, the drift speed and the time constant of the hygrometer. The lag error was measured to be 0.18 % for the slowest hygrometer in case of the lowest drift speed of 0.1 %/min. So it is possible to calibrate even the slowest hygrometers at drift speed 0.1 %/min without significantly increasing measurement uncertainty. For the higher drift speeds of 0.5 %/min and 1 %/min the relative lag errors for hygrometer no 1 are quite satisfying (0.14 % and 0.22 %, respectively) but for the slowest hygrometer these are not acceptable (0.84 % and 1.31 %, respectively) for calibration since these estimates exceed the corresponding expanded uncertainty range (0.33…1.2) %.

6. REFERENCES

[1] http://www.npl.co.uk/publications/good-practice-online-modules/humidity/humidity-basics/why-is-humidity-important/

[2] S. Bell. The expanding horizons of humidity measurement. *TEMPMEKO 1999: 7th International Symposium on Temperature and Thermal Measurement in Industry and Science, Proceedings* **1999**, Vol. 1, 11–18.

[3] Heinonen M, Cavallarin L, Dell'Isola M, Ebert V, Fernicola V, Georgin E, Hudoklin D, Nielsen J, Østergaard P F, Peruzzi A, Pietari T, Wagner S and Werhahn O. Metrology for humidity at high temperatures and transient conditions. *17th international congress of metrology,* **2015**.

[4] S. Bell. The beginner's guide to humidity measurement - Stephanie Bell, National Physical Laboratory, **2012.**

[5] W. Wagner. International equations for the pressure along the melting and along the sublimation curve of ordinary water substance. JOURNAL OF PHYSICAL AND CHEMICAL REFERENCE DATA, Volume 23 Issue: 3 Pages: 515-525. May-June **1994**.

[6] P. Atkins, J. de Paula, Physical Chemistry, Oxford University press, **2010**.

[7] A. Wexler, Humidity and moisture. Measurement and Control in Science and Industry. New York, Reinhold Publishing Corp. **1965**, Vol III.

[8] National Physical Laboratory, A Guide to the Measurement of humidity, **1996**.

[9] B. Hardy. Trust but verify – practical approaches to humidity generation and measurement. TEMPMEKO 2004: 9th International Symposium on Temperature and Thermal Measurement in Industry and Science, Proceedings, **2004**, Vol. 1, 23– 32.

[10] H. Kishan, B. SINGH, Mixed Flow Relative Humidity Generator, *MAPAN - Journal of Metrology Society of India, Vol. 23, No. 1*, **2008**; p. 21-24.

[11] http://www.npl.co.uk/publications/good-practice-online-modules/humidity/hygrometers/electrical-impedance-hygrometer/

[12] D. Hudoklin, E. Barukčić, J. Drnovšek. Engaging Frost Formation in a Chilled-Mirror Hygrometer. Springer Science and Business Media **2008.**

[13] A. S. Morris, Measurement and Instrumentation Principles. Oxford, Butterworth-Heinemann, **2001.**

[14] Pieter R. Wiederhold. Water Vapor Measurement, Methods and Instrumentation. Marcel Dekker, New York, NY. **1997**.

[15] Guideline DKD-R 5–7, Calibration of Climatic Chambers, **2009**.

[16] C. Rauta, F. Helgesen, T. Magnussen. Investigation of the measurement uncertainty in a climatic chamber used for calibration of the RH sensors. TEMPMEKO 2001: 8th International Symposium on Temperature and Thermal Measurement in Industry and Science, Proceedings, **2002**, Vol. 2, 917–922.

[17] http://www.jma.go.jp/jma/jma-eng/jma-center/ric/material/1_Lecture_Notes/CP3-Humidity.pdf

[18] J.V. Nicholas and D.R. White, Traceable Temperatures, John Wiley & Sons Ltd, **2001**.

[19] S. Bell. A Beginner's guide to uncertainty of measurement, National Physical Laboratory, **1999.**

[20] M. Vilbaste. Uncertainty sources and analysis methods in realizing SI units of air humidity in Estonia. Doctoral thesis. Tartu **2014**.

[21] GUM-JCGM 100:2008, Evaluation of measurement data — Guide to the expression of uncertainty in measurement, **2008.**

[22] Salgaduge Dinesh Indika Dias. Two-flow system for calibration of hygrometers at room temperature. Master's thesis. Tartu **2015**.

[23] D. Sonntag, Advancements in the field of hygrometry, Meteorologische Zeitschrift, N.F. 3, **1994**, p.51-66.

Hügromeetrite kalibreerimine fluktueeruvates ja siirdetingimustes

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7. KOKKUVÕTE

Õhuniiskuse mõõtmised on olulised paljudes elu valdkondades. Lisaks sellele, et õhuniiskus on üks enim kliimat mõjutavaid suurusi, mõjutab see ka palju teisi valdkondi (tootmine, säilitamine, katsetamine).

Hügromeetrid vajavad kalibreerimist, selleks et õhuniiskuse mõõtmised oleksid täpsemad. Ideaalsel juhul peaks kalibreerimisi läbi viima stabiilsetes tingimustes, kuid alati ei ole see võimalik. Kliimakambris, milles hügromeetreid tihti kalibreeritakse, võib suhteline niiskus fluktueeruda ennekõike keskmistel suhtelise niiskuse väärtustel. Osa käesolevast tööst on pühendatud mõõtmistele, et hinnata, kui palju nimetatud fluktuatsioonid mõjutavad kalibreerimise tulemusi.

Käesoleva töö esimeses etapis mõõdeti hügromeetrite ajategureid. Kaks mahtuvuslikku hügromeetrit kolmest kaeti erinevate vasktorust valmistatud katetega, selleks, et muuta need aeglasemaks ja nende ajategurid mõõdeti uuesti.

Kahe-voolu meetodit kasutati selleks et kalibreerida katmata hügromeetreid stabiilsetel suhtelise niiskuse väärtustel. Kasutades seda meetodit kalibreeriti hügromeetreid erinevatel suhtelise niiskuse väärtustel vahemikus (30…70) %.

Pärast seda viidi katmata hügromeetrite kalibreerimine läbi kliimakambris suhtelise niiskuse vahemikus (20…90) %. Nende kahe meetodi võrdlus näitas, et kliimakambri meetod sobib kaasaegsete hügromeetrite kalibreerimiseks isegi keskmistel tugevasti fluktueeruvatel suhtelise niiskuse väärtustel, kuna nende kahe meetodi abil leitud suhtelise niiskuse parandite erinevused olid väikesed võrreldes vastavate laiendmääramatustega.

Erineva ajateguriga hügromeetrite kalibreerimine fluktueeruvates tingimustes viidi läbi kolmel suhtelise niiskuse väärtusel: 30 %, 50 % ja 70 %. Selle eksperimentaalse meetodi korral võeti punkte kalibreerimiseks eraldi ainult suhtelise niiskuse fluktuatsioonikõvera miinimum- ja maksimumväärtustel. Nimetatud lähenemine valiti selleks, et mõõta suurim võimalik suhtelise niiskuse fluktuatsioonide mõju. Juhul kui hügromeetrit kalibreeritakse fluktueeruvatel suhtelise niiskuse väärtustel, võetakse praktikas suhtelise niiskuse väärtuseid juhuslikult üle kogu fluktuatsioonikõvera. See tähendab, et fluktuatsioonide mõju kalibreerimisele on oluliselt väiksem kui 0,8 %, mis leiti olevat fluktuatsioonide suurim võimalik mõju kalibreerimisele. Seega on võimalik kalibreerida isegi kõige aelasemaid hügromeetreid kliimakambris fluktueeruvatel suhtelise niiskuse väärtustel ilma mõõtemääramatust oluliselt suurendamata.

Hügromeetrite kalibreerimisel triivivatel suhtelise niiskuse väärtustel ei mõõdetud selle mõju katmata hügromeetritele. Seda saab arvutada teoreetiliselt viitaja vea (lag error) kaudu (Vt. valem 2.4). Triivimise kiirusel 0,1 %/min arvutati katmata hügromeetri Nr.3 viitaja vea väärtuseks 0,13 %min. Kahe kaetud hügromeetri suhtelised viitaja vead mõõdeti kliimakambris suhtelise niiskuse triivimise kiirustel 0,1 %/min, 0,5 %/min ja 1 %/min. Üldiselt sõltub hügromeetrite viitaja viga triivivatel suhtelise niiskuse väärtustel kahest suurusest, milleks on triivimise kiirus ja hügromeetri ajategur. Kõige aeglasema hügromeetri suhtelise niiskuse viitaja viga mõõdeti olevat 0,18 %, juhul kui suhtelise niiskuse triivimise kiirus oli 0,1 %/min. Seega on võimalik ilma mõõtemääramatust oluliselt suurendamata kalibreerida isegi kõige aeglasemaid hügromeetreid, juhul kui suhteline niiskus triivib kiirusega 0,1 %/min. Suhtelise niiskuse triivimise kiirustel 0,5 %/min ja 1 %/min on esimese hügromeetri suhtelised viitaja vead (0,14 % ja 0,22 %) rahuldavad, kuid aeglaseima hügromeetri jaoks ei ole need (0,84 % ja 1,31 %) kalibreerimiseks vastuvõetavad, kuna ületavad vastavat laiendmääramatuse vahemikku (0,33…1,2) %.

8. APPENDICES

Appendix 1

Detailed description and example of time constant calculation

After calculating $RH(\tau_0)$, the next step is to calculate time constant itself. For this, the exact time that RH reaches the value $RH(\tau_0)$ has to be known. A stopwatch is used for measuring the exact time the hygrometer is put in or pulled out of the climatic chamber. The values of RH and time are saved to the computer every 2 or 4 seconds (according to how it is programmed) in the following form:

Table 11. Data for time constant calculation.

Time (hour)	Temperature (^oC)	Corrected *RH* (%)
16:01:45	22.24	27.68
16:01:49	22.25	40.13
16:01:53	22.29	59.97
16:01:57	22.33	66.32

Usually $RH(\tau_0)$ stands between two of the RH values saved to the computer. In order to calulate the time point that corresponds exactly to the $RH(\tau_0)$ value, linear interpolation is used.

Three time points are used to calculate the time constant:

t_0, the initial time point when hygrometer is put in the chamber (or pulled out respectively). It is calculated using a stopwatch. The stopwatch is synchronised with the computer time, in order to make the comparison of their values possible.

t_1, the first time point of linear interpolation.

t_2, time point corresponding to $RH(\tau_0)$.

Time between points t_0 and t_1 is easily calculated with a simple subtraction of the two points' values. Time between points t_1 and t_2 is calculated with linear interpolation.

Time constant value is the time interval between points t_0 and t_2.

In Table 11, time point t_0 was measured with the stopwatch and it was at 16:01:48.1.

$RH(\tau_0)$ value for this example was 59.01 %, which stands between 40.13 % and 59.97 % (table 11). So time point t_1 is 16:01:49 which corresponds to RH value 40.13%. With linear interpolation the time difference between points t_2 and t_1 can be calculated

$$t_2 - t_1 = \frac{4 \text{ sec } \times (59.01\ \% - 40.13\ \%)}{59.97\ \% - 40.13\ \%} = 3.8 \text{ s}$$

Also the time difference between points t_1 and t_0 can be calculated

$$t_1 - t_0 = 16{:}01{:}49 - 16{:}01{:}48.1 = 0.9 \text{ s}$$

Therefore, in this example the time constant value, which is the time difference between t_2 and t_0 can be calculated by adding the two values calculated above:

$$\tau_0 = t_2 - t_0 = 4.7 \text{ s}$$

Appendix 2

Detailed RH_{corr} calculation under fluctuating conditions.

RH corrections of the three hygrometers for measurements performed on the high and low peaks of the fluctuation curves are presented in Tables 12, 13 and 14. The differences between the relative humidity corrections at peak values and at stable conditions are presented in the same tables (12, 13 and 14).

Finally net relative humidity correction differences of hygrometers with covered probes with respect to the uncovered hygrometer are presented in Table 15.

Table 12. Comparison of stable state and fluctuating state relative humidity corrections for probe no 1 at peak values on the fluctuation curve.

RH	High peak correction (%)	$\bar{s}$ (%)	Correction without cover, under stable conditions (%)	Difference (%)	*U* (k=2)
70 %	1.00	0.24	1.27	-0.27	0.86
50 %	0.31	0.29	0.32	-0.01	0.79
30 %	-1.18	0.23	-1.02	-0.16	0.57
RH	Low peak correction (%)	$\bar{s}$ (%)	Correction without cover, under stable conditions (%)	Difference (%)	*U* (k=2)
70 %	0.53	0.23	1.27	-0.74	0.84
50 %	-0.73	0.20	0.32	-1.05	0.65
30 %	-1.68	0.07	-1.02	-0.66	0.35

Table 13. Comparison of stable state and fluctuating state relative humidity corrections for probe no 2 at peak values on the fluctuation curve.

RH	High peak correction (%)	$\bar{s}$ (%)	Correction without cover, under stable conditions (%)	Difference (%)	*U* (k=2)
70 %	0.73	0.37	0.46	0.27	1.0
50 %	-0.50	0.38	-0.99	0.49	0.93
30 %	-2.43	0.30	-2.47	0.04	0.69
RH	Low peak correction (%)	$\bar{s}$ (%)	Correction without cover, under stable conditions (%)	Difference (%)	*U* (k=2)
70 %	-0.12	0.37	0.46	-0.58	1.0
50 %	-2.26	0.22	-0.99	-1.27	0.68
30 %	-3.22	0.15	-2.47	-0.75	0.44

Table 14. Comparison of stable state and fluctuating state relative humidity corrections for probe no 3 at peak values on the fluctuation curve.

RH	High peak correction (%)	$\bar{s}$ (%)	Correction without cover, under stable conditions (%)	Difference (%)	*U* (k=2)
70 %	-1,62	0.20	-1.05	-0.57	0.82
50 %	-1,64	0.30	-1.48	-0.16	0.81
30 %	-2,51	0.24	-2.32	-0.19	0.59
RH	Low peak correction (%)	$\bar{s}$ (%)	Correction without cover, under stable conditions (%)	Difference (%)	*U* (k=2)
70 %	-1,63	0.21	-1.05	-0.58	0.82
50 %	-2,53	0.20	-1.48	-1.05	0.65
30 %	-2,93	0.08	-2.32	-0.61	0.36

Table 15. Net RH_{corr} differences with respect to the uncovered probe for hygrometers number 1 and 2.

	High peak correction differences with respect to stable state conditions			Net differences	
RH	Hygrometer no 1 RH_{corr} (%)	Hygrometer no 2 RH_{corr} (%)	Hygrometer no 3 RH_{corr} (%)	Hygrometer no 1 RH_{corr} (%)	Hygrometer no 2 RH_{corr} (%)
70 %	-0.27	0.27	-0.57	0.30	0.84
50 %	-0.01	0.49	-0.16	0.15	0.65
30 %	-0.16	0.04	-0.19	0.03	0.23
	Low peak corrections differences with respect to stable state conditions			Net differences	
RH	Hygrometer no 1 RH_{corr} (%)	Hygrometer no 2 RH_{corr} (%)	Hygrometer no 3 RH_{corr} (%)	Hygrometer no 1 RH_{corr} (%)	Hygrometer no 2 RH_{corr} (%)
70 %	-0.74	-0.58	-0.58	-0.16	0.00
50 %	-1.05	-1.27	-1.05	0.00	-0.22
30 %	-0.66	-0.75	-0.61	-0.05	-0.14

Appendix 3

Uncertainty components.

Table 16. Typical uncertainty estimates for calibrating hygrometer no 1 in the climatic chamber at 50 % relative humidity level.

<table>
<tr><th colspan="3">Standard uncertainty component</th><th>Value</th></tr>
<tr><td colspan="2" rowspan="3">$u(RH_{meas})$</td><td>u_A</td><td>0.45 %</td></tr>
<tr><td>$u_{B\ resoluion}$</td><td>0.0289 %</td></tr>
<tr><td>$u_{B\ hysterisis}$</td><td>0.3 %</td></tr>
<tr><td rowspan="8">$u(RH_{ref})$</td><td rowspan="4">T</td><td>$u_{A\ stability}$</td><td>0.01 K</td></tr>
<tr><td>$u_{B\ resoluion}$</td><td>$2.89\cdot10^{-3}$ K</td></tr>
<tr><td>$u_{B\ inhomogeneity}$</td><td>0.0577 K</td></tr>
<tr><td>$u_{B\ instrument}$</td><td>0.02 K</td></tr>
<tr><td rowspan="4">T_d</td><td>$u_{A\ stability}$</td><td>0.15 K</td></tr>
<tr><td>$u_{B\ resoluion}$</td><td>$2.89\cdot10^{-3}$ K</td></tr>
<tr><td>$u_{B\ inhomogeneity}$</td><td>0.0577 K</td></tr>
<tr><td>$u_{B\ instrument}$</td><td>0.035 K</td></tr>
</table>

Information sheet

“Hügromeetrite kalibreerimine fluktueeruvates ja siirdetingimustes”

Hügromeetreid kalibreeritakse tavaliselt stabiilsetel niiskuse väärtustel. Suhteline niiskus fluktueerub kliimakambris üsna palju keskmistel väärtustel. Käesolevas magistritöös mõõdeti, kui palju suhtelise niiskuse fluktueerumine kliimakambris mõjutab hügromeetrite kalibreerimist. Samuti mõõdeti erinevate hügromeetrite ajategureid ja kalibreeriti hügromeetreid triivivatel suhtelise niiskuse väärtustel.

Suhtelise niiskuse fluktueerumise mõju kalibreerimise tulemusele on väike, vaatamata sellele et suhtelise niiskus fluktueerub kliimakambris keskmistel väärtustel tugevasti. Isegi kõige aeglasemaid hügromeetreid saab kalibreerida fluktueeruvatel tingimustel. Triivivatel suhtelise niiskuse väärtustel sõltub kalibreerimise täpsus triivimise kiirusest ja hügromeetri ajategurist. Kõige aeglasemate hügromeetrite kalibreerimine suhtelise niiskuse triivimise kiirusel 0,5 %/min ja 1 %/min põhjustab olulisi viitaja vigu (lag errors).

Võtmesõnad: õhuniiskus, hügromeeter, kalibreerimine, ajategur, kliimakamber, fluktuatsioonid, triiv

“Calibration of hygrometers at fluctuating and transient conditions”

Hygrometers are normally calibrated under stable conditions. Relative humidity values in the climatic chamber fluctuate quite much at medium levels. In this work it was measured how much the relative humidity fluctuation in the climatic chamber affects the calibration of hygrometers. Also the time constants of different hygrometers were measured and the hygrometers were calibrated at drifting relative humidity values.

Even though the relative humidity values fluctuate in the climatic chamber at medium levels, this fluctuation has a minor effect in calibration. Even the slowest hygrometers can be calibrated under fluctuating conditions. Under drifting conditions the accuracy of calibration depends on the speed of the drift and the time constant of the hygrometer. The calibration of slowest hygrometers at drift speeds 0.5 %/min and 1 %/min can lead to significant lag errors.

Keywords: humidity, hygrometer, calibration, time constant, climatic chamber, fluctuation, drift

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