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Hygrostat based on adsorption processes controlled by a high precision chilled dew point mirror

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ABSTRACT

This work is concerned with the calibration of humidity sensors with a hygrostat. The moist air is produced by a hygrostat and measured with a reference sensor.

In this work a chilled mirror dew point hygrometer is used, to achieve the necessary absolute accuracy. The used hygrometer developed by ConSens GmbH forces a thermal gradient on the mirror surface with its average temperature corresponds to the dew point temperature. So when the equilibrium is reached, one half of the mirror is bedewed and the other half is dry. This reduces problems with undercooled vapor, which becomes problematical with a lack of condensation nuclei. Also an interpolation can be used to estimate the temperature at the boundary line between dry and bedewed area. Even when this line moves out of the middle of the mirror, the frontier line between the dry and bedewed area can be estimated due to an optical detection system which allows measuring the dew point accurately and continuously even while it is drifting [2].

Index Terms – chilled mirror hygrometer, humidity control, water sorption

1. INTRODUCTION

Capacitive humidity sensors have a broad range of application, but they are not very precise and stable. However they are often used because of their low costs. To reduce their errors it is possible to calibrate them with a hygrostat, which produces air conditions with known humidity. In this work a setup is used, consisting of a closed circuit of moist flowing air. The two basic parts of the setup are the thermal hygrostat and a chilled dew point mirror.

The hygrostat makes use of the temperature-dependent adsorption of water at the surface of solid bodies. To increase the amount of adsorbed water, the macroporous and microporous structures of silica gel are used. Dependent on the humidity of the adjacent air and the temperature of the surface, water is evaporating or condensing until equilibrium is reached. With control of the silica temperature by a thermoelectric module the equilibrium can be influenced and therefore the humidity of the air [1]. This equilibrium also depends on the initial state of the system, by the time the air circuit was closed. This initial state is proper for choosing the wanted range of humidity to be generated by the hygrostat. However this state cannot be well known, so there is a need to precisely measure the humidity by a hygrometer as shown in Figure 1. The necessary reference sensor is the dew point mirror described in [2], while the specimen is a capacitive hygrometer of type SHT11.

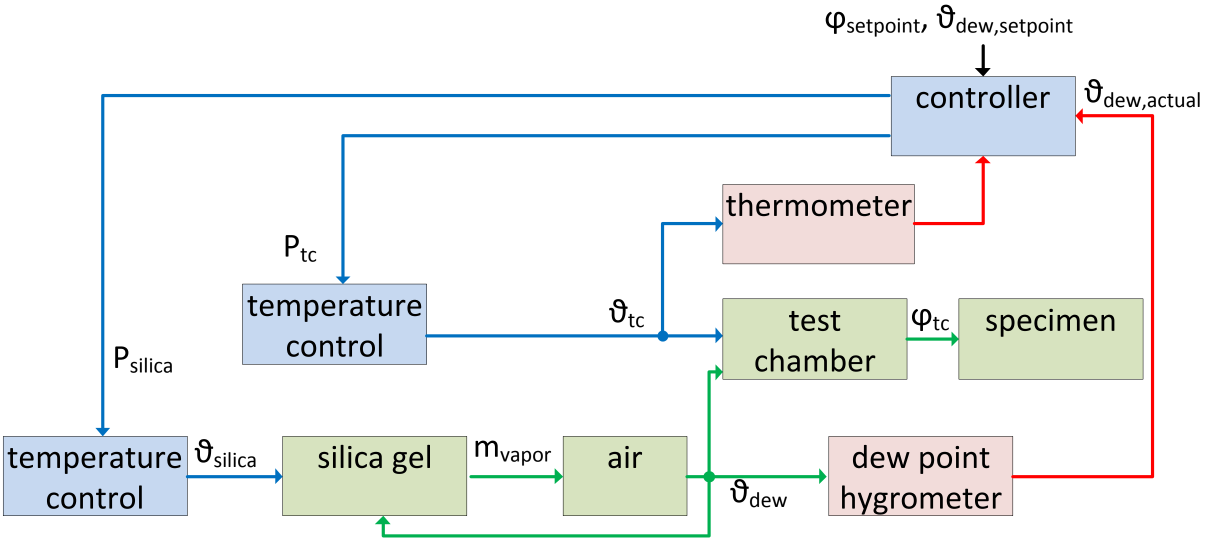


Figure 1: Schematic of a setup for humidity control

With this setup it is possible to achieve stable and well known dew point temperature of the air in the closed circuit. Combined with an accurate measurement of the air temperature, it the dew point temperature can be converted into other dimensions of humidity as described by Sonntag [3].

2. MODELING OF MOISTURE TRANSPORT PHENOMENA

2.1 Sorption isotherm of silica gel

The used hygrostat makes use of the temperature dependend sorption of water on surface to control the humidity of an air volume. According to a change of temperature the surface interchanges water with the adjacent air to reach its equilibrium state. This leads also to a change in the air's humidity. To model the behavior of the thermal hygrostat, the water amount on the silica gel surface has to be known. For simulation purposes a sorption isotherm for silica gel as described by Busweiler [4] was used:

$$\frac{\mathrm{X}(\varphi)}{X_m} = \frac{b\cdot\varphi}{1-\varphi}\cdot\frac{2(b-\varphi)\cdot\varphi + 2(\mathrm{b}-1)^2\cdot\varphi^2 + (Nh+2h)\cdot\varphi^{N+2} + \cdots}{2[1+2(b-1)\cdot\varphi - (b-1)^2\cdot\varphi^2 + h\cdot\varphi^{N+2} + \cdots}$$
$$\frac{\cdots + (2b + N^2\cdot b^2 + 2N\cdot b - 2b^2 - N\cdot b^2 - 2h - 2N\cdot h)\cdot\varphi^{N+1}}{\cdots (b^2 + h - 2b - N\cdot b^2)\cdot\varphi^N + (N\cdot b^2 + 2b - 2b^2 - 2h)\cdot\varphi^{N+1}]} \qquad (2.1)$$

with: $X_m(T) = X_m(T_0)\cdot exp[\frac{-h_m}{R_D}\cdot(\frac{1}{T_0} - \frac{1}{T})]$

It describes the nonlinear dependencies of the sorbed amount of water X as a function of relative humidity φ and surface temperature T. The parameters b, N, T_0 and h_m were taken from [4], while R_D is the specific gas constant of water vapor. As the changed in temperature also implicates a change in relative humidity, the resulting equilibrium vapor concentration has to be found as solution of the implicit equation:

$$c(T) = c_0 + \frac{m_{SG}}{V_{air}} X(\varphi(c(T), T)) \tag{2.2}$$

While using equation (2.1) as description of the isotherm, there is no explicit analytical solution for this problem. This fact is problematical in particular for the dynamic simulation of the system's behavior. Although regarding to equation (2.2) it is obvious, that there are two important parameters defining the characteristics of the hygrostat. One is the ratio of silica gel mass m_{SG} in relation to the moistened air volume V_{air}. It defines the sensitivity of changes in the humidity according to changes in the silica gel temperature. The other important parameter is the initial concentration c_0, which determines the working point of the hygrostat. As shown above, the sensitivity is adjustable by means of the silica gel mass. But this possibility is limited due to the effect that the desired change in humidity also results in a change of sorbed water on the silica gel surface. With further increase of silica gel mass this conducts to a state where only slightly changes in sorbed amount of water occur whilst a great change in humidity. As boundary case the process can be considered as to be without change in sorbed amount of water. This consideration results in a curve of constant water loading, which defines the maximum achievable sensitivity. This maximum sensitivity depends slightly on the working point of the hygrostat, but apart from that only from the type of silica gel (see Figure 2).

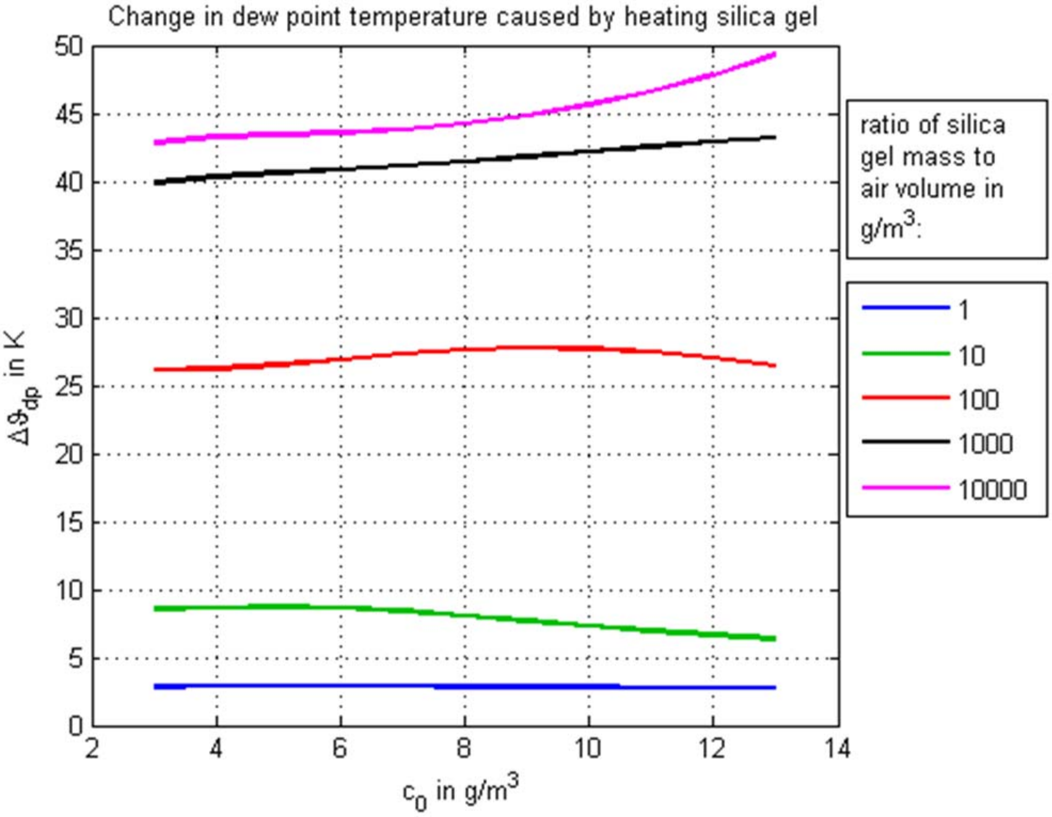


Figure 2: simulated change of dew point temperature (silica gel heated from 5 °C to 50 °C)

2.2 Transport in Air

The system's dynamic behaviour is described with a model based on an equivalent electrical circuit (Figure 3). In this model the material throughput of water is substituted with an electric current and the concentration of water is substituted with a voltage. In result the common mathematical description of electrical circuits can be applied. The system is divided into different parts, at which diffusion paths are represented by resistors and surfaces and air volumes are represented by capacities. The silica gel is treated as a variable capacitor controlled by an external signal. In this model the external signal is the silica gel temperature and in that way also an interconnection point to the thermal model of the system.

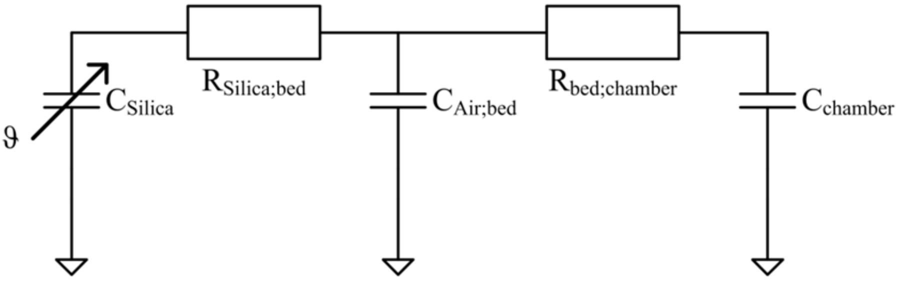


Figure 3: electrical equivalent circuit of the water transportation processes

In case of using the nonlinear sorption isotherm of the silica gel, the model indicates a faster desorption process than adsorption process. As shown in Figure 4 the same phenomenon is observed during measurement. One reason for the faster desorption is the instance of an increasing slope of the sorption isotherm during heating process. As in case of adsorption, the slope is decreasing, the process can be assumed as an isotherm sorption with convex sorption isotherm. This result in a faster desorption than adsorption, as shown in [6]

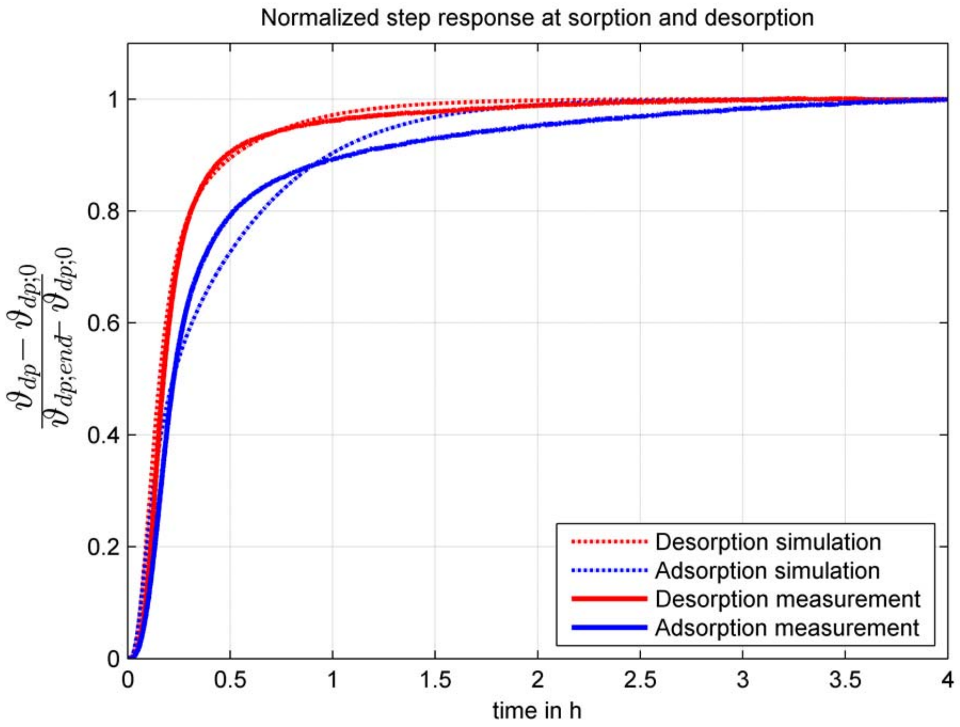


Figure 4: normalized step response at sorption and desorption

Especially for the adsorption process there is a higher error of the simulation. Possible reasons for these errors are simplifications for example in the thermal model. Also the dependency of the diffusion constant on the silica gel temperature was neglected. The consideration of this effect may increase the model accuracy, but is not reasonable due to the fact that the tolerances of the system characteristics are well known enough.

2.3 Temperature Modeling

Similar to the water transportation processes, the thermal behavior of the dew point mirror can be described with an equivalent electrical circuit. It shows a negligible thermal error for the temperature measurement of the mirror surface. The error is dominated by the characteristic error of the sensor elements, while the dynamics of the temperature control is limited by the thermoelectric coolers.

3. EXPERIMENTAL SETUP

The experiments in this work were performed with a closed air circuit, containing the chilled dew point mirror, the hygrostat, a membrane pump and the specimen sensor of type SHT11 (Figure 1). The hard- and software, necessary for controlling, is a proprietary development of ConSens GmbH. The hardware is included in an industrial PC housing, while the measurement and power control is running on a microcontroller. The user interface and the sequential control are implemented in an environment of a common operating system for PCs.

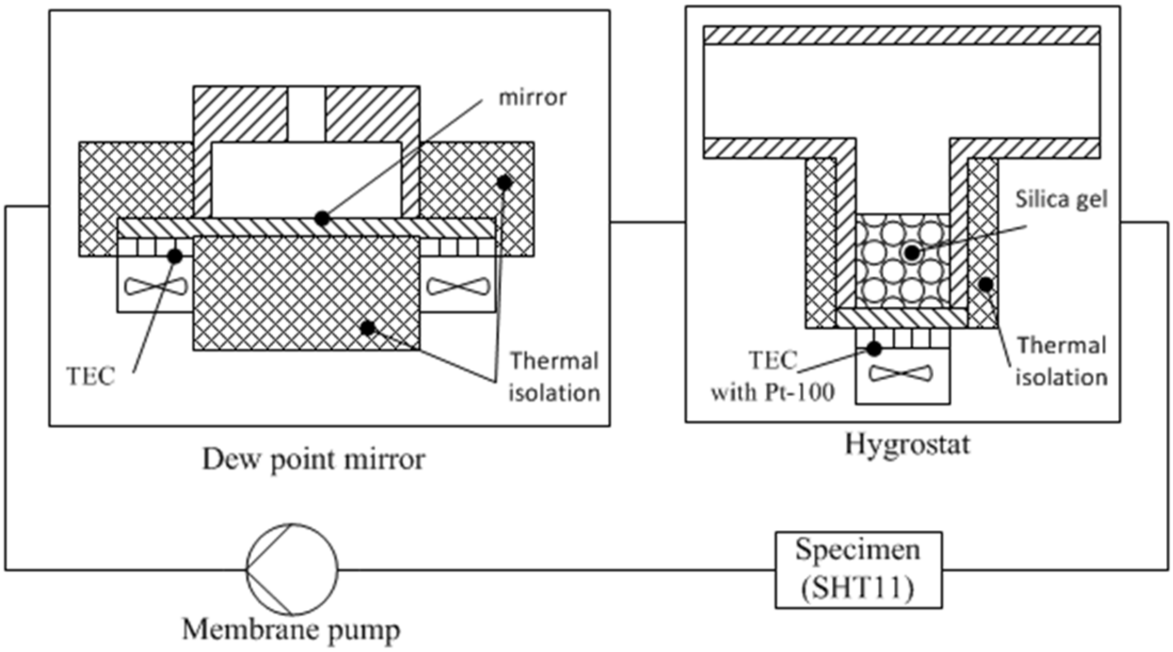
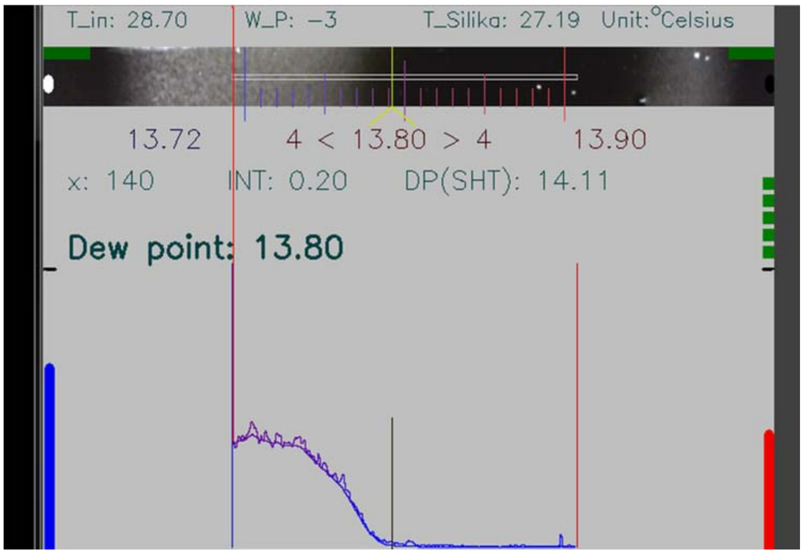


Figure 5: schematic sketch of the experimental setup

3.1 Dew point mirror

The used reference sensor is a chilled dew point mirror built up by ConSens Gmbh [2]. The dew point mirror consists of a metal plate with high thermal conductivity and the mirror surface on its top side. Both ends of the plate are coupled to a thermoelectric cooler each on the back side of the plate (see Figure 5). Both coolers are controlled in a manner to generate a thermal gradient on the plate surface. The controller cools the whole plate to the specific temperature, where the cool side of the surface is bedewed and the hot side is dry. The

controller input is provided by camera focused on the mirror surface. This surface is in contact with the air to be characterized. All other surfaces of the plate are thermally isolated to the environment. In the middle area there are located three temperature sensors to determine the surface temperature and the thermal gradient. The aim of the control algorithm is to generate a boundary line between bedewed and dry mirror surface in the middle of the plate. This setup is designed to reduce problems with undercooled vapor in connection with a lack of condensation nuclei. In static state there is always a layer of dew water, which results in an instant growth of the layer if an undercooling would occur.
The status of condensation such as graphical representation is displayed in the graphical user interface of the implemented software (Figure 6).



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T_in: 28.70   W_P: -3   T_Silika: 27.19   Unit:°Celsius
13.72   4 < 13.80 > 4   13.90
x: 140   INT: 0.20   DP(SHT): 14.11
Dew point: 13.80
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Figure 6: Screenshot of the software user interface

3.2 Hygrostat

The hygrostat in this work is based on the functional principle described in [1]. The temperature of the silica gel is controlled by a thermoelectric cooler attached to the bottom of the silica gel recipient (see Figure 6). The thermoelectric cooler can be used for heating and cooling in case of using a power supply, capable to drive current in both directions. This allows a broad range of temperature control and the possibility of active cooling and heating for dynamic purposes.
For an efficient moistening of the air, it is necessary to achieve a homogeneous temperature in the silica gel. In other respects the amount of silica gel, whose temperature is changed fewer would buffer the changes in humidity. Also a high ratio of silica gel to moistened air is of advantage, as shown in Figure 2. This aspect implies an optimization problem. With a big amount of silica gel the temperature control of the silica gel is problematic due to a limited electrical power allowed according to the thermoelectric cooler. In combination the demand for a homogeneous temperature field limits the reasonable amount of silica gel additionally. Also a greater amount of silica gel slows down the equalization processes in the silica gel grain bed [5].

4. CONTROLLER SETUP

According to Figure 1 there several control algorithms needed to build up the hygrostat. The first controller uses a thermoelectric cooler to ensure a specified silica gel temperature and is designed as standard PID-form. The second controller processes the information from the dew point mirror camera to provide the half bedewed state of the mirror surface described in section 3.1. Additionally the second controller provides information about the prevailing dew point temperature of the air. This temperature is also determined from the specimen measurement values. The third controller outputs the necessary silica gel temperature, to achieve a stable dew point temperature. As input for the third control algorithm the dew point temperature provided either by the dew point mirror or the specimen is applicable. A temperature control of the air was not realized, due to the circumstance, that only the dew point temperature was used as controlled quantity. For generation of a specific relative humidity, an additional temperature controller would be necessary.

In order to prevent mutual disturbances between the mirror controller and the overall control algorithm, the specimen's signal was used as controlled value. This allows controlling the air humidity in a stable condition, before the mirror controller is activated and the dewing process starts. After the activation the mirror temperature is slowly reduced until the condensation begins. In this moment a decrease in dew point temperature occurs and has to be compensated by the silica gel controller. The decrease is caused by the reduction of water vapor in the air by water condensation on the mirror surface. So it is necessary to prevent the control algorithms to interfere with each other.

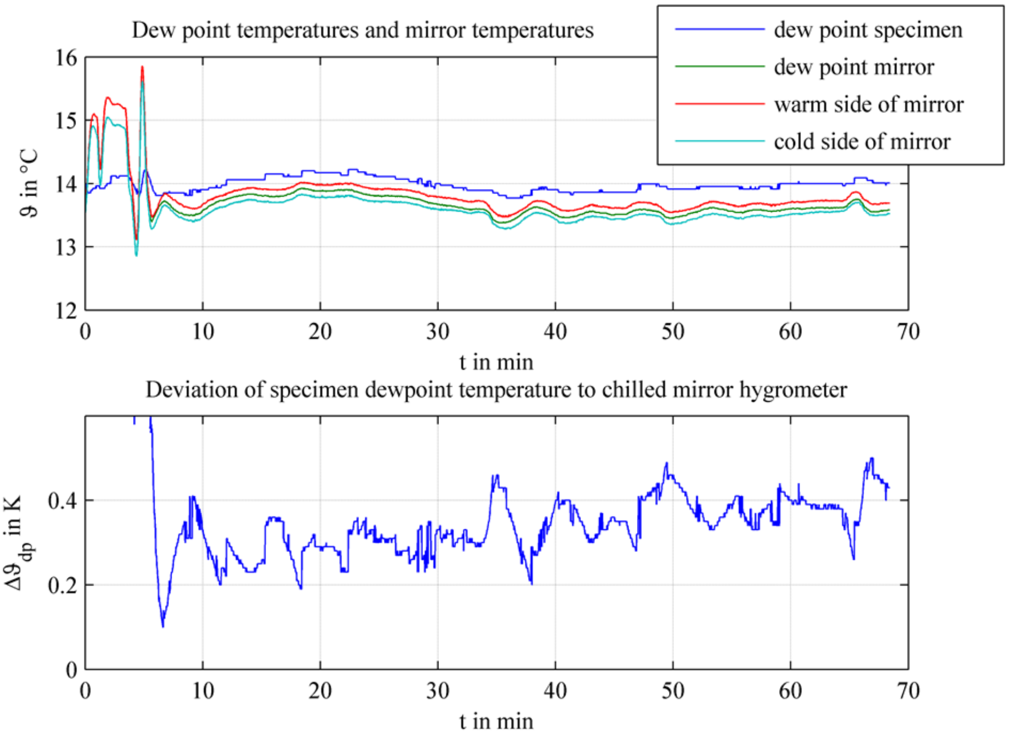

Figure 7:example of dew point control process

5. RESULTS

The trend of measured dew point temperatures is shown in Figure 7 such as the temperatures of the sensors near to the warm end and the cold end of the mirror surface. The deviation between specimen and child mirror oscillates due to different dynamic characteristics of both sensors. The dew point value itself oscillates because of the limited resolution of the controlled value in connection the slow processes of water transport in the silica gel grain. The mean value of the deviation of approximately 330 mK is in good compliance with the allowed deviation specified by the manufacturer. After duration of approximately 40 minutes when the oscillation reaches their minimum, the specimen deviation evens out to 400 mK with standard deviation of 80 mK. This dynamic effect has to be taken into concern, when the setup is used for static calibration. The better resolution of the chilled mirror was not used yet to avoid the mutual disturbances described in section 4.

6. CONCLUSIONS

In this work a new possibility for generation of specified air humidity conditions was shown. The manipulation of the humidity can be performed by the thermal regulation of a sorbent used in closed air circuit with a precise reference sensor.

Although a stable control of the dew point temperature was achieved, further work is necessary. This applies especially to improvements of the control algorithms by means of reducing the possibility of mutual disturbances and the oscillation of the controlled dew point temperature. This also implies a further optimization of the hygrostat geometry to improve its sensitivity to changes in silica gel temperature and its dynamical characteristics.

ACKNOWLEDGEMENTS

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