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Engaging Frost Formation in a Chilled-Mirror Hygrometer

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Abstract Precise humidity measurements conducted with a chilled-mirror hygrometer (CMH) in the frost-point range require the determination of the condensate phase on the sensor's mirror. Undetected supercooled water (SCW) on the surface of the mirror can lead to an error in frost point reading of up to 2 K or more. A recent trend in CMH design is implementation of supercooled water detection or elimination abilities. Elimination of SCW can also be performed manually by cooling, though with some concerns regarding the reliability of the process and the reproducibility of the frost-point measurements. The purpose of this article is to present the possible automation of this process without compromising the instrument, especially in the case of calibration standards lacking elimination ability, when a long and valuable calibration history cannot be jeopardized. At the same time, the purpose of this investigation is also to study the reliability of automation and the effect of the process on the reproducibility of frost point. A special control device was developed to upgrade the instrument's control loop without electrically compromising the instrument itself. In order to assess the SCW elimination process by cooling and to determine its optimal parameters, comparisons were conducted against the primary dew-point generator to obtain a stable environment. Our experiments have proven the reliability of the automation and the reproducibility of the frost point was within 0.012°C.

Keywords Frost transition · Dew-point sensor · Humidity measurement

1 Introduction

A dew-point sensor cools a mirror to a temperature where water vapor from gas passing over it condenses on the surface. The sensor then controls the thickness of the

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condensate layer, usually by measuring light reflecting from the mirror. At mirror temperatures below the freezing point, the condensate normally becomes solid ice. The transition time between the liquid and solid phases can be quite long in a pure environment and, if the mirror is cooled carefully, the liquid water can supercool by as much as −40°C. When conducting precise dew/frost point measurements, the sensor must either detect this meta-stable phase or force its transition. Otherwise, a false reading of approximately 10% (e.g., −1°C at a frost point of −10°C) between the frost point and the dew point could be recorded.

For this reason, the latest chilled-mirror hygrometers (CMHs) are able to detect or freeze the supercooled water (SCW) in different ways. Different detection processes were presented by others, including the detection of reflected scattered light [1], the measurement of surface acoustic waves [2], or by visually observing the condensate on the sensor's mirror and using pattern recognition software [3,4]. The advantage of these processes is that they do not thermally disturb the microenvironment around the sensor's mirror. The disadvantage is that they can lack reliability, as the mirror condensate often contains a mixture of SCW and ice. The second approach is to eliminate SCW by forcing it to freeze. The process of crystallization is accelerated by introducing a disturbance, such as a mechanical vibration or electrostatic discharge. Another way to eliminate SCW is to cool the mirror to a low temperature, where ice will be certain to form, and then heat it to the expected frost point. This approach, although more reliable, could introduce a large thermal disturbance, especially when the cooling parameters are not optimally determined. If the instrument does not have SCW detection or elimination capabilities, elimination can be performed manually by cooling the mirror (latter approach) by applying maximum cooling power to the Peltier cooling element. This requires a lot of skill from the operator and a successful frost transition is difficult to achieve. For this reason, automation of this process is considered and explained in the article. The automation is also important in the case of dew-point reference instruments with a long and valuable calibration history. This history should not be discarded by replacing the reference by a new instrument, simply because it lacks a SCW freezing feature. In such cases, automation should be realized, but without compromising the instrument's electronics in order not to jeopardize the control parameters and the calibration history.

In order to assess freezing the SCW by a cooling process and to determine its optimal parameters, we must provide gas with a stable dew point to the instrument. A stable dew point is important also to determine the reproducibility of the frost point with SCW elimination. Thus, the instrument was connected to our primary dew-point generator with a frost point stable to within 5 mK at −10°C.

2 Automation of Supercooled Water Elimination by Cooling

2.1 Process Identification

In order to automate the SCW elimination process, a standalone control device was developed and connected to the dew-point meter. The device controls the instrument

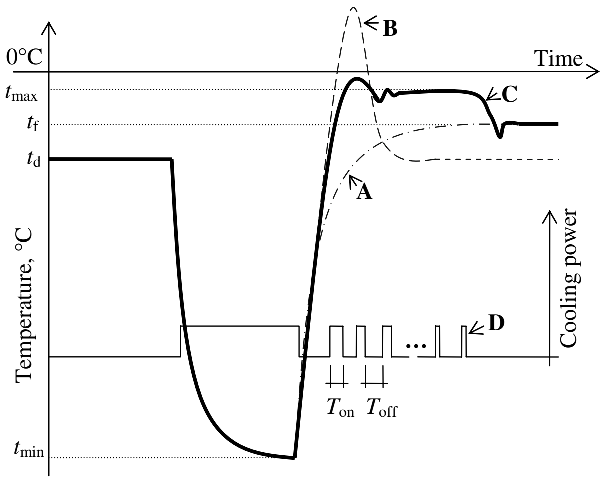

Fig. 1 Supercooled water elimination by cooling. External control of the mirror temperature: A—without 0°C overshoot; B—with 0°C overshoot (unsuccessful elimination); C—externally-limited overshoot to $t_{\max} < 0°C$ (to avoid melting)

externally by reading the mirror temperature through a serial port and by switching on and off the maximum cooling power to the mirror.

The automation of SCW elimination by cooling is a three-stage process. The first stage starts by switching on maximum cooling. When the mirror temperature reaches a certain predefined temperature $t_{\min}$, all condensate on the mirror should freeze and become ice. At this point, the cooling is switched off—the beginning of the second stage—and the sensor takes over the control and heats the mirror to the expected frost-point temperature (see curve A in Fig. 1). We can calculate the expected frost point t_f from the dew point, t_d, at which SCW is present, according to the following equation:

$$t_\mathrm{f} = e_\mathrm{is}^{-1}\left[e_\mathrm{ws}\left(t_\mathrm{d}\right)\right], \tag{1}$$

where e_is denotes the water vapor saturation formulae with respect to ice [5], e_is^{-1} is its inverse function, and e_ws is the water vapor saturation formulae with respect to water [5]. These formulae are relatively complex for a microcontroller to compute. For this reason, we can estimate t_f according to Eq. 2 with a maximum error of 1% in the range from −30 to 0°C. Both t_f and t_d are in °C.

$$t_\mathrm{f} \approx 0.89 t_\mathrm{d}. \tag{2}$$

During the heating of the mirror, the sensor's control electronics must not allow the mirror temperature to overshoot 0°C, because the ice layer on the mirror would melt and the elimination process would be unsuccessful (see curve B in Fig. 1). In some cases, when the instrument's control parameters are poorly set, the mirror can even get flooded and the sensor's optics may need to be rebalanced. The overshoot depends on the control parameters of the specific sensor, the frost point it is measuring, and the temperature reached under maximum cooling, t_{min}. In order to avoid the 0°C overshoot during heating, the mirror temperature must be limited to a certain subzero temperature t_{max} slightly above the expected frost point until the frost layer thins enough for the sensor's control electronics to start the cooling process again (see curve C in Fig. 1). This is stage three of the elimination process, where we control the mirror temperature at t_{max} (see signal D in Fig. 1). This last control stage ends when the sensor starts to cool down again. The external control device then passes full control back to the sensor.

2.2 Avoiding the 0°C Overshoot

The key focus of the control device design is the third stage of the elimination process, where we prevent the mirror temperature from overshooting 0°C. Figure 2 shows the control diagram of this stage. As mentioned above, the control device has to control the mirror temperature at a predefined temperature t_{max} by alternately switching the maximum cooling on and off. Maximum cooling is turned on during time T_{on}, and turned off during time T_{off} (signal D in Fig. 1). The control parameter t_{max} is set a few degrees above the expected frost point (see Eq. 2) and below 0°C. Higher values of t_{max} mean faster response due to faster evaporation of the mirror condensate during the second stage of control. On the other hand, setting t_{max} too close to 0°C can result in the controller being unable to hold the mirror temperature below 0°C at all times. The PI controller (see Fig. 2) with its proportional and integral terms sets the time interval T_{off}, while T_{on} is kept at a fixed value (in our case 100 ms). The output of the controller, T_{off}, is calculated according to Eq. 3,

$$T_{\mathrm{off}} = K_{\mathrm{P}} e(t) + K_{\mathrm{I}} \int_{t} e(\tau)\,\mathrm{d}\tau, \quad e(T) = t_{\mathrm{max}} - t_{\mathrm{mirror}}(T), \tag{3}$$

where K_{P} and K_{I} are the proportional and integral parameters (gains) of the controller, respectively. Their values depend on the sample rate of the mirror temperature and they are obtained experimentally. The parameter T denotes time.

As mentioned above, this control stage ends when the condensate layer on the mirror is thin enough. Then, the sensor itself tries to reach the frost point by cooling the mirror. The control device detects this transition by observing the mirror temperature and its change, at which point it passes full control back to the sensor.

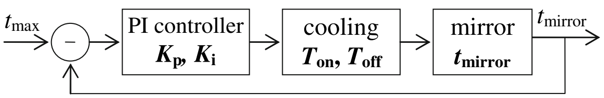

Fig. 2 Control diagram of the last stage of the supercooled water elimination process, where the sensor's internal control is prevented from overshooting 0°C by keeping the mirror temperature around t_{max} (<0°C)

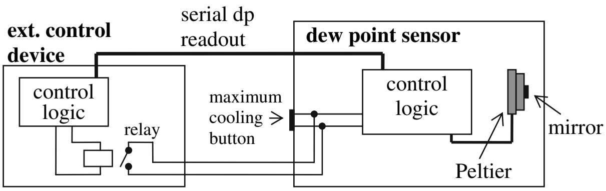

Fig. 3 External control device connection to the dew point sensor in order to automate the SCW elimination process

Fig. 4 A standalone control device for SCW elimination

2.3 Control Device Realization

The external control device must not electrically jeopardize the instrument's electronics and, consequently, its calibration history in the case of a reference calibration standard. For this reason, the device samples the mirror temperature through the serial interface, which is the common interface for most state-of-the-art dew-point sensors. An actuator activates the sensor's cooling by electrically short-circuiting the maximum cooling button, which is also a commonly present feature of dew-point sensors. If the sensor lacks this option, we can realize the maximum cooling by connecting maximum power to the Peltier element. Figure 3 shows the schematics of the external control device and its connection to the dew point sensor.

For test purposes, the control device was first realized in the form of a Labview subroutine as a part of the laboratory's automation software. Later, we developed a stand-alone control circuit, which includes microcontroller-based control logic, a serial communication interface, and an actuator with a relay. Figure 4 shows the stand-alone circuit.

3 Measurements

We evaluated the SCW elimination process by cooling through tests undertaken using a precision dew-point sensor, a Michell S4020 with several years of calibration history.

In order to obtain reliable results, we connected the sensor to our primary dew-point generator with a stable frost-point output (standard uncertainty of frost point is 0.016°C in the testing range from −30 to 0°C).

Prior to evaluation, we observed the natural phase transition of mirror condensate to assess the cleanliness of the system and the need for the SCW elimination process. Going forward, our objective was to determine the optimal parameters that would result in a reliable elimination process. Measurements were performed at frost points of −15, −10, and −5°C. For each of these set points, the maximum cooling temperature t_{min} was altered to determine, first, where the frost transition starts, and, second, to determine the influence of cooling on the reproducibility of the measured frost point. As mentioned above, extensive cooling can potentially introduce high thermal disturbance to the sensor, causing the measured frost point to deviate. The value of t_{min} was therefore set in the interval from −20 to −50°C, with −50°C being the minimum achievable temperature for the test sensor. In addition, it is also a temperature at which the frost transition would definitely start, and therefore the lower control temperature is not needed. A higher t_{min}, on the other hand, means less potential for thermal disturbance. For each t_{min} at the frost point set by the primary generator, we initiated the elimination process twice. The first one was initiated with prior removal of frost (heating above 0°C and formation of SCW) to observe both the thermal disturbance and the reliability of the elimination process. The second was initiated without removal of SCW, to observe only the thermal disturbance.

The value of t_{max} was set to −3°C at frost points of −5 and −10°C, and it was set to −10°C for a frost point of −15°C.

4 Results

Before the evaluation, we recorded approximately 1 week of natural phase transitions of SCW to ice.

Our evaluation showed successful operation of the SCW elimination process when we cooled the mirror to $t_{min} = -20$°C at a frost point of −5°C. For lower frost points (−10 and −15°C), cooling down to −20°C did not result in a successful frost transition process. Obviously, the success of the process depends not only on the value of t_{min} alone, but also on the cooling time—the time of the first control stage—to allow condensate to grow. At a frost point of −15°C and cooling to $t_{min} = -30$°C, the sensor control circuit does not overshoot 0°C, and therefore the third stage of the SCW elimination process, where the mirror temperature is limited to t_{max}, was not required. Figure 5 shows an example of the mirror temperature during the SCW elimination process at a frost point of −5°C for $t_{min} = -30$°C. Figure 6 shows the frost points measured after successful elimination processes for different t_{min}. The results show no significant trend of the frost point with respect to t_{min}, which indicates that no significant thermal disturbance of the SCW elimination process on the measured frost point. Table I shows the reproducibility of results for the different frost points.

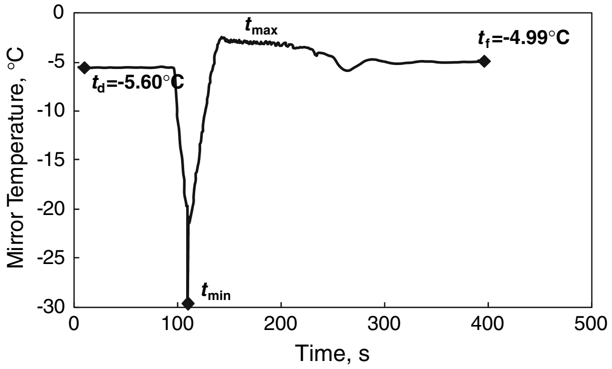

Fig. 5 Mirror temperature during the SCW elimination process at a frost point of −5°C for $t_{min} = -30$°C

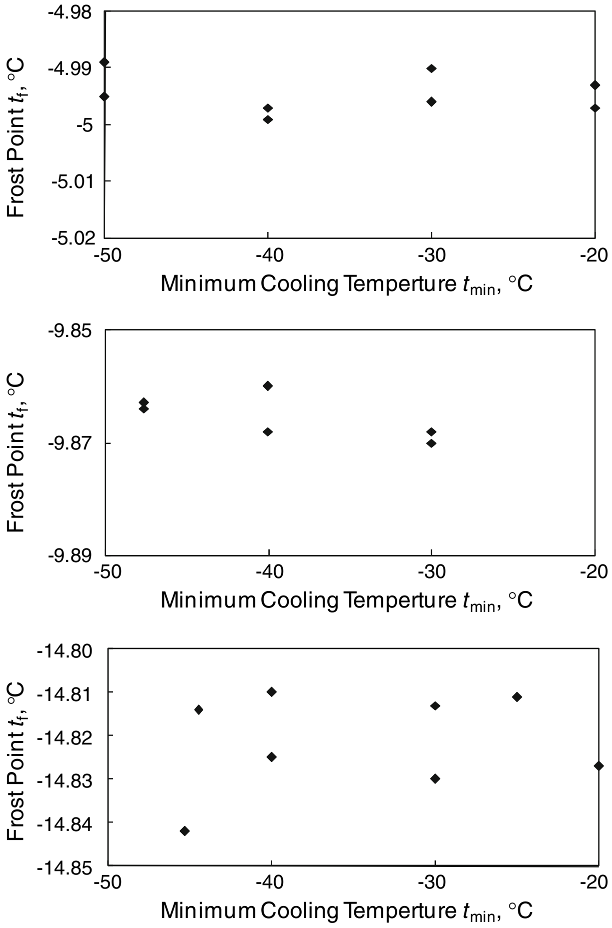

Fig. 6 Frost points measured after successful elimination processes for different t_{min}

Table 1 Reproducibility of results for different frost points set by the generator

Frost point set (°C)	Reproducibility (°C)
−5	0.004
−10	0.010
−15	0.012

5 Conclusion

For a precision dew-point sensor, the automation of supercooled water elimination by cooling was thoroughly tested and was proven to be an efficient process. In the experiments described, pre-cooling of the mirror showed no significant influence on the measured frost point. The reproducibility of the frost point due to the SCW elimination process by cooling was within 0.012°C, including the reproducibility of the instrument itself and the repeatability of the generated reference frost point. In order to determine such a small reproducibility, we carried out the experiments with our primary generator. The standard uncertainty associated with the stability of the generated dew point was 5 mK. The total uncertainty in the test range down to −30°C was 16 mK. An external control device that we developed to automate the SCW elimination process can be used for different precision dew-point sensors by applying only minor changes to software control parameters.

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