Int J Thermophys (2008) 29:1652–1659
DOI 10.1007/s10765-007-0367-8

# The New LMK Primary Standard for Dew-Point Sensor Calibration: Evaluation of the High-Range Saturator Efficiency

**Domen Hudoklin · Janko Drnovšek**

Published online: 25 January 2008


**Abstract** In the field of hygrometry, a primary dew-point standard can be realized according to several proven principles, such as single-pressure (1-P), two-pressure (2-P), or divided flow. Different realizations have been introduced by various national laboratories, each resulting in a stand-alone complex generation system. Recent trends in generator design favor the single-pressure principle without recirculation because it promises theoretically lower uncertainty and because it avoids problems regarding the leak tightness of the recirculation. Instead of recirculation, the efficiency of saturation, the key factor, is increased by preconditioning the inlet gas entering the saturator. For preconditioning, a presaturator or purifier is used to bring the dew point of the inlet stream close to the saturator temperature. The purpose of the paper is to identify the minimum requirements for the preconditioning system and the main saturator to assure efficient saturation for the LMK generator. Moreover, the aim is also to find out if the preconditioning system can be avoided despite the rather simple construction of the main saturator. If this proves to be the case, the generator design can be simplified while maintaining an accurate value of the generated dew point. Experiments were carried out within the scope of improving our existing primary generator in the above-ambient dew-point range up to +70°C. These results show the generated dew point is within the measurement uncertainty for any dew-point value of the inlet gas. Thus, the preconditioning subsystem can be avoided, which leads to a simplified generator design.

**Keywords** Dew-point generator · Humidity standard · Single-pass saturation

D. Hudoklin (✉) · J. Drnovšek
Laboratory of Metrology and Quality, Faculty of Electrical Engineering, University of Ljubljana, (MIRS/FE-LMK), Tržaška 25, 1000 Ljubljana, Slovenia
e-mail: domen.hudoklin@fe.uni-lj.si

## 1 Introduction

In the field of hygrometry, the reference value of the dew/frost point can be achieved by a primary dew-point generator. Generators with different basic operating principles have been constructed and described by some laboratories [1–6]. So far, generators working according to either the two-pressure (2-P) or single-pressure (1-P) principle [1–5] have attained the best results. From a theoretical point of view, the two principles are the same; however, the pressure drop with the 1-P implementation is so small that the uncertainty of the water vapor-pressure equations may be disregarded. In a two-pressure system, when all other uncertainties are minimized, the uncertainty of the water-vapor equations (including the enhancement factor) may become significant, especially in the low frost-point region, as reported by Wexler [7] and later by Hardy [8]. For both types of generators, saturation efficiency is the key factor. In the 1-P implementation, saturation efficiency can be increased by gas recirculation, eliminating the need for a large saturator. On the other hand, the recirculation scheme introduces additional considerations regarding the leak tightness of the pump, especially in the low frost-point range. Recent trends in dew-point generator design therefore favor 1-P generators without recirculation (single-pass system) [9], where the generator saturation efficiency is increased by preconditioning the inlet gas. For the dew-point range below ambient, the inlet gas must be dry. This can be achieved by using dry nitrogen or air; for very low frost points, purifiers are also used. For the dew-point range above ambient, the inlet gas needs to be humidified to compensate for the less-than-ideal saturator efficiency and also to lower the load on the saturator (consumption of water and thermal load due to evaporation).

This paper presents our investigations aimed at determining the lowest dew-point limits of the above-ambient preconditioning system for the LMK generator without recirculation that are required to achieve efficient saturation. A more efficient saturator requires less strict preconditioning, and the dew point of the inlet gas may deviate more from the one at the outlet. In the case of very efficient saturation, preconditioning might even be avoided, which would simplify the generator design.

The experiments were carried out within the scope of improving our primary generator in the dew-point range above ambient up to +70°C.

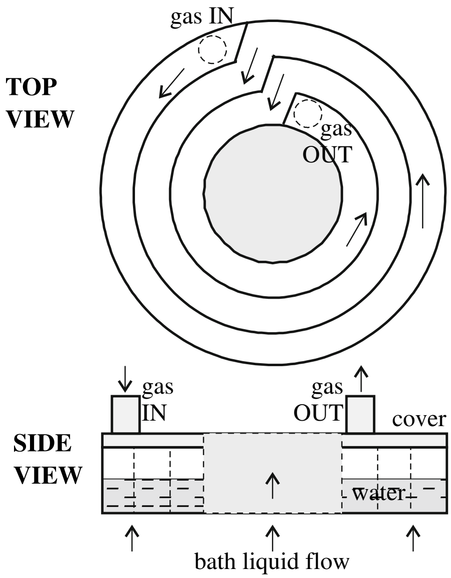
## 2 Design of the Generator

The high-temperature part of our dew-point generator works according to the single-pressure principle without recirculation. The most important parts of the generator are the saturator and the temperature-controlled liquid bath. Prior to saturation, gas is heated by a heat exchanger that is placed in the same liquid bath. The pre-conditioning part is thoroughly explained in the next section.

### 2.1 Saturator

In the generator without recirculation, the saturator must be sufficiently efficient to compensate for the difference in dew points between the inlet and outlet gas under a

**Fig. 1** Design of the saturator




gas flow that is sufficient to supply at least one hygrometer undergoing calibration. This means that the inlet gas must either take up water (humidify), or excess water must condense in the saturator, for the dew point of the outlet gas to be equal to the temperature of the saturator. Saturator dimensions are a compromise among several mutually dependent factors, such as the maximum saturation path length, the minimum mass, the bath characteristics, the required gas flow, and the amount of water (saturator load). Figure 1 shows the design of the saturator. The saturation path must be long enough to enable efficient saturation. The saturation path follows a spiral (see Fig. 1) to keep the volume of the saturator at a minimum for a given length. For our design, the saturation path is approximately 1.2 m long and 2 cm wide. The outer diameter of the saturator is approximately 20 cm. The latent heat of vaporization is another consideration regarding the size of the saturator. The larger the difference between the inlet and the outlet dew points of the gas, the more water that needs to evaporate in the saturator, causing the temperature of the gas to slightly decrease. To keep this effect small, the saturator dimensions are relatively large. In addition, the heat exchange between the last part of the saturation path and the bath liquid is increased by allowing for the bath liquid to flow through the center of the saturator (see bath liquid flow in Fig. 1). This hole also results in smaller temperature gradients across the saturator. The saturator is designed to operate with gas flows up to $1\,\mathrm{L} \cdot \mathrm{min}^{-1}$, which is enough for two typical chilled-mirror hygrometers to be calibrated in parallel.

## 2.2 Liquid Bath

A special liquid bath was designed for this purpose (see Fig. 2). The effective volume of the bath is approximately 60 l, which allows for a larger saturator to be placed within

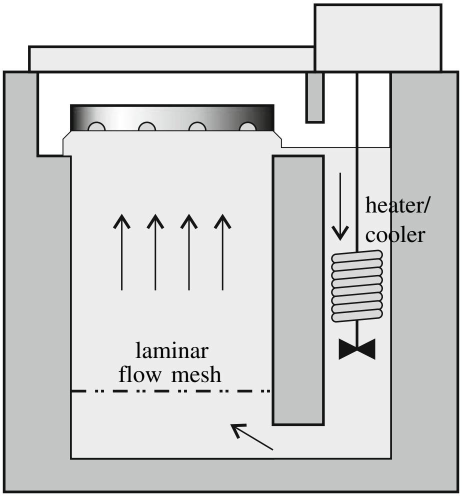



**Fig. 2** Temperature-controlled liquid bath with high stability and temperature homogeneity

it. The bath is filled with demineralized water, which can be heated from 20°C up to a stable temperature of +85°C in approximately 2 h. Special emphasis was given to temperature stability and temperature homogeneity; both are less than 5 mK over the complete range while the generator is loaded and running. Homogeneity was enhanced by installing laminar-flow mesh (see Fig. 2) and by ensuring efficient stirring.

## 2.3 Heat Exchanger

A simple heat exchanger was installed before the saturator to set the temperature of the gas to the temperature of the saturator. The heat exchanger is made of coiled stainless-steel tubing and is immersed in the bath. The inner and outer diameters of the tube are 10.2 mm and 12.7 mm, respectively. The length of the tube needed for efficient heating or cooling of the gas to the saturation temperature $T_{s,in}$ can be estimated according to a simple model of this heat exchanger (Eq. 1). To heat the gas for a certain mass flow $\dot{m}$ and specific heat $c_p$ at constant pressure from ambient temperature $T_a$ to the saturator temperature $T_{s,in}$, the heat transfer rate specific to this heat exchanger is needed:

$$\dot{m}c_p \left(T_a - T_{s,in}\right) = UA\Delta T_{ln}, \quad \Delta T_{ln} = \frac{T_a - T_{s,in}}{\ln \frac{T_a - T_{bath}}{T_{s,in} - T_{bath}}} \tag{1}$$

$U$ denotes the overall heat-transfer coefficient, $A$ is the heat-transfer area, and $\Delta T_{ln}$ is the logarithmic mean temperature difference. According to the model, the gas can never reach the temperature of the saturator $T_s$, which is the same as the temperature of the bath $T_{bath}$. Therefore, $T_{s,in}$ is set to 1 mK less than $T_{bath}$. The heat-transfer area is represented by the area of the inner and outer walls of the tube, $A_{in}$ and $A_{out}$, respectively. The product $UA$ is then calculated according to Eq. 2 by taking into account the heat transfer due to convection and conduction through the tube walls.

$$UA = \left( \frac{1}{\alpha_{\text{out}} A_{\text{out}}} + \frac{1}{\alpha_{\text{in}} A_{\text{in}}} + \frac{d \ \ln A_{\text{out}} / A_{\text{in}}}{\lambda \left( A_{\text{out}} - A_{\text{in}} \right)} \right)^{-1} \tag{2}$$

$\alpha_{\text{out}}$ and $\alpha_{\text{in}}$ represent the convective heat-transfer coefficients for the fluids outside and inside the tube, respectively. $\lambda$ is the thermal conductivity of the tube wall and $d$ is the wall thickness of the tube. Taking into account Eq. 1 and the cylindrical shape of the tube, the required length of the tube is calculated according to the following equation:

$$l = \frac{\dot{m} c_{\text{p}} \left( T_{\text{a}} - T_{\text{s,in}} \right)}{\Delta T_{\ln}} \cdot \left( \frac{1}{\alpha_{\text{out}} 2\pi r_{\text{out}}} + \frac{1}{\alpha_{\text{in}} 2\pi r_{\text{in}}} + \frac{d \ \ln r_{\text{out}} / r_{\text{in}}}{\lambda 2\pi \ \left( r_{\text{out}} - r_{\text{in}} \right)} \right) \tag{3}$$

The most critical parameter is $\alpha_{\text{in}}$, which is difficult to determine. Typical values of $\alpha_{\text{in}}$ for a gas are between 10 and $100\,\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$. $\alpha_{\text{out}}$ is not critical and is taken as $3{,}000\,\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ for water. Corresponding to the worst case scenario, $\alpha_{\text{in}}$ is taken as $10\,\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$, which gives the maximum value of the length $l$. To heat air at a flow rate of $1\,\text{L} \cdot \text{min}^{-1}$ from 20 to 69.999°C, at least 60 cm of stainless-steel tube is required. To design the heat exchanger for higher flow and to take into account the inaccuracy of the model, longer tubes should be used (in our case, approximately 4 m).

At the saturator exit, a thermal guard made of a coiled tube similar to the input heat exchanger is installed, but shorter than the heat exchanger preceding the saturator (approximately one-third of $l$). It thermally guards the saturator exit by preventing it from increasing in temperature due to heat flow coming from a heated enclosure at the end of the output tube outside the bath. The guard is shorter than the inlet exchanger because its purpose is not to change the temperature of the gas coming from the saturator, but only to extend the part of the output tube immersed in the bath and to keep it at the same temperature as the saturator by means of the bath fluid circulation.

### 2.4 Gas Circulation

Gas circulation is realized in two ways. If pressurized nitrogen is used as the sample gas, the flow is regulated by a mass-flow controller. If air is used, it is pumped from ambient by a diaphragm pump, which is installed downstream of the unit under test (UUT).

## 3 Measurements

### 3.1 Measurement Setup

The saturator efficiency was evaluated in the high-temperature range from 30 up to +70°C; however, the main focus was the evaluation at +70°C, where the effect is most pronounced. The latter temperature is also the limit of the precision dew-point sensor

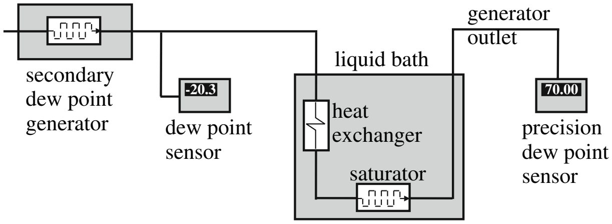



**Fig. 3** Experimental setup

that was used for the experiments. The sensor was calibrated against the NMi primary dew-point generator [3] and has several years of calibration history. The uncertainty of the sensor in dew-point measurements is 0.04°C over the complete range from −50 to +70°C. Our generator was supplied with air from a 2-P generator that we use for secondary calibrations. The dew point of the 2-P generator was measured by a secondary dew-point sensor that is calibrated and has an uncertainty of 0.07°C. Figure 3 shows the experimental setup. To establish the relationship between the temperature of the saturator and the dew point at the outlet of the primary generator, we measured the temperature of the bath using a reference platinum resistance thermometer (PRT) with an uncertainty of 0.01°C, the pressure at the saturator's exit, and the pressure after the precision dew-point sensor. The dew point of the generator was corrected for the pressure difference between the measured pressure points. The flow through the generator and through the sensor was measured in the tube behind the precision sensor.

### 3.2 Measurements

First, we wanted to determine the maximum difference in the dew point between the input gas and the output gas of the saturator (primary generator) that can be maintained without affecting the output dew point. The input dew point was set by the secondary 2-P dew-point generator. Measurements were taken at the highest saturator temperature, +70°C, where the maximum difference was expected. Table 1 shows the performance of the generator for different flow rates that were below the acceptable limit (see two paragraphs below) and for different input dew points. Measurements were carried out with a precision dew-point meter. The results show very good agreement of the generated (output) dew point within the standard uncertainty of the precision dew-point meter and the expected standard uncertainty of the generator (not less than 0.02°C). Moreover, the differences show no significant dependence on the input dew point, which demonstrates that the generator can be used without the preconditioning subsystem.

The difference in mixing ratios of the inlet gas with a frost point of −18.7°C and that of the output gas with a dew point of +70°C is very high and practically the same as the difference in mixing ratios of the output gas and that of a very dry gas. It is therefore expected that operation with dry gas would be sufficient to maintain efficient saturation with the generator.

**Table 1** Performance of the generator, measured by a precision dew-point meter for different input dew points and flow rates below or equal to 0.8 L · min$^{-1}$

| Generated dew point[a] (°C) | Input dew point (°C) | Indicated dew point[b] (°C) | Flow rate (L · min$^{-1}$) | $E^{c}$ (°C) |
|---|---|---|---|---|
| 70.074 | 16.1 | 70.066 | 0.3 | 0.008 |
| 70.068 | 16.1 | 70.064 | 0.5 | −0.004 |
| 70.089 | 12.7 | 70.077 | 0.5 | −0.012 |
| 70.081 | 5.4 | 70.082 | 0.4 | 0.001 |
| 70.082 | 0.9 | 70.084 | 0.7 | 0.002 |
| 70.083 | −14.6 | 70.083 | 0.3 | 0.000 |
| 70.073 | −14.6 | 70.082 | 0.7 | 0.009 |
| 70.072 | −18.7 | 70.067 | 0.8 | −0.005 |

[a] Saturator temperature, corrected for pressure drop
[b] Dew point, indicated by precision dew-point sensor
[c] Difference between generated dew point and indicated dew point

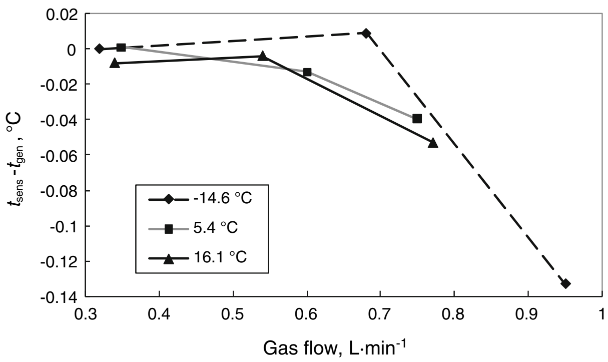



**Fig. 4** Differences between the dew point indicated by a precision sensor, $t_{\text{sens}}$, and the generator output dew point, $t_{\text{gen}}$, with respect to the gas flow for different input dew points (−14.6, 5.4, and 16.1°C)

At the same time, saturator efficiency was also tested for different values of gas flow through the saturator. Figure 4 shows the differences between the generator output dew point and the dew point indicated by the precision sensor with respect to gas flow for different input dew points. Our experiments show good efficiency of the saturator for gas flows below 0.6 L · min$^{-1}$.

The saturator was refilled with water each experimental day prior to the measurements. Water consumption was approximately 10% per day at +70°C, which shows a relatively low saturator load. This means that preconditioning of the input gas for the purpose of decreasing the saturator load is unnecessary.

Taking into account the maximum gas flow for efficient saturation, the load on the saturator, and the typical time constant of a precision chilled-mirror hygrometer in the high dew-point range, at least one UUT can be calibrated over its complete range in a single day.

### 3.3 Uncertainty Evaluation

A complete uncertainty analysis will be finalized after the system has been fully evaluated. The evaluation will be carried out in the same manner as for our existing primary generator for the low dew-point range [10]. The key focus will be on evaluating the uncertainty due to the efficiency of the saturator. The total uncertainty of the generated dew point will include the uncertainty of the thermometer, the uncertainty due to the temperature stability and uniformity of the saturator, the uncertainty due to saturator contamination, and the uncertainty due to the pressure drop. The latter is expected to be a significant source of uncertainty because of the larger sensitivity coefficient of the dew point with respect to pressure. The pressure drop is measured between the point of realization (saturator) and the point of use (output of the generator).

## 4 Conclusion

The extension of our primary dew-point generator, which works according to the single-pressure principle without recirculation, has been presented. Saturation efficiency has been tested at the upper limit of +70°C. Our results show that efficient saturation can be achieved, even when dry gas is supplied to the input of the generator, for gas flows below $0.6\,\mathrm{L} \cdot \mathrm{min}^{-1}$. This proves that the generator can be used for the calibration of precision dew-point sensors without the preconditioning subsystem, which significantly simplifies its design.

## References


1. B. Blanquart, B. Crétinon, Y. Hermier, in *Proceedings of 4th International Symposium on Humidity and Moisture*, Taipei, Taiwan (2002), pp. 26–32
2. M. Heinonen, Metrologia **39**, 3 (2002)
3. J. Nielsen, M.J. de Groot, Metrologia **41**, 3 (2004)
4. M. Stevens, in *Proceedings of TEMPMEKO '99, 7th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by J.F. Dubbeldam, M.J. de Groot (Edauw Johannissen bv, Delft, 1999), pp. 191–196
5. M. Stevens and S.A. Bell, Meas. Sci. Technol. **3**, 943 (1990)
6. P.G. Su, R.J. Wu, Measurement **36**, 1 (2004)
7. A. Wexler, J. Res. Natl. Bur. Stand. A Phys. Chem. **81A**, 5 (1977)
8. B. Hardy, in *Papers and Abstracts of the Third International Symposium on Humidity and Moisture*, vol. 1, NPL, Teddington, UK (1998), pp. 214–222
9. G.E. Scace, C.W. Meyer, W.W. Miller, J.T. Hodges, in *Proceedings of 5th International Symposium on Humidity and Moisture* (CD), Rio de Janeiro, Brazil (2006)
10. D. Hudoklin, J. Drnovšek, in *Proceedings of 5th International Symposium on Humidity and Moisture* (CD), Rio de Janeiro, Brazil (2006)