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Saturator Efficiency and Uncertainty of NMIJ Two-Pressure Two-Temperature Humidity Generator

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Abstract The primary dew-point standard of National Metrology Institute of Japan (NMIJ) over the dew-point range of −10 °C to 95 °C is a humidity generator based on the two-pressure two-temperature method. In this generator, the dew-point temperature of generated air is calculated by using the pressure and temperature, assuming that the air in the saturator is in equilibrium with liquid water. Therefore, the evaluation of the degree of saturation of water vapor in the saturator is important. In this study, the saturation efficiency of the NMIJ two-pressure two-temperature humidity generator has been re-evaluated. The NMIJ humidity generator has a presaturator that consists of a water bath and a bubbling element that can supply water vapor to the airflow into the main saturator. The amount of water vapor in the air output from the PS is altered by changing the PS temperature. The dew-point temperatures of the generated air were measured by a chilled-mirror hygrometer under various conditions of PS pressure and temperature. The saturator efficiency of the generator has been evaluated from the relationship between the measured dew-point temperature and the PS temperature. When the temperature of the PS was lower than that of the saturator, the amount of water in the air was insufficient to achieve saturation. When the temperature of the PS was slightly higher than that of the saturator, saturation was obtained.

Keywords Dew point · Humidity standard · Saturation · Saturator efficiency

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1 Introduction

Humidity is generally a scale of water vapor concentration in gases, such as air. There are two methods of realizing a primary standard of humidity: absolute measurement, in which humidity is measured in accordance with the definition of humidity, and a method involving the generation of an atmosphere with known humidity. In the absolute measurement, humidity is obtained by measuring the mass of water vapor in gases and the mass or volume of dry gases [1–3], which is based on the definition of humidity; however, it is difficult to use the absolute measurement as a humidity standard, because the process requires complex procedures and takes a long time. In many national metrology institutes, the primary standard of humidity is realized by generating a gas with constant humidity [4]. This method is based on the fact that the saturation water vapor pressure is a function of temperature. In this method, a gas saturated with water vapor is generated at constant temperature and pressure, and the arbitrary dew point and relative humidity are realized by changing the temperature and pressure of this gas. In order to produce a gas of constant humidity, there are three methods: the two-pressure method, in which only pressure is changed; the two-temperature method, in which only temperature is changed; and the two-pressure two-temperature method, in which both parameters are changed.

In order to obtain a humidity standard on the basis of water vapor pressure by using these methods, it is important to fully saturate the air with water vapor at a constant temperature and pressure, and an evaluation of the degree of saturation is required in determining the uncertainty of the humidity standard obtained [5,6]. Complete saturation of water vapor is expected to be achieved by placing a gas in contact with water for a long time. To evaluate the degree of saturation, the time during which the gas is in contact with water is changed by altering the flow rate of the gas introduced into the saturator within which a constant humidity is generated, and the humidity of the gas flowing from the saturator at that time is measured. This method is not always suitable for all humidity generators. For the standard humidity generator of the National Metrology Institute of Japan (NMIJ), which is designed such that saturation is ensured by placing a presaturator (PS) in front of a saturator [7], it is difficult to accurately evaluate the degree of saturation because the flow-rate dependence of the generated humidity was not clearly observed.

In this study, we used a two-pressure two-temperature humidity generator (a primary standard of humidity of NMIJ) and evaluated the efficiency of its saturator by controlling the temperature of the PS in order to change the amount of water vapor in the gas introduced into the saturator. The results are reported here.

2 Experimental Method

In the conventional evaluation of the degree of saturation, the flow rate Q of a gas supplied to the saturator is changed and the dew point of the gas released from the saturator is measured. Figure 1 shows a schematic diagram of a humidity generator. A simple generator without a PS is shown in Fig. 1a. When this generator is used, a gas with a dew point at the saturator inlet, T_{d1}, is supplied to the saturator at temperature

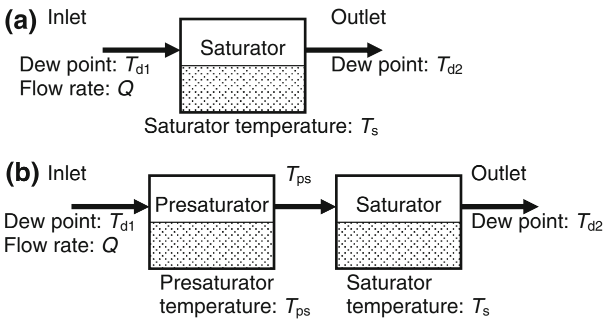

Fig. 1 Schematic diagram of humidity generator: (**a**) without presaturator and (**b**) with presaturator

T_s, and the dew point at the saturator outlet, T_{d2}, is measured. In this case, T_{d2} changes gradually as the inverse of the flow rate and is expected to approach a constant value. Assuming that the dew point generated is equal to the temperature of the saturator when the flow rate is infinitely small, the degree of saturation can be evaluated.

In the NMIJ standard humidity generator, this method was used, and when the applicable flow rate was 20 $L \cdot min^{-1}$ to 95 $L \cdot min^{-1}$, no change in the dew point at the saturator outlet could be detected, it leading to the assumption of complete saturation [7]. Because the unsaturated state cannot be observed with this method, it is difficult to accurately evaluate the degree of saturation.

The NMIJ standard humidity generator is equipped with a PS to add water vapor to the gas before introducing to the saturator so that complete saturation can be ensured. This case is shown in Fig. 1b. This generator is typically operated with the temperature of the PS, T_{ps}, higher than that of the saturator, T_s. In humidity generators with a PS, the change in the dew point at the saturator outlet, T_{d2}, is small, even when the flow rate of the gas is changed. However, it is complicated to evaluate the degree of saturation and the saturator efficiency on the basis of the flow-rate dependence of the dew point generated.

In this study, we changed the dew point of the gas introduced into the saturator by changing T_{ps}, and we evaluated the degree of saturation by measuring T_{d2}. The dew point at the saturator inlet is approximately equal to T_{ps}. Figure 2 shows a typical relationship between T_{d2} and T_{ps}. The solid line shows the case of $T_{d2} = T_{ps}$, in which the saturation efficiency is 0 %, i.e., the saturator is not working. The broken line shows the case where $T_{d2} = T_s$, indicating a completely saturated state. The dotted line shows the case of a typical intermediate state, in which T_{d2} is between T_s and T_{ps}. The slope of T_{d2} to T_{ps} is related to the efficiency of the saturator. When the efficiency of the saturator becomes 100 %, the slope of T_{d2} becomes zero and T_{d2} does not depend on T_{ps}. On the basis of the relationship between the experimentally obtained values of T_{d2} and T_s or T_{ps}, it is possible to evaluate the degree of saturation and the saturator efficiency.

3 Experimental Results

Using the NMIJ two-pressure two-temperature standard humidity generator, experiments to measure the relationship among the PS temperature (T_{ps}), the saturator

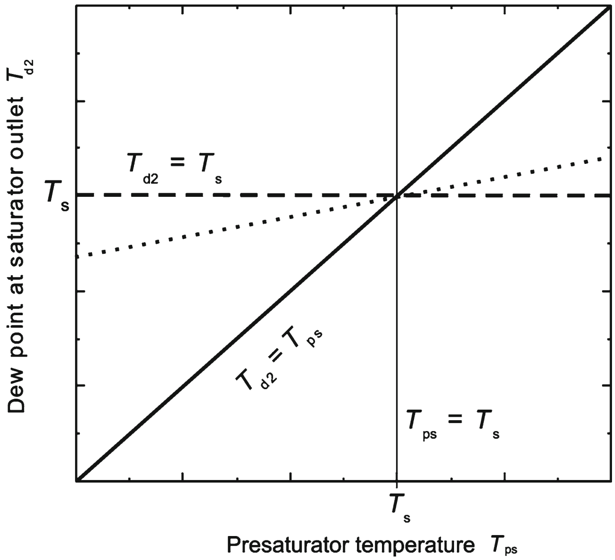

Fig. 2 Relationship between presaturator temperature T_{ps} and dew point at the saturator outlet T_{d2}

temperature (T_s), and the dew point of the generated gas (T_{d2}) were performed. The detail of the generator and the measurements of T_{ps} and T_s are reported in the literature [8]. T_{ps} is the set value of the PS. T_s is the gas temperature in the saturator chamber as shown later in Fig. 5. Figure 3 shows an example of a measurement result. In this measurement, where the aim is to generate a dew point of 90 °C, the saturator temperature T_s is 92.4 °C, the pressure is 110 kPa, and the flow rate of the gas is 3 standard liters per minute under a dry condition. PS temperature was increased in 1 °C steps from 90 °C to 100 °C. The dew point of the generated gas was measured using a dew-point meter at atmospheric pressure.

In Fig. 2, T_{d2} seems to change linearly with T_{ps}. However, in the experiment as shown in Fig. 3, T_{d2} did not change linearly but increased in the T_{ps} range from 90 °C to 93 °C and remained constant with further increases in T_{ps}. In this way, the behavior of T_{d2} becomes asymmetrical when T_{ps} approaches T_s. This is due to the structure of the saturator, and is explained later. The slope of T_{d2} at T_{ps} of 95 °C or higher is 0.0045. The fact that the slope of T_{d2} is small shows that the efficiency of the saturator is high in this T_{ps} range. Because T_{ps} is usually set approximately 2 °C higher than T_s, the systematic deviation of the dew point caused by the higher T_{ps} is 9 mK.

Figure 4 shows the temperatures of the water and the gas in the saturator chamber, as determined by the same measurement as that shown in Fig. 3. At $T_{ps} < 94$ °C, these temperatures decrease with T_{ps}. This indicates that the water is evaporating in the saturator chamber. At $T_{ps} \geq 94$ °C, however, the temperatures of the water and the gas are nearly equal and remain constant. This indicates that the rate of water evaporation was equal to that of water condensation within the saturator chamber. Regarding the dependence of T_{d2} on T_{ps}, a similar result was obtained in the T_s range from 6 °C to

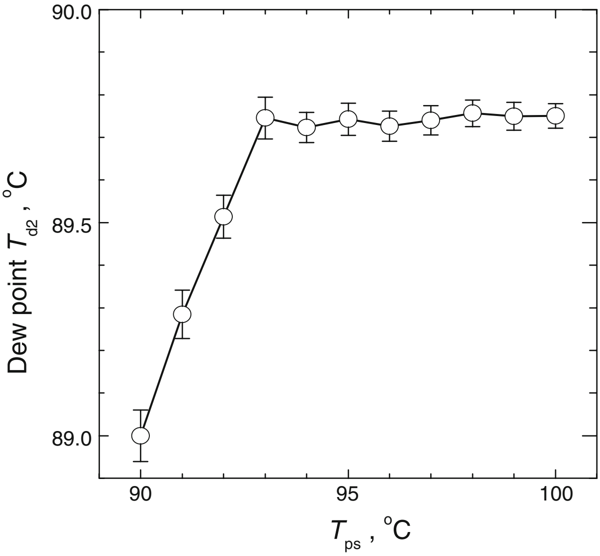

Fig. 3 Measured relationship between presaturator temperature T_{ps} and dew point at the saturator outlet T_{d2}. In this measurement, the saturator temperature T_s is 92.4 °C, the saturator pressure is 110 kPa, the flow rate of the gas is 3 $L \cdot min^{-1}$, and the dew point of the generated gas is about 90 °C

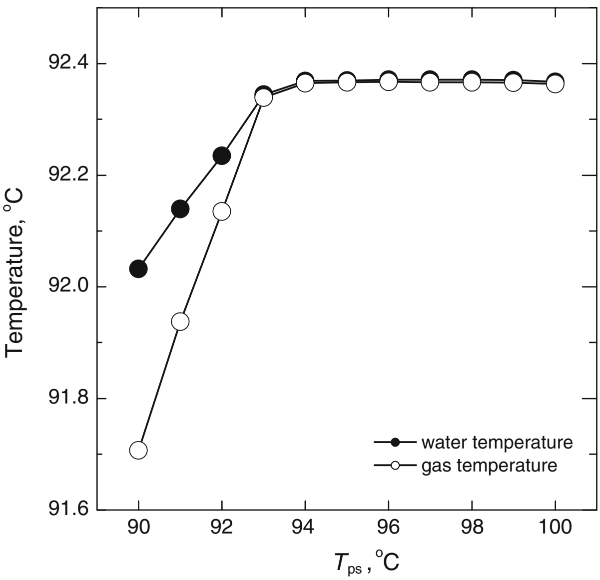

Fig. 4 Temperature changes of water and gas in the saturator chamber. In this measurement, the saturator chamber pressure is 110 kPa, the flow rate of the gas is 3 $L \cdot min^{-1}$, and the dew point of the generated gas is about 90 °C

97 °C, which is the operational temperature range for the NMIJ standard humidity generator.

4 Discussion

The state of saturation depends on the dew point of the gas introduced and the behaviors shown in Figs. 3 and 4 are due to the structure of the saturator, which is shown in Fig. 5 [7]. The entire body of the saturator is immersed in a constant-temperature water bath. The gas introduced from the PS passes through the coil-shaped heat exchanger and flows above the water surface in the saturator chamber. This generator is designed such that the temperature is controlled by the heat exchanger and the water vapor pressure is controlled by the saturator chamber. The outer diameter, length, and inner surface area of the heat exchanger tube are 19.05 mm, 5 m, and 0.267 m^2, respectively. The outer diameter and length of the saturator chamber are 50.8 mm and 1 m, respectively, and the surface area of the water in the saturator chamber is 0.049 m^2. The surface area of the saturator chamber is smaller than that of the heat exchanger.

When T_{ps} is higher than T_s, excess water vapor flows into the heat exchanger. As a result, condensation of the excess water occurs on the inner surface of the heat exchanger, promoting vapor-pressure equilibrium, which is achieved before the gas arrives at the saturator chamber. On the other hand, when T_{ps} is lower than T_s, vapor-pressure equilibrium is not achieved at the outlet of the heat exchanger. Although water evaporates from the surface of the saturator chamber under this condition, the

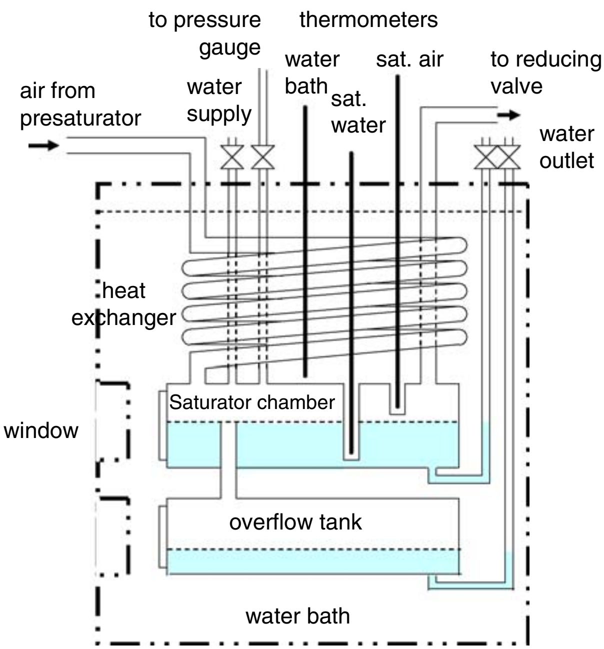

Fig. 5 Saturator of NMIJ humidity generator

surface area is small, and the amount of evaporated water is insufficient to achieve vapor-pressure equilibrium. Therefore, T_{d2} depends on T_{ps} when T_{ps} is lower than T_s. Moreover, T_s decreases because evaporation occurs.

We define a saturator efficiency η by the following equation:

$$\eta = \frac{(P_1/P_2)\,[f(P_2, T_s)/f(P_1, T_s)]\,e_w(T_{d2}) - e_w(T_{ps})}{e_w(T_s) - e_w(T_{ps})}, \tag{1}$$

where P_1 is the pressure in the saturator, P_2 the pressure at the position of the dew-point measurement, $e_w(T)$ is the saturation water vapor pressure at temperature T, and $f(P, T)$ is the enhancement factor at pressure P and temperature T. The first term of the numerator,

$$\left(\frac{P_1}{P_2}\right)\left[\frac{f(P_2, T_s)}{f(P_1, T_s)}\right] e_w(T_{d2}), \tag{2}$$

is the water vapor pressure of the gas exiting the saturator and the second term, $e_w(T_{ps})$, is the water vapor pressure of the inlet gas of the saturator. The numerator of Eq. 1 is the change of the water vapor pressure in the saturator. The denominator is the change of the water vapor pressure to achieve complete saturation. The ratio η of these two water vapor pressure changes is a measure of the saturation.

Figure 6 shows the η values calculated using Eq. 1. The measurement data are the same as those shown in Fig. 3. When T_{ps} approaches T_s, the efficiency η should become 1. However, as is evident from Eq.1, η is nondeterminable when T_{ps} is approximately

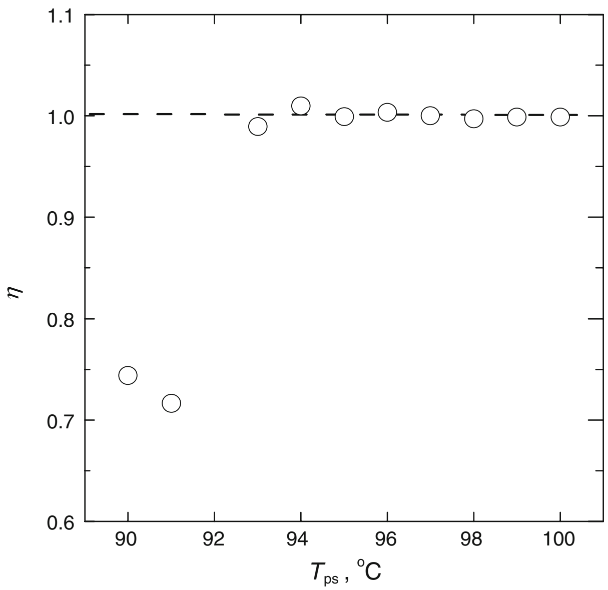

Fig. 6 Saturator efficiency η and T_{ps}. The saturator temperature T_s is 92.4 °C, and the flow rate of the gas is 3 L · min^{-1} at 25 °C and 100 kPa under dry conditions

T_s. When T_{ps} is lower than T_s, η is approximately 70 %; when T_{ps} is higher than T_s, η is approximately 100 %.

For the case of a dew-point generation of 23 °C at a saturator temperature of 26 °C, a similar result was obtained. Namely, η was approximately 70 % when T_{ps} was lower than T_s and 100 % when T_{ps} was higher than T_s.

5 Conclusion

In order to evaluate the degree of saturation, which is important when realizing a primary standard of humidity, we devised a method to evaluate the efficiency of the saturator of a standard humidity generator by changing the temperature of the PS. We applied this method to evaluate the NMIJ standard humidity generator, and found the following. In order to achieve water vapor-pressure equilibrium, it is effective to condense the excess water vapor in the heat exchanger. Because the saturator chamber is not 100 % efficient, it is more effective to condense the excess vapor. Evaporation from the surface of the water in the saturator chamber of the NMIJ standard humidity generator is insufficient to achieve equilibrium. When the temperature of the PS is higher than that of the saturator, the dew point increases by 0.0045 °C with each 1 °C increase in the temperature of the PS, and the systematic deviation of the dew point caused by the higher temperature of the PS is 9 mK.

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