SIM.T-K6.5 NIST / LACOMET
Final Report

BILATERAL KEY COMPARISON SIM.T-K6.5 ON HUMIDITY STANDARDS IN THE DEW/FROST-POINT TEMPERATURE RANGE FROM –30 °C TO +20 °C

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Abstract

A Regional Metrology Organization (RMO) Key Comparison of dew/frost point temperatures over the range –30 °C TO +20 °C was carried out by the National Institute of Standards and Technology (NIST, USA) and the Laboratorio Costarricense de Metrología (LACOMET, Costa Rica), between February 2015 and August 2015. The results of this comparison are reported here, along with descriptions of the humidity laboratory standards for NIST and LACOMET and the uncertainty budget for these standards. This report also describes the protocol for the comparison and presents the data acquired. The results are analyzed, determining the degree of equivalence between the dew/frost-point standards of NIST and LACOMET.

Keywords: Comparison, Humidity, Dew Point, Frost Point, Degree of Equivalence.

1. Introduction

The CIPM Mutual Recognition Arrangement (CIPM MRA) provides a framework for national metrology institutes (NMIs) to establish the degree of equivalence of their national measurement standards through comparison of measurements. The comparisons underpin the Calibration and Measurement Capabilities (CMCs) and there are two types: CIPM key comparisons and RMO key comparisons.

At its 20th meeting in April 2000, the Consultative Committee for Thermometry (CCT) called for a Key Comparison on humidity standards to be conducted by all major National Metrology Institutes. It asked CCT Working Group 6, WG6, (now CCT Working Group on Humidity Measurements, WG-Hu) to draw up a technical protocol for a CIPM key comparison named “CCT-K6”. The National Physical Laboratory (UK) and the National Metrology Institute of Japan were chosen to be the pilot laboratory and assistant pilot laboratory, respectively. The National Institute of Standards and Technology (NIST, USA) participated in this key comparison. The comparison report was recently published [1].

The Laboratorio Costarricense de Metrología (LACOMET, Costa Rica) did not participate in CCT-K6. Therefore, to relate the humidity standards of LACOMET to those of the CCT-K6 participants, a Regional Metrology Organization (RMO) Key Comparison of dew/frost-point temperatures $T_{DP/FP}$ was carried out by NIST and

LACOMET between February 2015 and August 2015; this comparison was designated SIM.T-K6.5. Here, it is assumed that $T_{DP/FP}$ is the dew-point temperature T_{DP} for $T_{DP/FP} \geq 0$ and $T_{DP/FP}$ is the frost-point temperature T_{FP} for $T_{DP/FP} < 0$. As an NMI, LACOMET meets the Mutual Recognition Arrangement requirements for participation in a key comparison. NIST was the pilot for this bilateral comparison. This bilateral comparison followed a similar technical procedure as for the CCT-K6, except that only one transfer standard was used. Also, a range of -30 °C $\leq T_{DP/FP} \leq +20$ °C was used instead of -50 °C $\leq T_{DP/FP} \leq +20$ °C.

2. Participants

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3. Comparison Method

The comparison between dew/frost-point temperatures realized at NIST and LACOMET was performed through use of a transfer standard (a chilled-mirror hygrometer). At a given nominal dew/frost point, each participant used its standard generator to produce moist air having a dew/frost-point temperature determined to be $T^{g}_{DP/FP}$. The transfer standard then measured the dew/frost-point temperature of the generated gas, $T^{m}_{DP/FP}$. The difference between the two values was

$$\Delta T_{DP/FP} = T^{g}_{DP/FP} - T^{m}_{DP/FP}$$

The comparison of NIST and LACOMET humidity standards was then performed by comparing the values of $\Delta T_{DP/FP}$ determined using the NIST humidity generator, $\Delta T_{DP/FP}$(NIST) , with those of the LACOMET humidity generator, $\Delta T_{DP/FP}$(LACOMET).

The measurements started at LACOMET. In February 2015, measurements of dew/frost points in humid air produced by the LACOMET standard generator were conducted using the transfer hygrometer at the dew/frost-point temperatures required. The transfer hygrometer was then shipped to NIST, where it measured dew-frost points of humid air produced by the NIST standard generator. After this, the transfer standard hygrometer was shipped back to LACOMET, where a second set of comparison measurements was performed with the LACOMET generator to check for shifts in the measurement results of the transfer hygrometer due to the shipping process. Both participants had 6 weeks to complete each set of measurements.

4. Generators

The NIST humidity generator used in the comparison was the NIST Hybrid Humidity Generator (HHG). Its principle of operation depends on the desired value of $T_{DP/FP}$.

For $T_{DP/FP} \geq -15$ °C, the HHG operates as a conventional two-pressure generator, saturating air with water at a temperature T_s and pressure P_s to produce moist air with a molar fraction x_g given by

$$x_g = \frac{e(T_s)}{P_s} \, f(T_s, P_s). \quad 1)$$

Here, $e(T_s)$ is the water vapour pressure at T_s, calculated using [2-3], and $f(T_s, P_s)$ is the water-vapour enhancement factor, calculated using [4]. The saturator temperature is measured by a standard platinum resistance thermometer (SPRT) immersed in the same temperature-controlled bath as the saturator. The saturator pressure, which can vary from ambient to 500 kPa, is measured by a strain-gauge pressure transducer that is connected by a tube to the saturator at a point near its outlet.

For $T_{DP/FP} \leq -15$ °C, the HHG uses the divided flow method, which involves diluting the saturated gas with dry gas using precisely-metered streams of gas. The molar fraction after dilution is

$$x_g = \frac{\dot{n}_s x_s + \dot{n}_p x_p}{\dot{N}} \quad 2)$$

where $\dot{n}_s$ and $\dot{n}_p$ are the molar flows of the saturated gas and pure (dry) gas, respectively, and $\dot{N}$ is the total molar flow. Also, x_s is the molar fraction of water in the saturated gas and x_p is the residual molar fraction of water in the pure gas. For the HHG in divided flow mode, the saturator is operated at a temperature of 1 °C and a pressure of 300 kPa, resulting in $x_s \approx 0.0022$.

The generated dew/frost-point temperature is obtained from x_g by measuring the pressure P_c using a strain-gauge pressure transducer at the inlet of the chilled-mirror hygrometer. $T_{DP/FP}$ is then obtained by iteratively solving the equation

$$x_g = \frac{e(T_{DP/FP})}{P_c} \, f(T_{DP/FP}, P_c) \quad 3)$$

Here, $e(T_{DP/FP})= e_w(T_{DP})$ for $T_{DP/FP} \geq 0$, where e_w is the saturated vapor pressure for water, calculated using [1-2]. Also, $e(T_{DP/FP})= e_i(T_{FP})$ for $T_{DP/FP} < 0$, where e_i is the saturated vapor pressure for ice, calculated using [5-6]. The value of $f(T_{DP/FP}, P_s)$ is calculated using [4]. A more complete description of the NIST HHG may be found in [7].

To ensure the stability of the HHG results, the HHG pressure gauges are calibrated yearly. The HHG SPRT resistance at the triple point of water R_{TPW} is also calibrated yearly. The pressure gauge and SPRT calibrations are performed at NIST. The policy of the HHG laboratory is that if the change in R_{TPW} from that of the original calibration ever corresponds to a temperature drift of more than 10 mK, a full calibration will be performed. Finally, NIST employs check standards during every customer calibration for the purpose of detecting any possible errors or long-term drifts.

The LACOMET humidity generator, constructed at LACOMET, is a single-temperature, single-pressure generator. The design is similar to those described in [8–9]. The design and validation of the LACOMET generator is discussed in [10]. The generator is composed of a saturator system submersed in a temperature-controlled liquid bath. A 100 Ω platinum resistance thermometer (PRT) is used to control the temperature of the bath. For dew/frost points generated over the range –50 °C to 20 °C, the bath fluid used is ethyl alcohol, and for higher dew points it is a water/ethylene-glycol mixture. To generate air with a known dew/frost point, the air first passes through a pre-saturator that is partially submersed in the bath. After exiting the pre-saturator, the air passes through the main saturator at a pressure near 100 kPa. A 25 Ω standard platinum resistance thermometer (SPRT) is used to measure the bath temperature; the main saturator is assumed to be in thermal equilibrium with the bath. The gas is assumed to be saturated once it exits the main saturator; this assumption has been validated by tests with a chilled-mirror hygrometer that show no noticeable flow dependence of the dew/frost point over the flow ranges used. Some of the air leaving the main saturator passes through the chilled-mirror hygrometers being calibrated, and the rest is recirculated through the generator using a pump. An absolute pressure sensor is used to measure the pressure at the point where it leaves the main saturator, and it is assumed that the pressure inside the hygrometers is the same. During the validation of generator, measurements were made of the actual pressure drop between the generator and the hygrometer, and it was found to be very small. The results of this pressure-drop test have been used to estimate the uncertainty of the above assumption in the generator's uncertainty budget.

The SPRT calibration is traceable to the SI through the LACOMET Temperature Laboratory (calibration measurement capabilities published in the BIPM database). It is calibrated at thermometric fixed points annually or when any significant change is detected. The pressure sensor is calibrated by the LACOMET pressure laboratory, where the pressure standards are traceable to the SI through calibration by CEM (Spain).

The generator, shown in Fig. 1, has a total height of 55 cm. It consists of two stainless steel chambers, one for the pre-saturator and the other for the main saturator, as well as a coil. The generator components are connected in series. The gas flows first through the pre-saturator, then through the main saturator, and finally through the coil. The flow rate through the generator is between 0.5 L/min and 1.5 L/min.

Both chambers are of equal size (height 20 cm and outer diameter 4.8 cm). At the bottom of each chamber is a layer of water of height 2.54 cm and total volume 40 cm^3, as shown in the figure. Inside each chamber there is a circular plate 5 cm from the bottom that serves as a barrier between the lower chamber and upper chamber. Incoming gas flows through 0.64 cm diameter tubes that penetrate the top of each chamber and lead the gas into the lower chamber. In the lower chamber the gas mixes with saturated water vapor evaporated from the water layer. The air then passes through a small opening in the barrier and enters the upper chamber, where it mixes with itself to minimize concentration non-uniformities. A second 0.64 cm diameter tube leads the gas from the upper chamber to the outside of the chamber through its bottom, as shown in Fig. 1. In the pre-saturator chamber, there is a 3 cm thick layer of stainless-steel wool in the upper chamber that is used to promote mixing; this stainless-steel wool is not present in the final saturator.

The coils around the chambers are used to condense out excess moisture, ensuring that the gas exiting the saturator chamber is not oversaturated. The coils are made of stainless-steel tubes with outer diameter 0.64 cm and inner diameter 0.46 cm. The coils around the pre-saturator and saturator have lengths of 1.8 m and 2.5 m, respectively.

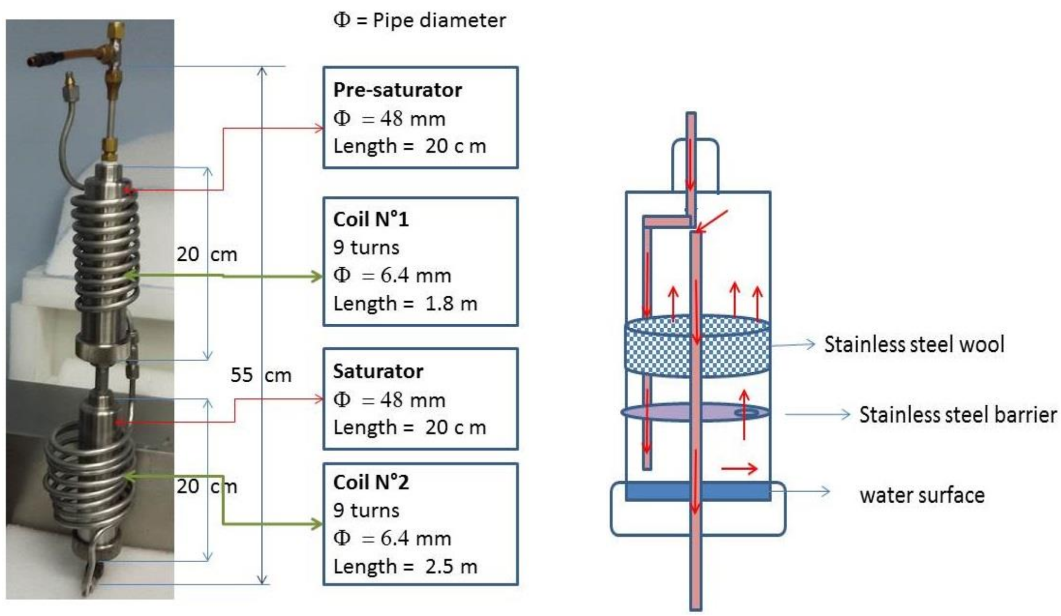

Figure 1. Photograph of the LACOMET humidity generator (left) and schematic diagram (right) of the interior of its pre-saturator chamber. In the schematic, the arrows show the direction of the gas flow through the chamber.

5. Transfer Standard

Instrument type:	Chilled-mirror hygrometer
Measurand:	dew/frost-point temperature
Model:	RH Systems 973 [11]
Serial Number:	10-0226
Size (in Packing case):	62.5 cm × 30.5 cm × 49.5 cm
Weight (in Packing case):	32 kg
Manufacturer:	RH Systems, USA
Owner:	LACOMET, Costa Rica
Electrical supply:	120 V / 60 Hz

6. Measurement process

Before performing measurements with the transfer standard, each participant cleaned the mirror surface of the hygrometer with distilled or de-ionised water.

Sample air with $T_{DP/FP}$ realized by a participant's generator was introduced into the inlet of the transfer standard hygrometer through a stainless steel tube. The tube was attached to the transfer standard using a ¼" (0.635 cm) Swagelok fitting. The flow rate of the sample air through the hygrometer was 0.5 litres per minute. Dew/frost-point data was acquired from the hygrometer using the instrument's serial port. Once the measured dew/frost point was stable, at least 10 data points were acquired over a period of time between 10 min and 20 min.

A total of four dew/frost-point temperatures were used for the comparison: +20 °C, 1 °C, −10 °C and −30 °C. Each participant made four independent measurements for each dew/frost-point temperature, reforming the condensate on the hygrometer's mirror each time.

7. Measurement data

Table 1 shows the results of the generator/hygrometer comparisons for both LACOMET and NIST. Table 2 shows the difference between generated and measured dew/frost-point temperatures $\Delta T_{DP/FP}$ for four measurements at each nominal dew/frost point. For a given nominal value of $\Delta T_{DP/FP}$, the results of LACOMET and NIST are shown on separate rows. The results for each of the four measurements are shown in separate columns. The mean and standard deviation of these measurements are shown in the last two columns. The data shown in Table 2 is plotted in Fig. 2.

Table 1. Results of generator/hygrometer comparisons.

Hygrometer RH Systems 973, S/N 10-0226				
Nominal $T_{DP/FP}$ (°C)	Meas. #	Realized $T_{DP/FP}$ (°C)	Measured $T_{DP/FP}$ (°C)	$\Delta T_{DP/FP}$ (°C)
LACOMET				
20	1	19.976	19.985	–0.009
20	2	19.986	19.996	–0.010
20	3	19.988	19.994	–0.006
20	4	19.943	19.957	–0.014
NIST				
20	1	20.053	20.053	0.000
20	2	20.005	20.009	–0.004
20	3	19.996	20.003	–0.007
20	4	19.992	20.000	–0.008
LACOMET				
1	1	1.050	1.053	–0.003
1	2	0.998	1.002	–0.004
1	3	0.997	1.004	–0.007
1	4	1.003	1.008	–0.005
NIST				
1	1	0.931	0.941	–0.010
1	2	0.932	0.948	–0.015
1	3	1.010	1.032	–0.022
1	4	1.003	1.035	–0.032
LACOMET				
–10	1	–9.977	–9.987	0.011
–10	2	–9.979	–9.990	0.011
–10	3	–9.999	–10.001	0.002
–10	4	–9.987	–9.995	0.008
NIST				
–10	1	–9.941	–9.967	0.026
–10	2	–9.986	–9.998	0.011
–10	3	–10.010	–10.017	0.007
–10	4	–10.002	–10.008	0.006
LACOMET				
–30	1	–29.943	–29.957	0.014
–30	2	–29.962	–29.975	0.013
–30	3	–29.971	–29.989	0.018
–30	4	–29.978	–29.989	0.011
NIST				
–30	1	–29.889	–29.875	–0.014
–30	2	–30.030	–30.036	0.006
–30	3	–30.023	–30.053	0.030
–30	4	–30.063	–30.076	0.013

Table 2. Difference between realized and measured dew/frost-point temperatures ΔTDP/FP for NIST and LACOMET

Nominal $T_{DP/FP}$ (°C)	NMI	Meas. 1 $\Delta T_{DP/FP}$ (°C)	Meas. 2 $\Delta T_{DP/FP}$ (°C)	Meas. 3 $\Delta T_{DP/FP}$ (°C)	Meas. 4 $\Delta T_{DP/FP}$ (°C)	$\overline{\Delta T}_{DP/FP}$ (°C)	$\sigma(\Delta T_{DP/FP})$ (°C)
20	LACOMET	–0.009	–0.010	–0.006	–0.014	–0.010	0.003
20	NIST	0.000	–0.004	–0.007	–0.008	–0.005	0.003
1	LACOMET	–0.003	–0.004	–0.007	–0.005	–0.005	0.002
1	NIST	–0.010	–0.015	–0.022	–0.032	–0.020	0.009
−10	LACOMET	0.011	0.011	0.002	0.008	0.008	0.004
−10	NIST	0.026	0.011	0.007	0.006	0.012	0.009
−30	LACOMET	0.014	0.013	0.018	0.011	0.014	0.003
−30	NIST	–0.014	0.006	0.030	0.013	0.009	0.019

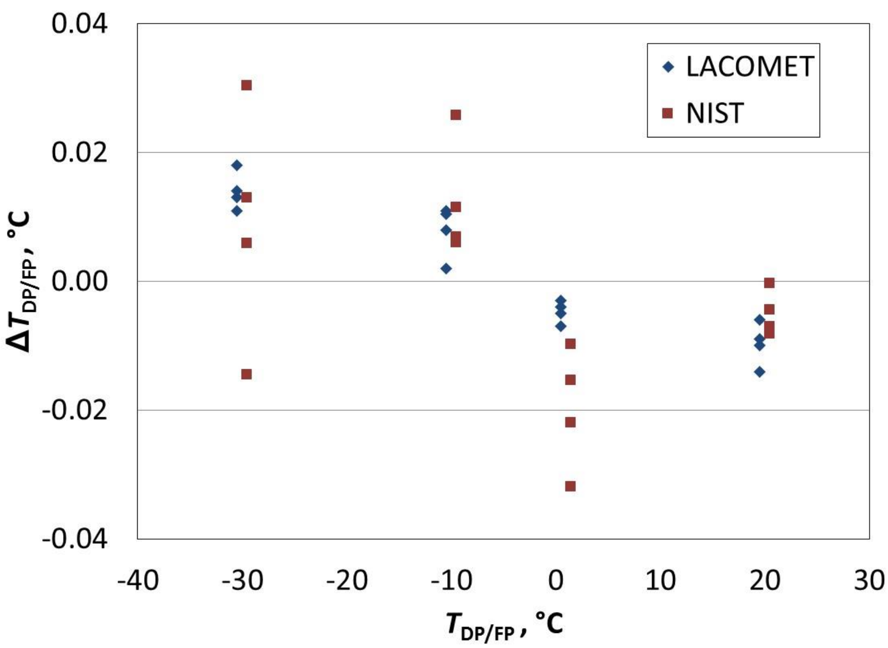

Figure 2. Difference between realized and measured dew/frost-point temperatures $\Delta T_{DP/FP}$ for NIST and LACOMET. Note: data from the two NMIs are slightly offset horizontally to facilitate viewing.

8. Comparison Uncertainty

For a set of determinations of $\Delta T_{DP/FP}$ made at a nominal $T_{DP/FP}$ the standard uncertainty of the generator/hygrometer comparison $u_c(\Delta T_{DP/FP})$ is given by

$$u_c(\Delta T_{DP/FP}) = \left[u_A^2(\Delta T_{DP/FP}) + u^2\left(T_{DP/FP}^{g}\right)\right]^{1/2} \quad 4)$$

Descriptions of $u_A(\Delta T_{DP/FP})$ and $u\left(T_{DP/FP}^{g}\right)$ are given below.

Table 3. Uncertainty elements and their standard uncertainty values for the NIST generator, for the four nominal values of $T_{DP/FP}$.

Uncertainty for NIST generator:	T_{DP} = +20 °C	T_{DP} = +1 °C	T_{FP}= −10 °C	T_{FP}= −30 °C
Saturator Temperature Measurement				
Calibration uncertainty	0.001 °C	0.001 °C	0.001 °C	0.001 °C
Long-term stability	0.001 °C	0.001 °C	0.001 °C	0.001 °C
Saturator Pressure Measurement				
Calibration uncertainty	18 Pa	47 Pa	39 Pa	42 Pa
Long-term stability	7 Pa	7 Pa	7 Pa	7 Pa
Hygrometer Pressure Measurement				
Calibration uncertainty	18 Pa	18 Pa	18 Pa	18 Pa
Long-term stability	7 Pa	7 Pa	7 Pa	7 Pa
Flow measurement (divided flow method):				
Calibration uncertainty	----	----	----	0.05%
Long-term stability	----	----	----	0.02%
Calculation:				
Saturation vapor pressure formula(e)	0.15 Pa	0.10 Pa	0.06 Pa	0.04 Pa
Water vapor enhancement formula(e)	0.0002	0.0006	0.0005	0.0006

Table 4. Contribution of the uncertainty elements in Table 3 to $u\left(T^{g}_{DP/FP}\right)$ for NIST, in °C, for the four nominal values of $T_{DP/FP}$. The combined standard uncertainty is shown in the last row.

Uncertainty for NIST generator:	T_{DP} = +20 °C	T_{DP} = +1 °C	T_{FP}= −10 °C	T_{FP}= −30°C
Saturator Temperature Measurement				
Calibration uncertainty	0.001	0.001	0.001	0.001
Long-term stability	0.001	0.001	0.001	0.001
Saturator Pressure Measurement				
Calibration uncertainty	0.003	0.002	0.002	0.001
Long-term stability	0.001	0.000	0.000	0.000
Hygrometer Pressure Measurement				
Calibration uncertainty	0.003	0.002	0.002	0.002
Long-term stability	0.001	0.001	0.001	0.001
Flow measurement (divided flow method):				
Calibration uncertainty	----	----	----	0.003
Long-term stability	----	----	----	0.001
Calculation:				
Saturation vapor pressure formula(e)	0.002	0.001	0.002	0.003
Water vapor enhancement formula(e)	0.004	0.009	0.007	0.006

Combined standard uncertainty:	**0.006**	**0.010**	**0.008**	**0.008**

Table 5. Uncertainty elements and their standard uncertainty values for the LACOMET generator, for the four nominal values of $T_{DP/FP}$.

Uncertainty for LACOMET generator:	T_{DP} = +20 °C	T_{DP} = +1 °C	T_{FP}= −10 °C	T_{FP}= −30°C
Saturation temperature (Thermometer and Saturator)				
Calibration uncertainty (sensor and indicator unit) °C	0.0050	0.0050	0.0050	0.0050
Long-term stability (sensor and indicator) °C	0.0050	0.0050	0.0050	0.0050
Self-heating and residual heat fluxes (sensor) °C	0.0060	0.0060	0.0060	0.0060
Resolution and accuracy or linearity (indicator unit) °C	0.0005	0.0005	0.0005	0.0005
Temperature homogeneity °C	0.0100	0.0100	0.0100	0.0100
Temperature stability °C	0.0060	0.0060	0.0060	0.0100
Saturation pressure (Pressure gauge)				
Calibration uncertainty (sensor and indicator unit) Pa	2.4	2.4	2.4	2.4
Long-term stability (sensor and indicator) Pa	1	1	1	1
Resolution and accuracy or linearity (indicator unit) Pa	1	1	1	1
Pressure differences in the saturator cell Pa	20	20	20	20
Stability of the pressure Pa	10	10	10	10
Gas pressure at the generator outlet (Pressure gauge)				
Calibration uncertainty (sensor and indicator unit) Pa	10	10	10	10
Long-term stability (sensor and indicator) Pa	20	20	20	20
Resolution (indicator unit) Pa	20	20	20	20
Stability of the pressure Pa	10	10	10	10
Effect of the tubing between the saturator and the pressure gauge Pa	50	50	50	50
Saturation efficiency °C	0.0080	0.0080	0.0080	0.0080
Uncertainty due to formulae/calculations				
Saturation vapor pressure formula(e) °C	0	0	0	0
Water vapor enhancement formula(e) °C	0	0	0	0
Other				
Pressure drop between point of realization and measuring instrument Pa	25	25	25	25
Water contaminations °C	0.0010	0.0010	0.0010	0.0010

First, $u_A(\Delta T_{DP/FP})$ is the type A uncertainty for the determination of $\Delta T_{DP/FP}$. This uncertainty includes the reproducibility of the generator and the chilled-mirror hygrometer. The value of $u_A(\Delta T_{DP/FP})$ for each NMI at each value of $T_{DP/FP}$ is given by $\sigma(\Delta T_{DP/FP})$ in Table 2. Secondly, $u\left(T^{g}_{DP/FP}\right)$ is the type B uncertainty of the generated value of $T_{DP/FP}$. The source of the values $u\left(T^{g}_{DP/FP}\right)$ for NIST is [7], which contains a complete uncertainty budget for the NIST Hybrid Humidity Generator. Table 3 shows the uncertainty elements and their standard uncertainty values for the NIST generator, for the four nominal values of $T_{DP/FP}$. Table 4 shows the contribution of these uncertainty elements to $u\left(T^{g}_{DP/FP}\right)$. Similarly, Table 5 shows the values of these standard uncertainties for the LACOMET generator and Table 6 shows their contribution to $u\left(T^{g}_{DP/FP}\right)$ for

LACOMET. Table 7 shows the calculated value of $u_c(\Delta T_{DP/FP})$ and its components for each value of $T_{DP/FP}$ and each participating NMI.

Table 6. Contribution of the uncertainty elements in Table 5 to $u\left(T^{\mathrm{g}}_{\mathrm{DP/FP}}\right)$ for LACOMET, in °C, for the four nominal values of $T_{\mathrm{DP/FP}}$. The combined standard uncertainty is shown in the last row.

Uncertainty for LACOMET generator:	T_{DP} = +20 °C	T_{DP} = +1 °C	T_{FP}= −10 °C	T_{FP}= −30°C
Saturation temperature (Thermometer and Saturator)				
Calibration uncertainty (sensor and indicator unit)	0.0050	0.0050	0.0050	0.0050
Long-term stability (sensor and indicator)	0.0050	0.0050	0.0050	0.0050
Self-heating and residual heat fluxes (sensor)	0.0060	0.0060	0.0060	0.0060
Resolution and accuracy or linearity (indicator unit)	0.0005	0.0005	0.0005	0.0005
Temperature homogeneity	0.0100	0.0100	0.0100	0.0100
Temperature stability	0.0060	0.0060	0.0060	0.0100
Saturation pressure (Pressure gauge)				
Calibration uncertainty (sensor and indicator unit)	0.0004	0.0004	0.0003	0.0003
Long-term stability (sensor and indicator)	0.0002	0.0002	0.0001	0.0001
Resolution and accuracy or linearity (indicator unit)	0.0002	0.0002	0.0001	0.0001
Pressure differences in the saturator cell	0.0037	0.0032	0.0026	0.0022
Stability of the pressure	0.0019	0.0016	0.0013	0.0011
Gas pressure at the generator outlet (Pressure gauge)				
Calibration uncertainty (sensor and indicator unit)	0.0019	0.0016	0.0013	0.0011
Long-term stability (sensor and indicator)	0.0037	0.0032	0.0026	0.0022
Resolution (indicator unit)	0.0037	0.0032	0.0026	0.0022
Stability of the pressure	0.0019	0.0016	0.0013	0.0011
Effect of the tubing between the saturator and the pressure gauge	0.0093	0.0080	0.0065	0.0055
Saturation efficiency	0.0080	0.0080	0.0080	0.0080
Uncertainty due to formulae/calculations				
Saturation vapor pressure formula(e)	0	0	0	0
Water vapor enhancement formula(e)	0	0	0	0
Other				
Pressure drop between point of realization and measuring instrument	0.0046	0.0040	0.0032	0.0028
Water contaminations	0.0010	0.0010	0.0010	0.0010
Combined standard uncertainty	**0.024**	**0.023**	**0.022**	**0.023**

Table 7. Standard uncertainty of the determinations of $\Delta T_{\mathrm{DP/FP}}$ for NIST and LACOMET. The column headings are described in the text.

Nominal $T_{\mathrm{DP/FP}}$ (°C)	Participating Institute	$u_{\mathrm{A}}\left(\Delta T_{\mathrm{DP/FP}}\right)$ (°C)	$u(T^{\mathrm{g}}_{\mathrm{DP/FP}})$ (°C)	$u_{\mathrm{c}}\left(\Delta T_{\mathrm{DP/FP}}\right)$ (°C)
20	LACOMET	0.003	0.024	0.024
20	NIST	0.003	0.006	0.007
1	LACOMET	0.002	0.023	0.023
1	NIST	0.009	0.010	0.013
−10	LACOMET	0.004	0.022	0.022
−10	NIST	0.009	0.008	0.012
−30	LACOMET	0.003	0.023	0.023

−30	NIST	0.019	0.008	0.021

Note that the contributions of the uncertainties of the saturation vapor pressure formula and water vapor enhancement formula for the LACOMET generator are both assumed to be zero because it is a single pressure generator.

9. Drift of the Transfer Standard Hygrometer

The first generator/hygrometer comparison measurements were made at LACOMET in February 2015. Afterwards, the transfer standard hygrometer was sent to NIST so that it could perform its generator/hygrometer comparison measurements. The hygrometer was returned to LACOMET in July 2015, and the second set of LACOMET comparison measurements were made in August 2015. These results are tabulated in Table 8.

Table 8. Results of August 2015 generator/hygrometer comparisons at LACOMET.

Nominal $T_{DP/FP}$ (°C)	Meas. #	Realized $T_{DP/FP}$ (°C)	Measured $T_{DP/FP}$ (°C)	$\Delta T_{DP/FP}$ (°C)
20	1	19.979	19.997	– 0.018
20	2	19.977	20.003	– 0.026
20	3	19.984	20.006	– 0.022
20	4	19.980	20.002	– 0.022
1	1	0.989	0.984	0.005
1	2	0.994	0.990	0.004
1	3	0.995	0.993	0.002
1	4	0.997	0.995	0.002
–10	1	– 9.983	– 9.991	0.008
–10	2	– 9.981	– 9.995	0.014
–10	3	– 9.985	– 9.997	0.012
–10	4	– 9.989	– 9.993	0.004
–30	1	– 29.921	– 29.938	0.017
–30	2	– 29.940	– 29.957	0.017
–30	3	– 29.953	– 29.971	0.018
–30	4	– 29.957	– 29.973	0.016

Drift of the transfer standard between February 2015 and August 2015 may be estimated by examining the difference between the LACOMET generator/hygrometer comparisons performed in February 2015 and August 2015. This difference is shown in Fig. 3. The maximum magnitude of the difference between the February 2015 comparisons and the August 2015 comparisons (at the 20 °C comparison point) is 0.012 °C. In our uncertainty budget for the comparison, we have added a type B uncertainty component due to the possibility of transfer standard drift. Based on the results of Fig. 3, we have estimated it to contribute a standard uncertainty of $u_{\mathrm{drift}} = 0.012\ °\mathrm{C}/\sqrt{3} = 0.007\ °\mathrm{C}$ to the LACOMET-NIST comparison.

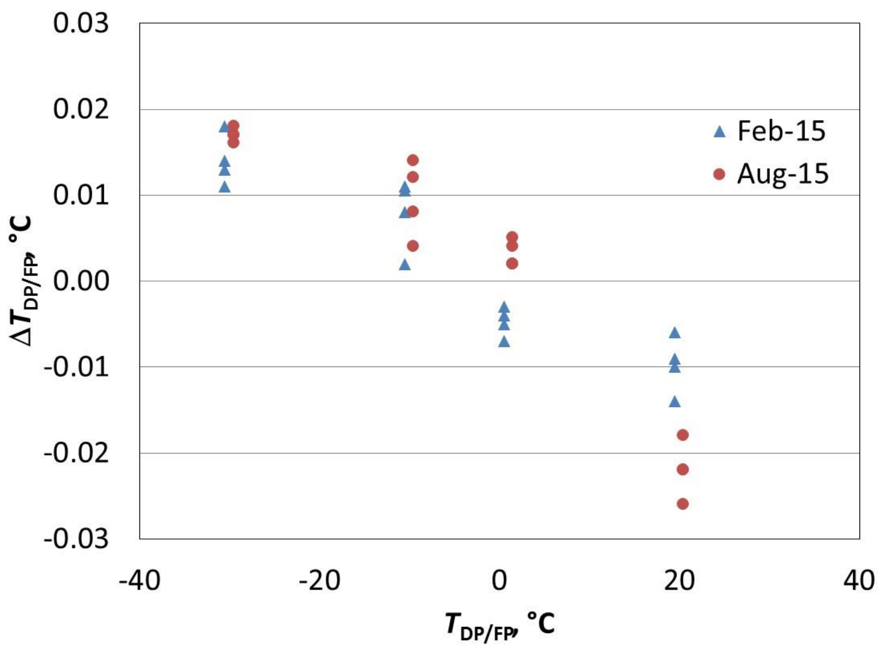

Figure 3. Difference between the LACOMET generator/hygrometer comparisons performed in February 2015 and in August 2015. The values of $T_{\mathrm{DP/FP}}$ have been slightly offset to aid the viewer.

10. Degree of Equivalence

We define the degree of equivalence between the values of $T_{\mathrm{DP/FP}}$ realized by LACOMET and those of NIST, $D_{\mathrm{LACOMET/NIST}}$ as

$$D_{\mathrm{LACOMET/NIST}}\left(T_{\mathrm{DP/FP}}\right) \equiv \left[\Delta T_{\mathrm{DP/FP}}\right]_{\mathrm{LACOMET}} - \left[\Delta T_{\mathrm{DP/FP}}\right]_{\mathrm{NIST}} \qquad 5)$$

The uncertainty of the degree of equivalence $u(D_{\text{LACOMET/NIST}}(T_{\text{DP/FP}})$ is the combination of $u_c(\Delta T_{\text{DP/FP}})$ for LACOMET, $u_c(\Delta T_{\text{DP/FP}})$ for NIST, and the uncertainty u_{drift} due to possible drift of the transfer standard:

$$u[D_{\text{LACOMET/NIST}}(T_{\text{DP/FP}})] = \left\{[u_c^2(\Delta T_{\text{DP/FP}})]_{\text{LACOMET}} + [u_c^2(\Delta T_{\text{DP/FP}})]_{\text{NIST}} + u_{\text{drift}}^2\right\}^{1/2}. \qquad 6)$$

The expanded (k=2, 95% confidence level) uncertainty for the degree of equivalence is

$$U(D_{\text{LACOMET/NIST}}) = 2u(D_{\text{LACOMET/NIST}}), \qquad 7)$$

The results are presented in Table 9 and plotted in Fig. 4. All values of $D_{\text{LACOMET/NIST}}$ are within the expanded uncertainties.

Table 9. Degree of equivalence between $T_{\text{DP/FP}}$ values at LACOMET and at NIST, and its expanded uncertainty (k=2) in a comparison of four dew/frost points.

Nominal $T_{\text{DP/FP}}$ (°C)	$D_{\text{LACOMET/NIST}}$ (°C)	$U(D_{\text{LACOMET/NIST}})$ (°C)
20	–0.005	0.052
1	0.015	0.055
−10	–0.005	0.052
−30	0.005	0.064

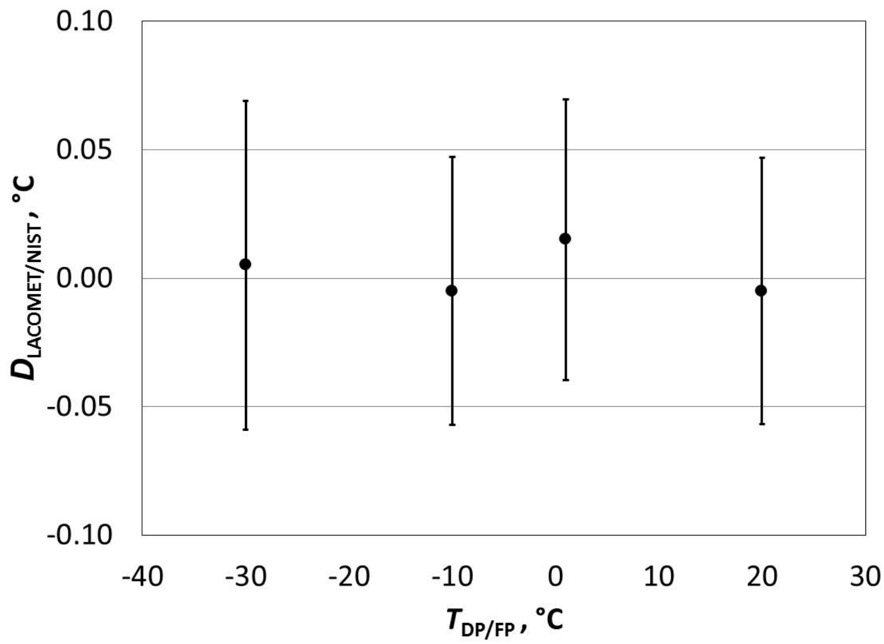

Figure 4. The degree of equivalence $D_{\mathrm{LACOMET/NIST}}$ of four dew/frost-point temperature standards at LACOMET and NIST, as defined in Eq. 5. The uncertainty bars represent the expanded (k = 2) uncertainty of the degree of equivalence, as defined in Eq. 7.

11. Linkage to the CCT-K6 KCRV

Because NIST participated in the CCT-K6 multilateral key comparison, some of the results of this bilateral comparison may be linked to the key comparison reference value (KCRV) for $T_{DP/FP}$ [1]. The degree of equivalence between $T_{DP/FP}$ realized by a NMI and the KCRV, $D_{NMI/KCRV}$, is defined as

$$D_{NMI/KCRV}(T_{DP/FP}) \equiv [\Delta T_{DP/FP}]_{NMI} - [\Delta T_{DP/FP}]_{KCRV}. \qquad 8)$$

Since LACOMET did not participate in CCT-K6, Eq. 5 and Eq. 8 may be used to determine $D_{LACOMET/KCRV}$:

$$D_{LACOMET/KCRV}(T_{DP/FP}) = D_{LACOMET/NIST}(T_{DP/FP}) + D_{NIST/KCRV}(T_{DP/FP}). \qquad 9)$$

with corresponding uncertainty

$$U^2(D_{LACOMET/KCRV}) = U^2(D_{LACOMET/NIST}) + U^2(D_{NIST/KCRV}) \qquad 10)$$

The NIST/LACOMET comparison was performed at the exact same nominal $T_{DP/FP}$ values as the CCT-K6 comparison, except for the −50 °C value used in the CCT-K6 comparison. The points at 20 °C, 1 °C, and −10 °C are suitable for linkage because the NIST HHG was the standard generator used at those points for both the CCT comparison and the NIST/LACOMET comparison. The −30 °C comparison point made in the CCT-K6 comparison will not be considered here because a different NIST humidity generator was used in the CCT comparison at that value.

The relevant values of $D_{NIST/KCRV}$ and $U(D_{NIST/KCRV})$ from [1] are given in Table 10:

Table 10. Degree of equivalence between $T_{DP/FP}$ realized by NIST and the KCRV, $D_{NIST/KCRV}$, and its expanded uncertainty (k = 2), $U(D_{NIST/KCRV})$, at $T_{DP/FP}$ values of +20 °C, 1 °C, and −10 °C, as given by Tables 7.3 and 7.4 in [1].

Nominal $T_{DP/FP}$ (°C)	$D_{NIST/KCRV}$ (°C)	$U(D_{NIST/KCRV})$ (°C)
20	−0.006	0.050
1	−0.011	0.060
−10	−0.039	0.043

Combining the results of Tables 9-10 using Eqs. 9-10 yields the values of $D_{LACOMET/KCRV}$ and $U(D_{LACOMET/KCRV})$, shown in Table 11 and plotted in Fig.5. As shown in the figure, they are all within the k=2 uncertainty values $U(D_{LACOMET/KCRV})$.

Table 11. Degree of equivalence between $T_{DP/FP}$ realized by LACOMET and the KCRV, $D_{LACOMET/KCRV}$, and its expanded uncertainty (k = 2), $U(D_{LACOMET/KCRV})$, at $T_{DP/FP}$ values of +20 °C, 1 °C, and −10 °C.

Nominal $T_{DP/FP}$ (°C)	$D_{LACOMET/KCRV}$ (°C)	$U(D_{LACOMET/KCRV})$ (°C)
20	−0.011	0.072
1	0.004	0.081
− 10	−0.044	0.068

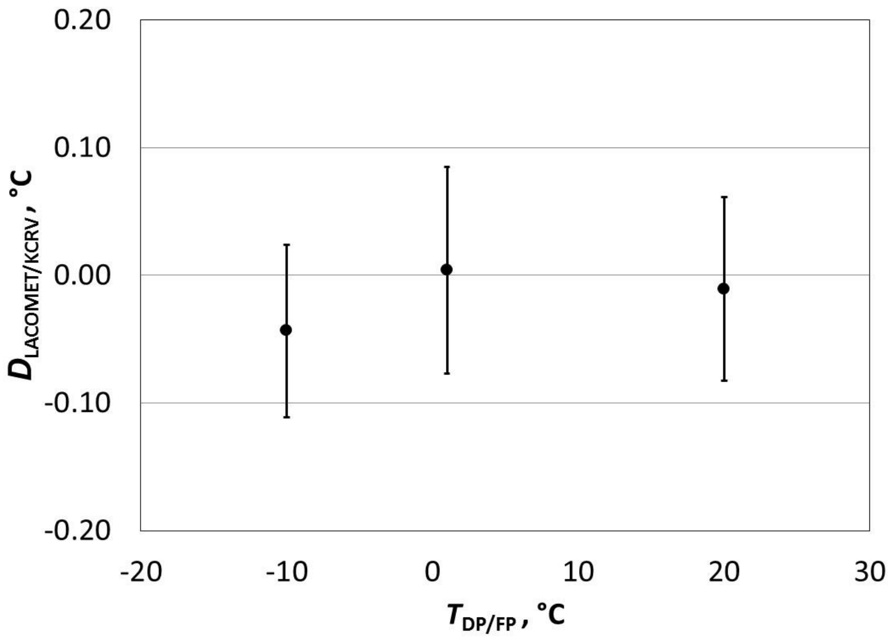

Figure 5. The degree of equivalence $D_{LACOMET/KCRV}$ between the dew/frost-point standards of LACOMET, $[T_{DP/FP}]_{LACOMET}$, and the key comparison reference values (KCRVs), $[T_{DP/FP}]_{KCRV}$, as determined by Eq. 9. The uncertainty bars represent the expanded (k = 2) uncertainty of the degree of equivalence, as determined by Eq. 10.

12. Summary

NIST and LACOMET have completed a bilateral comparison of their humidity standards. The quantity compared was the dew/frost-point temperature. NIST realized this quantity using its Hybrid Humidity Generator while LACOMET used its standard humidity generator. The nominal dew/frost-point temperatures used for the comparison were

+20 °C, 1°C, −10 °C and −30 °C. The comparisons have determined the degree of equivalence between $[T_{\mathrm{DP/FP}}]_{\mathrm{LACOMET}}$ and $[T_{\mathrm{DP/FP}}]_{\mathrm{NIST}}$ at these points. For all dew/frost-point temperatures within the range studied, the degree of equivalence is less than 0.02 °C. All values for the degree of equivalence are within their expanded k = 2 uncertainties. The results allow a calculation of the degree of equivalence between $[T_{\mathrm{DP/FP}}]_{\mathrm{LACOMET}}$ and $[T_{\mathrm{DP/FP}}]_{\mathrm{KCRV}}$ at +20 °C, +1 °C, and –10 °C. All values for this degree of equivalence are within 0.05 °C and within the expanded k = 2 uncertainties.

13. References

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