SIM.T-K6.5 NIST / LACOMET
Draft B

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

C.W. Meyer[1] and A. Solano[2]

[1]National Institute of Standards and Technology (NIST), USA
[2]Laboratorio Costarricense de Metrología (LACOMET), Costa Rica

Abstract

A Regional Metrology Organization (RMO) Key Comparison of dew/frost point temperatures 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 procedures as for the CCT-K6, except that the LACOMET standard, which is a portable hygrometer, was transported to NIST and directly compared to NIST humidity standards. Also, a range of −30 °C ≤ $T_{DP/FP}$ ≤ +20 °C was used instead of −50 °C ≤ $T_{DP/FP}$ ≤ +20 °C.

2. Participants

NIST	**Christopher Meyer** National Institute of Standards and Technology 100 Bureau Drive Gaithersburg, MD 20899 USA	Tel.: 301-975-4825 Fax: 301-548-0206 e-mail : cmeyer@nist.gov
LACOMET	**Adrian Solano** **Luis Chavez Santacruz** Ciudad de la Investigación, University of Costa Rica, San Pedro, San José, Costa Rica	Tel.: 506-2283-6580 Fax: 506-2283-6580 e-mail: asolano@lacomet.go.cr lchavez@lacomet.go.cr

3. Comparison Method

The NIST laboratory standard is a humidity generator and the LACOMET laboratory standard is humidity generator and a chilled-mirror hygrometer with a calibration traceable to PTB, (Physikalisch-Technische Bundesanstalt, Germany). The measurements started at LACOMET. In February 2015, measurements of dew/frost points in humid air produced by the LACOMET (non-standard) generator were conducted using the LACOMET standard hygrometer at the dew/frost-point temperatures required. The LACOMET hygrometer was then shipped to NIST, where it measured dew-frost points of humid air produced by the NIST standard generator. After this, the LACOMET 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.

For the LACOMET standard hygrometer, the process for measuring the dew/frost-point temperatures realized by the humidity generators at LACOMET and NIST was as follows. At a given nominal dew/frost point, the generator was used to produce moist air having a dew/frost-point temperature determined to be $T^{g}_{DP/FP}$. The LACOMET hygrometer 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 performed directly when the LACOMET standard hygrometer measured the dew/frost points of humid air generated by the NIST standard generator.

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

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

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-vapor 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

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

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

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

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. It was designed specifically as a stable humidity source for the comparison of two chilled-mirror hygrometers. The design is similar to those described in [8–9]. The generator is composed of a saturator system submersed in a liquid bath. The carrier gas (air) first passes through a pre-saturator that is partially submersed in the same liquid bath. The saturator temperature can be varied from –50 °C to 50 °C. The saturator pressure is kept near 100 kPa. The generator uses a 100 Ω platinum resistance thermometer to measure the saturator temperature at the location where the gas exits the main saturator (where it is assumed to be saturated) and one 25 Ω SPRT to measure the fluid temperature bath. A pump re-circulates the gas over the saturator system and the chilled mirror hygrometer(s). The generator does not include any temperature sensors. Instead, it assumes that the pressure in the saturator is the same as that inside the hygrometer that is measuring the dew point of the moist gas produced by the generator. The generator can function as a one-pass system or as a closed-circuit system fed with filtered dry air.

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 saturator, with their respective coils. The generator components are connected in series. The gas flows first through the pre-saturator and then through the pre-saturator coil, saturator, and saturator coil. The flow rate used 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 0.48 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, which 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 each chamber is not oversaturated. The coils are made of stainless-steel tubes with diameter 0.64 cm. The coils around the pre-saturator and saturator have lengths of 1.8 m and 2.5 m, respectively.

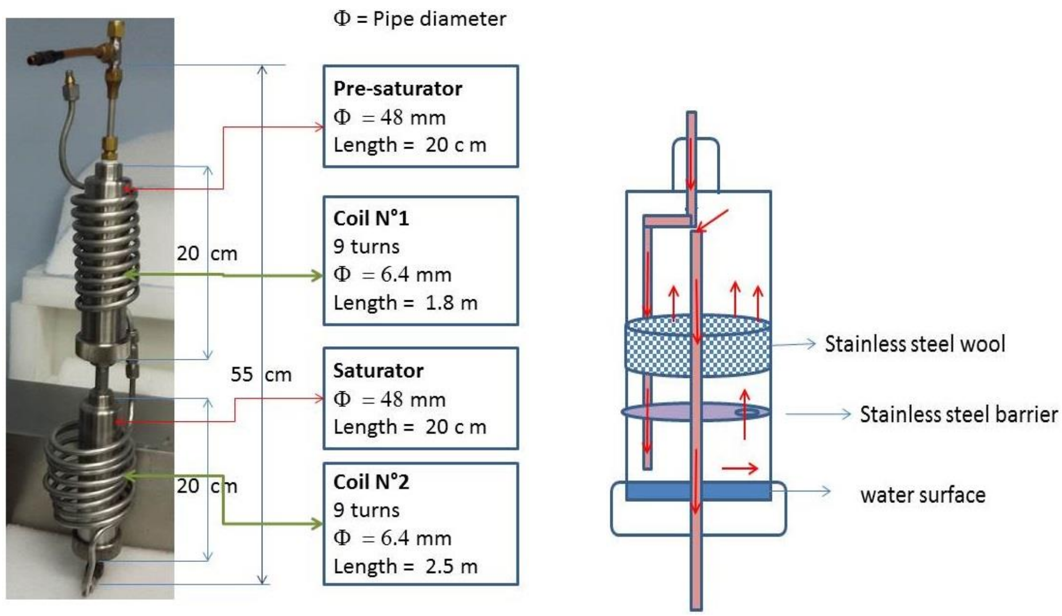

Figure 1. Photograph of the LACOMET humidity generator (left) and schematic diagram (right) of the interior of its pre-saturator chamber. In the schematic, the arrows show the direction of the gas flow through the chamber.

5. LACOMET Standard Hygrometer

Instrument type:	Chilled-mirror hygrometer
Measurand:	dew/frost-point temperature
Model:	RH Systems 973 [10]
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 LACOMET standard hygrometer, 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 LACOMET 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, 0 °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 NIST/LACOMET generator/hygrometer comparisons. 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. 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 NIST (generator) / LACOMET (hygrometer) comparisons.

Nominal $T_{DP/FP}$ (°C)	Meas. #	$\left[T^{g}_{DP/FP}\right]_{NIST}$ (°C)	$\left[T^{m}_{DP/FP}\right]_{LACOMET}$ (°C)	$\Delta T_{DP/FP}$ (°C)
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
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
–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
–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 generated (NIST) and measured (LACOMET) dew/frost-point temperatures $\Delta T_{DP/FP}$.

Nominal $T_{DP/FP}$ (°C)	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	0.000	–0.004	–0.007	–0.008	–0.005	0.003
1	–0.010	–0.015	–0.022	–0.032	–0.020	0.009
−10	0.026	0.011	0.007	0.006	0.012	0.009
−30	–0.014	0.006	0.030	0.013	0.009	0.019

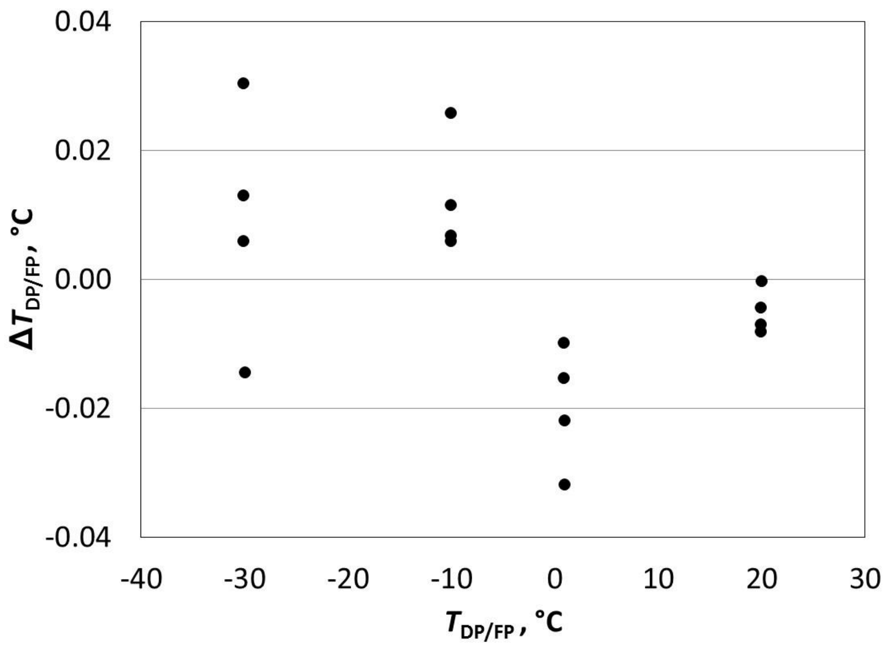

Figure 2. Difference between the dew/frost-point temperatures produced by the NIST Hybrid Humidity Generator and those measured by the LACOMET standard hygrometer.

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

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

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

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.

Unfortunately, for a given NMI, four measurements at one value of $T_{DP/FP}$ is not a large ensemble for statistically determining u_A. Therefore, after observing no systematic variation of u_A with $T_{DP/FP}$, we chose to assume that u_A is independent of $T_{DP/FP}$ and determine a value for u_A based on all measurements (quadrupling the size of the ensemble), thereby obtaining a better estimate for u_A. The value of $u_A(\Delta T_{DP/FP})$ was determined as the average value of $\sigma(\Delta T_{DP/FP})$ for the four nominal $T_{DP/FP}$ values. The individual values of $\sigma(\Delta T_{DP/FP})$ are given 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 $u\left(T^{g}_{DP/FP}\right)$.

For LACOMET, $u\left(T^{m}_{DP/FP}\right)$ is the type B uncertainty of the value of $T_{DP/FP}$ measured by its laboratory-standard chilled-mirror hygrometer. The source of the values $u\left(T^{m}_{DP/FP}\right)$ is based on the specifications of the standard chilled-mirror hygrometer and its historical behavior. Tables 5 show the values of these standard uncertainties.

Table 6 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.

9. Drift of the LACOMET Standard Hygrometer

The first generator/hygrometer comparison measurements were made at LACOMET in February 2015. Afterwards, the LACOMET standard hygrometer was sent to NIST so that it could perform the bilateral comparison measurements. The hygrometer was returned to LACOMET in July 2015, and the next comparison measurements were made in August 2015.

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 tabulated in Table 7 and shown in Fig. 3. The maximum magnitude of the difference between the February 2015 comparisons and the August 2015 comparisons is less than 0.02 °C. Based on the results of Fig. 3, we have concluded that the drift observed between February 2015 and August 2015 is consistent with the LACOMET hygrometer uncertainty element due to drift.

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 $u\left(T_{DP/FP}^{g}\right)$ 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 for $u\left(T_{\mathrm{DP/FP}}^{\mathrm{m}}\right)$ 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 standard:	T_{DP} = +20 °C	T_{DP} = +1 °C	T_{FP}= −10 °C	T_{FP}= −30 °C
Calibration uncertainty of the hygrometer	0.025	0.025	0.035	0.035
Resolution of the hygrometer	0.001	0.001	0.001	0.001
Drift of the hygrometer	0.050	0.050	0.050	0.050
Ambient/head temperature	0.005	0.005	0.005	0.01
Combined standard uncertainty:	**0.056**	**0.056**	**0.061**	**0.062**

Table 6. Standard uncertainty of the determinations of $[\Delta T_{\mathrm{DP/FP}}]_{\mathrm{NIST/LACOMET}}$.
The column headings are described in the text.

Nominal $T_{\mathrm{DP/FP}}$ (°C)	$u_{\mathrm{A}}\left(\Delta T_{\mathrm{DP/FP}}\right)$ (°C)	$u(T_{\mathrm{DP/FP}}^{\mathrm{g}})$ (°C)	$u(T_{\mathrm{DP/FP}}^{\mathrm{m}})$ (°C)	$u_{\mathrm{c}}\left(\Delta T_{\mathrm{DP/FP}}\right)$ (°C)
20	0.003	0.006	0.056	0.057
1	0.009	0.010	0.056	0.058
−10	0.009	0.008	0.061	0.062
−30	0.019	0.008	0.062	0.065

Table 7. Results of generator/hygrometer comparisons at LACOMET.

Nominal $T_{DP/FP}$ (°C)	Meas. #	$\left[T^{g}_{DP/FP}\right]_{LACOMET}$ (°C)	$\left[T^{m}_{DP/FP}\right]_{LACOMET}$ (°C)	$\left[\Delta T_{DP/FP}\right]_{LACOMET}$ (°C)
February 2015				
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
August 2015				
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
February 2015				
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
August 2015				
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
February 2015				
–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
August 2015				
–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
February 2015				
–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
August 2015				
–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

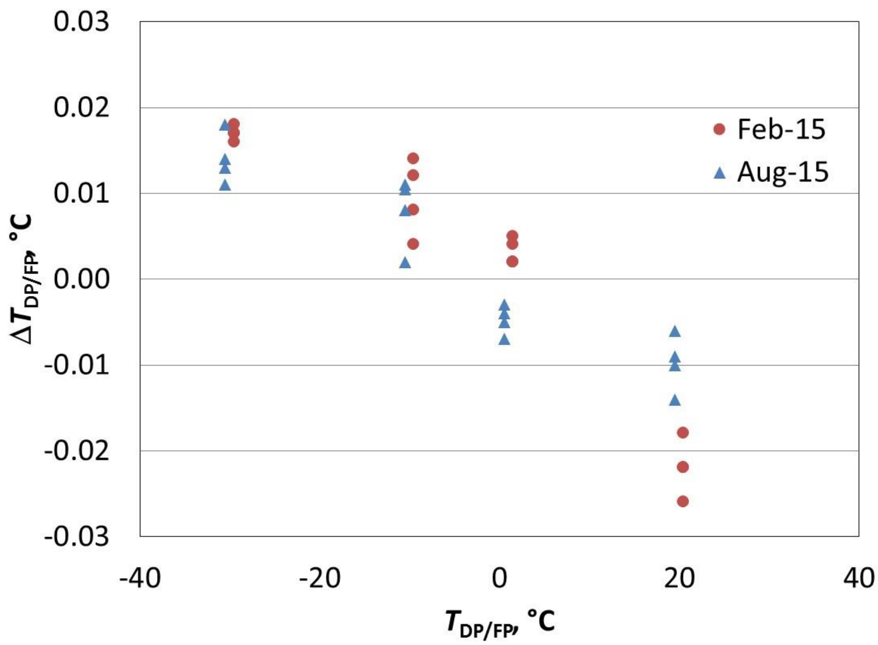

Figure 3. Difference between the LACOMET generator/hygrometer comparisons performed in February 2015 and in August 2015. The values of $T_{DP/FP}$ have been slightly offset to aid the viewer.

10. Degree of Equivalence

We define the degree of equivalence between the $T_{DP/FP}$ standards of LACOMET and NIST, $D_{LACOMET/NIST}$ as

$$D_{LACOMET/NIST}(T_{DP/FP}) \equiv -[\Delta T_{DP/FP}(T_{DP/FP})]_{NIST/LACOMET} = [T^{m}_{DP/FP}]_{LACOMET} - [T^{g}_{DP/FP}]_{NIST}, \quad 5)$$

where $[\Delta T_{DP/FP}(T_{DP/FP})]_{NIST/LACOMET}$ is the value of $\Delta T_{DP/FP}(T_{DP/FP})$ determined from the direct comparison of NIST/LACOMET standards for $T_{DP/FP}$ as shown in Table 1. The uncertainty of the degree of equivalence $u[D_{NIST/LACOMET}(T_{DP/FP})]$ is the value of $u_c(\Delta T_{DP/FP})$ for the comparison given in Table 6:

$$u[D_{LACOMET/NIST}(T_{DP/FP})] = u_c(\Delta T_{DP/FP})_{NIST/LACOMET} = \left[u_A^2(\Delta T_{DP/FP}) + u^2([T^{g}_{DP/FP}]_{NIST}) + u^2([T^{m}_{DP/FP}]_{LACOMET})\right]^{1/2}. \quad 6)$$

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

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

The results are presented in Table 8 and plotted in Fig. 4, where the values of $D_{LACOMET/NIST}$ are given by the average of the four measurements made at each nominal temperature. All values of $D_{LACOMET/NIST}$ are within the expanded uncertainties.

Table 8. Degree of equivalence between $T_{DP/FP}$ values at LACOMET and at NIST, and its expanded uncertainty (k = 2) in a comparison of four dew/frost points.

Nominal $T_{DP/FP}$ (°C)	$D_{LACOMET/NIST}$ (°C)	$U(D_{LACOMET/NIST})$ (°C)
20	0.005	0.11
1	0.020	0.12
−10	–0.012	0.12
−30	–0.009	0.13

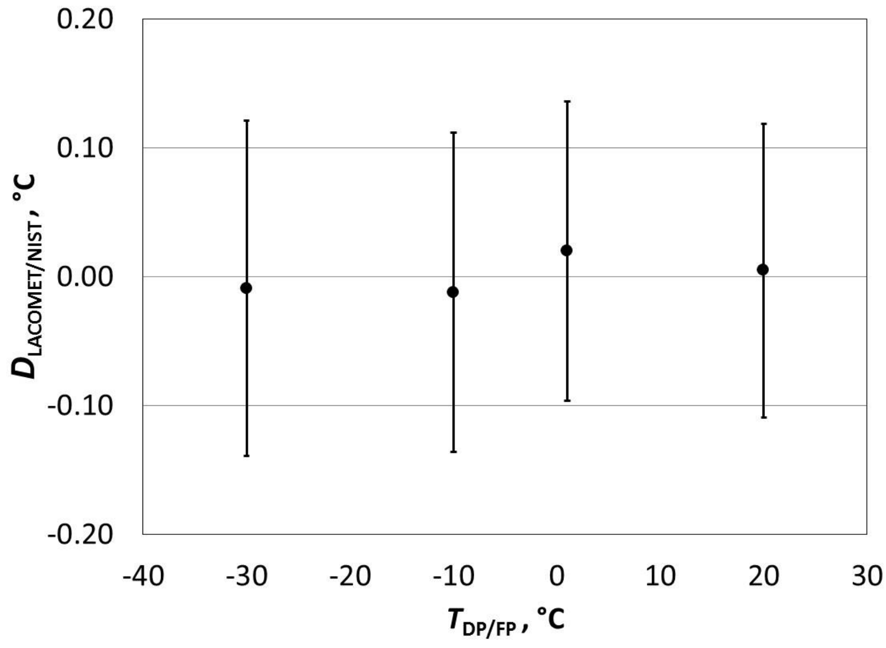

Figure 4. The degree of equivalence $D_{LACOMET/NIST}$ of four dew/frost-point temperature standards at LACOMET and NIST, as defined in Eq. 5. The uncertainty bars represent the expanded (k = 2) uncertainty of the degree of equivalence, as defined in Eq. 7.

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

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

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

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

with corresponding uncertainty

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

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 −30 °C comparison point made in the CCT-K6 comparison also 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 9:

Table 9. 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 8-9 using Eqs. 9-10 yields the values of $D_{LACOMET/KCRV}$ and $U(D_{LACOMET/KCRV})$:

Table 10. 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	− 0.001	0.12
1	0.009	0.13
− 10	− 0.051	0.13

The values of $D_{LACOMET/KCRV}$ are plotted in Fig. 5. As shown in the figure, they are all within the k=2 uncertainty values $U(D_{LACOMET/KCRV})$.

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 the LACOMET standard hygrometer measured it. The nominal dew/frost-point temperatures used for the comparison were +20 °C, 0 °C, −10 °C and −30 °C. The comparisons have determined the degree of equivalence between $[T_{DP/FP}]_{LACOMET}$ and $[T_{DP/FP}]_{NIST}$ at these points. For all dew/frost-point temperatures within the range studied, the degree of equivalence is 0.02 °C or less. 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 $[T_{DP/FP}]_{LACOMET}$ and $[T_{DP/FP}]_{KCRV}$ at +20 °C, +1 °C, and −10 °C. All values for this degree of equivalence are within 0.06 °C and within the expanded k = 2 uncertainties.

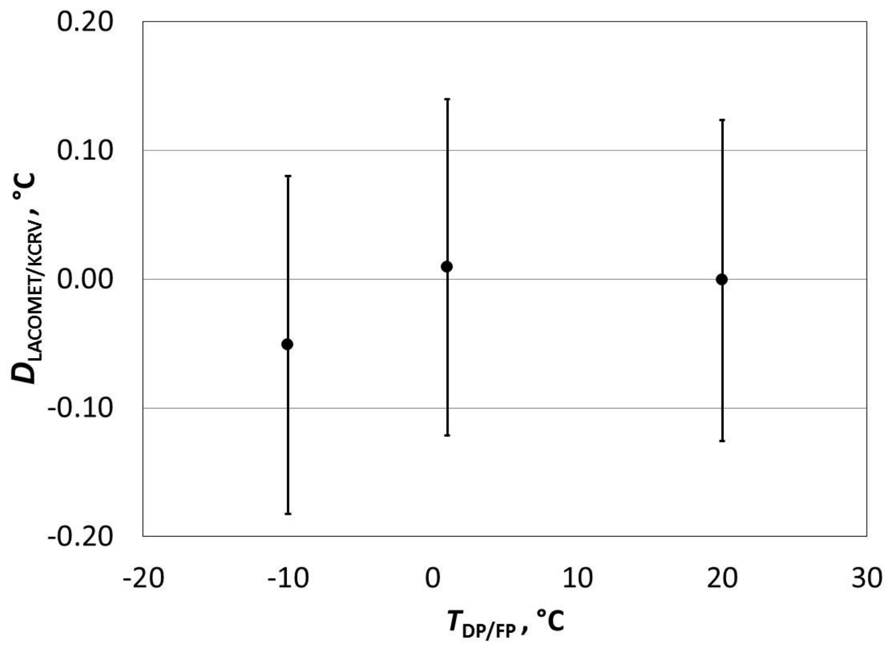

Figure 5. The degree of equivalence $D_{LACOMET/KCRV}$ between the dew/frost-point standards of LACOMET, $[T_{DP/FP}]_{LACOMET}$, and the key comparison reference values (KCRVs), $[T_{DP/FP}]_{KCRV}$, as determined by Eq. 9. The uncertainty bars represent the expanded (k = 2) uncertainty of the degree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

13. References

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