Published in final edited form as:

Metrologia. 2014 ; 51(1A): . doi:10.1088/0026-1394/51/1A/03002.

BILATERAL KEY COMPARISON SIM.T-K6.1 ON HUMIDITY STANDARDS IN THE DEW/FROST-POINT TEMPERATURE RANGE FROM -25°C TO $+20^{\circ}\text{C}$

C.W. Meyer¹ and K.D. Hill²

¹National Institute of Standards and Technology (NIST), USA

²National Research Council (NRC), Canada

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 National Research Council (NRC, Canada) between December 2014 and April, 2015. The results of this comparison are reported here, along with descriptions of the humidity laboratory standards for NIST and NRC 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 degree of equivalence between the dew/frost-point standards of NIST and NRC.

Keywords

Comparison; Humidity; Dew Point; Frost Point; Degree of Equivalence

1. Introduction

Key Comparisons determine differences between measurement standards of different National Metrology Institutes (NMIs). They play an important role in ensuring that the standards of all NMIs are in agreement.

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 [1] has been approved by the CCT Working Group on Key Comparisons and will soon be published.

The National Research Council (NRC, Canada) did not participate in CCT-K6. Therefore, to relate the humidity standards of NRC 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 NRC between December 2014 and April 2015; this comparison was designated SIM.T-K6.1. 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, NRC meets the Mutual Recognition Arrangement requirements for participation in a key comparison. NIST was the pilot for this bilateral comparison. This bilateral comparison followed the same technical procedures as for the CCT-K6, except that only one transfer standard was used. Also, a range of $-25\text{ }^{\circ}\text{C} \leq T_{DP/FP} \leq +20\text{ }^{\circ}\text{C}$ was used instead of $-50\text{ }^{\circ}\text{C} \leq T_{DP/FP} \leq +20\text{ }^{\circ}\text{C}$.

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
NRC	Ken Hill Sergey Dedyulin (current contact) National Research Council 1200 Montreal Road, M-36 Ottawa, K1A 0R6 Canada	Tel.: 613-998-6077 Fax: 613-952-1394 e-mail : Sergey.Dedyulin@nrc-cnrc.gc.ca

3. Comparison Method

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

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

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

4. Generators

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

For $T_{DP/FP} \geq -15\text{ }^{\circ}\text{C}$, 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 vapor 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 $T_{DP/FP} = -15$ °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 NRC humidity generator used was a commercially-made generator (Thunder Scientific Model 2500* [8-10]. It operates as a two-pressure generator (see Eq. 1) over its entire range. The saturator temperature can be varied from 0 °C to 70 °C and the saturator pressure can be

varied from ambient to 1.03 MPa. The generator uses four 10 k Ω thermistors to measure and control the saturator temperature. It uses two piezoresistive pressure transducers to measure and control the saturator pressure, one designed for the range 0-50 psia (0-0.34 MPa) and the other for the range 0-150 psia (0-1.03 MPa); the first is used to measure pressures below 0.34 MPa and the second to measure pressures from 0.34 MPa to 1.03 MPa. A more complete description may be found in [8]. However, it is important to note that NRC has modified the generator by adding temperature and pressure sensors that provide traceability to national measurement standards. A Rosemount 162C SPRT measures the temperature of the bath in which the saturator is immersed and MKS Model 690A Baratron's measure the saturator and chamber pressures. Calculations of $T_{\text{DP/FP}}$ were made from T_s and P_s using Eq. 1 and Eq. 3, using the formulations for e_w , e_i , and f given in [2-6]. A more complete description may be found in [10].

The Rosemount SPRT is calibrated yearly against NRC temperature standards and the MKS pressure transducers are calibrated yearly against NRC pressure standards. These actions ensure the stability of the NRC generator results and the traceability of its pressure and temperature measurements to national standards.

5. Transfer standard

Instrument type:	Chilled-mirror hygrometer
Measurand	dew/frost-point temperature
Model:	RH Systems 373H
Serial Number:	09-0819
Size (in Packing case):	63 cm $\times$ 53 cm $\times$ 40 cm
Weight (in Packing case):	36.4 kg
Manufacturer:	RH Systems, USA
Owner:	NRC, Canada
Electrical supply:	110 V / 60 Hz
Approximate value for insurance and customs declaration:	US\$ 42,700

6. Measurement process

Sample air with $T_{\text{DP/FP}}$ realized by a participant's standard generator was introduced into the inlet of a transfer-standard hygrometer through a stainless steel tube. The tube was attached to the transfer standard using a 6.35 mm Swagelok fitting. A 100-ohm platinum resistance thermometer (PRT) embedded beneath the surface of the transfer standard's mirror measured the dew/frost-point temperature. The current applied through the PRT was nominally 1 mA. At NIST, the resistance of the PRT was measured using a commercial AC resistance bridge using a 100 Ω standard resistor as its reference. At NRC, the resistance of the PRT was measured using an Agilent 3458A multimeter. The multimeter had been calibrated against NRC national standards and it was autocalibrated daily before the comparison

*Certain commercial products are identified in this paper but only in order to adequately specify the procedure. Such identification neither constitutes nor implies recommendation or endorsement by either the U.S. government or the National Institute of Standards and Technology.

measurements. For both NIST and NRC, the measured resistance was converted to a nominal dew/frost-point temperature using the reference function given in IEC 60751, as described in Appendix 3 of the CCT-K6 protocol.

A total of four dew/frost-point temperatures were used for the comparison: +20 °C, 0 °C, −10 °C and −25 °C. Each participant made four independent measurements for each dew/frost-point temperature, reforming the condensate on the hygrometer's mirror each time. At each measured dew/frost point, the PRT resistance readings were monitored until they drifted less than 0.010 Ω (0.025 °C) over a period of 20 minutes (dew points) or 40 minutes (frost points); at that point they were assumed to be in a steady state. Afterwards, multiple readings of the resistance of the PRT were recorded, and the mean and standard deviation of these readings were recorded.

7. Measurement data

Table 1 shows the results of the generator/hygrometer comparisons for both NRC and NIST. For $T_{DP/FP} \approx 0$ °C it is assumed that the condensate on the hygrometer mirror is always water (never ice). Based on the difference between the dew point and frost point temperatures at the dew/frost-point values realized at $T_{DP/FP} \approx 0$ °C, we estimate the standard uncertainty for this assumption to be less than 0.005 °C.

Table 2 shows the difference between generated and measured dew/frost-point temperatures $T_{DP/FP}$ for four measurements. For a given nominal value of $T_{DP/FP}$, the results of NRC 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. 1.

8. Comparison Uncertainty

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

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

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

First, $u_A(T_{DP/FP})$ is the type A uncertainty for the determination of $T_{DP/FP}$. This uncertainty includes the reproducibility of the generator, the chilled-mirror hygrometer, and the multimeter making the resistance measurements. 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 . For each NMI, $u_A(T_{DP/FP})$ was determined as the average value of $\sigma(T_{DP/FP})$ for the four nominal $T_{DP/FP}$ values. For NRC and NIST these average values were 0.007 °C and 0.004 °C, respectively. The individual values of $\sigma(T_{DP/FP})$ are given in Table 2.

Secondly, $u(T_{DP/FP}^g)$ is the type B uncertainty of the generated value of $T_{DP/FP}$. The source of the values $u(T_{DP/FP}^g)$ for NIST is [7], which contains a complete uncertainty budget for the NIST Hybrid Humidity Generator. The source of the values $u(T_{DP/FP}^g)$ for NRC is [10], which provides an uncertainty analysis for the Thunder Scientific Model 2500. 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 $u(T_{DP/FP}^g)$. Similarly, Table 5 shows the values of these standard uncertainties for the NRC generator and Table 6 shows their contribution to $u(T_{DP/FP}^g)$ for NRC.

Finally, $u(T_{DP/FP}^m)$ is the type B uncertainty of the measured value of $T_{DP/FP}$. It is given by the type B uncertainty of the resistance measurement of the multimeter measuring the resistance of the PRT in the chilled mirror hygrometer. The values of $u(T_{DP/FP}^m)$ were 0.002 °C for NRC and 0.001 °C for NIST.

Table 7 shows the calculated value of $u_c(T_{DP/FP})$ and its components for each value of $T_{DP/FP}$ and each participating NMI. Note that in this table we have adjusted the values of $u(T_{DP/FP}^g)$ at 0 °C to account for the uncertainty of whether dew or frost has condensed on the mirror of the hygrometer. For this, we have added a standard uncertainty of 0.005 °C in quadrature to these values.

9. Drift of Transfer Standard

The first generator/hygrometer comparison measurements were made at NRC in December 2014-January 2015. Afterwards, the transfer standard was sent to NIST so that it could perform its comparison measurements. The transfer standard was returned to NRC in March 2015, and the next comparison measurements were made in March-April 2015.

Drift of the transfer standard during the course of the NRC-NIST comparison may be estimated by examining the difference between the NRC generator/hygrometer comparisons performed in December 2014-January 2015 and March-April 2015. This difference is shown in Fig. 2. The average magnitude of the difference between the December 2014-January 2015 comparisons and the March-April 2015 comparisons is approximately 0.031 °C. In our uncertainty budget we have added a type B uncertainty component due to the possibility of transfer standard drift. Based on the results of Fig. 2, we have estimated it to contribute a standard uncertainty of 0.018 °C ($0.031^\circ\text{C}/\sqrt{3}$) to the NRC-NIST comparison.

10. Degree of Equivalence

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

$$D_{NRC/NIST}(T_{DP/FP}) \equiv [\Delta T_{DP/FP}]_{NRC} - [\Delta T_{DP/FP}]_{NIST} \quad 5)$$

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

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

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

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

The results are presented in Table 8 and plotted in Fig. 3. All values of $D_{NRC/NIST}$ are within the expanded uncertainties.

We note that the values of $D_{NRC/NIST}$ are largest for the +20 °C and 0 °C points. However, if the NRC data from March-April 2015 were used instead (see Fig. 2), the values of $D_{NRC/NIST}$ at +20 °C and 0 °C would be 0.011 °C and -0.006 °C, respectively. Overall, this second set of data agrees better with the NIST data. If the average of both sets of NRC data were used, the values of $D_{NRC/NIST}$ at +20 °C and 0 °C would be -0.010 °C and -0.028 °C, respectively. It is currently unclear why the two sets of NRC results are so different from each other at these two dew points.

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

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

with corresponding uncertainty

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

The CCT-K6 comparison was performed at $T_{DP/FP}$ values of +20 °C, 1 °C, -10 °C, -30 °C, and -50 °C. The last two values will not be considered here because the NIST/NRC

comparison was not performed at them. While the CCT-K6 comparison was performed at 1 °C and the NIST/NRC comparison was performed at 0 °C, we consider these values acceptably close for linkage and assume that

$$D_{NRC/NIST}(1^{\circ}\text{C}) = D_{NRC/NIST}(0^{\circ}\text{C}). \quad (11)$$

The relevant values of $D_{NIST/KCRV}$ and $U(D_{NIST/KCRV})$ from [1] are given in Table 9:

Combining the results of Tables 8-9 using Eqs. 9-10 yields the values of $D_{NRC/KCRV}$ and $U(D_{NRC/KCRV})$:

The values of $D_{NRC/KCRV}$ are all within the $k=2$ uncertainty values $U(D_{NRC/KCRV})$.

12. Summary

NIST and NRC have completed a bilateral comparison of their humidity standards. The quantity compared was the dew/frost-point temperature produced by the generators of the two NMIs. A chilled-mirror hygrometer was used as the transfer standard. The nominal dew/frost-point temperatures used for the comparison were +20 °C, 0 °C, −10 °C and −25 °C. The comparisons have determined the degree of equivalence between $[T_{DP/FP}]_{NRC}$ and $[T_{DP/FP}]_{NIST}$ at these points. For all dew/frost-point temperatures over the range studied, the degree of equivalence is within 0.06 °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 $[T_{DP/FP}]_{NRC}$ and $[T_{DP/FP}]_{KCRV}$ at +20 °C, +1 °C, and −10 °C. All values for this degree of equivalence are within 0.07 °C and within the expanded $k = 2$ uncertainties.

References

1. Bell S, et al. Final report to the CCT on key comparison CCT-K6 – Comparison of local realisations of dew-point temperature scales in the range −50 °C to +20 °C. *Metrologia*. accepted for publication.
2. Saul A, Wagner W. International Equations for the Saturation Properties of Ordinary Water Substance. *J. Phys. Chem. Ref. Data*. 1987; 16:893–901.
3. Wagner W, Pruss A. International Equations for the Saturation Properties of Ordinary Water Substance--Revised According to the International Temperature Scale of 1990. *J. Phys. Chem. Ref. Data*. 1993; 22:783–787.
4. Hyland RW, Wexler A. Formulations for the Thermodynamic Properties of Dry Air from 173.15 K to 473.15 K, and of Saturated Moist Air from 173.15 K to 372.15 K. Pressures to 5 MPa. 1983:520–535. *ASHRAE Trans*. 89-IIa.
5. International Association for the Properties of Water and Steam, Revised Release on the Pressure along the Melting and Sublimation Curves of Ordinary Water Substance. 2011. available at www.iapws.org
6. Wagner W, Riethmann T, Feistel R, Harvey AH. New Equations for the Sublimation Pressure and Melting Pressure of H₂O Ice Ih. *J. Phys. Chem. Ref. Data*. 2011; 40:043103.
7. Meyer CW, et al. Calibration of Hygrometers with the Hybrid Humidity Generator. NIST Special Publication. 2008:250–83.
8. Thunder Scientific Model 2500 Data Sheet. http://www.thunderscientific.com/humidity_equipment/model_2500.html

9. Thunder Scientific Model 2500 Owners Manual. http://www.thunderscientific.com/tech_info/manuals/2500-System-Manual-Ed13.pdf
10. Hill KD, NRC Humidity Calibration Facility. Report Prepared in Support of SIM.T-K6.1: Realizations of local scales of dew/frost-point temperature of humid air. Apr.2015 (attached).

NIST Author Manuscript

NIST Author Manuscript

NIST Author Manuscript

Figure 1. Difference between realized and measured dew/frost-point temperatures $T_{DP/FP}$ for NIST and NRC. Note: data from the two NMIs are slightly offset horizontally to facilitate viewing.

Figure 2.
Difference between the NRC generator/hygrometer comparisons performed in December 2014-January 2015 and in March-April 2015.

Figure 3.

The degree of equivalence $D_{NRC/NIST}$ between the four dew/frost-point temperatures realized by the standard generator of NRC, $[T_{DP/FP}]_{NRC}$ and that of NIST, $[T_{DP/FP}]_{NIST}$, as defined in Eq. 5. The uncertainty bars represent the expanded ($k = 2$) uncertainty of the degree of equivalence, as defined in Eq. 7.

Figure 4.

The degree of equivalence $D_{NRC/KCRV}$ between the dew/frost-point temperatures realized by the standard generator of NRC, $[T_{DP/FP}]_{NRC}$ 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.

Table 1

Results of generator/hygrometer comparisons.

Hygrometer RH Systems 373H, S/N 09-0819					
Nominal $T_{DP/FP}$ (°C)	Meas. #	Realized $T_{DP/FP}$ (°C)	Measured PRT Resistance (Ω)	Measured $T_{DP/FP}$ (°C)	$T_{DP/FP}$ (°C)
NRC					
20	1	20.044	107.7762	19.955	0.088
20	2	20.042	107.7648	19.926	0.116
20	3	20.047	107.7679	19.934	0.113
20	4	20.050	107.7672	19.932	0.118
NIST					
20	1	19.949	107.7199	19.811	0.138
20	2	19.993	107.7371	19.855	0.138
20	3	19.985	107.7319	19.841	0.144
20	4	19.977	107.7298	19.836	0.141
NRC					
0	1	0.000	99.9672	-0.084	0.084
0	2	0.000	99.9686	-0.080	0.080
0	3	-0.002	99.9667	-0.085	0.083
0	4	-0.001	99.9678	-0.082	0.081
NIST					
0	1	0.125	99.9925	-0.019	0.144
0	2	0.114	99.9939	-0.016	0.129
0	3	0.115	99.9947	-0.013	0.129
0	4	0.122	99.9964	-0.009	0.131
NRC					
-10	1	-10.009	96.0180	-10.173	0.164
-10	2	-10.008	96.0198	-10.169	0.161
-10	3	-10.008	96.0193	-10.170	0.162
-10	4	-10.008	96.0195	-10.169	0.161
NIST					
-10	1	-9.994	96.0232	-10.160	0.165
-10	2	-9.990	96.0261	-10.153	0.163
-10	3	-9.977	96.0314	-10.139	0.162
-10	4	-9.982	96.0298	-10.143	0.161
NRC					
-25	1	-25.030	90.1295	-25.159	0.129
-25	2	-25.046	90.1223	-25.178	0.132
-25	3	-25.067	90.1069	-25.217	0.150
-25	4	-25.083	90.1022	-25.229	0.146

Hygrometer RH Systems 373H, S/N 09-0819					
Nominal $T_{\text{DP/FP}}$ (°C)	Meas. #	Realized $T_{\text{DP/FP}}$ (°C)	Measured PRT Resistance (Ω)	Measured $T_{\text{DP/FP}}$ (°C)	$T_{\text{DP/FP}}$ (°C)
NIST					
−25	1	−25.032	90.1173	−25.191	0.158
−25	2	−25.019	90.1196	−25.185	0.165
−25	3	−25.034	90.1154	−25.195	0.161
−25	4	−25.020	90.1239	−25.174	0.153

Table 2Difference between realized and measured dew/frost-point temperatures $T_{\text{DP/FP}}$ for NIST and NRC

Nominal $T_{\text{DP/FP}}$ (°C)	NMI	Meas. 1 $T_{\text{DP/FP}}$ (°C)	Meas. 2 $T_{\text{DP/FP}}$ (°C)	Meas. 3 $T_{\text{DP/FP}}$ (°C)	Meas. 4 $T_{\text{DP/FP}}$ (°C)	— $T_{\text{DP/FP}}$ (°C)	$\sigma(T_{\text{DP/FP}})$ (°C)
20	NRC	0.088	0.116	0.113	0.118	0.109	0.014
20	NIST	0.138	0.138	0.144	0.141	0.140	0.003
0	NRC	0.084	0.080	0.083	0.081	0.082	0.002
0	NIST	0.144	0.129	0.129	0.131	0.133	0.007
−10	NRC	0.164	0.161	0.162	0.161	0.162	0.001
−10	NIST	0.165	0.163	0.162	0.161	0.163	0.002
−25	NRC	0.129	0.132	0.150	0.146	0.139	0.010
−25	NIST	0.158	0.165	0.161	0.153	0.159	0.005

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:	$T_{DP} = +20\text{ }^{\circ}\text{C}$	$T_{DP} = 0\text{ }^{\circ}\text{C}$	$T_{FP} = -10\text{ }^{\circ}\text{C}$	$T_{FP} = -25\text{ }^{\circ}\text{C}$
Saturator Temperature Measurement				
Calibration uncertainty	0.001 $^{\circ}\text{C}$	0.001 $^{\circ}\text{C}$	0.001 $^{\circ}\text{C}$	0.001 $^{\circ}\text{C}$
Long-term stability	0.001 $^{\circ}\text{C}$	0.001 $^{\circ}\text{C}$	0.001 $^{\circ}\text{C}$	0.001 $^{\circ}\text{C}$
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:	$T_{DP} = +20\text{ °C}$	$T_{DP} = 0\text{ °C}$	$T_{FP} = -10\text{ °C}$	$T_{FP} = -25\text{ °C}$
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 NRC generator, for the four nominal values of $T_{DP/FP}$.

Uncertainty for NRC generator:	$T_{DP} = +20\text{ }^{\circ}\text{C}$	$T_{DP} = 0\text{ }^{\circ}\text{C}$	$T_{FP} = -10\text{ }^{\circ}\text{C}$	$T_{FP} = -25\text{ }^{\circ}\text{C}$
Saturator Temperature Measurement				
Sensor Calibration uncertainty	0.0085 $^{\circ}\text{C}$	0.0085 $^{\circ}\text{C}$	0.0085 $^{\circ}\text{C}$	0.0085 $^{\circ}\text{C}$
Temperature Homogeneity	0.010 $^{\circ}\text{C}$	0.010 $^{\circ}\text{C}$	0.010 $^{\circ}\text{C}$	0.010 $^{\circ}\text{C}$
Temperature Stability	0.003 $^{\circ}\text{C}$	0.003 $^{\circ}\text{C}$	0.003 $^{\circ}\text{C}$	0.004 $^{\circ}\text{C}$
Saturator Pressure Measurement				
Calibration uncertainty	12 Pa	35 Pa	47 Pa	50 Pa
Pressure stability	355 Pa	217 Pa	426 Pa	1650 Pa
Hygrometer Pressure Measurement				
Calibration uncertainty	6 Pa	6 Pa	6 Pa	6 Pa
Pressure stability	140 Pa	21 Pa	39 Pa	161 Pa
Saturator Efficiency	0.005 $^{\circ}\text{C}$	0.005 $^{\circ}\text{C}$	0.005 $^{\circ}\text{C}$	0.005 $^{\circ}\text{C}$
Calculation:				
Saturation vapor pressure formula(e)	0.15 Pa	0.12 Pa	0.06 Pa	0.06 Pa
Water vapor enhancement formula(e)	0.0002	0.0008	0.0012	0.0017

Table 6

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

Uncertainty for NRC generator:	$T_{DP} = +20\text{ °C}$	$T_{DP} = 0\text{ °C}$	$T_{FP} = -10\text{ °C}$	$T_{FP} = -25\text{ °C}$
Saturator Temperature Measurement				
Calibration uncertainty	0.004	0.004	0.004	0.004
Self-heating and residual heat fluxes	0.001	0.001	0.001	0.001
Temperature Homogeneity	0.009	0.008	0.007	0.007
Temperature Stability	0.004	0.003	0.002	0.002
Saturator Pressure Measurement				
Calibration uncertainty	0.001	0.001	0.001	0.001
Pressure stability	0.008	0.004	0.003	0.003
Hygrometer Pressure Measurement				
Calibration uncertainty	0.001	0.001	0.001	0.001
Pressure stability	0.001	0.003	0.001	0.001
Saturator Efficiency	0.004	0.004	0.004	0.004
Calculation:				
Saturation vapor pressure formula(e)	0.002	0.001	0.0004	0.004
Water vapor enhancement formula(e)	0.005	0.007	0.008	0.017
Combined standard uncertainty:	0.015	0.013	0.013	0.020

Table 7

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

Nominal $T_{\text{DP/FP}}$ (°C)	Participating Institute	$u_A (T_{\text{DP/FP}})$ (°C)	$u(T_{\text{DP/FP}}^g)$ (°C)	$u(T_{\text{DP/FP}}^m)$ (°C)	$u_c (T_{\text{DP/FP}})$ (°C)
20	NRC	0.007	0.015	0.002	0.017
20	NIST	0.004	0.006	0.001	0.007
0	NRC	0.007	0.013	0.002	0.015
0	NIST	0.004	0.011	0.001	0.012
−10	NRC	0.007	0.013	0.002	0.015
−10	NIST	0.004	0.008	0.001	0.009
−25	NRC	0.007	0.020	0.002	0.021
−25	NIST	0.004	0.008	0.001	0.009

Table 8

Degree of equivalence between $T_{\text{DP/FP}}$ realized by NRC and that of NIST, and its expanded uncertainty ($k = 2$) in a comparison of four dew/frost points.

Nominal $T_{\text{DP/FP}}$ (°C)	$D_{\text{NRC/NIST}}$ (°C)	$U(D_{\text{NRC/NIST}})$ (°C)
20	−0.031	0.051
0	−0.051	0.053
−10	−0.001	0.050
−25	−0.020	0.058

Table 9

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

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

Table 10

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

Nominal $T_{\text{DP/FP}}$ (°C)	$D_{\text{NRC/KCRV}}$ (°C)	$U(D_{\text{NRC/KCRV}})$ (°C)
20	−0.037	0.071
1	−0.062	0.080
−10	−0.040	0.066