**SIM.T-K6.3 NIST / INMETRO**
**Final Report**

# BILATERAL KEY COMPARISON SIM.T-K6.3 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 was carried out by the National Institute of Standards and Technology (NIST, USA) and the Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO, Brazil) between October, 2009 and March, 2010. The results of this comparison are reported here, along with descriptions of the humidity laboratory standards for NIST and INMETRO 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 INMETRO.

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) on Humidity Measurements (WG6) to draw up a technical protocol for an International Committee on Weights and Measures (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 Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO, Brazil) did not participate in CCT-K6. Therefore, to relate the humidity standards of INMETRO 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 INMETRO between October 2009 and March 2010; this comparison was designated as SIM.T-K6.3. 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, INMETRO meets the Mutual Recognition Agreement 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 $-30\ °C \leq T_{DP/FP} \leq 20\ °C$ 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 temperature standards at NIST and INMETRO was performed through use of a transfer standard (a chilled-mirror hygrometer). At a given nominal dew/frost point, each participant used his generator to produce moist air having a constant dew/frost-point temperature. The participant then used his laboratory standard to determine the dew/frost point temperature to be $T^{l}_{DP/FP}$. For NIST, the laboratory standard was the generator itself. For INMETRO, the laboratory standard was a chilled-mirror hygrometer measuring the dew/frost point from the generator. The transfer standard determined the dew/frost-point temperature of the generated gas to be $T^{t}_{DP/FP}$. The difference between the two values was

$$\Delta T_{DP/FP} = T^{l}_{DP/FP} - T^{t}_{DP/FP}$$

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

## 4. Laboratory Humidity Standards

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

For $T_{DP/FP} \geq -15$ °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

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

Here, $e(T_s)$ is the water vapor pressure at $T_s$, calculated using [1-2] and $f(T_s, P_s)$ is the water-vapor enhancement factor, calculated using [3]. 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

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

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. $T^1_{DP,FP}$ is then obtained by iteratively solving the equation

$$x_g = \frac{e\left(T^1_{DP,FP}\right)}{P_c} \ f\left(T^1_{DP,FP}, P_c\right) \tag{3)}$$

Here, $e\left(T^1_{DP,FP}\right) = e_w\left(T^1_{DP,FP}\right)$ for $T_{DP/FP} \geq 0$ ºC, where $e_w$ is the saturated vapor pressure for water, calculated using [1-2]. Also, $e\left(T^1_{DP,FP}\right) = e_i\left(T^1_{DP,FP}\right)$ for $T_{DP/FP} < 0$ ºC, where $e_i$ is the saturated vapor pressure for ice, calculated using [4-5]. The value of $f\left(T^1_{DP,FP}, P_c\right)$ is calculated using [3]. A more complete description of the NIST HHG may be found in [6].

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 INMETRO laboratory humidity standard used was a chilled-mirror hygrometer (Michell S4000, indicator S/N 103549 and sensor S/N 103550) [7] with a calibration traceable to the SI through the National Physical Laboratory (NPL, UK). The calibration certificate number was E08040408 and it was issued by NPL on 26 August 2008. The calibration provided both display values and mirror-PRT resistance values for the Michell S4000, but only the display value calibrations have been used by INMETRO for bilateral comparisons and customer calibrations. The hygrometer operates in the dew/frost point temperature range from –75 ºC to +20 ºC. In this instrument, light shines onto a polished mirror surface, the temperature of which is controlled by a thermoelectric heat-pump. A sensitive photo-detector measures the intensity of the direct reflection. When the mirror is clean and dry, the intensity of the reflected light is at its maximum. Conversely, a cold mirror with water vapor condensed on its surface scatters the light, resulting in less light directly reflected and in reduced signal intensity. Using this received light signal as feedback in a closed loop control system, the mirror may be cooled to the temperature at which the thickness of the condensed layer, detected through the intensity of the received light, remains constant. A condensate layer of constant thickness, with no further net increase or decrease in condensation, is in dynamic equilibrium with the gas surrounding the mirror. In this equilibrium condition, the dew or frost point temperature of the gas is determined by measuring the temperature of the mirror. If the condensate is known to be in liquid form, even for temperatures below freezing, then the measured mirror temperature is taken as the dew point. If the condensate is known to be in a solid form as ice or frost, then the measured mirror temperature is taken as the frost point. Specifications for the hygrometer may be found in [8].

To ensure the stability of the INMETRO laboratory Standard, it is calibrated at NPL at three-year intervals. The calibration used for the comparison reported here was performed in 2008.

The INMETRO laboratory humidity standard measured the dew/frost point of moist air produced by a commercially-made humidity generator. This generator (Michell divided-flow generator, model DG-4) [7] operates over the dew/frost point range from –75 ºC to +20 ºC. In this generator, dried gas is divided into two streams of which one passes through a water saturator and is mixed with the other stream to produce a certain gas sample. Dew/frost point temperatures can be selected via a front panel keypad, through factory pre-set values, or by manually mixing the wet and dry gases by means of metering valves mounted on its front panel. In the comparison reported here, the Michell DG-4 was used for $T_{\mathrm{DP/FP}} < 0$ ºC.

The other equipment used for the generation of the air samples was a Weiss Technik climatic chamber, model WK3-340/40, which operates in the dew/frost point temperature range from -20 ºC to +94 ºC. In the comparison reported here, the Weiss Technik WK3-340/40 was used for $T_{\mathrm{DP/FP}} \geq 0$ ºC.

## 5. Transfer standard

| | |
|---|---|
| Model: | MBW 373 |
| Serial Number: | 00-0805 |
| Size (in Packing case): | 63 cm x 53 cm x 40 cm |
| Weight (in Packing case): | 20.1 kg |
| Manufacturer: | MBW Elektronik AG., Switzerland |
| Owner: | INMETRO, Brazil |
| Electrical supply: | 220 V / 50 Hz |
| Approximate value for insurance and customs declaration: | US$ 18,421.00 |

## 6. Measurement process

Sample air with $T_{\mathrm{DP/FP}}$ 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 6.35 mm Swagelok fitting. The dew point temperature shown on the hygrometer display was then recorded as $T^{\mathrm{t}}_{\mathrm{DP/FP}}$ . For INMETRO, the sample air was also introduced into the inlet of its standard chilled-mirror hygrometer through a stainless steel tube in parallel with the tube leading to the transfer standard; the dew/frost point temperature shown on the hygrometer display was then recorded as $T^{\mathrm{l}}_{\mathrm{DP/FP}}$ . For NIST, the dew/frost point temperature calculated from measurements of the generator’s relevant parameters was recorded as $T^{\mathrm{l}}_{\mathrm{DP/FP}}$ .

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. At each measured dew/frost point, hygrometer display readings were monitored until they drifted less than 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 dew point temperature 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 INMETRO and NIST.

**Table 1.** Results of laboratory/transfer standard comparisons

| Hygrometer MBW 373, S/N 00-0805 | | | | |
|---|---|---|---|---|
| Nominal $T_{DP/FP}$ (°C) | Meas. # | Laboratory Standard $T^{l}_{DP/FP}$ (°C) | Transfer Standard $T^{t}_{DP/FP}$ (°C) | $\Delta T_{DP/FP}$ (°C) |
| INMETRO | | | | |
| 20 | 1 | 19.24 | 19.18 | 0.06 |
| 20 | 2 | 19.24 | 19.15 | 0.09 |
| 20 | 3 | 19.28 | 19.15 | 0.13 |
| 20 | 4 | 19.19 | 19.12 | 0.07 |
| NIST | | | | |
| 20 | 1 | 20.00 | 19.91 | 0.09 |
| 20 | 2 | 20.11 | 20.02 | 0.09 |
| 20 | 3 | 20.13 | 20.07 | 0.06 |
| 20 | 4 | 20.01 | 19.97 | 0.04 |
| INMETRO | | | | |
| 1 | 1 | 1.39 | 1.27 | 0.12 |
| 1 | 2 | 1.34 | 1.21 | 0.13 |
| 1 | 3 | 1.27 | 1.13 | 0.14 |
| 1 | 4 | 1.31 | 1.16 | 0.15 |
| NIST | | | | |
| 0 | 1 | 0.02 | –0.05 | 0.07 |
| 0 | 2 | −0.02 | –0.11 | 0.09 |
| 0 | 3 | 0.03 | –0.06 | 0.09 |
| 0 | 4 | −0.01 | –0.10 | 0.09 |
| INMETRO | | | | |
| –10 | 1 | −9.96 | –10.03 | 0.07 |
| –10 | 2 | −9.98 | –10.11 | 0.13 |
| –10 | 3 | −10.05 | –10.18 | 0.13 |
| –10 | 4 | −10.03 | –10.15 | 0.12 |
| NIST | | | | |
| –10 | 1 | −10.03 | –10.07 | 0.04 |
| –10 | 2 | −9.96 | –9.99 | 0.03 |
| –10 | 3 | −9.95 | –9.97 | 0.02 |
| –10 | 4 | −9.98 | –10.01 | 0.03 |
| INMETRO | | | | |
| –30 | 1 | −30.44 | –30.40 | −0.04 |
| –30 | 2 | −30.39 | –30.37 | −0.02 |
| –30 | 3 | −30.49 | –30.43 | −0.06 |
| –30 | 4 | −30.06 | –29.99 | −0.07 |
| NIST | | | | |
| –30 | 1 | −29.93 | –29.90 | − 0.03 |
| –30 | 2 | −29.87 | –29.89 | 0.02 |
| –30 | 3 | −30.04 | –29.98 | − 0.06 |
| –30 | 4 | −29.96 | –30.00 | 0.04 |

For the second nominal dew point, INMETRO used a value of $T_{DP/FP}$ = 1 °C while NIST used a value of $T_{DP/FP}$ = 0 °C. This introduces two additional uncertainties for this point. The first uncertainty is due to the assumption that at $T_{DP/FP} \approx 0$ °C 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 0.005 °C. The second uncertainty comes from choosing the nominal value for the second point to be 1 °C (for consistency with the CCT K6 comparison). Because of this, an uncertainty must be estimated for the difference between the NIST value of $\Delta T_{DP/FP}$ at $T_{DP/FP}$ = 0 °C and that which it would be at $T_{DP/FP}$ = 1 °C. Based upon the difference between the average value of $\Delta T_{DP/FP}$ at $T_{DP/FP}$ = 0 °C and that at $T_{DP/FP}$ = –10 °C, we estimate this standard uncertainty to be 0.005 °C.

Table 2 shows the difference between the laboratory standard and transfer standard dew/frost-point temperatures $\Delta T_{DP/FP}$ for four measurements. For a given nominal value of $\Delta T_{DP/FP}$, the results of INMETRO 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 differences ($\overline{\Delta T_{DP/FP}}$ and $\sigma(\Delta T_{DP/FP})$, respectively) are shown in the last two columns. The data shown in Table 2 is plotted in Fig. 1.

**Table 2.** Difference between laboratory-standard and transfer-standard dew/frost-point temperatures $\Delta T_{DP/FP}$ for NIST and INMETRO. The mean and standard deviation of these differences ($\overline{\Delta T_{DP/FP}}$ and $\sigma(\Delta T_{DP/FP})$, respectively) are shown in the last two columns.

| 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 | INMETRO | 0.06 | 0.09 | 0.13 | 0.07 | 0.088 | 0.031 |
| 20 | NIST | 0.09 | 0.09 | 0.06 | 0.04 | 0.070 | 0.024 |
| 0 | INMETRO | 0.12 | 0.13 | 0.14 | 0.15 | 0.135 | 0.013 |
| 0 | NIST | 0.07 | 0.09 | 0.09 | 0.09 | 0.085 | 0.010 |
| −10 | INMETRO | 0.07 | 0.13 | 0.13 | 0.12 | 0.113 | 0.029 |
| −10 | NIST | 0.04 | 0.03 | 0.02 | 0.03 | 0.030 | 0.008 |
| −30 | INMETRO | −0.04 | −0.02 | −0.06 | −0.07 | −0.048 | 0.022 |
| −30 | NIST | −0.03 | 0.02 | −0.06 | 0.04 | −0.008 | 0.046 |

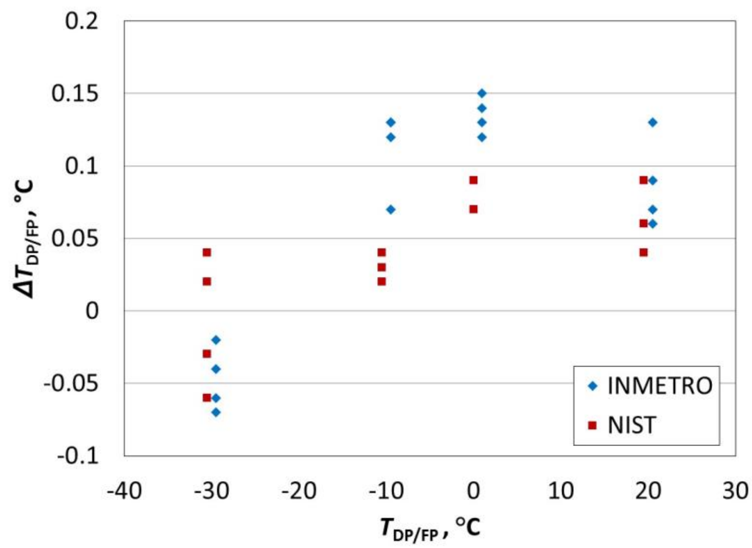


**Figure 1.** Difference between laboratory standard and transfer standard dew/frost-point temperatures, $\Delta T_{\mathrm{DP/FP}}$, for NIST and INMETRO. Note: the data at -30 °C, -10 °C, and 20 °C from the two NMIs are slightly offset horizontally to facilitate viewing.

## 8. Comparison Uncertainty

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

$$u_{\mathrm{c}}\left(\Delta T_{\mathrm{DP/FP}}\right)=\left[u_{\mathrm{A}}^{2}\left(\Delta T_{\mathrm{DP/FP}}\right)+u^{2}\left(T_{\mathrm{DP/FP}}^{1}\right)\right]^{1/2} \qquad 4)$$

Descriptions of $u_{\mathrm{A}}(\Delta T_{\mathrm{DP/FP}})$ and $u\left(T_{\mathrm{DP/FP}}^{1}\right)$ are given below.

First, $u_{\mathrm{A}}(\Delta T_{\mathrm{DP/FP}})$ is the type A uncertainty for the determination of $\Delta T_{\mathrm{DP/FP}}$. For NIST, this uncertainty includes the reproducibility of the generator and the transfer-standard chilled-mirror hygrometer. For INMETRO, it includes the reproducibility of the laboratory-standard and transfer-standard chilled-mirror hygrometers. For both NIST and INMETRO, $u_{\mathrm{A}}(\Delta T_{\mathrm{DP/FP}})$ also includes resolution errors arising from rounding off the values of $\Delta T_{\mathrm{DP/FP}}$ to two digits after the decimal point. For simplicity and a more accurate determination, it was assumed that $u_{\mathrm{A}}(\Delta T_{\mathrm{DP/FP}})$ is independent of $T_{\mathrm{DP/FP}}$. For each NMI, $u_{\mathrm{A}}(\Delta T_{\mathrm{DP/FP}})$ was determined as the average value of $\sigma(\Delta T_{\mathrm{DP/FP}})$ for the four nominal $T_{\mathrm{DP/FP}}$ values. For INMETRO and NIST these average values were 0.024 °C and 0.022 °C, respectively. The individual values of $\sigma(\Delta T_{\mathrm{DP/FP}})$ are given in Table 2.

For NIST, $u\left(T_{\mathrm{DP/FP}}^{1}\right)$ is the type B uncertainty of the generated value of $T_{\mathrm{DP/FP}}$. The source of the values $u\left(T_{\mathrm{DP/FP}}^{1}\right)$ for NIST is Ref. 6, 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 $T_{\mathrm{DP/FP}}$. Table 4 shows the contribution of these uncertainty elements to $u\left(T_{\mathrm{DP/FP}}^{1}\right)$.

**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** | $T_{DP}$ = **0 °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 $u\left(T^{1}_{\mathrm{DP/FP}}\right)$ 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** | $T_{DP}$ = **0 °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** |

For INMETRO, $u\left(T^{1}_{\mathrm{DP/FP}}\right)$ is the type B uncertainty of the value of $T_{\mathrm{DP/FP}}$ measured by its laboratory-standard chilled-mirror hygrometer. The source of the values $u\left(T^{1}_{\mathrm{DP/FP}}\right)$ for INMETRO is [9], which provides an uncertainty analysis for the INMETRO standard.

Tables 5 shows the values of these standard uncertainties for the INMETRO standard hygrometer and the combined type B uncertainty, $u\left(T^{1}_{\mathrm{DP/FP}}\right)$.

**Table 5.** Contribution of the uncertainty elements in Table 5 to $u\left(T^{1}_{\mathrm{DP/FP}}\right)$ for INMETRO, in °C, for the four nominal values of $T_{\mathrm{DP/FP}}$. The combined standard uncertainty is shown in the last row.

| **Uncertainty for INMETRO standard:** | **$T_{\mathrm{DP}}$ = 20 °C** | **$T_{\mathrm{DP}}$ = 1 °C** | **$T_{\mathrm{FP}}$= -10 °C** | **$T_{\mathrm{FP}}$= -30 °C** |
|---|---|---|---|---|
| Calibration uncertainty of the hygrometer | 0.02 | 0.02 | 0.02 | 0.03 |
| Resolution of the hygrometer | 0.003 | 0.003 | 0.003 | 0.003 |
| Drift of the hygrometer | 0.038 | 0.038 | 0.038 | 0.038 |
| Fitting of the hygrometer correction curve | 0.074 | 0.074 | 0.074 | 0.074 |
| **Combined standard uncertainty:** | **0.086** | **0.086** | **0.086** | **0.088** |

Table 6 shows the calculated value of $u_{\mathrm{c}}(\Delta T_{\mathrm{DP/FP}})$ and its components for each value of $T_{\mathrm{DP/FP}}$ and each participating NMI. Note that in this table we have adjusted the NIST value of $u(T^{1}_{\mathrm{DP/FP}})$ at 1 °C from 0.010 °C to 0.012 °C to account for the uncertainty due to the NIST measurements being performed at 0 °C (see discussion in section 7).

**Table 6.** Standard uncertainty of the determinations of $\Delta T_{\mathrm{DP/FP}}$ for NIST and INMETRO. 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) | $u(T^{1}_{\mathrm{DP/FP}})$ (°C) | $u_{\mathrm{c}}\left(\Delta T_{\mathrm{DP/FP}}\right)$ (°C) |
|---|---|---|---|---|
| 20 | INMETRO | 0.024 | 0.086 | 0.089 |
| 20 | NIST | 0.022 | 0.006 | 0.023 |
| 1 | INMETRO | 0.024 | 0.086 | 0.089 |
| 1 | NIST | 0.022 | 0.012 | 0.025 |
| −10 | INMETRO | 0.024 | 0.086 | 0.089 |
| −10 | NIST | 0.022 | 0.008 | 0.023 |
| −30 | INMETRO | 0.024 | 0.088 | 0.091 |
| −30 | NIST | 0.022 | 0.008 | 0.023 |

## 9. Drift of the Transfer Standard

The first comparison between laboratory humidity standard and transfer standard was made at INMETRO from October to November in 2009. Afterwards, the transfer standard was sent to

NIST so that it could perform its comparison measurements. The transfer standard arrived back at INMETRO in June 2010, and in July 2010 measurements were repeated at two of the four dew/frost-point temperatures.

Drift of the transfer standard during the course of the INMETRO-NIST comparison may be estimated by examining the measurements at the dew/frost point temperatures performed at INMETRO in October/November 2009 and July 2010. The difference between the average of the October/November 2009 measurements and the July 2010 measurements is approximately 0.06 °C, as shown in Figure 2. It is quite possible that this difference is due to reproducibility uncertainty rather than to drift. Nevertheless, 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 0.033 °C to the INMETRO-NIST comparison.

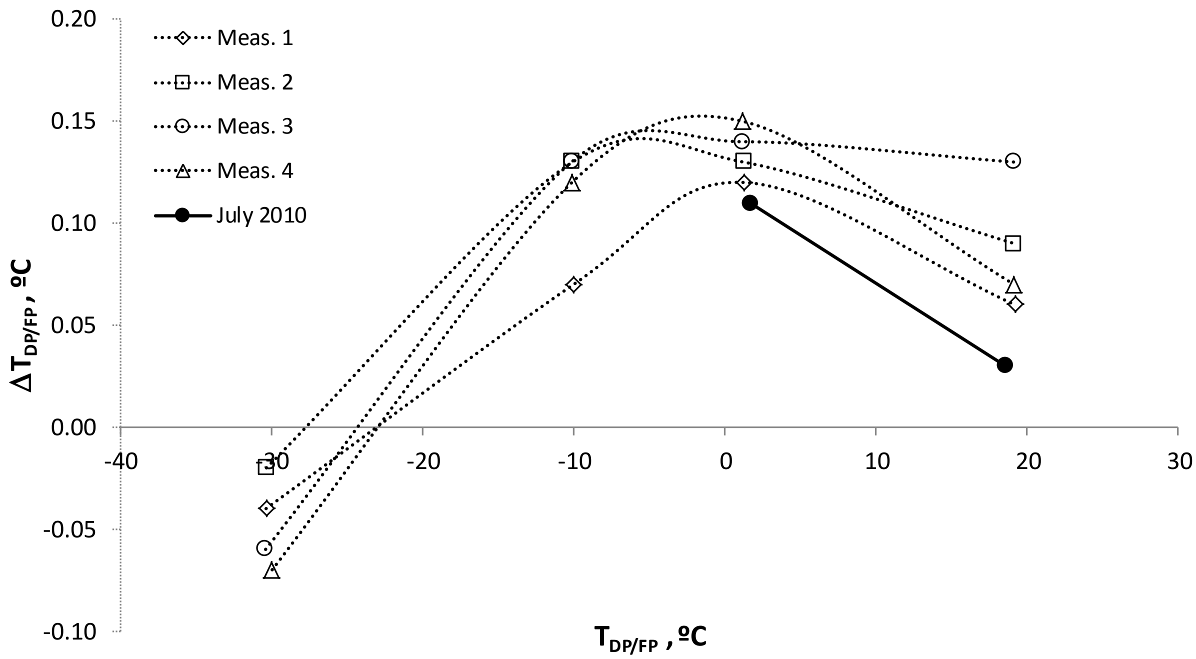


**Figure 2.** Difference between the INMETRO measurements performed in Oct./Nov. 2009 (Meas. 1,2,3, and 4) and July 2010.

## 10. Degree of Equivalence

The values $\Delta T_{\mathrm{DP/FP}}$ given in Table 1 may be used to determine the degree of equivalence $D_{\mathrm{INMETRO}}(T_{\mathrm{DP/FP}})$ between the values of $T_{\mathrm{DP/FP}}$ realized by INMETRO and reference values of $T_{\mathrm{DP/FP}}$, $[T_{\mathrm{DP/FP}}]_{\mathrm{Ref}}$ :

$$D_{\mathrm{INMETRO}}(T_{\mathrm{DP/FP}}) = [T_{\mathrm{DP/FP}}]_{\mathrm{INMETRO}} - [T_{\mathrm{DP/FP}}]_{\mathrm{Ref}} \qquad 5)$$

Once Draft B for the report of CCT K6 Key Comparison is approved, $[T_{\text{DP/FP}}]_{\text{Ref}}$ will be $[T_{\text{DP/FP}}]_{\text{KCRV}}$, the CCT K6 Key Comparison Reference Value (KCRV) for $T_{\text{DP/FP}}$. In the meantime we shall define

$$[T_{\text{DP/FP}}]_{\text{Ref}} \equiv [T_{\text{DP/FP}}]_{\text{NIST}}, \qquad 6)$$

since NIST is a participant in CCT K6 and will later be able to provide linkage to $[T_{\text{DP/FP}}]_{\text{KCRV}}$. Therefore, for the purposes of this report,

$$D_{\text{INMETRO}}(T_{\text{DP/FP}}) = [T_{\text{DP/FP}}]_{\text{INMETRO}} - [T_{\text{DP/FP}}]_{\text{NIST}} = [\Delta T_{\text{DP/FP}}]_{\text{INMETRO}} - [\Delta T_{\text{DP/FP}}]_{\text{NIST}} \qquad 7)$$

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

$$u[D_{\text{INMETRO}}(T_{\text{DP/FP}})] = \left\{ [u_{\text{c}}^2(\Delta T_{\text{DP/FP}})]_{\text{INMETRO}} + [u_{\text{c}}^2(\Delta T_{\text{DP/FP}})]_{\text{NIST}} + u_{\text{drift}}^2 \right\}^{1/2}. \qquad 8)$$

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

$$U(D_{\text{INMETRO}}) = 2u(D_{\text{INMETRO}}), \qquad 9)$$

The results are presented in Table 7 and plotted in Fig. 3. As can be seen in Table 7 and Fig. 3, all values of $D_{\text{INMETRO}}$ are within their expanded uncertainties.

**Table 7.** Degree of equivalence between INMETRO and NIST and its expanded uncertainty ($k$ = 2) in a comparison of four humidity levels

| **Nominal $T_{\text{DP/FP}}$ (°C)** | **$D_{\text{INMETRO}}$ (°C)** | **$U(D_{\text{INMETRO}})$ (°C)** |
|---|---|---|
| 20 | 0.018 | 0.20 |
| 0 | 0.050 | 0.20 |
| −10 | 0.083 | 0.20 |
| −30 | −0.040 | 0.20 |

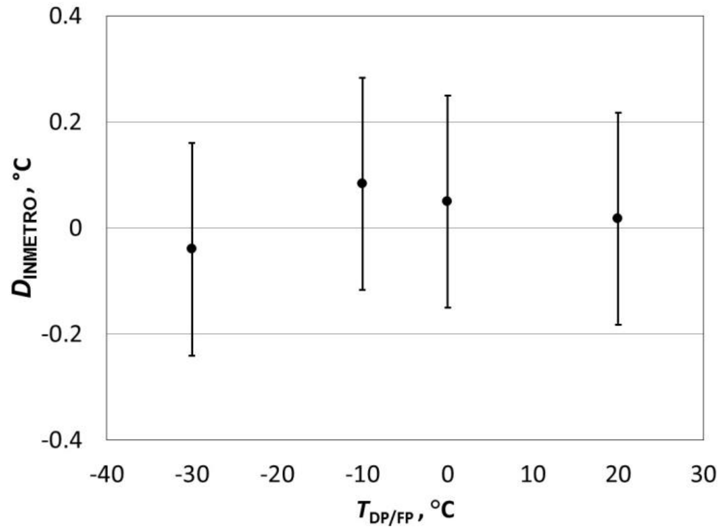


**Figure 3.** The degree of equivalence between the four dew/frost-point temperatures realized by the INMETRO laboratory humidity standard, $[T_{\mathrm{DP/FP}}]_{\mathrm{INMETRO}}$ and the corresponding reference values $[T_{\mathrm{DP/FP}}]_{\mathrm{Ref}}$ (represented by $[T_{\mathrm{DP/FP}}]_{\mathrm{NIST}}$ ), as defined in Eq. 7.

## 11. Summary

NIST and INMETRO have completed a bilateral comparison of their humidity standards. The quantity compared was the dew/frost-point temperature. The NIST laboratory standard was a humidity generator and the INMETRO laboratory standard was a chilled-mirror hygrometer. The transfer standard used was a chilled-mirror hygrometer. At NIST, the dew/frost point was produced by the NIST laboratory standard and measured by the transfer standard. At INMETRO, the dew/frost point temperatures were produced by a stable generator and measured by both the INMETRO laboratory standard and the transfer standard. 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 $[T_{\mathrm{DP/FP}}]_{\mathrm{INMETRO}}$ and a reference value for $T_{\mathrm{DP/FP}}$, presently defined as $[T_{\mathrm{DP/FP}}]_{\mathrm{NIST}}$ . For all dew/frost-point temperatures over the range studied, the degree of equivalence was within 0.09 °C and well within its expanded uncertainty of 0.2 °C.

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[7] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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