COOMET.T-K6.1
Final Report

Bilateral key comparisons of dew point temperature standards of national metrological institutes

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Abstract

A Regional Metrology Organization (RMO) Key Comparison of dew/frost point temperatures was carried out by the The Federal State Unitary Enterprise «All-Russian Scientific Research Institute of Physical, Technical and Radio Engineering Measurements» (VNIIFTRI, Russia) and the RSE «Kazakhstan Institute of Standardization and Metrology» (KazStandard, Kazakhstan) between September, 2024 and February, 2025. The results of this comparison are reported here, along with descriptions of the humidity laboratory standards for VNIIFTRI and KazStandard 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 VNIIFTRI and KazStandard.

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 Federal State Unitary Enterprise «All-Russian Scientific Research Institute of Physical, Technical and Radio Engineering Measurements» (VNIIFTRI, Russia) participated in this key comparison [1].

RSE «Kazakhstan Institute of Standardization and Metrology» (KazStandard, Kazakhstan) did not participate in CCT-K6. Therefore, to relate the humidity standards of KazStandard 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 VNIIFTRI and KazStandard between September, 2024 and February, 2025; this comparison was designated COOMET.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, KazStandard meets the Mutual Recognition Arrangement requirements for participation in a key comparison. KazStandard 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. The range of -50 °C ≤ $T_{DP/FP}$ ≤ +20°C was also used as CCT-K6.

2. Participants

Organization	Address	Contact person	Email address, Phone Number
KazStandard	010000, Republic of Kazakhstan, Astana, Korgalzhyn highway, 13/5	Zhumagali Assylbek	a.zhumagali@ksm.kz, +77787651305
VNIIFTRI	664056, Russia, Irkutsk, Borodina str. 57	Vinge Mikhail	vma@vniiftri-irk.ru +79025107041

3. Comparison Method

The comparison between dew/frost-point temperatures realized at VNIIFTRI and KazStandard 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 $T^{g}_{DP/FP}$. 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 VNIIFTRI and KazStandard humidity standards was then performed by comparing the values of $\Delta T_{DP/FP}$ determined using the VNIIFTRI humidity generator, $\Delta T_{DP/FP}$(VNIIFTRI), with those of the KazStandard humidity generator, $\Delta T_{DP/FP}$(KazStandard).

4. Generators

The VNIIFTRI humidity generator used was the State Primary Standard of Relative Humidity of Gases, Molar (Volume) Fraction of Moisture, Dew/Frost Point Temperature, Hydrocarbon Condensation Temperature Units Get 151-2020 [2].

The $T_{DP/FP}$ generation, the Get 151-2020 operates as a conventional one-pressure generator, saturating air with water at a temperature Ts and pressure Ps.

$$\frac{e(T_{DP/FP})f(P_0,T_{DP/FP})}{P_0} = \frac{e(T_S)f(P_S,T_S)}{P_S} \quad (1)$$

where e(T) is the saturation water vapor pressure of water/ice [3] at temperature T, and f(P, T) is the enhancement factor [4] at pressure P and temperature T. Note that $P_s \approx P_o$ in eq. 1) because the Get 151-2020 is a single pressure generator.

Here, e (T_s) is the water vapor pressure at T_s, calculated using [5-6] and f(T_s, P_s) is the water-vapor enhancement factor, calculated using [7]. 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, is measured by a strain-gauge pressure transducer that is connected by a tube to the saturator at a point near its outlet [8].

The KazStandard humidity generator is a single-pressure generator consisting of a temperature-controlled bath and a saturator with a heat exchanger. The heat exchanger is made of stainless steel, the diameter of the inner tube is 4 mm and the outer is 6 mm, the total length of the tube is 2.95 m, located together with the saturator in the Fluke 7380 liquid thermostat. The humidified air entering the heat exchanger is completely cooled/heated to the temperature of the thermostat and then enters the saturator. In the saturator, the air passes over the surface of the water/ice, providing full saturation. The saturator is a horizontally positioned oval vessel with a width of 15 mm, a height of 30 mm and a length of 200 mm to ensure a long-term passage of air flow over the surface of water / ice, which is almost half filled with water / ice. The source of dry air is the dew point generator DG-4 (Michell Instruments), which includes a PSD-2 dehumidifier and an oil-free air compressor with a 10-liter receiver. The temperature of the T_s saturator is measured using a standard platinum resistance thermometer Fluke 5699-S and ETS-100 (SPRT). The temperature T_s of the saturator at is equal to the temperature of the dew point/frost T_d, when the generator is operating at the same pressure, where $P_s \approx P_o$, using Eq. 1. Figure 1 shows the diagram of the KazStandard humidity generator.

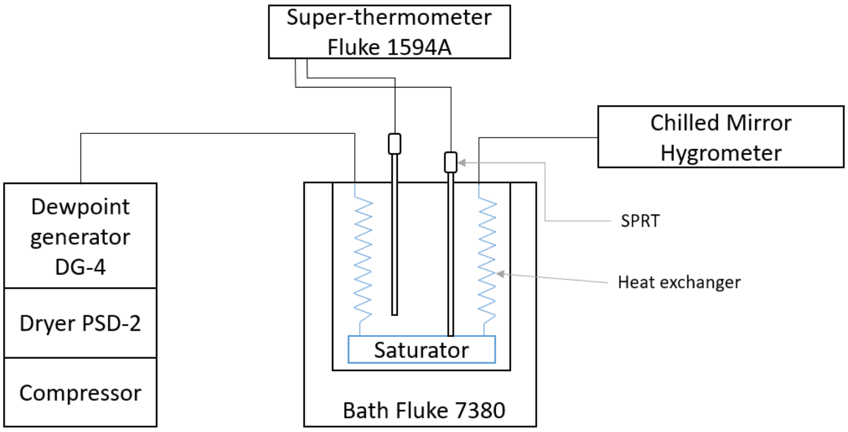

Figure 1. Diagram of the KazStandard humidity generator

5. Transfer standard

Instrument type	Chilled-mirror hygrometer
Measurand	dew/frost-point temperature
Model	S8000 RS
Serial number	143381
Size (in Packing case)	640 mm ×900 mm×470 mm
Weight (in Packing case)	38 kg
Manufacturer	Michell Instruments
Owner	KazStandard
Electrical supply	220 V/ 50 Hz
Approximate value for insurance and customs declaration:	60 000 $

6. Measurement process

Sample air with $T_{DP/FP}$ 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 ¼” VCR fitting. The dew point temperature shown on the hygrometer display was then recorded as $T^{m}_{DP/FP}$. For VNIIFTRI and KazStandard, the dew/frost point temperature calculated from measurements of the generator’s relevant parameters was recorded as $T^{g}_{DP/FP}$.

A total of five dew/frost-point temperatures were used for the comparison: –50 °C, –30 °C, –10 °C, 1 °C, and 20 °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 readings were monitored until they reached the laboratory’s criterion for being in a steady state. At VNIIFTRI, typical monitoring periods at –50 °C, –30 °C, –10 °C, 1 °C, and 20 °C were 4 h and 1 h, respectively. At KazStandard, the monitoring periods at –50 °C, –30 °C, –10 °C, 1 °C, and 20 °C were 3 h, 2 h, and 0.5 h, respectively. Afterwards, multiple readings hygrometer and standard generator were recorded, and the mean and standard deviation of these readings were recorded.

7. Measurement data

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

KazStandard 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 1 is plotted in Fig. 2.

Table 1. Difference between realized and measured dew/frost-point temperatures $\Delta T_{DP/FP}$ for VNIIFTRI and KazStandard

Nominal $\Delta T_{DP/FP}$ (°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)
-50	KazStandard	-0,243	-0,257	-0,230	-0,212	-0,236	0,019
-50	VNIIFTRI	-0,2401	-0,2367	-0,2512	-0,2486	-0,2442	0,007
-30	KazStandard	-0,101	-0,149	-0,125	-0,147	-0,131	0,022
-30	VNIIFTRI	-0,1689	-0,1495	-0,1466	-0,1631	-0,1570	0,011
-10	KazStandard	-0,088	-0,107	-0,089	-0,091	-0,094	0,009
-10	VNIIFTRI	-0,1118	-0,1085	-0,1124	-0,1178	-0,1126	0,004
1	KazStandard	0,007	0,011	0,013	0,015	0,012	0,003
1	VNIIFTRI	-0,0648	-0,0613	-0,0621	-0,0619	-0,0625	0,002
20	KazStandard	0,082	0,078	0,051	0,067	0,070	0,014
20	VNIIFTRI	-0,0970	-0,0401	-0,0287	-0,0344	-0,0501	0,032

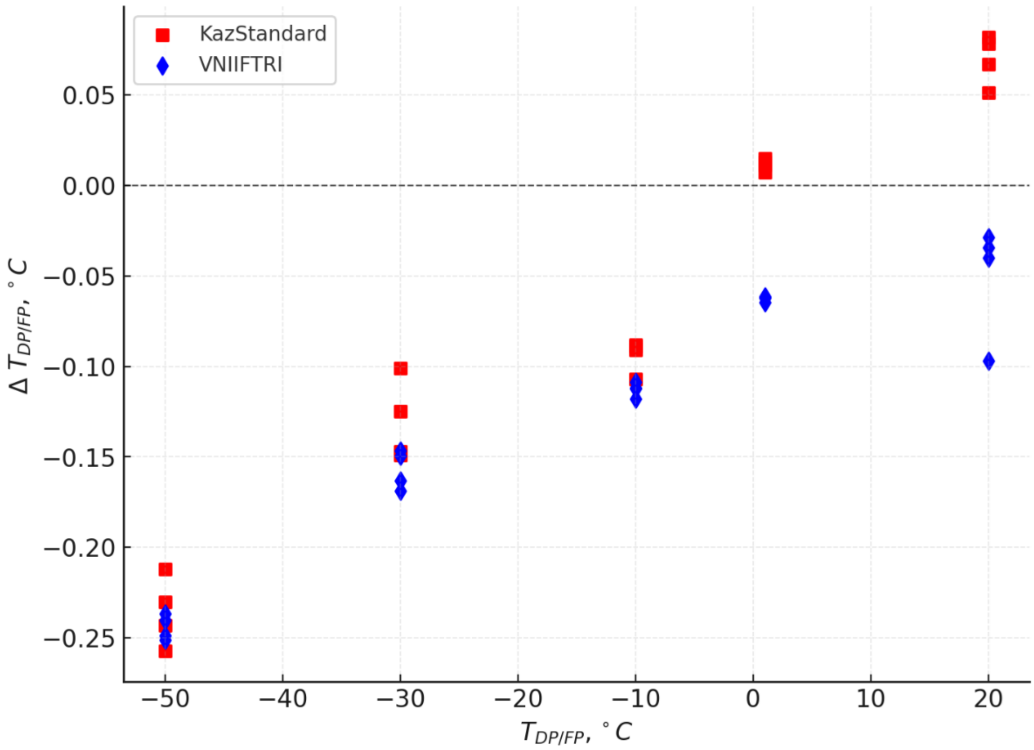

Figure 2. Difference between realized and measured dew/frost-point temperatures $\Delta T_{DP/FP}$ for VNIIFTRI and KazStandard

Table 2. Uncertainty elements and their standard uncertainty values for the VNIIFTRI generator, in °C, for the five nominal values of $T_{DP/FP}$

Uncertainty for VNIIFTRI generator:	**T_{DP}=20°C**	**T_{DP}=1°C**	**T_{FP}= -10°C**	**T_{FP}=-30°C**	**T_{FP}=-50°C**
Saturation temperature: Calibration uncertainty (sensor thermometer and indicator unit)	0,0054	0,0054	0,0059	0,0045	0,0054

Saturation temperature: Temperature homogeneity	0,0058	0,0057	0,0063	0,0048	0,0059
Saturation pressure: Calibration uncertainty (sensor pressure and indicator unit)	0,0097	0,0065	0,0216	0,0067	0,0050
Gas pressure at the generator outlet: Calibration uncertainty (sensor pressure and indicator unit)	0,0082	0,0072	0,0069	0,0051	0,0041
Saturation efficiency	0,0020	0,0020	0,0020	0,0020	0,0020
Saturation vapour pressure formula(e) (saturation)	0,0007	0,0005	0,0004	0,0002	0,0174
Water vapour enhancement formula(e) (saturation)	0,0008	0,007	0,0048	0,0193	0,0015
Saturation vapour pressure formula(e) (at generator outlet)	0,0005	0,0001	0,0017	0,0006	0,0136
Water vapour enhancement formula(e) (at generator outlet)	0,0011	0,0009	0,0019	0,0012	0,0016
Std uncert due to short-term stability generaror (type A)	0,0004	0,0007	0,0019	0,0006	0,0035
Combined standard uncertainty:	**0,0152**	**0,0127**	**0,0250**	**0,0222**	**0,0248**

Table 3. Uncertainty elements and their standard uncertainty values for the KazStandard generator, in °C, for the five nominal values of $T_{DP/FP}$

Uncertainty for KazStandard generator:	**T_{DP}=20°C**	**T_{DP}=1°C**	**T_{FP}= -10°C**	**T_{FP}=-30°C**	**T_{FP}=-50°C**
Calibration SPRT	0,003	0,003	0,003	0,003	0,005
Drift of SPRT	0,005	0,005	0,005	0,005	0,005
Hysteresis of SPRT	0,002	0,002	0,002	0,002	0,002
Self-heating SPRT	0,001	0,001	0,001	0,001	0,001
Resistance bridge calibration	0,00012	0,00012	0,00012	0,00012	0,00012
Resistance bridge resolution	0,000289	0,000289	0,000289	0,000289	0,000289
Resistance bridge drift	0,0002	0,0002	0,0002	0,0002	0,0002
Uniformity of bath temperature	0,012	0,012	0,012	0,012	0,012
Stability of bath temperature	0,012	0,012	0,012	0,012	0,012
Saturator efficiency	0,05	0,05	0,05	0,05	0,05
Combined standard uncertainty:	**0,053**	**0,053**	**0,053**	**0,053**	**0,053**

When calculating the standard uncertainty, the sensitivity coefficient of the Resistance bridge is 1Ohm/0,385°C.

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

$$u_c(\Delta T_{DP/FP})=\sqrt{u_A^2(\Delta T_{DP/FP})+u^2(T_{DP/FP}^g)+u^2(T_{DP/FP}^m)} \quad (3)$$

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. Secondly, $u(T_{DP/FP}^g)$ is the type B uncertainty of the generated value of $T_{DP/FP}$. The source of the values for VNIIFTRI is [8], which contains a complete uncertainty budget for the Get 151-2020. The source of the uncertainty values for KazStandard is the uncertainty analysis shown in Table 3. Table 2 shows the major uncertainty elements and their standard uncertainty values for the VNIIFTRI generator, for the five nominal values of $T_{DP/FP}$. Tables 3 shows the values of these standard uncertainties for the KazStandard generator humidity and the combined type B uncertainty, $u(T_{DP/FP}^g)$. Note that the sources of uncertainty from the KazStandard pressure values were not taken into account and not measured, since the generator operates under the single pressure, and the uncertainty value is minimal.

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 chilled mirror hygrometer display division. The values of were 0.003 °C for VNIIFTRI and 0.003 °C for KazStandard.

9. Drift of Transfer Standard

The first generator/hygrometer comparison measurements were made at KazStandard in September 2024- October 2024. Afterwards, the transfer standard was sent to VNIIFTRI so that it could perform its comparison measurements. The transfer standard was returned to KazStandard in December 2024, and the next comparison measurements were made in January 2025.

Drift of the transfer standard during the course of the KazStandard- VNIIFTRI comparison may be estimated by examining the difference between the KazStandard generator/hygrometer comparisons performed in September 2024- October 2024 and January 2025. This difference is shown in Fig. 3. The maximum magnitude of the difference between the September 2024- October 2024 comparisons and the January 2025 comparisons is approximately 0.014 °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. 3, we have estimated it to contribute a standard uncertainty of 0.008 °C ($0.014/\sqrt{3}$) to the KazStandard-VNIIFTRI comparison.

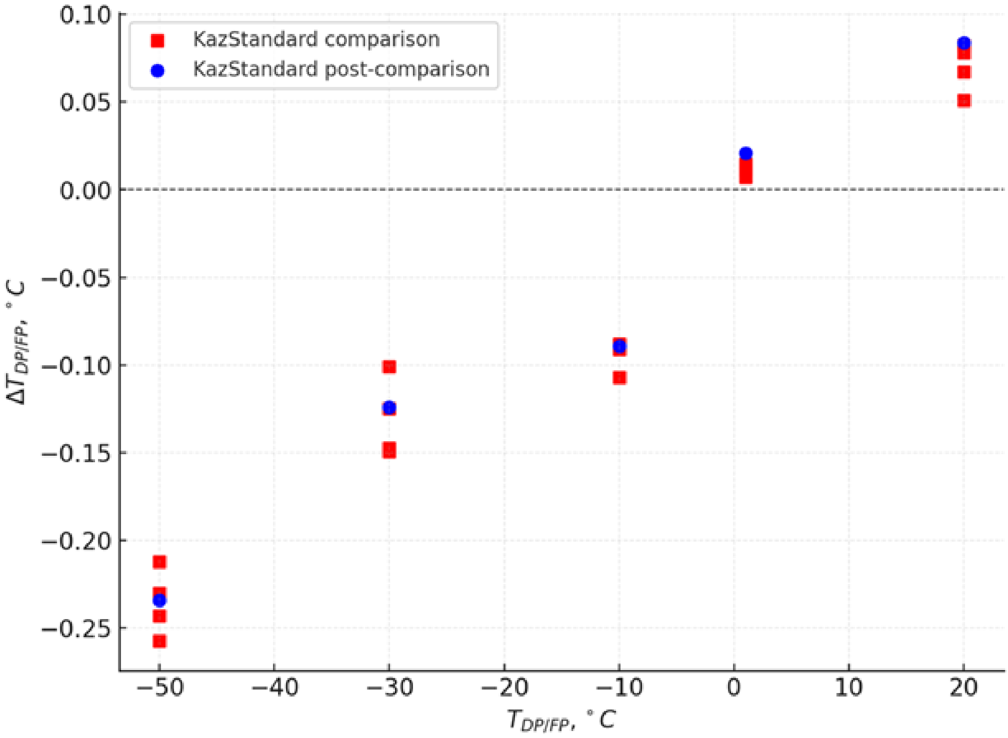

Figure 3. Difference between the KazStandard generator/hygrometer comparisons performed in September 2024- October 2024 and in January 2025.

Table 4. Standard uncertainty of the determinations of $\Delta T_{DP/FP}$ for KazStandard and VNIIFTRI. The column headings are described in the text.

Nominal $\Delta T_{DP/FP}$ (°C)	NMI	$u_A(\Delta T_{DP/FP})$, °C	$u(T^g_{DP/FP})$, °C	$u(T^m_{DP/FP})$, °C	$u_c(\Delta T_{DP/FP})$, °C
-50	KazStandard	0,019	0,053	0,003	0,056
-50	VNIIFTRI	0,007	0,025	0,003	0,026
-30	KazStandard	0,022	0,053	0,003	0,057
-30	VNIIFTRI	0,011	0,022	0,003	0,025
-10	KazStandard	0,009	0,053	0,003	0,054
-10	VNIIFTRI	0,004	0,025	0,003	0,025
1	KazStandard	0,003	0,053	0,003	0,053
1	VNIIFTRI	0,002	0,013	0,003	0,013
20	KazStandard	0,014	0,053	0,003	0,055
20	VNIIFTRI	0,032	0,015	0,003	0,035

10. Degree of Equivalence

We define the degree of equivalence between the values of $T_{DP/FP}$ realized by KazStandard and those of VNIIFTRI, $D_{KazStandard/VNIIFTRI}$ as

$$D_{KazStandard/VNIIFTRI}(T_{DP/FP})=[\Delta T_{DP/FP}]_{KazStandard} - [\Delta T_{DP/FP}]_{VNIIFTRI} \quad (4)$$

The uncertainty of the degree of equivalence $u(D_{KazStandard/VNIIFTRI}(T_{DP/FP}))$ is the combination of

$u_c(\Delta T_{DP/FP})$ for KazStandard, $u_c(\Delta T_{DP/FP})$ for VNIIFTRI, and the uncertainty u_{drift} due to possible drift of the transfer standard:

$$u[D_{KazStandard/VNIIFTRI}(T_{DP/FP})]=\sqrt{[u_c^2(\Delta T_{DP/FP})]_{KazStandard}+[u_c^2(\Delta T_{DP/FP})]_{VNIIFTRI}+u_{drift}^2} \quad (5)$$

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

$$U(D_{KazStandard/VNIIFTRI})=2u(D_{KazStandard/VNIIFTRI}) \quad (6)$$

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

Table 5. Degree of equivalence between $T_{DP/FP}$ realized by KazStandard and that of VNIIFTRI, and its expanded uncertainty (k = 2) in a comparison of five dew/frost points.

Nominal $T_{DP/FP}$, °C	$D_{KazStandard/VNIIFTRI}$, °C	$U(D_{KazStandard/VNIIFTRI})$, °C
20	0,120	0,131
1	0,075	0,110
-10	0,019	0,120
-30	0,026	0,126
-50	0,008	0,125

11. Linkage to the CCT-K6 KCRV

Because VNIIFTRI 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

$$D_{NMI/KCRV}(T_{DP/FP})=[\Delta T_{DP/FP}]_{NMI}-[\Delta T_{DP/FP}]_{KCRV} \quad (7)$$

Since KazStandard did not participate in CCT-K6, Eq. 4 and Eq. 7 may be used to determine $D_{KazStandard/KCRV}$:

$$D_{KazStandard/KCRV}(T_{DP/FP})= D_{KazStandard/VNIIFTRI}(T_{DP/FP})+ D_{VNIIFTRI/KCRV}(T_{DP/FP}) \quad (8)$$

with corresponding uncertainty

$$U^2(D_{KazStandard/KCRV})= U^2(D_{KazStandard/VNIIFTRI}) + U^2(D_{VNIIFTRI/KCRV}) \quad (9)$$

The relevant values of $D_{VNIIFTRI/KCRV}$ and $U(D_{VNIIFTRI/KCRV})$ from [1] are given in Table 6:

Table 6. Degree of equivalence between $T_{DP/FP}$ realized by VNIIFTRI and the KCRV, $D_{VNIIFTRI/KCRV}$, and its expanded uncertainty (k = 2), $U(D_{VNIIFTRI/KCRV})$, at $T_{DP/FP}$ values of +20 °C, 1 °C, −10 °C, −30 °C and −50 °C, as given by Tables 7.3 and 7.4 in [1].

Nominal $T_{DP/FP}$, °C	$D_{VNIIFTRI/KCRV}$, °C	$U(D_{VNIIFTRI/KCRV})$, °C
20	-0,003	0,046
1	-0,026	0,058
-10	-0,031	0,041
-30	-0,013	0,038
-50	-0,011	0,032

Combining the results of Tables 5-6 using Eqs. 8-9 yields the values of $D_{KazStandard/KCRV}$ and $U(D_{KazStandard/KCRV})$:

Table 7. Degree of equivalence between $T_{DP/FP}$ realized by KazStandard and the KCRV, $D_{KazStandard/KCRV}$, and its expanded uncertainty (k = 2), $U(D_{KazStandard/KCRV})$, at $T_{DP/FP}$ values of +20 °C, 1 °C, −10 °C, −30 °C and −50 °C.

Nominal $T_{DP/FP}$, °C	$D_{KazStandard/KCRV}$, °C	$U(D_{KazStandard/KCRV})$, °C
20	0,117	0,139
1	0,049	0,124
-10	-0,012	0,127
-30	0,013	0,132
-50	-0,003	0,129

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

12. Summary

KazStandard and VNIIFTRI 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, 1 °C, –10 °C, –30 °C and –50 °C. The comparisons have determined the degree of equivalence between $[T_{DP/FP}]_{KazStandard}$ and $[T_{DP/FP}]_{VNIIFTRI}$ 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 $[T_{DP/FP}]_{KazStandard}$ and $[T_{DP/FP}]_{VNIIFTRI}$ at +20 °C, 1 °C, –10 °C, –30 °C and –50 °C. All values for this degree of equivalence are within 0,14 °C and within the expanded k = 2 uncertainties.

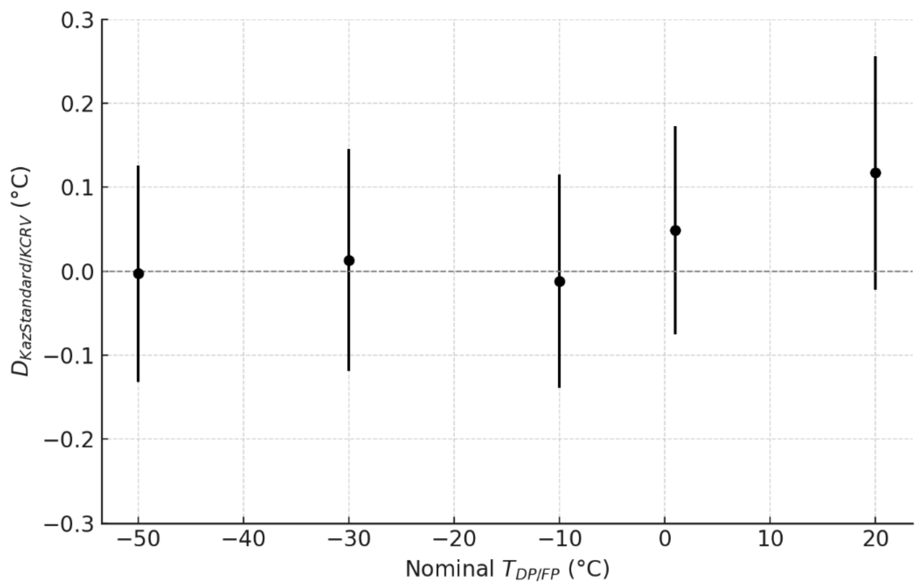

Figure 4. The degree of equivalence $D_{KazStandard/KCRV}$ between the dew/frost-point temperatures realized by

the standard generator of KazStandard, $[T_{DP/FP}]_{KazStandard}$ and the key comparison reference values (KCRVs), $[T_{DP/FP}]_{KCRV}$, as determined by Eq. 8. The uncertainty bars represent the expanded (k = 2) uncertainty of the degree of equivalence, as determined by Eq. 9.

13. References

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