Report to the CCT on the Comparison EURAMET.T-K6.1

Bilateral comparison of the realisations of local dew/frost-point temperature scales in the range -70 °C to +20 °C

Participants: HMI/FSB-LPM and MIKES

Final

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Contents

1. INTRODUCTION

As the European extension of the first CCT humidity key comparison, EURAMET.T-K6 was successfully completed in year 2008 [1-2]. After this comparison, a new low dew-point generator was introduced at LPM in Croatia as a result of progress in the EUROMET P912 project. With this new facility, the LPM uncertainties decreased significantly and the operating range became significantly wider. Therefore, it was decided to arrange a bilateral comparison between LPM and MIKES in Finland. As the coordinator of EURAMET.T-K6 and participant of CCT-K6, MIKES provided a link to these comparisons with an appropriate uncertainty level. This comparison was carried out in a manner similar to other K6 comparisons but only one transfer standard was used instead of two units and the measurement point -70 °C was added to the measurement scheme.

2. ORGANIZATION AND COMPARISON METHOD

2.1 Participants

Detailed information of the participating laboratories is given in Table 2.1. Information on the dew-point generators compared in this project is given in Table 2.2.

Table 2.1 Contact information of the participants

Name of the laboratory	Country	Address	Contact	e-mail
Centre for Metrology and Accreditation (MIKES)	Finland	Tekniikantie 1, FI-02151 Espoo	Martti Heinonen	martti.heinonen@mikes.fi
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Laboratory for Process Measurements (LPM)	Croatia	Faculty of Mechanical Engineering and Naval Architecture, Ivana Lucica 5, HR-10000 Zagreb	Davor Zvizdic	davor.zvizdic@fsb.hr

Table 2.2 Dew-point temperature realizations at LPM and MIKES

Laboratory	Type	Id	Description of traceability to SI base units	Reference to published description
MIKES	Single pressure dew-point generator	MDFG	MDFG is a primary dew-point temperature scale realisation with traceability to SI base units through calibrations of the thermometers and the digital barometer of the system. The calibrations are performed regularly at MIKES within the CMCs published at the BIPM website.	[4-6]
FSB-LPM	Single pressure dew-point generator	LRS	LRS is a primary dew-point temperature scale realisation with traceability to SI base units through calibrations of the thermometers and the digital barometer of the	[3]

			system. The calibrations are traceable to PTB and NIST.	

For measuring the resistance of the PRT embedded in the mirror of the transfer standard:

- MIKES used an ASL F700B resistance bridge with a 100 ohm Tinsley 5685A standard resistor calibrated at MIKES within the CMCs published at the BIPM website
- FSB-LPM used an ASL F18 resistance bridge calibrated at PTB and a 100 ohm Tinsley 5685A standard resistor calibrated at an accredited calibration laboratory SIQ-Slovenian Institute of Quality and Metrology within their CMCs.

The uncertainties related to calibrations of the resistance measurement instruments were negligible compared to uncertainties of dew-point temperature measurements.

2.2 Comparison scheme and measurements

Full sets of calibration measurements (MIKES1) were carried out at first at MIKES in March to April 2009 and then at LPM in October to December 2009. To monitor the long-term stability of the transfer standard, MIKES carried out a reduced set of calibration measurements (MIKES2) in February to March 2010. The full measurement set consisted of four repeated sets of measurements at the nominal points of -70 °C, -50 °C, -30 °C, -10 °C, +1 °C and +20 °C. Each nominal dew-point temperature was separately repeated (reproduced) four times to reduce the effect of any irreproducibility of the transfer standards.

For practical reasons, MIKES measurements at the nominal point of -70 °C were carried out as separate sets but they still fulfilled the requirement of reproduced measurements, i.e. the condensed layer on the mirror was reformed for each repetition. Also, the hygrometer was flushed with drier air prior to each measurement. When completing these measurements in the MIKES1 set, a small leak through the endoscope seal of the transfer standard was identified. Therefore, the complete measurement set at -70 °C was carried out also in MIKES2. To eliminate the error due to the leak, only the MIKES2 results were included in the final analysis of the -70 °C results. It was checked that the leak did not affect the rest of the MIKES1 results.

All calibrations were carried out using air at pressure from 102 kPa to 108 kPa. The temperature of the sensor head was 20 °C above the dew-point temperature.

3. TRANSFER STANDARD

3.1 Description of the transfer standards

Detailed information about the transfer standard is given below:

Model:	MBW 373 L
Tube connectors:	VCR Cajon ® ¼”
Accessories:	Endoscope, 4-wire cable for resistance measurements (3 m) rotameter
Serial number	03-0923

The effect of variations in sample air flow rate on the performance of the transfer standard had been tested but found negligible in the context of this comparison. It had also been found out that using the same measurement head settings in both laboratories ensures that a possible uncertainty due to head temperature variations can be omitted in the analysis of comparison results.

3.2 Performance of the transfer standards

3.2.1 Linearity

Figure 3.1 shows that the transfer standard becomes nonlinear in the range below -60 °C. These results were obtained at MIKES. Both MIKES and LPM carried out further studies with different flow rates through the instrument but no leak effect was identified. It is worth noticing that prior to manufacturing the instrument, the PRT embedded in the mirror was calibrated only in the range from -60 °C to +60 °C.

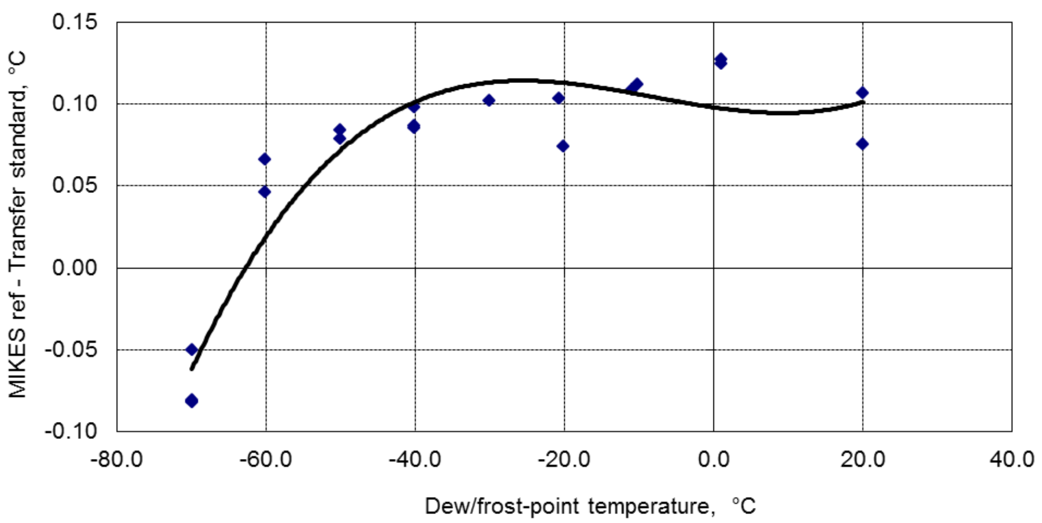

Figure 3.1 Results of MIKES calibrations showing the non-linearity of the transfer standard.

3.2.2 Difference between the resistance-based temperature and display readings

Display readings were recorded by hand or via serial port of the transfer standards. The display readings are compared with the results calculated from the resistance values recorded at the same time in figure 3.2.

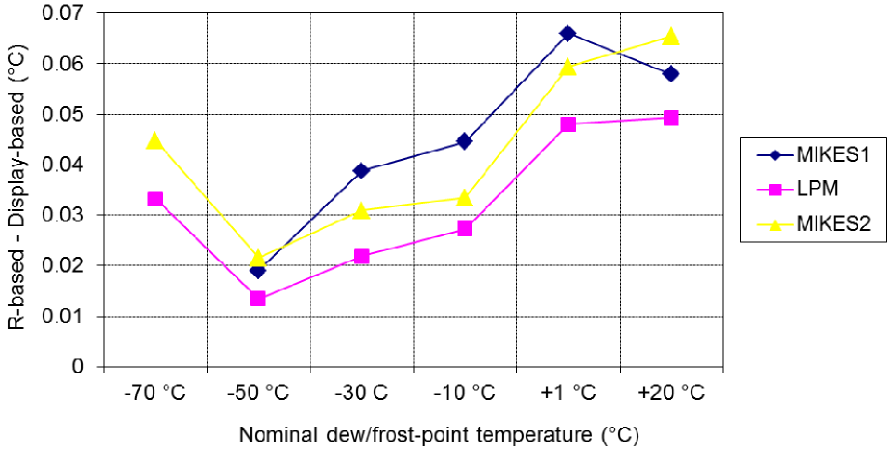

Figure 3.2 Difference between the results obtained by resistance measurements and display recording.

These results do not indicate a problem with the measurements of resistance used as the primary signal of the transfer standards.

3.2.3 Comparison of the results obtained the pilot laboratory

The drift of the transfer standard during the comparison was monitored by comparing the results obtained by the pilot laboratory (MIKES1 and MIKES2) to each other. This was carried out by fitting 2nd order polynomials to all results in the range between -50 °C and +20 °C in both sets of results and comparing the fittings to each other in the whole range from -70 °C to +20 °C. The standard deviations of the fitting residuals are 0.009 °C and 0.015 °C, respectively. As illustrated in figure 3.3, the maximum difference between the fittings is 0.014 °C. Because no time dependent correction due to the long-term instability is applied, the standard uncertainty due to the drift was estimated to 0.018 °C. Figure 3.3 suggests a slightly increasing drift towards lower dew-point temperatures and the uncertainty was estimated to 0.022 °C at the lowest point (-70 °C).

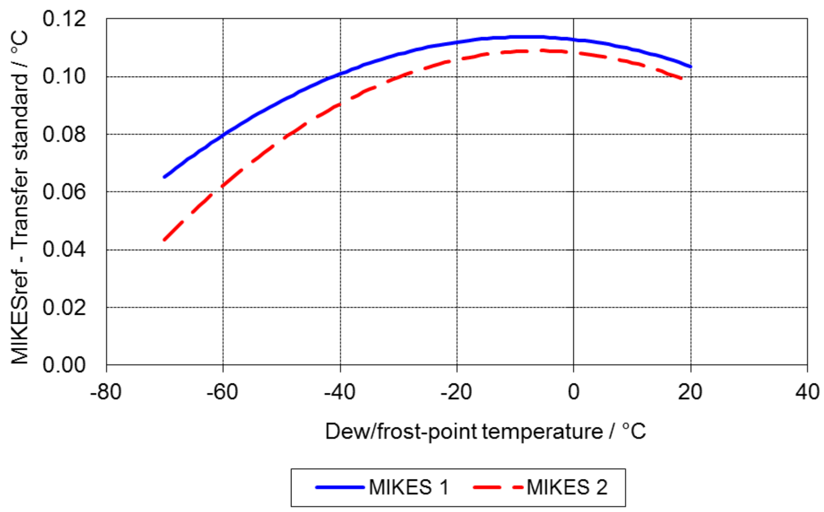

Figure 3.3 2nd order polynomials fitted to the MIKES1 and MIKES2 results in the range from -50 °C to +20 °C. The fitting curves are extrapolated down to -70 °C. The difference between the curves represents the drift of the transfer standard during the comparison.

4 MEASUREMENT RESULTS

A single result (R_{lab}) at each measurement point for each laboratory was derived in the following way: At first, all the mirror PRT resistance values reported by the laboratories were converted to corresponding temperature values using the equations presented in [6]. Then, the mean differences between the laboratory reference dew-point temperature values ($t_{\mathrm{dR}i}$) and the results obtained by the transfer standard ($R_{\mathrm{h},i}$) were calculated. Finally, the mean results were calculated from the four repetitions at the measurement point:

$$R_{lab} = \frac{1}{4}\left(\sum_{i=1}^{4} R_{lab,i}\right) + \delta_{\mathrm{rep},lab} = \frac{1}{4}\left(\sum_{i=1}^{4} (t_{\mathrm{dR}i} - R_{\mathrm{h},i})\right) + \delta_{\mathrm{rep},lab} \qquad (4.1)$$

where δ_{rep} is the correction due to non-ideal reproducibility of the results. Its estimate is zero but its standard uncertainty is calculated by:

$$u(\delta_{\mathrm{rep},lab}) = \frac{1}{2\sqrt{3}}\left[\max\left(R_{lab,i}\right) - \min(R_{lab,i})\right] \qquad (4.2)$$

Here, the type A variance was estimated for simplicity by assuming the range as a rectangular distribution. This may slightly underestimate the true size of the variance due to the small number of data. The mean differences $R_{\mathrm{lab},i}$ are correlated to each other in a large extent through the same equipment and measurement procedures. Therefore, an assumption of full correlation leads to only a small overestimation in the combined uncertainty. According to [7], the uncertainty $u(R_{\mathrm{lab}})$ can be obtained by the following equation:

$$\begin{aligned} u^2(R_{lab}) &= \left[\sum_{i=1}^{4} \frac{u(R_{lab,i})}{4}\right]^2 + u^2(\delta_{\mathrm{rep},lab}) \\ &= \left[\frac{1}{4}\sum_{i=1}^{4} [u(t_{\mathrm{dR},i}) + u(R_{\mathrm{h},i})]\right]^2 + \frac{1}{12}\left[\max(R_{lab,i}) - \min(R_{lab,i})\right]^2 \end{aligned} \qquad (4.3)$$

The uncertainties of the hygrometer results $u(R_{\mathrm{h},i})$ are contributed by the short-term instability and the uncertainty of resistance measurements. The MIKES results were obtained from the full sets of four repeated measurements, i.e. MIKES1 measurement set except at -70 °C where MIKES2 results were used (see Section 2.2). The results of both laboratories are presented graphically in Fig. 4.1

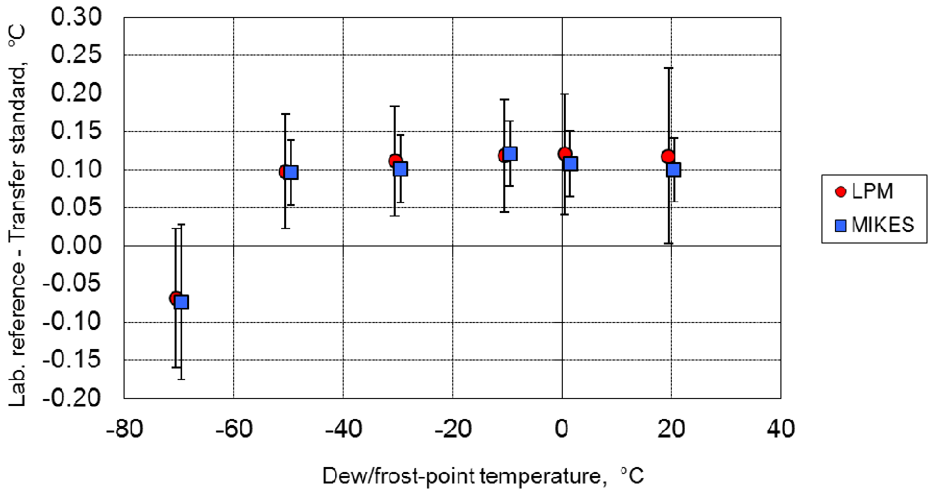

Fig. 4.1 Final results of MIKES (blue square) and LPM (red circle) calculated with equations (4.1) to (4.3). Error bars show the expanded uncertainties with k=2.

Because the uncertainty due to the reproducibility is not dominating and the probability distribution of each repeated calibration result is normal, we can assume that the combined standard uncertainties are normally distributed. Therefore, the coverage factor of 2 leads to about 95 % confidence level.

5. BILATERAL EQUIVALENCE

The bilateral equivalence between MIKES and LPM ($D_{\mathrm{MIKES,LPM}}$) is calculated as:

$$D_{\mathrm{MIKES,LPM}} = R_{\mathrm{MIKES}} - R_{\mathrm{LPM}} + \delta_{\mathrm{stab}} \tag{5.1}$$

and its standard uncertainty:

$$u(D_{\mathrm{MIKES,LPM}}) = \sqrt{u^2(R_{\mathrm{MIKES}}) + u^2(R_{\mathrm{LPM}}) + u^2(\delta_{\mathrm{stab}})} \tag{5.2}$$

A summary of the analysis is given in figure 5.1 and Table 1. It can be seen that in all cases $\left|D_{\mathrm{MIKES,LPM}}\right| < U(D_{\mathrm{MIKES,LPM}})$ indicating a good agreement between the laboratories.

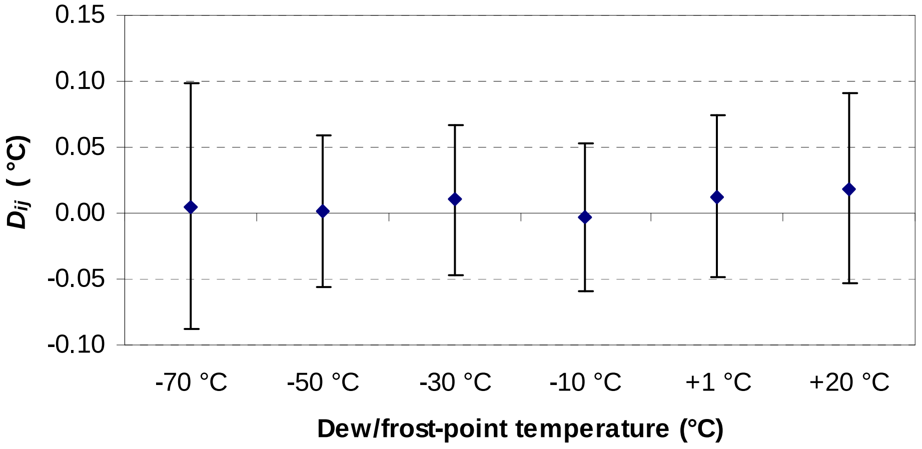

Fig. 5.1 Bilateral degrees of equivalence between MIKES and LPM. Error bars show the expanded uncertainties with k=2.

6. LINKING THE RESULTS TO THE EURAMET.T-K6 COMPARISON REFERENCE VALUES (ERV)

The LPM results in the range between -50 °C and +20 °C can be linked to the EURAMET.T-K6 Comparison Reference Values (ERV_{K6}) via MIKES results. Because the comparison reported in this paper was executed very soon after the EURAMET key comparison and MIKES used the very same dew-point temperature standard in both comparisons, the difference between the LPM results and ERV_{K6} (ΔR_{LPM}) can be determined simply by calculating:

$$\Delta R_{\mathrm{LPM}} = R_{\mathrm{LPM}} - ERV_{\mathrm{K6}} = (R_{\mathrm{LPM}} - R_{\mathrm{MIKES}}) - \Delta R_{\mathrm{MIKES}} = D_{\mathrm{MIKES,LPM}} - \Delta R_{\mathrm{MIKES}} \qquad (6.1)$$

where ΔR_{MIKES} is the difference between ERV_{K6} and the corresponding MIKES result determined in the EURAMET.T-K6 [1]. The corresponding uncertainty is calculated with:

$$u^2(\Delta R_{\mathrm{LPM}}) = u^2(D_{\mathrm{MIKES,LPM}}) + u^2(\Delta R_{\mathrm{MIKES}}) \qquad (6.2)$$

Figure 6.1 and Table 1 show the results obtained with equations (6.1) and (6.2). The deviation of the LPM results from ERV_{K6} is smaller than its expanded uncertainty at all K6 measurement points.

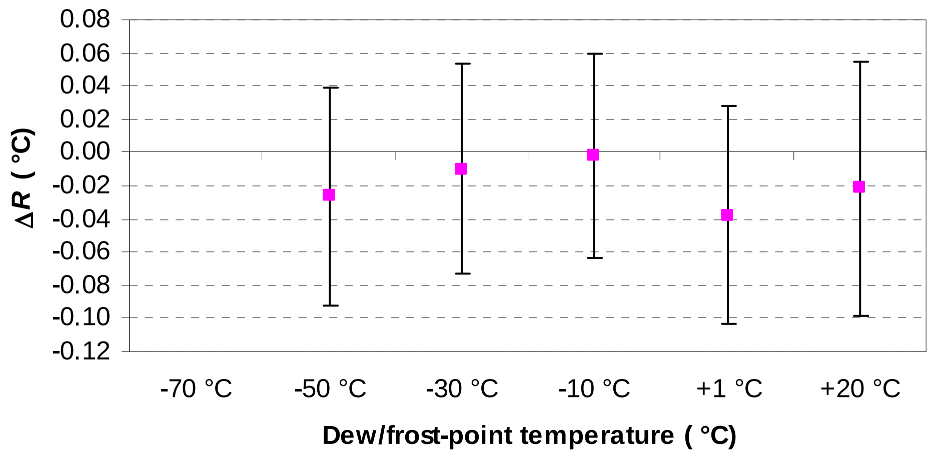

Fig. 6.1 Difference between the LPM results and ERV_{K6} ($\Delta R = R_{LPM} - ERV_{K6}$). Error bars show the expanded uncertainties with k=2.

Table 1 Summary of the analysis of the results. All values are given in degrees Celsius. D = bilateral degrees of equivalence (D) between MIKES and LPM. ΔR = difference between the linked LPM results and the EURAMET.T-K6 comparison reference values. Also, the EURAMET.T-K6 results of MIKES are shown. The expanded uncertainties (U) are given at the approximately 95 % confidence level (k=2).

	MIKES - LPM		*LPM - ERV*K6		*MIKES - ERV*K6		$u(\delta_{rep,lab})$		
t_d	D	$U(D)$	ΔR	$U(\Delta R)$	ΔR	$U(\Delta R)$	MIKES	LPM	$u(\delta_{stab})$
-70	0.005	0.144					0.008	0.020	0.022
-50	0.001	0.094	-0.026	0.099	-0.025	0.032	0.002	0.005	0.018
-30	0.010	0.092	-0.010	0.097	0.000	0.029	0.004	0.001	0.018
-10	-0.003	0.092	-0.002	0.096	-0.005	0.026	0.001	0.002	0.018
1	0.013	0.097	-0.038	0.100	-0.025	0.025	0.005	0.008	0.018
20	0.019	0.128	-0.022	0.131	-0.003	0.026	0.002	0.005	0.018

7. LINKAGE TO CCT-K6

After completion of CCT-K6, the LPM results presented in this report can be linked to the CCT-K6 results through MIKES.

8. CONCLUSION

The comparison reported here is a supplementary comparison providing link between the new LPM dew-point temperature standards in Croatia and the EURAMET.T-K6 comparison reference values. After completing CCT-K6, the results will be globally linked. All presented results show a good agreement between LPM and MIKES. Also the agreement with the EURAMET.T-K6 comparison reference values is good. In all cases, the mean difference is smaller than its expanded uncertainty (k=2).

Although the K6 comparisons were limited to the range -50 °C to +20 °C, the measurement point -70 °C was added into this comparison. The linearity of the transfer standard was not as good as in the other points but worked well enough with respect to the stated uncertainties of the laboratory references. Also at this lowest point, the results show a good agreement between LPM and MIKES..

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APPENDIX 1 MEASUREMENT RESULTS REPORTED BY THE PARTICIPANTS

Estimates

Lab		Hygrometer 1 = 0923 Applied dew point (°C)	Resistance output (ohms)	Output in °C	Difference (meas dp - applied dp) in °C
MIKES1					
MIKES1					
MIKES1					
MIKES1					
LPM	Meas 1	-70.011	72.340	-69.987	0.024
LPM	Meas 2	-70.002	72.357	-69.943	0.059
LPM	Meas 3	-69.997	72.380	-69.887	0.110
LPM	Meas 4	-69.995	72.368	-69.915	0.080
MIKES2	Meas 1	-70.065	72.340	-69.985	0.081
MIKES2	Meas 2	-70.074	72.338	-69.992	0.082
MIKES2	Meas 3	-70.072	72.338	-69.991	0.081
MIKES2	Meas 4	-70.070	72.326	-70.020	0.050

Lab		Hygrometer 1 = 0923 Applied dew point (°C)	Resistance output (ohms)	Output in °C	Difference (meas dp - applied dp) in °C
MIKES1	Meas 1	-50.068	80.241	-50.164	-0.095
MIKES1	Meas 2	-50.061	80.245	-50.154	-0.093
MIKES1	Meas 3	-50.029	80.255	-50.130	-0.101
MIKES1	Meas 4	-50.065	80.242	-50.161	-0.095
LPM	Meas 1	-49.983	80.270	-50.091	-0.108
LPM	Meas 2	-49.977	80.280	-50.065	-0.088
LPM	Meas 3	-49.953	80.286	-50.051	-0.098
LPM	Meas 4	-49.958	80.285	-50.054	-0.096
MIKES2	Meas 1	-49.344	80.526	-49.446	-0.102
MIKES2	Meas 2	-50.050	80.253	-50.134	-0.084
MIKES2	Meas 3	-50.049	80.255	-50.128	-0.079

		Hygrometer 1 = 0923 Applied dew point (°C)	Resistance output (ohms)	Output in °C	Difference (meas dp - applied dp) in °C
MIKES1	Meas 1	-30.441	88.011	-30.533	-0.092
MIKES1	Meas 2	-30.404	88.019	-30.515	-0.111
MIKES1	Meas 3	-30.394	88.027	-30.493	-0.100
MIKES1	Meas 4	-30.367	88.036	-30.470	-0.103
LPM	Meas 1	-29.996	88.178	-30.110	-0.114
LPM	Meas 2	-29.987	88.183	-30.097	-0.110
LPM	Meas 3	-29.972	88.189	-30.083	-0.111
LPM	Meas 4	-29.972	88.189	-30.083	-0.111
MIKES2	Meas 1	-29.981	88.189	-30.083	-0.102
MIKES2	Meas 2				
MIKES2	Meas 3				
MIKES2	Meas 4				

		Hygrometer 1 = 0923			
		Applied dew point (°C)	Resistance output (ohms)	Output in °C	Difference (meas dp - applied dp) in °C
MIKES1	Meas 1	-10.097	96.001	-10.216	-0.119
MIKES1	Meas 2	-10.083	96.006	-10.203	-0.120
MIKES1	Meas 3	-10.074	96.009	-10.197	-0.123
MIKES1	Meas 4	-10.060	96.013	-10.185	-0.125
LPM	Meas 1	-9.997	96.039	-10.119	-0.122
LPM	Meas 2	-10.002	96.040	-10.117	-0.115
LPM	Meas 3	-9.978	96.048	-10.097	-0.119
LPM	Meas 4	-9.967	96.053	-10.085	-0.118
MIKES2	Meas 1	-10.862	95.705	-10.970	-0.109
MIKES2	Meas 2	-10.164	95.978	-10.276	-0.112
MIKES2	Meas 3				
MIKES2	Meas 4				

		Hygrometer 1 = 0923			
		Applied dew point (°C)	Resistance output (ohms)	Output in °C	Difference (meas dp - applied dp) in °C
MIKES1	Meas 1	1.178	100.413	1.056	-0.122
MIKES1	Meas 2	1.181	100.420	1.075	-0.106
MIKES1	Meas 3	1.179	100.421	1.077	-0.103
MIKES1	Meas 4	1.182	100.422	1.081	-0.101
LPM	Meas 1	1.026	100.355	0.908	-0.118
LPM	Meas 2	1.044	100.353	0.904	-0.140
LPM	Meas 3	1.068	100.376	0.961	-0.107
LPM	Meas 4	1.079	100.375	0.960	-0.119
MIKES2	Meas 1	1.156	100.402	1.029	-0.127
MIKES2	Meas 2	1.156	100.403	1.032	-0.124
MIKES2	Meas 3				
MIKES2	Meas 4				

		Hygrometer 1 = 0923			
		Applied dew point (°C)	Resistance output (ohms)	Output in °C	Difference (meas dp - applied dp) in °C
MIKES1	Meas 1	20.118	107.798	20.013	-0.105
MIKES1	Meas 2	20.121	107.801	20.019	-0.102
MIKES1	Meas 3	20.119	107.802	20.023	-0.096
MIKES1	Meas 4	20.119	107.803	20.024	-0.095
LPM	Meas 1	19.895	107.712	19.791	-0.104
LPM	Meas 2	19.973	107.736	19.853	-0.120
LPM	Meas 3	20.087	107.779	19.963	-0.124
LPM	Meas 4	19.968	107.733	19.844	-0.124
MIKES2	Meas 1	20.101	107.791	19.995	-0.107
MIKES2	Meas 2	20.114	107.808	20.038	-0.075
MIKES2	Meas 3				
MIKES2	Meas 4				

Uncertainties

Measurement point: -70 °C

Lab		Hygrometer 1 = 0923			
		std.unc.ref (°C)	std.unc.short-term instab. (°C)	Resol./res. meas.std.unc. (°C)	combined std.unc.
MIKES1	Meas 1				
MIKES1	Meas 2				
MIKES1	Meas 3				
MIKES1	Meas 4				
LPM	Meas 1	0.038	0.007	0.000	0.039
LPM	Meas 2	0.038	0.008	0.000	0.039
LPM	Meas 3	0.038	0.003	0.000	0.038
LPM	Meas 4	0.038	0.007	0.000	0.039
MIKES2	Meas 1	0.050	0.000	0.000	0.050
MIKES2	Meas 2	0.050	0.000	0.000	0.050
MIKES2	Meas 3	0.050	0.000	0.000	0.050
MIKES2	Meas 4	0.050	0.000	0.000	0.050

Measurement point: -50 °C

		Hygrometer 1 = 0923			
		std.unc.ref (°C)	std.unc.short-term instab. (°C)	Resol./res. meas.std.unc. (°C)	combined std.unc.
MIKES1	Meas 1	0.021	0.001	0.000	0.021
MIKES1	Meas 2	0.021	0.001	0.000	0.021
MIKES1	Meas 3	0.021	0.000	0.000	0.021
MIKES1	Meas 4	0.021	0.001	0.000	0.021
LPM	Meas 1	0.037	0.006	0.000	0.037
LPM	Meas 2	0.037	0.006	0.000	0.037
LPM	Meas 3	0.037	0.006	0.000	0.037
LPM	Meas 4	0.037	0.005	0.000	0.037
MIKES2	Meas 1	0.023	0.000	0.000	0.023
MIKES2	Meas 2	0.023	0.001	0.000	0.023
MIKES2	Meas 3	0.024	0.000	0.000	0.024
MIKES2	Meas 4	#ARVO!	--	0.000	#ARVO!

Measurement point: -30 °C

		Hygrometer 1 = 0923			
		std.unc.ref (°C)	std.unc.short-term instab. (°C)	Resol./res. meas.std.unc. (°C)	combined std.unc.
MIKES1	Meas 1	0.021	0.002	0.000	0.021
MIKES1	Meas 2	0.021	0.003	0.000	0.021
MIKES1	Meas 3	0.021	0.000	0.000	0.021
MIKES1	Meas 4	0.021	0.000	0.000	0.021
LPM	Meas 1	0.036	0.003	0.000	0.036
LPM	Meas 2	0.036	0.004	0.000	0.036
LPM	Meas 3	0.036	0.004	0.000	0.036
LPM	Meas 4	0.036	0.003	0.000	0.036
MIKES2	Meas 1	0.021	0.000	0.000	0.021
MIKES2	Meas 2				
MIKES2	Meas 3				
MIKES2	Meas 4				

Measurement point: -10 °C

		Hygrometer 1 = 0923			
		std.unc.ref (°C)	std.unc.short-term instab. (°C)	Resol./res. meas.std.unc. (°C)	combined std.unc.
MIKES1	Meas 1	0.021	0.001	0.000	0.021
MIKES1	Meas 2	0.021	0.001	0.000	0.021
MIKES1	Meas 3	0.021	0.000	0.000	0.021
MIKES1	Meas 4	0.021	0.000	0.000	0.021
LPM	Meas 1	0.037	0.004	0.000	0.037
LPM	Meas 2	0.037	0.002	0.000	0.037
LPM	Meas 3	0.037	0.002	0.000	0.037
LPM	Meas 4	0.037	0.003	0.000	0.037
MIKES2	Meas 1	0.022	0.001	0.000	0.022
MIKES2	Meas 2	0.021	0.000	0.000	0.021
MIKES2	Meas 3				
MIKES2	Meas 4				

Measurement point: +1 °C

		Hygrometer 1 = 0923			
		std.unc.ref (°C)	std.unc.short-term instab. (°C)	Resol./res. meas.std.unc. (°C)	combined std.unc.
MIKES1	Meas 1	0.021	0.000	0.000	0.021
MIKES1	Meas 2	0.021	0.001	0.000	0.021
MIKES1	Meas 3	0.021	0.001	0.000	0.021
MIKES1	Meas 4	0.021	0.000	0.000	0.021
LPM	Meas 1	0.038	0.002	0.000	0.038
LPM	Meas 2	0.038	0.002	0.000	0.038
LPM	Meas 3	0.038	0.002	0.000	0.038
LPM	Meas 4	0.038	0.004	0.000	0.038
MIKES2	Meas 1	0.021	0.000	0.000	0.021
MIKES2	Meas 2	0.021	0.000	0.000	0.021
MIKES2	Meas 3				
MIKES2	Meas 4				

Measurement point: +20 °C

		Hygrometer 1 = 0923			
		std.unc.ref (°C)	std.unc.short-term instab. (°C)	Resol./res. meas.std.unc. (°C)	combined std.unc.
MIKES1	Meas 1	0.021	0.000	0.000	0.021
MIKES1	Meas 2	0.021	0.000	0.000	0.021
MIKES1	Meas 3	0.021	0.000	0.000	0.021
MIKES1	Meas 4	0.021	0.000	0.000	0.021
LPM	Meas 1	0.057	0.003	0.000	0.058
LPM	Meas 2	0.057	0.002	0.000	0.058
LPM	Meas 3	0.057	0.001	0.000	0.057
LPM	Meas 4	0.057	0.002	0.000	0.058
MIKES2	Meas 1	0.021	0.000	0.000	0.021
MIKES2	Meas 2	0.021	0.000	0.000	0.021
MIKES2	Meas 3				
MIKES2	Meas 4				

APPENDIX 2 UNCERTAINTY BUDGETS FOR THE REFERENCE DEW-POINT TEMPERATURE VALUES AS REPORTED BY THE PARTICIPANTS

Laboratory: LPM

Uncertainty analysis of dew-point temperature		Nominal value:	-70 °C	Lab name	LPM
Bilateral comparison between MIKES and LPM					
Quantity (symbol) Q_i	**Components**	**Standard uncertainty** $u_{(Qi)}$	**Degrees of freedom components evaluated by a type A method *** ν_i	**Sensitivity coefficient**	**Uncertainty contribution** u_i **in °C**
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.015		1	0.015
	Long-term stability (sensor and indicator)	0.006		1	0.006
	Self-heating and residual heat fluxes (sensor)	0.006		1	0.006
	Resolution and accuracy or linearity (indicator unit)	0.001		1	0.001
	Saturator:				
	Temperature homogeneity	0.022		1	0.022
	Temperature stability	0.008		1	0.008
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.007	0.00042
	Long-term stability (sensor and indicator)	0.05		0.007	0.00035
	Resolution and accuracy or linearity (indicator unit)	0.08		0.007	0.00056
	Pressure differences in the saturator cell	0.10		0.007	0.00070
	Stability of the pressure	0.22		0.007	0.00154
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.007	0.0035
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.007	0.00042
	Long-term stability (sensor and indicator)	0.05		0.007	0.00035
	Resolution (indicator unit)	0.08		0.007	0.00056
	Stability of the pressure	0.22		0.007	0.00154
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.007	0.00350
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.022		1	0.022
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	Saturation vapour pressure formula(e)				
	Water vapour enhancement formula(e)				
Other uncertainties					
	Pressure drop between MBW head and measuring instrument	0.28		0.007	0.002
Combined uncertainty					0.037
Effective degrees of freedom					
Expanded uncertainty					0.074

Uncertainty analysis of dew-point temperature

Nominal value: -50 °C | Lab name: LPM

Bilateral comparison between MIKES and LPM

Quantity (symbol) Q_i	Components	Standard uncertainty $u_{(Qi)}$	Degrees of freedom components evaluated by a type A method * ν_i	Sensitivity coefficient	Uncertainty contribution u_i in °C
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.015		1	0.015
	Long-term stability (sensor and indicator)	0.006		1	0.006
	Self-heating and residual heat fluxes (sensor)	0.006		1	0.006
	Resolution and accuracy or linearity (indicator unit)	0.001		1	0.001
	Saturator:				
	Temperature homogeneity	0.020		1	0.020
	Temperature stability	0.006		1	0.006
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.008	0.00048
	Long-term stability (sensor and indicator)	0.05		0.008	0.00040
	Resolution and accuracy or linearity (indicator unit)	0.08		0.008	0.00064
	Pressure differences in the saturator cell	0.10		0.008	0.00080
	Stability of the pressure	0.21		0.008	0.00168
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.008	0.00400
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.008	0.00048
	Long-term stability (sensor and indicator)	0.05		0.008	0.00040
	Resolution (indicator unit)	0.08		0.008	0.00064
	Stability of the pressure	0.22		0.008	0.00176
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.008	0.00400
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.022		1	0.022
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	Saturation vapour pressure formula(e)				
	Water vapour enhancement formula(e)				
Other uncertainties					
	Pressure drop between MBW head and measuring instrument	0.28		0.008	0.002
Combined uncertainty					0.035
Effective degrees of freedom					
Expanded uncertainty					0.071

Uncertainty analysis of dew-point temperature		Nominal value:	-30 °C	Lab name	LPM
Bilateral comparison between MIKES and LPM					
Quantity (symbol) Q_i	**Components**	**Standard uncertainty** $u_{(Qi)}$	**Degrees of freedom components evaluated by a type A method *** ν_i	**Sensitivity coefficient**	**Uncertainty contribution** u_i **in °C**
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.015		1	0.015
	Long-term stability (sensor and indicator)	0.006		1	0.006
	Self-heating and residual heat fluxes (sensor)	0.006		1	0.006
	Resolution and accuracy or linearity (indicator unit)	0.001		1	0.001
	Saturator:				
	Temperature homogeneity	0.018		1	0.018
	Temperature stability	0.004		1	0.004
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.009	0.00054
	Long-term stability (sensor and indicator)	0.05		0.009	0.00045
	Resolution and accuracy or linearity (indicator unit)	0.08		0.009	0.00072
	Pressure differences in the saturator cell	0.10		0.009	0.00090
	Stability of the pressure	0.25		0.009	0.00225
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.009	0.00450
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.009	0.00054
	Long-term stability (sensor and indicator)	0.05		0.009	0.00045
	Resolution (indicator unit)	0.08		0.009	0.00072
	Stability of the pressure	0.24		0.009	0.00216
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.009	0.0045
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.022		1	0.022
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	Saturation vapour pressure formula(e)				
	Water vapour enhancement formula(e)				
Other uncertainties					
	Pressure drop between MBW head and measuring instrument	0.28		0.009	0.003
Combined uncertainty					0.034
Effective degrees of freedom					
Expanded uncertainty					0.069

Uncertainty analysis of dew-point temperature

Nominal value: -10 °C | Lab name: LPM

Bilateral comparison between MIKES and LPM

Quantity (symbol) Q_i	Components	Standard uncertainty $u_{(Qi)}$	Degrees of freedom components evaluated by a type A method * ν_i	Sensitivity coefficient	Uncertainty contribution u_i in °C
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.015		1	0.015
	Long-term stability (sensor and indicator)	0.006		1	0.006
	Self-heating and residual heat fluxes (sensor)	0.006		1	0.006
	Resolution and accuracy or linearity (indicator unit)	0.001		1	0.001
	Saturator:				
	Temperature homogeneity	0.016		1	0.016
	Temperature stability	0.006		1	0.006
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.011	0.001
	Long-term stability (sensor and indicator)	0.05		0.011	0.001
	Resolution and accuracy or linearity (indicator unit)	0.08		0.011	0.001
	Pressure differences in the saturator cell	0.10		0.011	0.001
	Stability of the pressure	0.29		0.011	0.003
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.011	0.006
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.011	0.001
	Long-term stability (sensor and indicator)	0.05		0.011	0.001
	Resolution (indicator unit)	0.08		0.011	0.001
	Stability of the pressure	0.31		0.011	0.003
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.011	0.006
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.022		1	0.022
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	Saturation vapour pressure formula(e)				
	Water vapour enhancement formula(e)				
Other uncertainties					
	Pressure drop between MBW head and measuring instrument	0.19		0.011	0.002
Combined uncertainty					0.034
Effective degrees of freedom					
Expanded uncertainty					0.068

Uncertainty analysis of dew-point temperature

Nominal value: +1 °C   Lab name: LPM

Bilateral comparison between MIKES and LPM

Quantity (symbol) Qi	Components	Standard uncertainty $u_{(Qi)}$	Degrees of freedom components evaluated by a type A method * ν_i	Sensitivity coefficient	Uncertainty contribution u_i in °C
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.015		1	0.015
	Long-term stability (sensor and indicator)	0.006		1	0.006
	Self-heating and residual heat fluxes (sensor)	0.006		1	0.006
	Resolution and accuracy or linearity (indicator unit)	0.001		1	0.001
	Saturator:				
	Temperature homogeneity	0.014		1	0.014
	Temperature stability	0.006		1	0.006
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.014	0.001
	Long-term stability (sensor and indicator)	0.05		0.014	0.001
	Resolution and accuracy or linearity (indicator unit)	0.08		0.014	0.001
	Pressure differences in the saturator cell	0.10		0.014	0.001
	Stability of the pressure	0.30		0.014	0.004
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.014	0.007
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.014	0.001
	Long-term stability (sensor and indicator)	0.05		0.014	0.001
	Resolution (indicator unit)	0.08		0.014	0.001
	Stability of the pressure	0.29		0.014	0.004
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.014	0.007
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.022		1	0.022
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	Saturation vapour pressure formula(e)				
	Water vapour enhancement formula(e)				
Other uncertainties					
	Pressure drop between MBW head and measuring instrument	0.25		0.014	0.004
Combined uncertainty					0.034
Effective degrees of freedom					
Expanded uncertainty					0.068

Uncertainty analysis of dew-point temperature

Nominal value: +20 °C | Lab name: LPM

Bilateral comparison between MIKES and LPM

Quantity (symbol) Qi	Components	Standard uncertainty $u_{(Qi)}$	Degrees of freedom components evaluated by a type A method * ν_i	Sensitivity coefficient	Uncertainty contribution u_i in °C
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.015		1	0.015
	Long-term stability (sensor and indicator)	0.006		1	0.006
	Self-heating and residual heat fluxes (sensor)	0.006		1	0.006
	Resolution and accuracy or linearity (indicator unit)	0.001		1	0.001
	Saturator:				
	Temperature homogeneity	0.020		1	0.020
	Temperature stability	0.007		1	0.007
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.016	0.001
	Long-term stability (sensor and indicator)	0.05		0.016	0.001
	Resolution and accuracy or linearity (indicator unit)	0.08		0.016	0.001
	Pressure differences in the saturator cell	0.10		0.016	0.002
	Stability of the pressure	0.07		0.016	0.001
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.016	0.008
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	0.06		0.016	0.001
	Long-term stability (sensor and indicator)	0.05		0.016	0.001
	Resolution (indicator unit)	0.08		0.016	0.001
	Stability of the pressure	0.07		0.016	0.001
	Effect of the tubing between the saturator and the pressure gauge	0.50		0.016	0.008
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.045		1	0.045
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	Saturation vapour pressure formula(e)				
	Water vapour enhancement formula(e)				
Other uncertainties					
	Pressure drop between MBW head and measuring instrument	0.22		0.016	0.004
Combined uncertainty					0.054
Effective degrees of freedom					
Expanded uncertainty					0.108

Laboratory: MIKES

Uncertainty analysis of dew-point temperature		Nominal value:	-70 °C	Lab name	MIKES
Bilateral comparison between MIKES and LPM					
Quantity (symbol)	**Components**	**Standard uncertainty**	**Degrees of freedom components evaluated by a type A method ***	**Sensitivity coefficient**	**Uncertainty contribution**
Q_i		**$u_{(Qi)}$**	**ν_i**		**u_i in °C**
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.01309819		1	0.0131
	Long-term stability (sensor and indicator)				
	Self-heating and residual heat fluxes (sensor)	0.00100		1	0.0010
	Resolution and accuracy or linearity (indicator unit)	0.0002		1	0.0002
	Saturator:				
	Temperature homogeneity	0.0024		1	0.0024
	Temperature stability	0.00038		1	0.0004
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.000655	0.0013
	Long-term stability (sensor and indicator)	1.155		0.000655	0.0008
	Resolution and accuracy or linearity (indicator unit)	1		0.00131	0.0013
	Pressure differences in the saturator cell	17		0.000655	0.0111
	Stability of the pressure	2		0.00131	0.0026
	Effect of the tubing between the saturator and the pressure gauge	28		0.000655	0.0183
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.0000655	0.0001
	Long-term stability (sensor and indicator)	1.15470054		0.0000655	0.0001
	Resolution (indicator unit)	1		0.000131	0.0001
	Stability of the pressure	2		0.000131	0.0003
	Effect of the tubing between the saturator and the pressure gauge	28		0.0000655	0.0018
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.017		1	0.0170
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	incl. saturation vapour pressure and enhancement factor formula(e)	0.008		1	0.0080
Other uncertainties					
	effect of tubing etc.	0.038		1	0.0375
Combined uncertainty					0.0491
Effective degrees of freedom					
Expanded uncertainty					0.10

Uncertainty analysis of dew-point temperature

Nominal value: -50 °C | Lab name: MIKES

Bilateral comparison between MIKES and LPM

Quantity (symbol) Qi	Components	Standard uncertainty $u_{(Qi)}$	Degrees of freedom components evaluated by a type A method * ν_i	Sensitivity coefficient	Uncertainty contribution u_i in °C
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.0083769		1	0.0084
	Long-term stability included in calibr. unc.				
	Self-heating and residual heat fluxes (sensor)	0.00100		1	0.0010
	Resolution and accuracy or linearity (indicator unit)	0.0002		1	0.0002
	Saturator:				
	Temperature homogeneity	0.0024		1	0.0024
	Temperature stability	0.00018		1	0.0002
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.0000754	0.0002
	Long-term stability (sensor and indicator)	1.155		0.0000754	0.0001
	Resolution and accuracy or linearity (indicator unit)	1		0.000151	0.0002
	Pressure differences in the saturator cell	17		0.0000754	0.0013
	Stability of the pressure	2		0.000151	0.0003
	Effect of the tubing between the saturator and the pressure gauge	15		0.0000754	0.0011
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.0000754	0.0002
	Long-term stability (sensor and indicator)	1.15470054		0.0000754	0.0001
	Resolution (indicator unit)	1		0.000151	0.0002
	Stability of the pressure	2		0.000151	0.0003
	Effect of the tubing between the saturator and the pressure gauge	15		0.0000754	0.0011
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.017		1	0.0170
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	incl. saturation vapour pressure and enhancement factor formula(e)	0.008		1	0.0080
Other uncertainties					
Combined uncertainty					0.0208
Effective degrees of freedom					
Expanded uncertainty					0.04

Uncertainty analysis of dew-point temperature

Nominal value: -30 °C | Lab name: MIKES

Bilateral comparison between MIKES and LPM

Quantity (symbol) Q_i	Components	Standard uncertainty $u_{(Qi)}$	Degrees of freedom components evaluated by a type A method * ν_i	Sensitivity coefficient	Uncertainty contribution u_i in °C
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.0083769		1	0.0084
	Long-term stability included in calibr. unc.				
	Self-heating and residual heat fluxes (sensor)	0.00100		1	0.0010
	Resolution and accuracy or linearity (indicator unit)	0.0002		1	0.0002
	Saturator:				
	Temperature homogeneity	0.0024		1	0.0024
	Temperature stability	0.0002		1	0.0002
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.000093	0.0002
	Long-term stability (sensor and indicator)	1.155		0.000093	0.0001
	Resolution and accuracy or linearity (indicator unit)	1		0.000186	0.0002
	Pressure differences in the saturator cell	17		0.000093	0.0016
	Stability of the pressure	2		0.000186	0.0004
	Effect of the tubing between the saturator and the pressure gauge	15		0.000093	0.0014
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.000093	0.0002
	Long-term stability (sensor and indicator)	1.15470054		0.000093	0.0001
	Resolution (indicator unit)	1		0.000186	0.0002
	Stability of the pressure	2		0.000186	0.0004
	Effect of the tubing between the saturator and the pressure gauge	15		0.000093	0.0014
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.017		1	0.0170
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	incl. saturation vapour pressure and enhancement factor formula(e)	0.008		1	0.0080
Other uncertainties					
Combined uncertainty					0.0209
Effective degrees of freedom					
Expanded uncertainty					0.04

Uncertainty analysis of dew-point temperature		Nominal value:	-10 °C	Lab name	MIKES
Bilateral comparison between MIKES and LPM					
Quantity (symbol)	**Components**	**Standard uncertainty**	**Degrees of freedom components evaluated by a type A method ***	**Sensitivity coefficient**	**Uncertainty contribution**
Q_i		**$u_{(Qi)}$**	**ν_i**		**u_i in °C**
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.0083769		1	0.0084
	Long-term stability included in calibr. unc.				
	Self-heating and residual heat fluxes (sensor)	0.00100		1	0.0010
	Resolution and accuracy or linearity (indicator unit)	0.0002		1	0.0002
	Saturator:				
	Temperature homogeneity	0.0011		1	0.0011
	Temperature stability	0.0002		1	0.0002
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.000104915	0.0002
	Long-term stability (sensor and indicator)	1.155		0.000104915	0.0001
	Resolution and accuracy or linearity (indicator unit)	1		0.00020983	0.0002
	Pressure differences in the saturator cell	17		0.000104915	0.0018
	Stability of the pressure	2		0.00020983	0.0004
	Effect of the tubing between the saturator and the pressure gauge	15		0.000104915	0.0016
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.000104915	0.0002
	Long-term stability (sensor and indicator)	1.15470054		0.000104915	0.0001
	Resolution (indicator unit)	1		0.00020983	0.0002
	Stability of the pressure	2		0.00020983	0.0004
	Effect of the tubing between the saturator and the pressure gauge	15		0.000104915	0.0016
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.017		1	0.0170
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	incl. saturation vapour pressure and enhancement factor formula(e)	0.008		1	0.0080
Other uncertainties					
Combined uncertainty					0.0208
Effective degrees of freedom					
Expanded uncertainty					0.04

Uncertainty analysis of dew-point temperature

Nominal value: +1 °C | Lab name: MIKES

Bilateral comparison between MIKES and LPM

Quantity (symbol) Q_i	Components	Standard uncertainty $u_{(Qi)}$	Degrees of freedom components evaluated by a type A method * ν_i	Sensitivity coefficient	Uncertainty contribution u_i in °C
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.00371231		1	0.0037
	Long-term stability included in calibr. unc.				
	Self-heating and residual heat fluxes (sensor)	0.00100		1	0.0010
	Resolution and accuracy or linearity (indicator unit)	0.0002		1	0.0002
	Saturator:				
	Temperature homogeneity	0.0001		1	0.0001
	Temperature stability	0.0002		1	0.0002
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.000104915	0.0002
	Long-term stability (sensor and indicator)	1.155		0.000104915	0.0001
	Resolution and accuracy or linearity (indicator unit)	1		0.00020983	0.0002
	Pressure differences in the saturator cell	17		0.000104915	0.0018
	Stability of the pressure	2		0.00020983	0.0004
	Effect of the tubing between the saturator and the pressure gauge	22		0.000104915	0.0023
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.000104915	0.0002
	Long-term stability (sensor and indicator)	1.15470054		0.000104915	0.0001
	Resolution (indicator unit)	1		0.00020983	0.0002
	Stability of the pressure	2		0.00020983	0.0004
	Effect of the tubing between the saturator and the pressure gauge	22		0.000104915	0.0023
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.017		1	0.0170
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	incl. saturation vapour pressure and enhancement factor formula(e)	0.008		1	0.0080
Other uncertainties					
Combined uncertainty					0.0196
Effective degrees of freedom					
Expanded uncertainty					0.04

Uncertainty analysis of dew-point temperature		Nominal value:	+20 °C	Lab name	MIKES
Bilateral comparison between MIKES and LPM					
Quantity (symbol)	**Components**	**Standard uncertainty**	**Degrees of freedom components evaluated by a type A method ***	**Sensitivity coefficient**	**Uncertainty contribution**
Q_i		$u_{(Qi)}$	ν_i		u_i in °C
Primary dew-point generator					
Saturation temperature					
	Thermometer:				
	Calibration uncertainty (sensor and indicator unit)	0.00371231		1	0.0037
	Long-term stability included in calibr. unc.				
	Self-heating and residual heat fluxes (sensor)	0.00100		1	0.0010
	Resolution and accuracy or linearity (indicator unit)	0.0002		1	0.0002
	Saturator:				
	Temperature homogeneity	0.0001		1	0.0001
	Temperature stability	0.0002		1	0.0002
Saturation pressure					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.000153527	0.0003
	Long-term stability (sensor and indicator)	1.155		0.000153527	0.0002
	Resolution and accuracy or linearity (indicator unit)	1		0.000307054	0.0003
	Pressure differences in the saturator cell	17		0.000153527	0.0026
	Stability of the pressure	2		0.000307054	0.0006
	Effect of the tubing between the saturator and the pressure gauge	28		0.000153527	0.0043
Gas pressure at the generator outlet:					
	Pressure gauge:				
	Calibration uncertainty (sensor and indicator unit)	2		0.000153527	0.0003
	Long-term stability (sensor and indicator)	1.15470054		0.000153527	0.0002
	Resolution (indicator unit)	1		0.000307054	0.0003
	Stability of the pressure	2		0.000307054	0.0006
	Effect of the tubing between the saturator and the pressure gauge	30		0.000153527	0.0046
Flow measurement:					
	Flow meter				
	Stability of the flow				
	Reproducibility				
Saturation efficiency					
	Saturation efficiency	0.017		1	0.0170
Correlation between pressure and temperature measurement (if relevant)					
	Correlation between pressure and temperature measurement if relevant				
Uncertainty due to formulae/calculations					
	incl. saturation vapour pressure and enhancement factor formula(e)	0.008		1	0.0080
Other uncertainties					
Combined uncertainty					0.0204
Effective degrees of freedom					
Expanded uncertainty					0.04

APPENDIX 3: TECHNICAL PROTOCOL

Comparison of dew-point temperature scales at LPM and MIKES

Dew/Frost-Point Temperature -70 °C to +20 °C

Contents

1. INTRODUCTION

1.1 MIKES coordinated the EURAMET.T-S16 and EURAMET.T-K6 comparisons in 1999 to 2001 and in 2003 to 2008, respectively. MIKES also participates in the CCT-K6 comparison. LPM participated in the EUROMET.T-K6 comparison with an old dew-point calibration system. Since then, LPM has introduced two new generators for the ranges -70 °C to +5 °C and +1 °C to +60 °C. Because the uncertainty estimated for the dew-point temperature realisation is significantly better than for the old system, a bilateral comparison between MIKES and LPM was initiated in January 2009.

1.2 This comparison is carried out as a part of the EUROMET Project no. 912.

1.3 The procedures outlined in this document are similar to those followed in the EURAMET.T-K6. Due to much simpler comparison scheme, however, only one instrument is used as the transfer standard. Also, the measurement range was extended by including the point -70 °C in the measurement scheme.

1.4 This technical protocol has been drawn up by the pilot in consultation with the participant.

1.5 This comparison is aimed at establishing the degree of equivalence between realisations of local scales of dew/frost-point temperature of humid gas, in the range -70 °C to +20 °C, among the participating national metrology institutes.

2. ORGANIZATION

2.1 Participants

2.1.1 A list of participants representing is in table 1. Details of mailing and electronic addresses are given in Appendix 1.

2.1.2 MIKES provides the link to the EURAMET.T-K6 and to the CCT K6.

2.1.3 MIKES is the Coordinator of the this comparison.

2.1.4 Once the protocol and list of participants have been approved, no change to the protocol or list of participants may be made without prior agreement of all participants.

2.1.5 LPM will submit the uncertainty budget of the humidity standards used in this project to the coordinator.

Table 1 List of participants (*C*=Coordinator, *P*=Pilot)

Centre for Metrology and Accreditation (MIKES)	Finland	*C,P*
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Laboratory for Process Measurements (LPM)	Croatia	

2.2 Method of comparison

2.2.1 The key comparison is a comparison of the realisations of local scales of dew/frost-point temperature at the participating national institutes.

2.2.2 The comparison will be carried out by calibration of a transfer standard manufactured by the MBW Calibration Ltd (Switzerland) and owned by LPM.

2.2.3 Measurements will start in the pilot laboratory. The participant will then perform comparison measurements at the dew/frost-point temperatures required. The transfer standard is returned to the pilot of the loop to carry out final measurements to monitor drift.

2.2.5 All results are to be communicated directly to the Pilot of the corresponding loop within six weeks of the completion of the measurements by a laboratory.

2.3 Handling of artefacts

2.3.1 The artefact should be examined immediately upon receipt at the laboratory. All participants are expected to follow all instructions in the operator's manual provided by the instrument manufacturers for proper unpacking, subsequent packing and shipping to the next participant. During packing and unpacking, all participants should check the contents with the packing list including the operator's manual.

2.3.2 The transfer standard should only be handled by authorized persons and stored in such a way as to prevent damage.

2.3.3 During operation of the transfer standard, if there is any unusual occurrence, e.g., loss of heating or cooling control, the Pilot laboratory should be notified immediately before proceeding.

2.4 Transport of artefact

2.4.1 The transportation process begins when the artefact leaves the sending laboratory and does not end until it reaches the destination laboratory. All participants should follow the following general guidelines:

(1) Plan the shipment well in advance. The recipient should be aware of any customs issues in their country that would delay the testing schedule. The shipping laboratory must be aware of any national regulations covering the travelling standard to be exported;

(2) Mark the shipping container "FRAGILE SCIENTIFIC INSTRUMENTS" “TO BE OPENED ONLY BY LABORATORY STAFF” and with arrows showing "THIS WAY UP"; attach tip and shock indicators if such devices are available;

(3) Determine the best way to ship the travelling standard to the next participant;

(4) Obtain the recipient's exact shipping address. If possible, have it shipped directly to the laboratory;

(5) Coordinate the shipping schedule with the recipient. The sending laboratory should provide the recipient with the carrier, the exact travel mode, and the estimated time of arrival;

(6) Instruct the recipient to confirm receipt and condition upon arrival to the sender by e-mail.

2.4.2 The travelling standard is supplied with its shipping container, which is sufficiently robust to ensure safe transportation.

2.4.3 The artefact will be accompanied by a suitable customs ATA Carnet and documentation uniquely identifying the item.

2.5. Timetable

Activity	Start Month	Provisional date
Technical protocol prepared by MIKES		January 2009
Measurements at MIKES	Month 1	March to April 2009
Measurements at LPM	Month 2-3	April - May 2009
Final measurements at MIKES	Month 3	May 2009
Draft A ready	Month 4	June 2009
Draft B ready and submitted to THERM TC and CCT	Month 7	September

3. DESCRIPTION OF THE TRANSFER STANDARDS

3.1. Artefact

3.1.1 The transfer standard is state-of-the-art, commercially available chilled-mirror type of dew-point hygrometer. It is owned by LPM. It was used as one of the six transfer standards in the EUROMET.T-K6 comparison.

3.1.2 Details of transfer standards:
All the transfer standards are new and of the same type:

Model:	MBW 373 L
Size (in packing case):	75 x 69 x 41 cm
Weight (in packing case):	45 kg
Manufacturer:	MBW Calibration Ltd
Owner:	MBW Calibration Ltd
Electrical supply:	230 V / 50 Hz
Electrical connection:	Instrument socket IEC/EN 60320-2-2 (socket C14/plug C13) The instrument will be supolied with a Schuko (Continenetal Europe) plug Standard CEE 7/VII will be supplied)
Power:	300 W
Tube connectors:	VCR Cajon ® ¼”
Accessories:	Endoscope, 4-wire cable for resistance measurements (3 m)
Serial numbers	03-0923

4. MEASUREMENT INSTRUCTIONS

4.1 Measurement process

4.1.1 All participants should refer to the operating manuals for instructions and precautions for using the transfer standard. Participants may perform any initial checks of the operation of the hygrometer that would be performed for a normal calibration. In the case of an unexpected instrument failure at a participant institute, the pilot institute should be informed in order to revise the time schedule, if necessary, as early as possible.

4.1.2 Sample gas generated by a participant's standard generator, is introduced into the inlet of a transfer standard hygrometer through a stainless steel tube terminating with a ¼ inch VCR fitting. For dew points near ambient temperature (e.g. +20 °C) normal precautions (heating) should be used to protect against condensation in sample lines

4.1.3 Measurements are carried out at nominal dew-point temperatures of +20 °C and +1 °C and nominal frost-point temperatures of –10 °C, -30 °C, –50 °C and -70 °C. The value of +1 °C nominally represents 0 °C, while avoiding any complication due to phase change between water and ice.

4.1.4 In the range below 0 °C, a homogenous ice layer should cover the mirror and participants should report the applied condition in terms of frost-point temperature. The phase of condensate apparent on the mirrors of the transfer standards should also be reported.

4.1.5 Measurements should be done in rising order of dew/frost-point temperature.

4.1.6 Four repeated full set of measurements are carried out, i.e. each nominal dew/frost-point temperature should be separately repeated (reproduced) four times to reduce the effect of any irreproducibility of the transfer standards.

4.1.7 If the scope of a laboratory does not cover the whole range of this comparison, the laboratory is allowed to limit measurements to the nominal dew/frost-point temperatures that are within the scope.

4.1.8 The condensate should be cleared and re-formed for each value or repetition of dew/frost-point temperature.

4.1.9 The values of dew/frost-point temperature applied to the transfer standards should be within ±0.5 °C of the six agreed nominal values for the comparison, and ideally closer than this. Deviations greater than this may increase the uncertainty in the comparison, for a particular result.

4.1.10 Operation with the transfer standards

Before any humidity measurements, initial actions should be taken:

1) Read the manual “Operating Instructions” delivered by the manufacturer (a copy of the instruction is in the transport case).

2) The pressure indication of the hygrometer is checked with a pressure gauge of the laboratory at two static pressure levels (no gas flow through the instrument): the ambient pressure and a pressure corresponding the sample gas pressure during dew/frost-point measurements.

3) The flow rate indication of the hygrometer is checked with a flow meter of the laboratory at 0.5 l/min according to the indication (at a pressure corresponding the sample gas pressure during dew/frost-point measurements)

4) When the hygrometer is in a standby mode (i.e. mirror temperature control and pre-cooler temperature control are switched off), the dew/frost-point temperature indication, resistance of a PRT embedded in the mirror and dew/frost-point temperature reading from the RS-232 port are recorded during ten minutes (at least ten measurements).

5) Check that ORIS is switched off (Menu Keys: “Control Setup” → “Dew/Frost Control”: the square beside ”Enable ORIS Below” should **not** be green)

6) Check that Force Frost function is switched on with a set point of -5 °C(Menu Keys: → “Control Setup” → “Dew/Frost Control”: the square beside ”Force Frost Below” should be green and the value “–5”)

7) Set the hygrometer ready for cleaning with “Mirror Cleaning”.

8) Remove the endoscope following carefully with separate instructions (a copy of the instruction is in the transport case).

9) Open the measuring head following carefully with separate instructions (a copy of the instruction is in the transport case).

10) Clean the mirror surface using cotton tips with distilled or de-ionised water preceded by initial cleaning with alcohol if necessary.

11) Close the measuring head following carefully with separate instructions (a copy of the instruction is in the transport case).

12) Replace the endoscope following carefully with separate instructions (a copy of the instruction is in the transport case).

<u>Dew/frost-point temperature measurements:</u>

1) Clean the mirror if needed according to the instructions above.

2) Set the indicated flow rate of sample gas at 0.5 l/min.

3) Set the pre-cooler control to Delta Mode with the target value 20 °C (Menu Keys: “Control Setup” → “Pre Cooler”→”Delta Mode Target”)

4) Start measurements with “Dew/Frost Control” and “PreCooler” keys at the bottom bar (Fixed Function Keys)

5) A homogenous condensate should appear on the mirror; if not, the condensate should be cleared and re-formed with “Mirror Check” (Fixed Function Keys). If necessary, the mirror is cleaned according to the instructions above.

6) After reaching a stable reading, set the pre-cooler control to Fixed Mode with the target value 20 °C **above** the nominal dew/frost-point temperature (Menu Keys: “Control Setup” → “Pre Cooler”→”Fixed Mode Target”)

7) After appropriate time of stabilisation, measurements are carried out collecting data described below (chapter 4.2).

8) Before changing the sample gas dew/frost-point temperature, the pre-cooler control of the hygrometer is set to Delta Mode (see instructions above).

9) Before measuring at the next measurement point, the condensate should be cleared and re-formed with “Mirror Check” or “Mirror Cleaning” (Fixed Function Keys)

4.1.11 Participants should avoid lengthy additional measurements, except those necessary to give confidence in the results of this comparison.

4.1.12 The transfer standards used in this comparison must not be modified, adjusted, or used for any purpose other than described in this document, nor given to any party other than the participants in the comparison.

4.1.13 The Pilot will make an assessment of any drift in the transfer standards during the comparison, based on measurements at the Pilot laboratory at the beginning and end of the comparison period. If drift is found, this will be taken into account in the final analysis of the comparison results.

4.1.14 If poor performance or failure of a transfer standard is detected, the Pilot of the loop will propose a course of action, subject to agreement of the participants.

4.2. Data collection

4.2.1 In the transfer standards, there are two 100-ohm platinum resistance thermometers (PRT) embedded beneath the surface of the chilled-mirror to measure the dew/frost-point temperature. One is used for system measurement and control. The resistance of the other one is measured via a Lemo connector in the rear panel. Dew/frost-point temperature readings used primarily in this comparison are obtained from the resistance of the second PRT. The current input to the PRT should be nominally 1 mA. The resistance of the PRT should be measured using a calibrated multi-meter or a resistance bridge, and then converted to a corresponding dew/frost-point temperature using the reference function of IEC 60751 as shown in Appendix 3. This reference function should be used to convert resistance to (arbitrary nominal) temperature.

4.2.2 Each measured value (incl. its experimental standard uncertainty) is obtained calculating the mean and standard deviation of at least 10 readings of the resistance of the PRT recorded during 10 to 20 minutes.

4.2.3 Participants may apply their own criteria of stability for acceptance of measurements.

4.2.4 As a supporting measurement, the digital display readings (and/or digital signal through a serial port in the rear panel) for dew/frost-point temperature, head temperature, pre-cooler temperature, flow rate and head pressure in the transfer standards should be monitored. The mean and standard deviation a set of at least 10 readings, taken over the same period as the frost point measurements should be reported.

4.2.4 Values reported for dew/frost-point temperatures produced by a participant's standard generator should be the value applied to the instruments, after any allowances for pressure and temperature differences between the point of realisation (laboratory standard generator or reference hygrometer) and the point of use (transfer standards).

4.2.5 The data reported for the pair of instruments should be for simultaneous or near-simultaneous measurement of the same applied condition.

5. REPORTING OF MEASUREMENT RESULTS

5.1 Participants must report their measurement results of four repeated experiments, within six weeks of completing their measurements.

5.2 The parameter to be compared between the laboratories in this comparison is the difference found between the transfer standards and the laboratory dew-point temperature standard. Note that the values of dew-point temperature reported are “arbitrary” values calculated from the measured resistance output. The transfer standards are used simply as comparators.

5.4 Participants should report results to the pilot in terms of dew/frost-point temperature. The main measurement results comprise:

- values of dew/frost-point applied to the transfer standard, and associated standard uncertainty
- values measured using both transfer standard simultaneously (and their associated uncertainties derived from standard deviation of the set of readings)
- values of difference between applied dew/frost point and measured dew/frost point.

A provisional template for reporting results is shown in Appendix 5, and will be made available to participants in electronic form as an Excel spreadsheet. Use of this format, including calculations of means and differences, allows participants to see clearly the values and uncertainties of the parameters they are submitting for comparison.

5.5 From the data measured by each participant, results will be analysed in terms of differences between applied and measured dew-point temperatures. In each case, the difference will be taken between the applied (realised) value and the mean (mid-point) between the two hygrometer values.

5.6 The participants should report the conditions of realisation and measurement, as background information to support the main results. These conditions may include, pressure and temperature in saturator or reference hygrometer, pressure difference between saturator or reference hygrometer and transfer standards, measurement traceability, frequency of AC (or DC) resistance measurement, and other items. A provisional template for reporting conditions of measurement is shown in Appendix 4, and will be made available to participants in electronic form as an Excel spreadsheet.

5.7 Any information obtained relating to the use of any results obtained by a participant during the course of the comparison shall be sent only to the pilot laboratory and as quickly as possible.

6. UNCERTAINTY OF MEASUREMENT

6.1 The uncertainty of the key comparison results will be derived from:

- the quoted uncertainty of the dew/frost-point realisation (applied dew/frost point temperature)
- the estimated uncertainty relating to the short-term stability of the transfer standard at the time of measurement
- the estimated uncertainty due to any drift of the transfer standard over the period of the comparison (estimated by the Pilots)
- the estimated uncertainty in mean values due to dispersion of repeated results (reflecting the combined reproducibility of laboratory standard and transfer standards)
- the estimated uncertainty due to the non-linearity of the transfer standard in any case where measurements are significantly away from the agreed nominal value
- the estimated covariance between applied (laboratory standard) and measured (transfer standard) values of dew/frost-point temperature (if found significant)
- any other components of uncertainty that are thought to be significant

6.2 Participants are required to submit detailed analyses of uncertainty for their dew-point standards. Uncertainty analysis should be according to the approach given in the ISO Guide to the Expression of Uncertainty of Measurement. A list of the all significant components of the uncertainty budget should be evaluated, and should support the quoted uncertainties. Type B estimates of uncertainty may be regarded as having infinite degrees of freedom, or an alternative estimate of the number of degrees of freedom may be made following the methods in the ISO Guide.

6.3 The pilot laboratory will collect draft uncertainty budgets as background information to the uncertainties quoted by participants for the comparison measurements.

7. LINK TO THE EUROMET-T.K6 AND EURAMET.T-S16

7.1 The outputs of the key comparison are expected to be:

- Results of individual participants for comparison of the hygrometer against their dew point reference in terms of mean values for each hygrometer at each measured value, estimated standard uncertainty of each mean result and estimated standard uncertainty of comparison process (e.g. effect of long-term stability and non-linearity of the transfer standards) if necessary.
- Estimates of bilateral equivalence between the participants at each measured dew-point temperature. The equivalence is expressed in terms of the Degree of Equivalence (DOE) given as a difference and its uncertainty (Δ ±U), in °C
- Estimates of equivalence of the LPM results to the ERV (European comparison reference value) of the EURAMET.T-K6 and the EURAMET.T-S16. This might be expressed in terms of the Degree of Equivalence (DOE) given as a difference and its uncertainty (Δ ±U), in °C.

7.2 MIKES results provide the link to the EURAMET.T-K6, EURAMET.T-S16 and CCT-K6 comparisons.

7.4 The Pilot will make an assessment of any drift in the transfer standard during the comparison. The assessment will be based on initial and final measurements done by the Pilots. If drift is found, this will be taken into account in the final analysis of the comparison results. If the drift is small compared with uncertainty values reported by the participants, an estimate for the drift may be set to zero with a standard uncertainty calculated according to the ISO Guide.

7.5 If the transfer standard fails or performs poorly during the comparison, the Pilot will propose a course of action, subject to agreement of the participants.

APPENDIX 1. DETAILS OF PARTICIPATING INSTITUTES

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APPENDIX 2. IEC 60751 RELATIONSHIP

Based on the IEC 60751 (1995-07), a nominal resistance-temperature characteristic of the PRT in the travelling standard can be defined as follows:

for the temperature above 0 °C:

$$R_t = R_0(1 + At + Bt^2) \tag{1}$$

for the temperature below 0 °C:

$$R_t = R_0[1 + At + Bt^2 + C(t\text{-}100)t^3] \tag{2}$$

where:

t = temperature (ITS-90), °C,
R_t = resistance at temperature t,
R_0 = nominal resistance of 100 Ω at 0 °C,
A = 3.9083 × 10^{-3} °C^{-1},
B = -5.775 ×10^{-7} °C^{-2}, and
C = -4.183 × 10^{-12} °C^{-4}.

APPENDIX 3. PROVISIONAL TEMPLATE FOR REPORTING OF RESULTS

Refer to Sheet “Measurement results” in accompanying MS Excel file “P912comparison_Appendices 3to4_020409.xls”.

APPENDIX 4. PROVISIONAL TEMPLATES FOR REPORTING OF CONDITIONS OF MEASUREMENT

Background information to the key comparison measurements are reported using the templates/guidance in the accompanying MS Excel file "P912comparison_Appendices 3to4_020409.xls":

This information is likely to be of secondary information but will become important if there should be any need to resolve anomalies which might appear in the results.