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Interlaboratory Comparison of Reference Surface Temperature Apparatus at NMIs

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Abstract During 2001 and 2002, the first international comparison of surface temperature measurements at national metrology institutes (NMIs) was organized under EUROMET Project No 635. The coordinator for this project was the National Office of Measures (OMH) in Hungary. Among the participants were the Swedish National Testing and Research Institute (SP) from Sweden, the Centre for Metrology and Accreditation (MIKES) in Finland, and Justervesenet (JV) in Norway. The comparison showed a need for better apparatus to reduce the differences in the results from the different laboratories. As a result, a new apparatus was designed at SP and MIKES made some changes to their apparatus. To test the new and modified apparatus, SP took the initiative to arrange and coordinate a new comparison. In this recent comparison, measurements were made at temperatures from 50 to 300°C on surfaces of aluminum and stainless steel. The comparison was arranged and performed during 2005 and 2006. Participants in the comparison were OMH, MIKES, RISOE, JV, and SP. The comparison results using the newly developed apparatus show improved agreement with the earlier EUROMET intercomparison, but also indicate a need for a

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more standardized calibration method and apparatus to be able to perform calibrations in different laboratories with good agreement.

Keywords Calibration · Comparison · Sensor · Surface · Temperature · Thermometer

1 Introduction

Many different types of contact sensors for surface-temperature measurements are used in industry and society. In order to calibrate these instruments and sensors, different types of apparatus have been developed at national metrology institutes (NMIs). During 2001 and 2002, the first ever comparison of surface temperature apparatus was organized by EUROMET as Project No 635 [1]. The National Office of Measures (OMH) in Hungary coordinated the comparison. Eleven NMIs took part in that comparison. The Centre for Metrology and Accreditation (MIKES) in Finland, Justervesenet (JV) in Norway, and the Swedish National Testing and Research Institute (SP) in Sweden were among the participants. The comparison indicated a need for better apparatus to ensure better agreement in the measurements among different NMIs. SP developed a new apparatus, and MIKES improved their apparatus. To test and compare the new and improved apparatus, SP took the initiative to organize a new comparison involving the NMIs of the Nordic countries and also OMH.

2 Measurements

2.1 Transfer Standards

A package containing one indicator (TESTO 945), two sensors (Testo, Type K, Model 0603 0392 and Type OMEGA, Model 88010), and one protecting tube of aluminum was circulated among the participating laboratories.

2.2 Measuring Instructions

The goal of the comparison was to compare the reference surface temperature apparatus of the participating NMIs by means of transfer surface temperature standards. The participating laboratories carried out measurements on two samples of different thermal conductivity—aluminum and stainless steel. The reference surface was required to be flat and with a thickness of at least 10 mm. The roughness of the surface should be low to maximize the heat transfer from the surface to the sensor.

Each laboratory calibrated two contact sensors of different types. The reference surface was directed horizontally, and the sensor was applied vertically. The sensors were applied manually to the surface, taking a maximum value of the thermometer reading. The mean value of three such measurements was given in the tables. Ambient temperature was 23 ± 1°C during the measurements in all laboratories.

The traveling standards passed through the following measuring sequence:

(1) Before the contact with the reference surface, measurements were performed by immersing the two types of sensors in a liquid bath at two temperatures, using the circulated protection tube (that is, performing an ordinary calibration in a liquid bath).
(2) Measurements were made by the contact method with the two sensors at five different temperatures on two different surfaces.
(3) After the measurements using the different surfaces, the sensors were tested in a liquid bath at 0°C, using the protecting tube.

After checking the instruments by the immersion method, the laboratory calibrated the two sensors with the indicator in the temperature range between 50 and 300°C, at nominally 50, 75, 100, 200, and 300°C.

The calibration procedure involved the determination of the surface temperature before applying the sensor. The surface temperature had to stay within ±2°C of the nominal temperature, in order to avoid the need to correct for the difference between the nominal set-point and the actual temperature of the surface. The surface sensor was then applied manually, in a vertical position, on aluminum and stainless steel heat-plates, taking the maximum reading of the thermometer. Three measurements were taken at each calibration point. The mean of three measurements defined the temperature read by the sensor. After withdrawing the sensor, the surface temperature was once again determined. The average surface temperature defines the reference temperature, which is the mean value between the temperature before and after applying the sensor.

2.3 Characteristics of the Apparatus Used by the Participants

The characteristics of the apparatus are presented in Table 1.

2.4 Stability of the Transfer Standards

The stability of the transfer standards was checked at the beginning and at the end of the comparison by SP, who coordinated the project. There were no significant differences in the values, and therefore the drifts in reference values are of no consequence in drawing conclusions from the comparison.

3 Results

3.1 Measurement Results

The measurement results are grouped considering the two types of material and the two types of sensors. All participating laboratories performed measurements and reported their results according to the specifications in the technical protocol [2], except for RISOE in Denmark. RISOE reported measurements using two different apparatus,

Table 1 Characteristics of the apparatus used by the participants

Laboratory	Standards	Material of the reference blocks	Geometrical parameters of the reference blocks
OMH	Thermocouple type: K	Pure aluminum 99.9% $\lambda = 270\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ Stainless steel XcrNi 18/10 $\lambda = 30\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	Diameter: 100 mm Thickness: 10 mm Holes diameter: 1.6 mm
SP	Thermocouple type: K	Aluminum SS 4212 $\lambda = 172\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ Stainless steel SS 2343 $\lambda = 15\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	Diameter: 100 mm Thickness: 40 mm Holes diameter: 3.1 mm
MIKES	Thermocouple type: K	AlSi1MgT6/EN2011-T8/T6 $\lambda = 209\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ AISI 304 SS 2333 $\lambda = 50\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	Diameter: 100 mm Thickness: 97.5 mm Holes diameter: 2.56 mm
RISOE 1	Thermocouple type: K	Aluminum Stainless steel	Diameter: 30 mm Thickness: 150 mm Holes diameter: 1.5 mm
RISOE well	SPRT	Stainless steel	Diameter: 18 mm Thickness: 250 mm
JV	PRT	Aluminum $\lambda = 201\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ Stainless steel 316L $\lambda = 150\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	Diameter: 140 mm Thickness: 55 mm Holes diameter: 3.7 mm

Table 2 Reported results from measurements with ‘Testo’ sensor on aluminum

Testo Al	50°C		75°C		100°C		200°C		300°C	
Laboratory	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)
OMH	−0.1	0.2	−0.5	0.2	−0.9	0.5	−2.5	0.9	−3.2	1.1
SP before	−0.2	0.3	−0.6	0.4	−0.5	0.5	−2.0	0.8	−4.4	1.2
MIKES	−1.9	0.9	−2.6	1.0	−4.3	1.3	−5.4	1.4	−6.1	1.5
RISOE	−0.9	0.5	−0.3	0.5	0.1	0.5	0.1	1.0	0.2	1.0
JV	−0.34	0.54	−0.39	0.56	−0.44	0.60	−2.23	0.94	−3.0	1.5
SP after	−0.3	0.3	−0.2	0.4	−0.4	0.5	−1.8	0.8	−4.0	1.2

none of which is a heated plate. The extrapolation method used for heated plates was not possible to apply directly to their methods that use a dry well in liquid baths and blocks heated in oil baths (the blocks have three thermocouples in the top end to calculate the surface temperature, but not arranged in a way that made it possible to extrapolate the surface temperature according to the technical protocol).

Tables 2–5 summarize the reported results and the combined expanded standard uncertainties ($k = 2$) given by the participants for each sensor, each material, and each surface temperature. The results given by each participant are the arithmetic mean of three measurement values.

Table 3 Reported results from measurements with 'Testo' sensor on stainless steel

Testo SS	50°C		75°C		100°C		200°C		300°C	
Laboratory	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)
OMH	−0.3	0.3	−0.9	0.4	−1.8	0.7	−5.0	1.1	−6.6	1.4
SP before	−0.5	0.4	−1.1	0.5	−1.3	0.8	−3.4	1.1	−5.8	1.7
MIKES	−2.6	1.2	−4.0	1.1	−6.3	1.3	−9.6	1.7	−13.6	3.2
RISOEwell	−0.5	0.5	−0.6	0.5	−0.8	0.5	−2.9	1.0	−4.5	1.0
RISOE	−1.5	1.0	−1.4	1.0	1.0	2.0	2.4	2.0	0.3	2.0
JV	−0.8	1.8	−1.8	1.9	−2.0	2.0	−5.3	3.0	−9.0	4.2
SP after	−0.4	0.4	−0.8	0.5	−1.1	0.8	−4.3	1.1	−6.9	1.7

Table 4 Reported results from measurements with 'Omega' sensor on aluminum

Omega Al	50°C		75°C		100°C		200°C		300°C	
Laboratory	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)
OMH	−0.1	0.2	−0.4	0.2	−0.7	0.5	−2.1	0.9	−2.9	1.1
SP before	−0.2	0.3	−0.3	0.4	−0.1	0.5	−0.4	0.8	−2.4	1.2
MIKES	−1.9	0.9	−2.6	1.0	−3.9	1.3	−5.1	1.5	−5.4	1.5
RISOE	−0.1	0.5	0.0	0.5	−0.3	0.5	−0.7	1.0	−1.2	1.0
JV	−0.71	0.58	−0.99	0.56	−1.21	0.60	−3.31	0.84	−5.1	1.4
SP after	−0.2	0.3	−0.3	0.4	−0.3	0.5	−1.0	0.8	−2.1	1.2

Table 5 Reported results from measurements with 'Omega' sensor on stainless steel

Omega SS	50°C		75°C		100°C		200°C		300°C	
Laboratory	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)
OMH	−0.4	0.3	−0.9	0.4	−1.8	0.7	−4.6	1.1	−6.0	1.4
SP before	−0.5	0.4	−0.7	0.5	−0.4	0.8	−1.0	1.1	−3.4	1.7
MIKES	−2.5	1.0	−3.8	1.1	−5.7	1.4	−8.4	1.3	−11.2	1.9
RISOEwell	0.0	0.5	0.3	0.5	0.5	0.5	0.7	1.0	−0.1	1.0
RISOE	−1.1	0.5	−1.4	1.0	−1.6	2.0	1.1	2.0	0.1	2.0
JV	−1.0	1.9	−1.9	2.0	−2.3	2.4	−6.0	4.0	−10.0	5.6
SP after	−0.4	0.4	−0.8	0.5	−0.9	0.8	−2.2	1.1	−4.0	1.7

3.2 Calculation of the Reference Value and Evaluation of the Results

3.2.1 Calculation of the Reference Value

The reference values and uncertainties were evaluated according to the proposal by Cox [3] using Procedure A to determine the weighted mean. The procedure was tested with the results from OMH, MIKES, JV, and SP "after". RISOE was not included in this calculation as their apparatus did not match the technical protocol. The SP "before" value was excluded due to the fact that including two values from the same participant would weigh the reference value in favor of SP. The chi-square check failed when the values from all participants were included. After excluding the results from MIKES, the chi-square test did not fail for the 'Testo' sensor. For the 'Omega' sensor, the test failed for temperatures of 200 and 300°C. The results with the 'Omega' sensor are much less consistent than those made with the 'Testo' sensor. The reference values and uncertainties used in the following evaluation of the measurement results are those calculated in the second test using measurement results from OMH, JV, and SP "after". The indicator and 'Testo' sensor were used in the EUROMET Project No. 635. The difference between the reference values for the 'Testo' sensor from this comparison and those obtained under the auspices of Project No. 635 are in the range 0.00–0.14°C for aluminum and in the range 0.01–0.41°C for stainless steel. This is regarded as good agreement, and indicates that the results of the two comparisons are comparable.

The reference values and uncertainties used to evaluate the measurement results are presented in Tables 6–9.

Table 6 Reference values as weighted mean and uncertainty for 'Testo' sensor on aluminum

50°C		75°C		100°C		200°C		300°C	
Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)
−0.18	0.16	−0.44	0.17	−0.60	0.31	−2.14	0.51	−3.44	0.72

Table 7 Reference values as weighted mean and uncertainty for 'Testo' sensor on stainless steel

50°C		75°C		100°C		200°C		300°C	
Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)
−0.34	0.24	−0.89	0.31	−1.53	0.51	−4.69	0.76	−6.86	1.05

Table 8 Reference values as weighted mean and uncertainty for 'Omega' sensor on aluminum

50°C		75°C		100°C		200°C		300°C	
Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)
−0.17	0.16	−0.44	0.17	−0.68	0.31	−2.10	0.49	−3.18	0.70

Table 9 Reference values as weighted mean and uncertainty for 'Omega' sensor on stainless steel

50°C		75°C		100°C		200°C		300°C	
Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)	Error (°C)	U (°C)
−0.41	0.24	−0.89	0.31	−1.45	0.52	−3.49	0.76	−5.36	1.05

Table 10 E_n values for the reported measurements

Laboratory	50°C	75°C	100°C	200°C	300°C
E_n values for 'Testo' sensor on aluminum					
OMH	0.30	0.25	0.52	0.34	0.18
SP before	0.07	0.38	0.16	0.15	0.69
MIKES	1.89	2.13	2.77	2.19	1.60
RISOE	1.38	0.26	1.19	2.00	2.96
JV	0.29	0.08	0.23	0.08	0.26
SP after	0.36	0.54	0.33	0.36	0.40
E_n values for 'Testo' sensor on stainless steel					
OMH	0.12	0.03	0.31	0.23	0.15
SP before	0.33	0.36	0.24	0.97	0.53
MIKES	1.84	2.73	3.42	2.64	2.00
RISOEwell	0.28	0.49	1.02	1.43	1.63
RISOE	1.12	0.49	1.23	3.32	3.17
JV	0.25	0.48	0.23	0.20	0.49
SP after	0.12	0.15	0.45	0.29	0.02
E_n values for 'Omega' sensor on aluminum					
OMH	0.29	0.14	0.03	0.00	0.21
SP before	0.07	0.31	1.00	1.81	0.56
MIKES	1.89	2.13	2.41	1.90	1.34
RISOE	0.14	0.83	0.65	1.26	1.62
JV	0.89	0.95	0.78	1.25	1.23
SP after	0.07	0.31	0.65	1.17	0.78
E_n values for 'Omega' sensor on stainless steel					
OMH	0.02	0.03	0.40	0.83	0.36
SP before	0.19	0.32	1.10	1.86	0.98
MIKES	2.03	2.55	2.85	3.25	2.68
RISOEwell	0.74	2.02	2.72	3.33	3.61
RISOE	1.25	0.49	0.07	2.15	2.41
JV	0.31	0.50	0.35	0.62	0.81
SP after	0.02	0.14	0.58	0.97	0.68

3.2.2 Evaluation of the Measurement Results

The figure of merit E_n can be calculated using the following equation:

$$E_n = \frac{|T_{\text{lab}} - T_{\text{ref}}|}{\sqrt{\left(U_{\text{lab}}^2 + U_{\text{ref}}^2\right)}}$$

where U is the combined uncertainty with a coverage factor $k = 2$, T is the measurement result, subscript lab represents the individual results of each laboratory, and subscript ref represents the reference value.

The E_n values are reported in Table 10.

3.3 Analysis of the Measurement Results

3.3.1 Results from Measurements on Heated Plates

The discrepancies in the measurements are larger for the 'Omega' sensor than for the 'Testo' sensor. The reason for this is probably that the 'Omega' sensor, with greater mass in contact with the surface, influences the thermal equilibrium more than the 'Testo' sensor. The greater mass for the 'Omega' sensor also influences the time to reach thermal stability, when trying to find the maximum value of the thermometer. Every time the sensor is lowered onto the surface, it is preheated. This means that, if the surface temperature is the same over the surface, the thermometer indication will be higher for each trial until thermal equilibrium is reached. The time to find the maximum reading of the thermometer was not stipulated in the technical protocol. Different approaches in different laboratories may be the reason for the discrepancies in the result.

3.3.2 Model Test of a Recessed Surface

In the report from EUROMET Project No. 635, a model test of a lowered, recessed surface was reported. The test evaluated how large an impact a recessed surface can have on the results, when using 'Testo' and 'Omega' sensors. The test compared the measurement results with and without a ring, 180 mm in diameter and 50 mm in height, surrounding the heated plate. The results showed that the reading for the 'Testo' sensor was 0.8°C higher at 300°C with the ring and 1.8°C higher for the 'Omega' sensor. This may be the reason for the RISOE dry well having low errors for the 'Omega' sensor.

The test indicates that there are factors influencing the measurement results associated with the free convection of heat around the sensor. In the laboratory, the ambient temperature is controlled, meaning that air must move from inlet to outlet. This influences the measurements. We do not just have free convection around the sensor; rather, forced convection is dominant. The test suggests the magnitude of the impact on the measurement, and may explain some of the discrepancies between laboratories.

3.3.3 Uncertainties

Determination of surface temperature necessitates first and foremost the determination of the temperature in the wells inside the reference block. The extrapolated surface temperature is then associated with the surface temperature indicated by the surface sensor.

The temperature of the reference surface was determined using the temperatures indicated by the sensors inside the reference block (thermocouples or resistance thermometers), the distances between these sensors, and the distance between a sensor and the surface. The uncertainties estimated by the participating laboratories did not take into account the differences in the apparatus used at the different laboratories, the influence of differences in the time to determine the maximum value indicated by the thermometer, the differences in ambient conditions at the participating laboratories, and any operator effect.

4 Conclusions

The objective of the project was to compare the reference surface temperature apparatus at different NMIs by comparing transfer surface temperature standards. Five National Metrology Institutes took part in the comparison and results from six different apparatus are presented in this report. It seems that the instrument and the probes were stable during the circulation, based on the "SP before" and "SP after" values; therefore, drift in the reference values has negligible influence. On the other hand, there seem to be large systematic differences between the participating laboratories. These systematic effects may be caused by the handling of the probe, the time of contact between the sensor and the heated surface, and also effects related to the two different designs of the probes. It may be stated that the 'within laboratory' repeatability is rather good, but the 'between laboratory' reproducibility suffers from effects related to small differences in understanding the procedure described in the protocol. The comparison indicates a need for a more standardized calibration method and apparatus to be able to perform calibrations in different laboratories with good agreement.

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