COMPARISON OF A RADIATION THERMOMETER IN THE RANGE FROM 600 °C TO 1500 °C BETWEEN MIRS/UL-FE/LMK AND NPL

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Abstract: The article presents the results of comparison in the field of radiation thermometry, where the transfer artefact was a radiation thermometer, which is used as the reference radiation thermometer (national standard) in Slovenia. The comparison was performed between MIRS/UL-FE/LMK and NPL to compare the realization of the ITS-90 through the calibration of the transfer radiation thermometer. Results confirmed the calibration measurement capabilities (CMCs) of MIRS/UL-FE/LMK which will be entered to the Key Comparison Database (KCDB) of the Bureau International des Poids et Mesures (BIPM).

Keywords: radiation thermometer, interlaboratory comparison, blackbody, size of source effect

1. Introduction

The Slovenian holder of a national standard for thermometry MIRS/UL-FE/LMK agreed with the UK national measurement institute NPL a comparison of the realization of the ITS-90 through the calibration of a radiation thermometer in the range from 600 °C to 1500 °C. The chosen radiation thermometer is one of the Slovenian national standards for temperature and provides traceability of radiation thermometry in Slovenia in the range from 1000 °C to 1500 °C. The broader range for the comparison (i.e. from 600 °C to 1000 °C) was agreed to verify the calibration measurement capabilities of MIRS/UL-FE/LMK in the field of radiation thermometry, in which the last extensive interlaboratory comparison within EURAMET TC Thermometry was conducted more than 15 years ago in the project called TRIRAT [1]. MIRS/UL-FE/LMK joined the project in the last stage but due to the problems with the reference radiation thermometer we were not able to perform the measurements.

The comparison of ITS-90 realization in the field of radiation thermometry between MIRS/UL-FE/LMK and NPL was agreed in the scope of EURAMET TC Thermometry project number 1366 in March 2015. For the comparison measurements the protocol was written in which the details of preparation, execution and analysis of results were given. The comparison measurements were carried out over the period from March to September 2015.

2. Protocol of comparison

It was agreed that the coordinator for the comparison was MIRS/UL-FE/LMK which also provided the transfer standard and all necessary provisions (protocol, spreadsheets for analysis of results, final report) for the comparison to be executed successfully. Measurements were performed first at the MIRS/UL-FE/LMK, then at the NPL and repeated at the MIRS/UL-FE/LMK.

At each set temperature (600 °C, 800 °C, 1000 °C, 1250 °C and 1500 °C) at least 12 measurements of the thermometer reading and the temperature of the blackbody source were taken and results were entered to the template (Excel spreadsheet) provided by the coordinator. The positioning (centering, aligning and focusing) of the radiation thermometer in front of the blackbody furnaces was made following the own procedures of both participants. Besides the comparison measurements also ambient conditions (temperature, relative humidity) and other relevant data about the equipment used (reference standards and their traceability, emissivity, the size of aperture, dimensions, shape and temperature homogeneity of a blackbody) were given.
The measurements to determine the size-of-source effect (SSE) of the transfer standard were performed at 1000 °C in front of the sodium heat pipe blackbody by the direct method. The value of SSE was used as one component in the uncertainty budget. The measurements were carried out to confirm the difference in the results of measurements at different distances in the first series of measurements at both institutes.

2.1 Transfer standard

The transfer standard used was the radiation thermometer Heitronics KT 19.01 II. The detector type B has a spectral range from 2.0 µm to 2.7 µm and operates in the temperature range from 350 °C to 2000 °C. Its nominal target size is 12.7 mm at the distance of 733 mm. The emissivity setting resolution is 0.001 and the emissivity was set to 1.000. The response time was 1 second. The time allowed for the thermometer to stabilize after switch on before starting measurements was 1 hour.

2.2 Blackbodies

In the temperature range from 600 °C to 1000 °C the measurements were performed in both institutes against a sodium heat pipe blackbody. Both heat pipes have an aperture diameter of 40 mm and emissivity of 0.9994. The emissivity of the MIRS/UL-FE/LMK blackbody was taken according to the manufacturer's specification. The emissivity for the NPL cavity was estimated by calculation using the commercial STEEP3 software, with an assumed estimated emissivity of the oxidized Inconel of 0.8 and taking into account the measured temperature gradients. Both cavities have a cylindrical shape with the bottom cone of 120°. The reference temperature was determined with the reference thermocouples (MIRS/UL-FE/LMK type S, U(2s)=0.5 K (up to Ag) and NPL type Au/Pt U(2s)=0.2 K (up to Ag).

The temperature stability of the MIRS/UL-FE/LMK blackbody (manufacturer Advanced Cooling Technologies Inc. (ACT), USA) was 0.3 K (2s) over a period of 5 minutes while the temperature homogeneity was 0.9 K (2s). The homogeneity was measured by two thermocouples in two wells one in the front and one in the rear of the heat pipe. The thermocouple inserted from the front of the heat pipe had a sensor in a close proximity of the cavity bottom and remained in the same position during the measurement of homogeneity, while the thermocouple inserted from the rear was moved along the cavity to determine the temperature at different positions along the heat pipe cavity.
The temperature stability of the NPL blackbody (manufacturer ACT) was typically 0.04 K (2s) (standard deviation of measurements over the 2-minute measurement period) while temperature homogeneity was within 1 K (2s) along the blackbody cavity, again measured by moving a thermocouple along a thermometer well running along the length of the heat pipe.

In the range from 1000 °C to 1500 °C NPL used a Thermogauge graphite blackbody source with an aperture diameter of 38 mm and emissivity of 0.995. The emissivity was estimated using the commercial STEEP 3 software assuming an emissivity of the graphite of 0.9 and allowing for the measured temperature gradients along the cavity walls. The cavity has a cylindrical shape with a flat bottom. The reference temperature was determined with the reference linear radiation thermometer

LP3 focused on the back wall of the blackbody, with uncertainty of U(2s) ≤0.05 % of measured Celsius temperature.

In the same range MIRS/UL-FE/LMK used a Land high temperature furnace with the silicon carbide blackbody and an aperture diameter of 50 mm and emissivity of 0.995 according to the manufacturer's specification. The cavity has a cylindrical shape with the bottom cone of 120°. The reference temperature was determined with the reference thermocouple type S with uncertainty U(2s)=0.7 K (961.78 °C to 1084.62 °C); 1.5 K (1084.62 °C to 1554.8 °C).

1000 °C (sodium heat pipe)	description	quantity	probability distribution	value / mK
Blackbody	calibration temperature (standard deviation)	$u_{1A}(T)$	normal	35
	calibration temperature (reference thermometer)	$u_{1B}(T)$	normal	250
	blackbody emissivity, non-isothermal	$u_5(T)$	rectangular	100
	reflected ambient radiation	$u_6(T)$	normal	10
	cavity bottom heat exchange	$u_7(T)$	rectangular	100
	convection	$u_8(T)$	rectangular	100
	cavity bottom uniformity	$u_9(T)$	normal	100
	ambient conditions	$u_{10}(T)$	normal	0
Radiation thermometer	size of source effect	$u_{11}(S)$	rectangular	330
	resolution		rectangular	290
	repeatability		normal	50
	non-linearity	$u_{12}(S)$	normal	0
	reference temperature	$u_{13}(T)$	normal	0
	ambient temperature	$u_{14}(S)$	normal	0
	athmosferic absorption	$u_{15}(S)$	normal	0
	gain ratios	$u_{16}(S)$	normal	0
	noise	$u_{17}(S)$	normal	0
			combined standard uncertainty	547
			expanded uncertainty / K	1.09
			rounded uncertainty / K	1.1

Table 2: Uncertainty budget of NPL at 1000 °C in sodium heat pipe

1000 °C (sodium heat pipe)	description	quantity	probability distribution	value / mK
Blackbody	calibration temperature (standard deviation)	*u1A (T)*	normal	6
	calibration temperature (reference thermometer)	*u1B (T)*	normal	112
	blackbody emissivity, non-isothermal + isothermal	*u5 (T)*	rectangular	94
	reflected ambient radiation	*u6 (T)*	normal	9
	cavity bottom heat exchange	*u7 (T)*	rectangular	75
	convection	*u8 (T)*	rectangular	7
	cavity bottom uniformity	*u9 (T)*	normal	30
	ambient conditions	*u10 (T)*	normal	0
Radiation thermometer	size of source effect	*u11 (S)*	rectangular	333
	Resolution		rectangular	290
	repeatability		normal	180
	non-linearity	*u12 (S)*	normal	0
	reference temperature	*u13 (T)*	normal	0
	ambient temperature	*u14 (S)*	normal	0
	atmospheric absorption	*u15 (S)*	normal	0
	gain ratios	*u16 (S)*	normal	0
	noise	*u17 (S)*	normal	0
			combined standard uncertainty	505
			expanded uncertainty / K	1.0
			rounded uncertainty / K	1.0

3. Results

The results of comparison measurements in terms of difference between temperature of the blackbody and reading of the radiation thermometer and associated uncertainties as well as claimed CMCs are given in Table 3 (Note: NPL has few published CMCs related to radiation thermometry on the BIPM KCDB. The quoted values are instead NPL's current accredited CMCs (accredited by the United Kingdom Accreditation Service (UKAS), calibration laboratory number 0478). The same results are also presented for all measured temperatures in Figures 1 to 6. The most important parameter in the period of performing the comparison was the known importance of the size of source effect but yet its influence strongly affected the course of measurements. Namely in the first round of measurements at MIRS/UL-FE/LMK the radiation thermometer was set to the distance of 733 mm from the lens to the bottom of the blackbody cavity at all temperature points. The same distance was used at NPL in the range from 1000 °C with the high temperature (Thermogauge) furnace. However, in the range covered by the sodium heat pipe (600 °C to 1000 °C) the distance of 1183 mm to the bottom of the blackbody was set at NPL. The reason for this was due to differing calibration methodology at NPL and MIRS/UL-FE/LMK. At NPL, when using the heat pipe blackbody sources, the working distance of the thermometer is measured to the defining aperture of the blackbody, which is a water-cooled plate set immediately in front of the source. For calibrations using the Thermogauge blackbody both the test and reference thermometers are set at the specified working distance from the cavity back wall, due to the poorer temperature uniformity of the Thermogauge blackbody. At MIRS/UL-FE/LMK the working distance is set from the back wall of the blackbody cavity for all sources. At 1183 mm distance from the back wall (i.e. 733 mm from the defining aperture, plus 450 mm length of sodium heatpipe including the insulation immediately in front of the heat pipe etc.) the smallest target size of the radiation thermometer 12.7 mm emerged at the aperture of the sodium heat pipe,). It was believed that homogeneity of the heat pipe was good enough not to jeopardize the measurement results. As seen in the Figures 1, 2 and 3 measurements marked as MIRS/UL-FE/LMK 1 are lower by approximately 3 K compared to the NPL measurements. MIRS/UL-FE/LMK carried out its second set of measurements, MIRS/UL-FE/LMK 2 at a distance of 733 mm from the aperture; this second set of measurements is in much better agreement with the NPL results.

In order to investigate the problem, the SSE measurements were performed at MIRS/UL-FE/LMK at 1000 °C in front of the sodium heat pipe at the distance of 733 mm from the aperture of the blackbody. We used a dedicated system for measuring the SSE with the direct method [3]. It consisted of a water-cooled copper holder for aluminum plates with apertures of a different diameter and thickness of 2 mm. We used apertures with diameters from 60 mm to 20 mm. The results of measurements are presented in Figure 7, where the measurement with 20 mm aperture is omitted because the radiation thermometer measured 967,7 °C (i.e. the aperture size was too small for the field-of-view of the radiation thermometer). The specification regarding the nominal target size for this radiation thermometer is shown in Figure 8. At the distance of 1183 mm the approximate target size is 35 mm, which is less than the diameter of the blackbody cavity; at 733 mm the approximate target size is 12.7 mm; at 283 mm from the aperture (equivalent to 733 mm from the back wall) the approximate target size is 23 mm. The unexpected results of comparison were discussed also with the manufacturer of the radiation thermometer, which promised to conduct further investigation on the matter because such differences due to measurement distance were not expected neither were justified.

As an additional tool of acceptable level of equivalence also the E_n number (Equation 1) was calculated for each measured temperature, where X is a measured value and U is the expanded measurement uncertainty at particular temperature. The E_n numbers for all measured temperatures are given in Table 3.

$$E_n = \frac{X_{\mathrm{LMK}} - X_{\mathrm{NPL}}}{\sqrt{U_{\mathrm{LMK}}^2 + U_{\mathrm{NPL}}^2}} \qquad (1)$$

The results of the comparison under the same or very similar conditions (i.e. same calibration configuration (distance measured from blackbody aperture)) confirmed the acceptable level of equivalence between MIRS/UL-FE/LMK and NPL in realization of the ITS-90 through the calibration of a radiation thermometer in the range from 600 °C to 1500 °C.

Table 3: Results of comparison measurements

	MIRS-UL/FE-LMK			NPL			
Set	t_{BB}-t_{RT}	*U (95%)*	CMC	t_{BB}-t_{RT}	*U (95%)*	CMC†	E_n
°C	K	K	K	K	K	K	/
600	1.0	1.0	1.0	1.2	0.7	0.3	-0.22
800	-0.3	1.0	1.1	0.3	0.9	0.3	-0.39
1000	-1.1	1.1	1.1	-0.5	1.0	0.3	-0.40
1000	0.1	2.8	3.0	-1.0	1.8	0.5	0.31
1250	-1.2	3.6	4.0	-2.3	2.4	0.7	0.25
1500	0.3	4.6	5.0	-2.8	3.0	0.8	0.54

† UKAS –accredited CMCs

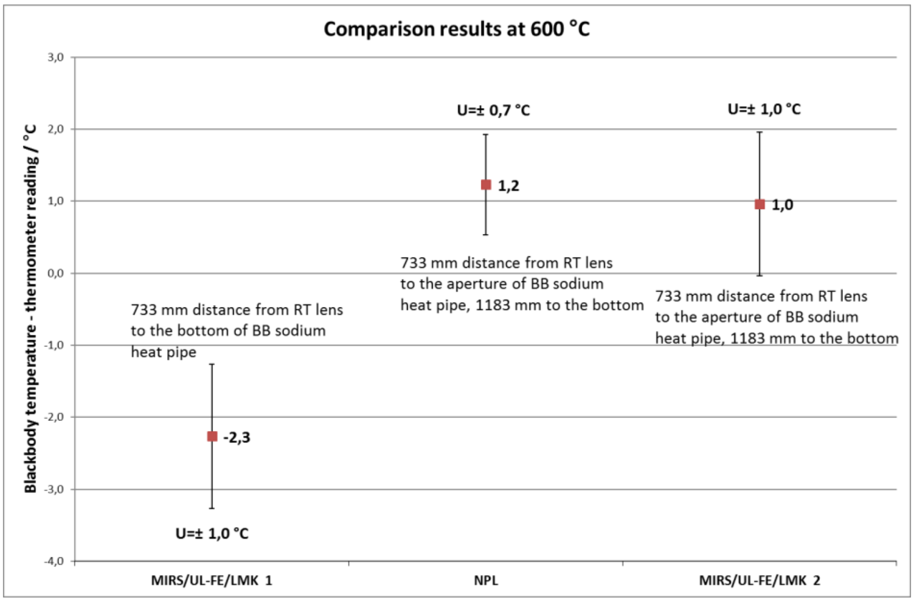

Figure 1: Results of comparison between MIRS/UL-FE/LMK and NPL at 600 °C

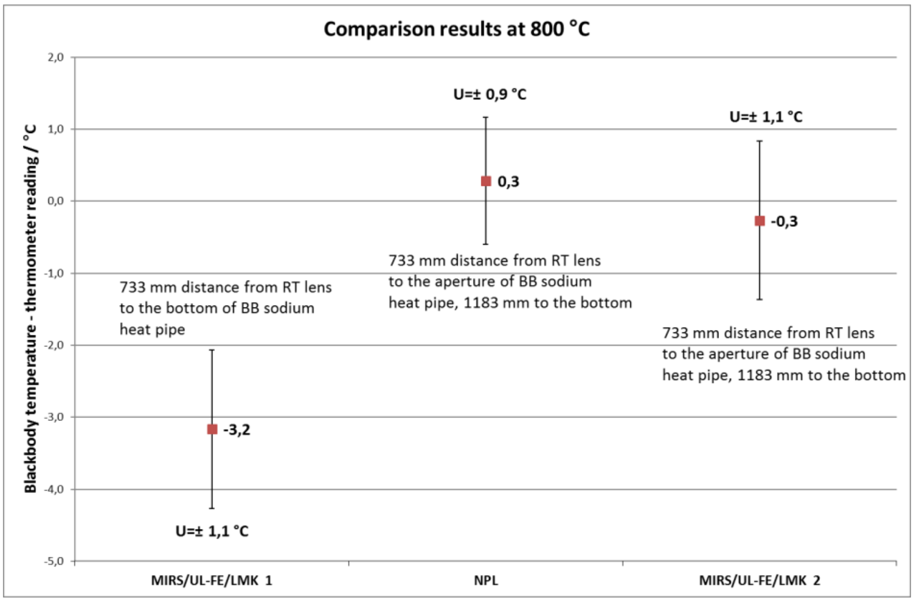

Figure 2: Results of comparison between MIRS/UL-FE/LMK and NPL at 800 °C

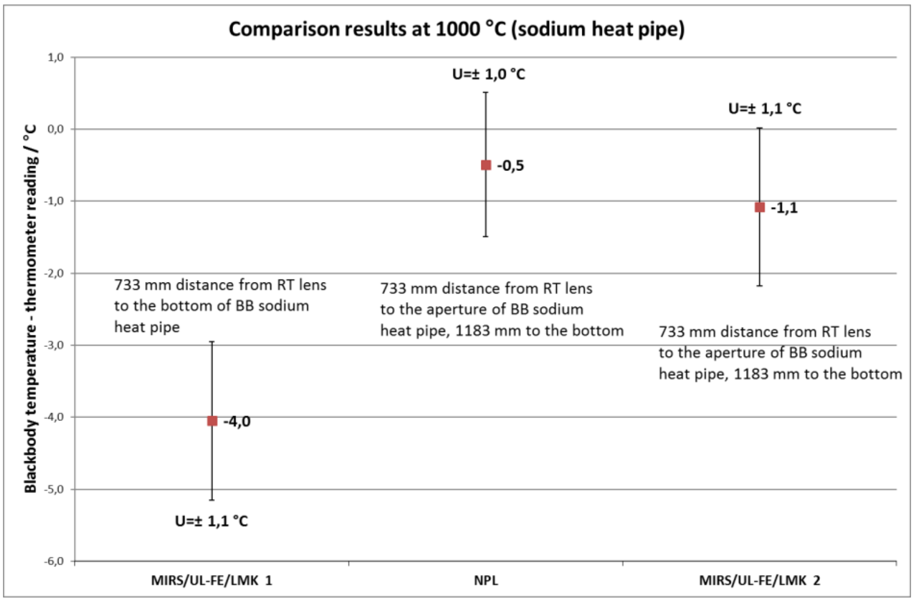

Figure 3: Results of comparison between MIRS/UL-FE/LMK and NPL at 1000 °C

Figure 4: Results of comparison between MIRS/UL-FE/LMK and NPL at 1000 °C

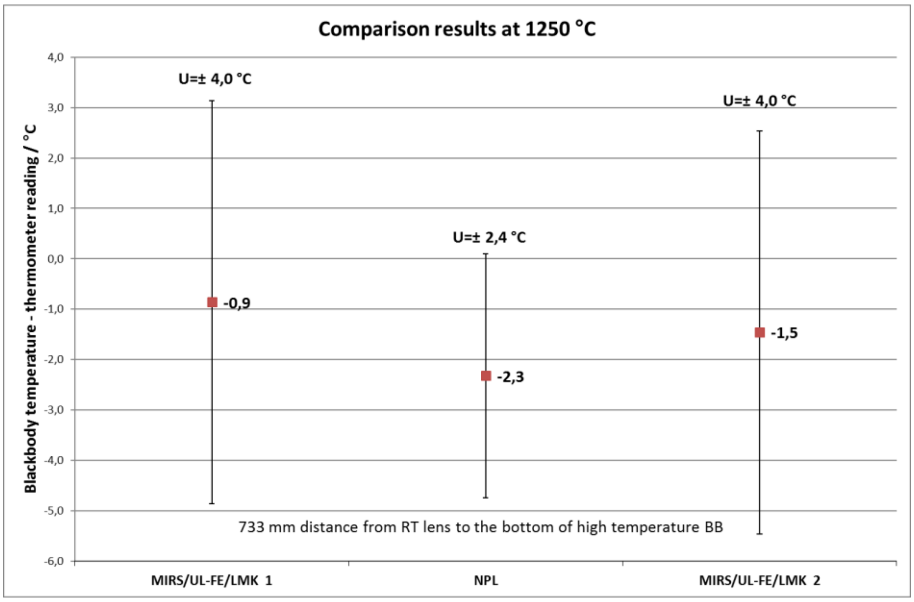

Figure 5: Results of comparison between MIRS/UL-FE/LMK and NPL at 1250 °C

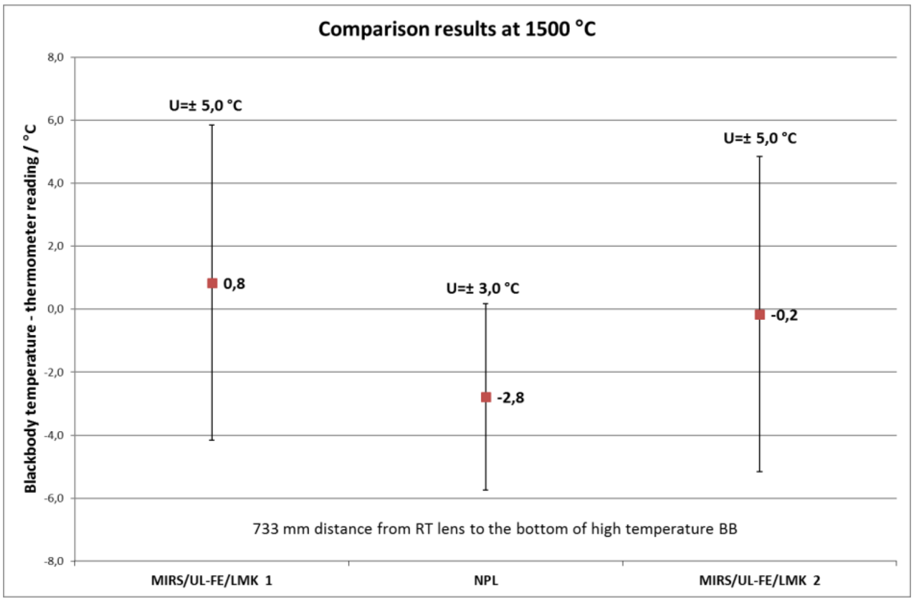

Figure 6: Results of comparison between MIRS/UL-FE/LMK and NPL at 1500 °C

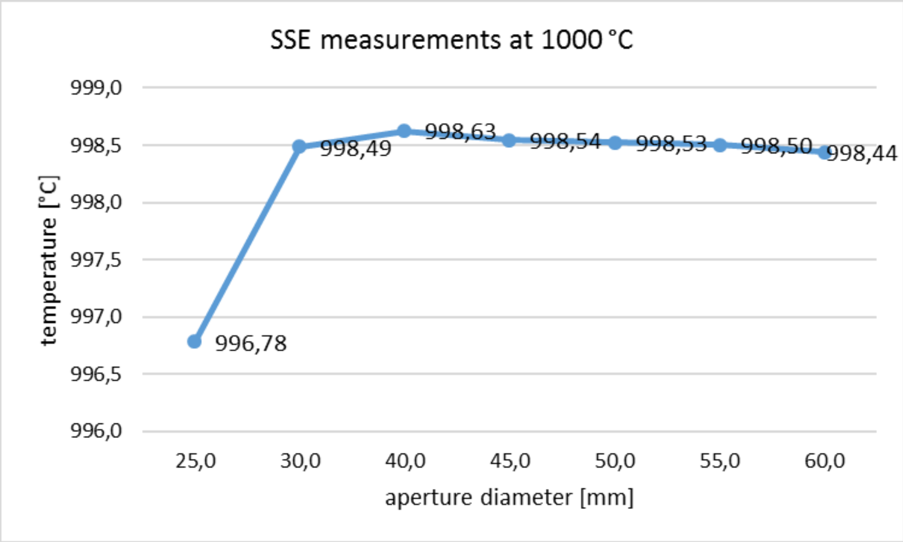

Figure 7: Results of SSE measurements at 1000 °C at a distance of 733 mm from the blackbody aperture

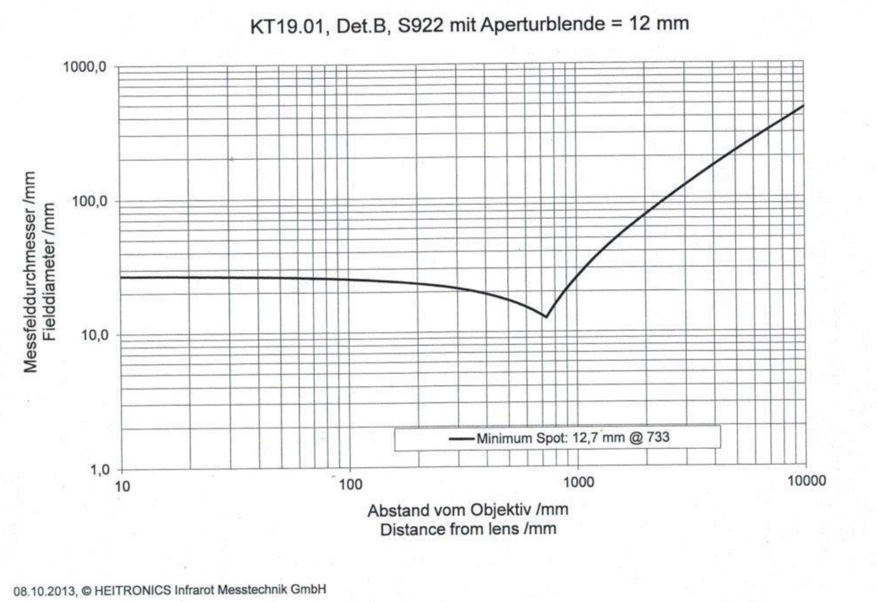

Figure 8: Target size specification for Heitronics KT 19.01

4. Discussion and conclusions

The main objective of the comparison was to confirm the CMCs of MIRS/UL-FE/LMK which will be submitted to the KCDB of the BIPM. The results showed good agreement of realizations of the ITS-90 in both institutes within the measurement uncertainties but in the range from 600 °C to 1000 °C only after repeated measurements at MIRS/UL-FE/LMK with same calibration configuration as that used at NPL. Namely, in the first round of measurement the results were different by approximately 3 K, which was more than reported measurement uncertainty of both institutes. As explained above the problem was that measurements in the range from 600 °C to 1000 °C at NPL were performed at the distance of 733 mm from the defining aperture of the blackbody (1183 mm from the bottom of the blackbody cavity), while at MIRS/UL-FE/LMK they were performed at the distance of 733 mm from the bottom of the cavity. After the measurements at MIRS/UL-FE/LMK were repeated at the distance of 1183 mm from the bottom of the blackbody cavity the results agreed well within the uncertainty.

The SSE measurements by the direct method were performed at 1000 °C in front of the sodium heat pipe at distance(s) of 733 mm, but the results could not justify the observed differences. The results surprised even the manufacturer which announced further investigation of this matter for this radiation thermometer. The conclusion is that the distance of a radiation thermometer from the bottom of a blackbody or the defining aperture and its diameter must be stated in the protocol of any measurement to avoid SSE and/or distance problems, which was the main source of disagreement in the first part of this comparison.

There are also strong demands for regional ILCs in radiation thermometry, especially because the last major comparison within EURAMET TC Thermometry (TRIRAT)was dated 20 years ago (October 1996 to April 2002), although a smaller comparison, involving fewer laboratories, was carried out more recently (the EURAMET 658 extension project, measurements carried out between 2007 and 2009). Such ILCs are not only important for those institutes which would like to submit their CMCs to the KCDB but also to regularly check the performance of national laboratories.

References

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