A study on infrared thermometer measurement capabilities in the calibration laboratories and the user community in Japan

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ABSTRACT

A comparison circulating a standard infrared thermometer, a handy infrared thermometer, and a thermal imager was conducted among eleven participants from the industrial user, academic user, and calibration laboratory communities of these thermometers in Japan. The result revealed that the scatter width of the reported value for the handy type thermometer was as large as 31 °C at 450 °C. Investigation into the cause of the discrepancy showed that the treatment of emissivity of the source was one large factor, which is relevant when using contact thermometer or a near infrared radiation thermometer as the reference. Large SSE of the handy thermometer linked to the definition of the targeting distance of the thermometer on the blackbody cavity also played a major role. The comparison successfully identified the shortcomings of the current calibration practices, and the result can be utilized to greatly improve the reliability of the infrared thermometer scale in future.

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1. Introduction

Infrared thermometers operating in the wavelength range of 8–14 μm are used in various scenes of our lives, such as in industrial sites, scientific investigations, health care, and hygiene control. The widespread use owes mostly to reduction in price and improvement in quality of infrared detectors. Most notably, two-dimensional array sensors are becoming widely used in thermal imagers, which have become an essential tool for screening potential carriers of infectious diseases in the wake of the COVID-19 pandemic crisis. Thermal imagers had mostly been means of obtaining images in the infrared for visual inspection, but recently they are playing increasingly important roles as thermometric instruments.

The reliability of measurement with infrared thermometers, including thermal imagers, is not as well established as other non-contact thermometers measuring higher temperature ranges. Most countries have traceability systems in place for these thermometers. However, equivalence of different traceability schemes or the capabilities of individual calibration laboratories have not been sufficiently assessed so far.

International comparisons among national metrology institutes are being conducted extensively under the framework of Mutual Recognition Arrangement (MRA) within the Comité international des poids et mesures (CIPM) [1]. In the field of radiation thermometry, however, for infrared thermometers in the low temperature range (above −50 °C), no comparisons are listed on the Key Comparison Data Base (KCDB) for any regional metrology organizations except for clinical ear thermometers [2].

At the industrial calibration laboratory level, to the authors’ knowledge, only one scientific report can be found for infrared thermometer comparison. This is for one conducted between an industrial calibration laboratory and a national metrology institute [3]. Although this enhances reliability of the calibration and measurement capability for this laboratory, it falls short of demonstrating that this is attainable for calibration laboratories in general.

In Japan, calibration laboratories of infrared thermometers are relying on several different traceability schemes. The National Metrology Institute of Japan (NMIJ) is providing calibration service of reference

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standard infrared thermometers in the temperature range of $-30\,^\circ\text{C}$ to $500\,^\circ\text{C}$, of which temperatures below $160\,^\circ\text{C}$ is operated as the national standards provision system of the Japan Calibration Service System (JCSS). Laboratories often rely on other routes as well, such as traceability within JCSS through radiation thermometers of different wavelength (at temperatures above $420\,^\circ\text{C}$), traceability through contact thermometers traceable to the national standards in accordance to the specifications in the Japanese Industrial Standards, or to accredited calibration services overseas. It is not clear, however, if calibrations based on these various schemes agree with each other, since no clear evidence of equivalence has been established for the infrared thermometers. It is also of concern whether non-direct traceability routes such as those involving contact thermometers or radiation thermometers of different wavelengths will present additional inherent difficulties.

From these points of view, a working group was established in the Thermometry Committee of the 36th Committee on Industrial Instrumentation, Japan Society for the Promotion of Science. The 25 members consisted of thermometer users in industry, thermometer manufacturers, calibration laboratories, national research institutes, and universities. Of these, eleven laboratories participated in the comparison including the NMIJ, who acted as the pilot. Three artefacts were circulated: a standard infrared radiation thermometer, a low-cost handy infrared thermometer, and a thermal imager. Results of the comparison are presented in this article, and discussions are made on the findings.

2. Overview of the interlaboratory comparison

2.1. Objective

Before starting the comparison, the participants agreed that the intention was not to conduct a proficiency test to grade the qualifications of the laboratories, but rather to gain insight into the current level of agreement achievable by different traceability routes, different facilities, and various treatment of measurement data. Furthermore, it was acknowledged that the test was meant to be a pilot comparison to reveal, if any, problems inherent in the traceability systems, calibration facilities and current practices. It was, therefore, decided that the laboratory names would not be linked to the comparison result data, that no reference value will be used for the evaluation, and that the laboratories did not need to report their uncertainties. The scatter and trends of the reported values was what the pilot comparison needed to look at as the result of the investigation.

2.2. Travelling artefacts

The standard infrared thermometer was circulated with the intention to test the agreement of the realized temperature scale itself. A standard infrared thermometer (model: TRT-IV.82, manufacturer: Heitronics) was chosen for its relatively good targeting characteristics and stability. The instrument has a fixed focal distance of 380 mm and a target size of 6.8 mm.

A low-cost handy infrared thermometer has generally a large size-of-source effect (SSE) and a poor short-term stability. This means there will be influence of the ambient, the facilities and the method of handling by the operator. To test these effects, an infrared thermometer (model: PT-S80, manufacturer: OPTEX) was sent around. This particular instrument was selected for its relatively good performance in terms of SSE and stability when compared with other similar instruments in the same category. It has a distance factor of $D:S = 33:1$, where $D$ is the distance and $S$ is the target size. The emissivity setting is pre-set to 0.95 (switchable to 0.85 or 0.7).

The third instrument was a thermal imager (model: SC620, manufacturer: FLIR). This has $640 \times 480$ pixel resolution, with a field-of-view of $24\,^\circ \times 18\,^\circ$ at the minimum focal distance of 0.3 m.

The artefacts were circulated with attachment tools to aid the mounting. The main specifications of the three instruments are shown in Table 1. Hereafter, the standard infrared thermometer, the handy-type infrared thermometer and the thermal imager will be called Heitronics, OPTEX and FLIR, respectively.

2.3. Participating laboratories, facilities and traceabilities

Out of the eleven participants, one was a national metrology institute (NMIJ), two were calibration laboratories, five were instrument manufacturers, one was a distributor of instrument from overseas and two were users of thermometers in science and industry.

Various facilities were utilized at these laboratories. As blackbody sources, either variable temperature furnaces with blackbody cavities or flat plate calibrators were used. As reference thermometers, some used an infrared thermometer, others used, in temperature ranges possible, a near infrared standard radiation thermometer, both of which are traceable to a national metrology institute, while some others had traceability through the contact thermometer monitoring the furnace temperature. Flat plate calibrators traceable to a national standard were also used. Most relied on a variety of traceability routes to cover the temperature range. Traceability sources were either the NMIJ or an overseas’ accredited quality system.

The NMIJ measurements were made traceable through the quality system established and registered for the JCSS, where available, or for the AIST calibration service, although calibration of thermal imagers or handy type infrared thermometers is not a regular part of this service at the NMIJ. To be specific, in the
temperature range $-30\,^\circ\text{C}$ to $160\,^\circ\text{C}$, all three traveling standard thermometers were calibrated against reference platinum resistance thermometers (PRTs) monitoring the temperature of variable-temperature stirred liquid baths having blackbody cavities immersed in the liquid. The PRTs, in turn, were calibrated at the liquid baths having blackbody cavities immersed in a vertically-aligned carbon nano-tube furnace with high-emissivity black coating applied on the cavity bottom [5]. Heitronics then served as the reference for the calibration of OPTEX and FLIR at and above $160\,^\circ\text{C}$. The participants were instructed not to change these and were asked to report the readings when the instruments measured a blackbody source at the prescribed temperatures at these settings. An optional measurement was requested to report the readings by OPTEX when it viewed a grey-body source of emissivity 0.95.

For FLIR, only the temperature value of the central area of the field of view was reported. On the finder display of the instrument, a square area corresponding to $10\,\text{mm} \times 10\,\text{mm}$ at the measurement distance of $500\,\text{mm}$ was marked, and the average temperature within this area was taken as the final NMIJ calibration result.

An overview of the NMIJ radiation thermometer calibration facilities can be found in [7].

### 2.4. Comparison scheme

Based on the calibration service ranges and capabilities of the participants’ facilities, it was agreed that the participants will report the calibration results at the temperatures and under the conditions laid out in Table 2. Here, the measurement distance is defined as the distance from the front tip of the instrument including the lens tube. Where these conditions could not be met, the actual conditions were reported, and corrections were applied at the pilot. When the full temperature range could not be covered, calibration within a limited range was conducted.

Emissivity settings for Heitronics and FLIR were preset to one. OPTEX had fixed emissivity setting that was not one, and this was pre-set to 0.95. The participants were instructed not to change these and were asked to report the readings when the instruments measured a blackbody source at the prescribed temperatures at these settings. An optional measurement was requested to report the readings by OPTEX when it viewed a grey-body source of emissivity 0.95.

For FLIR, only the temperature value of the central area of the field of view was reported. On the finder display of the instrument, a square area corresponding to $10\,\text{mm} \times 10\,\text{mm}$ at the measurement distance of $500\,\text{mm}$ was marked, and the average temperature within this area was taken.

To minimize the risk of instability of the artefacts, the comparison was conducted in a “semi-collapsed star” configuration. First, the artefacts were sent from the pilot to the first participant, which were then handed over to other participants one after another until three or four participants completed the measurements, and then the artefacts were returned to the pilot for intermediate check. This was repeated three times until all participants completed the measurements. Transfer of the artefacts were done through hand carry where possible, and by commercial carrier service otherwise. The measurements at the participants were completed in one year.

Before and after the participant measurement campaign, the pilot made a full calibration of the three artefacts. At intermediate checks, the pilot made check measurements of their stability at one temperature ($250\,^\circ\text{C}$) by comparison with the $1.6\,\mu\text{m}$ reference.
standard radiation thermometer for Heitronics, and subsequently by comparison with this for OPTEX and FLIR. Checks for any change in SSE characteristics were also made.

SSE functions of the travelling thermometers were measured by the direct method applying the flat-plate calibrator as the source and placing blackened disks having apertures with varying diameters in between the source and the instrument at the focal plane. Measurements were conducted at 100°C, 250°C and 450°C, and the results were extrapolated to −15°C and 950°C, taking into account the effect of thermal radiation from the aperture. The pilot applied the SSE corrections based on these measurements to the values reported by the participants.

For the measurement by the OPTEX with a grey-body source of emissivity 0.95, a "Rotor-Blade" filter with effective transmittance of 0.95 was placed in front of a blackbody source. This high-transmittance optical neutral-density filter consists of a rotating-sector optical chopper with coverage fraction of 5% [8].

3. Measurement results

3.1. Stability of travelling artefacts

The stabilities of the travelling artefacts were evaluated from measurements made at the pilot before and after the comparison measurements, as well as from the two intermediate check measurements at 250°C as described in section 2.4. Heitronics showed a step change of approximately 0.5°C at 250°C in between May and August 2018, after which no change was observed. Three participants made measurements during this period, and for these three laboratories a correction amounting to half the drift was applied. For OPTEX and FLIR, the observed drift was within the instrument measurement resolution of 1°C at 250°C and therefore no corrections were applied.

3.2. SSE of travelling artefacts

An example of measured SSE for the three instruments are shown in Figure 1. Measurement distances were 380 mm, 250 mm and 500 mm, respectively, for Heitronics, OPTEX and FLIR. Heitronics shows a curve that effectively levels off above 40 mm diameter, while curves for OPTEX and FLIR continue to increase. For Heitronics and OPTEX, corrections for diameter above 100 mm were determined by linearly extrapolating the curves, shown by the dotted line.

In the following, all results have been corrected for SSE at the pilot.

3.3. Comparison results

3.3.1. Heitronics

Figure 2 shows the comparison result of all participants for Heitronics. Same colour represents the same participant throughout the article. One participant reported two results with slightly different calibration methods, and these are treated as independent results in all of the following. The results are evaluated as the difference from the NMIJ value \(T_i - T_{NMIJ}\). Here \(T_i\) is the reported value for the \(i\)th participant, \(T_{NMIJ}\) is that for the pilot. The uncertainty of the calibration and measurement capability (CMC) \((k = 2)\) at NMIJ is shown by the lines, so as to serve as an indication of the level of agreement that can be expected among skilled participants. The uncertainty was estimated by combining the uncertainties evaluated for the calibration of the reference standard contact thermometer, for the blackbody (stability, emissivity estimation, heat loss), and for measurement repeatability, in the case of calibration with the liquid bath (i.e. at and below 160°C). For temperatures above 160°C, uncertainty in the reference standard near infrared thermometer (calibration by fixed-point blackbodies, stability, SSE), in the blackbody furnace (cavity effective emissivity, thermal diffusivity and emissivity of carbon nanotubes, temperature gradient, background radiance), and in the measurement (repeatability, alignment, target size, device under test (DUT) SSE, DUT stability, noise) are considered.

As can be seen, the full scatter width is smallest at 100°C (roughly 0.7°C) and increases to 4.0°C at 450°C. The scatter at 950°C is reduced to 2.6°C,
although this may be due to fewer participants making measurements at this temperature.

To better understand the cause of this scatter, the data were grouped and plotted according to the type of reference standards. In Figure 3(a) those with reference contact thermometers monitoring the furnace temperature are plotted. In Figure 3(b) the reference standards are infrared radiation thermometers, while in Figure 3(c) they are near infrared thermometers with wavelength 0.9 μm. The scatters are relatively large for Figure 3(a) and (c).

In Figure 3(a) there are clearly plots by some participants that decrease linearly with temperature (with the exception of one data at 950 °C, which is a separate facility) and another that increase, with cross over point at around room temperature. This suggests that a possible cause of the scatter is related to treatment of emissivity. Further scrutiny on the calibrations performed by the participants revealed that some used cavity type blackbodies without applying emissivity corrections (white plots with outlining circle), while others used flat plate sources applying emissivity corrections (plots in square).

### 3.3.2. OPTEX (for source emissivity: 1.0)

The reported values for measurements of blackbodies (source emissivity 1.0) at the temperatures in Table 2 with fixed instrument emissivity setting of 0.95 for OPTEX were compared. In Figure 4, the difference from the NMIJ reported values, \((T_i - T_{\text{NMIJ}})_{\text{OPTEX}}\), are plotted. The scatter is the smallest at 100 °C, and is approximately 6 °C. This is almost one order of magnitude larger than the scatter for Heitronics at the same temperature. The scatter increases as the temperature departs from room temperature and reaches approximately 31 °C at 450 °C.

In order to look into the cause of the discrepancy, the difference between Figure 2 and Figure 4 are evaluated, namely, the difference of the differences from NMIJ for OPTEX and Heitronics, \(\Delta(T_i - T_{\text{NMIJ}})_{\text{OPTEX}} - (T_i - T_{\text{NMIJ}})_{\text{Heitronics}}\), and are depicted in Figure 5(a) and (b). The scatter among all the participants is not reduced, indicating that the main cause of the scatter is not the difference in the participant scale. In Figure 5(a), results for participants who used cavity-type blackbody sources are plotted. For these participants, it was found that the target point where the measurement distance is defined differed from one participant to another: one defined the target point at the bottom of the cavity, most others defined it at the cavity opening, while another placed an aperture plate in front of the furnace and defined it there. Therefore, even if the participants claimed to have made measurements under the reference condition of \(D/L = 0.2\) as in Table 2, where \(L\) is the measurement distance and \(D\) is the source diameter, the actual arrangements were quite different. From the figure, it is seen that the plots for the participant who targeted the cavity bottom have a trend that increases linearly with temperature. For the one that applied the aperture plate in front of the furnace, the plots show the opposite trend. There was another participant that targeted the cavity opening but
used a reference radiation thermometer with emissivity setting of 0.95. The plots for this participant also have a decreasing trend with temperature.

Figure 5(b) shows the results for those who used a flat plate source. One participant reported values with a source partly covered with an optional aperture plate, and this shows the largest scatter. The scatter is generally smaller than those of Figure 5(a), with the largest scatter being approximately 8 °C.

### 3.3.3. OPTEX (for source emissivity: 0.95)

The same was conducted as the previous subsection for a source with emissivity of 0.95. This corresponds to what is usually required when calibrating instruments such as the OPTEX which has fixed or switchable emissivity setting of 0.95 and not equal to 1. This is a difficult task since no real greybody source exists whose emissivity is exactly 0.95. In the protocol nothing was stated on how the measurement should be conducted, and rather it was left to the participant to choose an appropriate method or to improvise one. Five participants submitted their results for this part of the comparison.

One laboratory besides the NMII applied high-transmittance optical neutral-density filter utilizing the rotating-sector optical chopper in combination with a cavity blackbody source. Another participant used a Ge glass as an optical neutral density filter with expected transmittance of 0.95. All others used a flat plate source. Among these, one participant simply relied on the manufacturer quoted emissivity, which was 0.94, while the rest used the built-in feature of the source to shift the source temperature so as to make the apparent emissivity 0.95.

The results in Figure 6 shows that the scatter is now slightly reduced when compared with Figure 4 and is approximately 20 °C. To eliminate the scatter caused by the scale and identify the accuracy in the treatment of the 0.95 emissivity alone, the difference of $\Delta(T_i - T_{NMII})$ for emissivity 0.95 ($\Delta(T_i - T_{NMII})_{0.95}$) from that for emissivity 1.0 ($\Delta(T_i - T_{NMII})_{1.0}$) is evaluated.

$$\Delta^2(T_i - T_{NMII}) = \Delta(T_i - T_{NMII})_{0.95} - \Delta(T_i - T_{NMII})_{1.0}.$$  

In Figure 7(a) and (b), the plots are separately shown for those measured with a blackbody cavity source and a flat plate source, respectively. Of the two participants that participated with a blackbody cavity source, the one with the Ge glass filter reported values that showed decreasing trend with increasing temperature.

Of the three participants with the flat plate source (Figure 7(b)), the participant that relied on the manufacturer claimed emissivity of 0.94 showed an upward trend with temperature.

### 3.3.4. FLIR

The comparison result for FLIR is shown in Figure 8. Here, the difference from the NMII value ($T_i - T_{NMII}$) is evaluated. Except for $-15$ °C, for which only a small number of laboratories participated, the scatter is smallest at 100 °C and is approximately 2 °C, and increases with temperature and reaches approximately 9 °C at 450 °C. This is roughly 1/4 of the scatter for OPTEX.

The difference of these from the same for Heitronics ($\Delta(T_i - T_{NMII}) \equiv (T_i - T_{NMII})_{FLIR} - (T_i - T_{NMII})_{Heitronics}$) is evaluated and is depicted in Figure 9. The scatter is only slightly reduced. The results are separately plotted for those with blackbody cavity sources (Figure 9(a)) and flat-place sources (Figure 9(b)). The result is similar to Figure 5(a) and (b) for OPTEX and the targeting position has a large influence on the result.
Figure 7. Difference in the comparison result for OPTEX for source emissivity 0.95 and for source emissivity 1.0. Plots in cross are with Ge glass filter. Plots in white with outlining circle are with flat plate source with accompanying aperture applied.

Figure 8. Comparison result for FLIR (all participants).

4. Discussions

4.1. Effect of emissivity

Since Heitronics has relatively small SSE and shows good stability, the scatter can be interpreted to be representative of the difference in the reference standard scale at the laboratory including the difference in traceability sources. The observed discrepancy of a few degrees in Figure 2 is too large to be explained by difference in traceability routes, as can be speculated from the NMIJ CMC curve, and other sources of error needs to be searched.

From the results of Figure 3, the treatment of source emissivity is singled out as a major cause. Participants that did not make corrections for source emissivity when using blackbody cavities while making reference to a contact thermometer are the main outliers. The amount of required correction depends on the cavity, and some have larger discrepancy than others. For flat plate sources, inaccurate correction can be detected in one case (square plots in Figure 3(a)). Emissivity does not play a role only when a non-contact thermometer with the same wavelength is used as the reference since both the reference and the traveling artefacts are affected by the same amount. This is confirmed in the relatively small scatter in Figure 3(b). Emissivity will have different effect on temperature readings depending on wavelength. Furthermore, temperature gradients exist along the cavity side walls, which will lead to difference in effective emissivity for different wavelengths. These are evidenced in the relatively large scatter of Figure 3(c).

In relation to the calibration of OPTEX with fixed emissivity setting of 0.95, the true Ge glass transmittance is apparently lower than this, which led to the large error. Another participant utilized the manufacturer quoted emissivity of the flat plate source, and resulted in an opposite trend. The true emissivity is most likely higher.

One participant made measurement of OPTEX with a reference radiation thermometer with emissivity setting of 0.95. This is an operational error since what was required was to report the reading of this instrument when viewing a source of emissivity 1 at the listed temperature. The result was a downward trend observed in Figure 5(a). This can be regarded as a
typical kind of confusion that can occur at calibration laboratories when calibrating instruments with fixed non-unity emissivity setting.

4.2. Effect of SSE

The scatter of the comparison result of Figure 5(a) for OPTEX with cavity sources reflects how well the measurement condition prescribed in Table 2 has been met by each participant. When the operator defines the target plane to be at the bottom of the cavity, the thermometer actually sees the side wall of the cavity which appears to the thermometer as a source larger than the cavity bottom. This will lead to higher temperature reading through SSE. The opposite can be said of the participant that placed an aperture outside the furnace. The thermometer is placed further away from the cavity opening, and the thermometer sees the cold part behind the aperture in front of the cavity opening, and the effective source diameter is smaller than the aperture size, resulting in lower reading.

In contrast, when the source is a flat-plane source, as in Figure 5(b), the distance and source diameter are easy to define. Therefore, uncertainty in the SSE correction can be made small, resulting in small scatter.

FLIR also has relatively large SSE. The result has similar trend as with OPTEX but with smaller scatter. In Figure 9(b), the largest outlier is the laboratory utilizing the accompanying aperture of the flat plane calibrator to reduce the source size. The reason for the apparent upward trend with temperature is not understood.

5. Conclusion

The pilot comparison conducted among the 10 participants showed disagreements among the reported values that increased as the temperature deviated from room temperature, and at 450 °C it was approximately 4 °C for the standard thermometer, 31 °C for the handy thermometer, and 9 °C for the thermal imager, which are too large to be attributed to difference in traceability sources.

Several items were identified as the cause of the discrepancies. Treatment of source emissivity was found to be crucial, and laboratories who used contact thermometer as reference and made no attempt to correct for the blackbody cavity emissivity were found to be low, by an amount depending on the participant and the facility used. Laboratories who used near infrared radiation thermometer as reference also showed a large scatter related to the emissivity of the cavities.

SSE also presented itself as a large source of uncertainty, especially for the handy infrared thermometer in combination with a cavity type blackbody source. Some targeted the cavity bottom while others targeted an aperture placed in front of the furnace. These resulted in positive and negative SSE effects remaining after correction. Thermal imagers also showed similar trends although at a reduced magnitude.

Comparison of calibration of the handy infrared thermometer with fixed emissivity setting of 0.95, with a source emissivity of 0.95, revealed that there is an inherent difficulty in calibrating such instruments. For handy infrared thermometers, it is quite common to find instruments with fixed emissivity settings of 0.95 or 0.98.

The flat-plate sources showed advantage over cavity-type sources in the ease of use. Cavity-type blackbody sources can exhibit high performance only if the operator has good understanding of the effect of SSE and emissivity. It is advisable to target the cavity opening because the source size can be defined more precisely.

The agreement among the Japanese participants demonstrated in this comparison is by no means satisfactory, if one considers, for example, the accuracy of a contact body thermometer is 0.1 °C. It should not, however, be interpreted to indicate a performance inferior to other countries. To the contrary, it provides the Japanese thermometry community, as well as the community worldwide, an opportunity to improve the reliability of the infrared thermometer measurement capabilities.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

[1] BIPM. Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes [cited 4 Nov 2020]. https://www.bipm.org/utils/en/pdf/CIPM-MRA-2003.pdf.
[2] https://www.bipm.org/kcdb/ [cited 4 Nov 2020].
[3] Liebmann FE, Kolat T, Coleman MJ, et al. Radiometric comparison between a national laboratory and an industrial laboratory. Int J Thermophys 2011;32:2533–2543.
[4] BIPM. Mise en pratique for the definition of the kelvin in the SI MeP-K. https://www.bipm.org/utils/en/pdf/si-mep/SI-App2-kelvin.pdf.
[5] Shimizu Y, Ishii J. Blackbody thermal radiator with vertically aligned carbon nanotube coating. Jpn J Appl Phys 2014;53:068004.
[6] Oikawa H, Shimizu Y, Yamada Y, et al. Development of a blackbody furnace with carbon-nanotube. Proc. 35th Sensing Forum. 2018, pp. 212–215 (in Japanese).
[7] Ishii J, Yamada Y, Sasajima N, et al. Radiation thermometer standards at NMIJ from –30°C to 2800°C. Temp Meas Contr Sci Ind. 2013;8:666–671.
[8] Ishii J, Yamada Y. High-transmission filters for realizing gray-body radiators. Int J Thermophys. 2015;36: 1743–1756.