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A High-Emissivity Blackbody with Large Aperture for Radiometric Calibration at Low-Temperature

Hsin-Yi Ko · Bor-Jiunn Wen · Shu-Fei Tsa · Guo-Wei Li

Abstract A newly designed high-emissivity cylindrical blackbody source with a large diameter aperture (54 mm), an internal triangular-grooved surface, and concentric grooves on the bottom surface was immersed in a temperature-controlled, stirred-liquid bath. The stirred-liquid bath can be stabilized to better than 0.05 °C at temperatures between 30 °C and 70 °C, with traceability to the ITS-90 through a platinum resistance thermometer (PRT) calibrated at the fixed points of indium, gallium, and the water triple point. The temperature uniformity of the blackbody from the bottom to the front of the cavity is better than 0.05 % of the operating temperature (in °C). The heat loss of the cavity is less than 0.03 % of the operating temperature as determined with a radiation thermometer by removing an insulating lid without the gas purge operating. Optical ray tracing with a Monte Carlo method (STEEP 3) indicated that the effective emissivity of this blackbody cavity is very close to unity. The size-of-source effect (SSE) of the radiation thermometer and the effective emissivity of the blackbody were considered in evaluating the uncertainty of the blackbody. The blackbody uncertainty budget and performance are described in this paper.

Keywords Cylindrical blackbody · Emissivity · Size-of-source effect

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H.-Y. Ko (✉) · B.-J. Wen · S.-F. Tsa · G.-W. Li
Industrial Technology Research Institute, CMS, Hsinchu, 300 Taiwan, ROC
e-mail: Shelley_Ko@itri.org.tw

B.-J. Wen
e-mail: Jiunner@itri.org.tw

S.-F. Tsa
e-mail: Shu-Fei_Tsai@itri.org.tw

G.-W. Li
e-mail: GWLee@itri.org.tw

1 Introduction

In order to provide manufacturers and users of radiation thermometers with traceability to the International Temperature Scale of 1990 (ITS-90), the Center for Measurement Standards (CMS) has developed a low and near-ambient-temperature large-aperture reference standard blackbody source to provide radiance temperatures from 30 °C to 70 °C. The evaluation of the blackbody has shown it to be capable of providing radiance temperatures as low as 30 °C with a stirred water bath and without a cooling system.

2 Description

The blackbody reference source consists of three main components: the blackbody cavity, a reference thermometer, and a stirred water bath. The layout of the liquid-bath blackbody cavity is shown in Fig. 1.

2.1 Blackbody Cavity

In order to design a high-quality blackbody cavity with a large aperture, the emissivity of the cavity surface must be increased artificially. We therefore developed a cavity

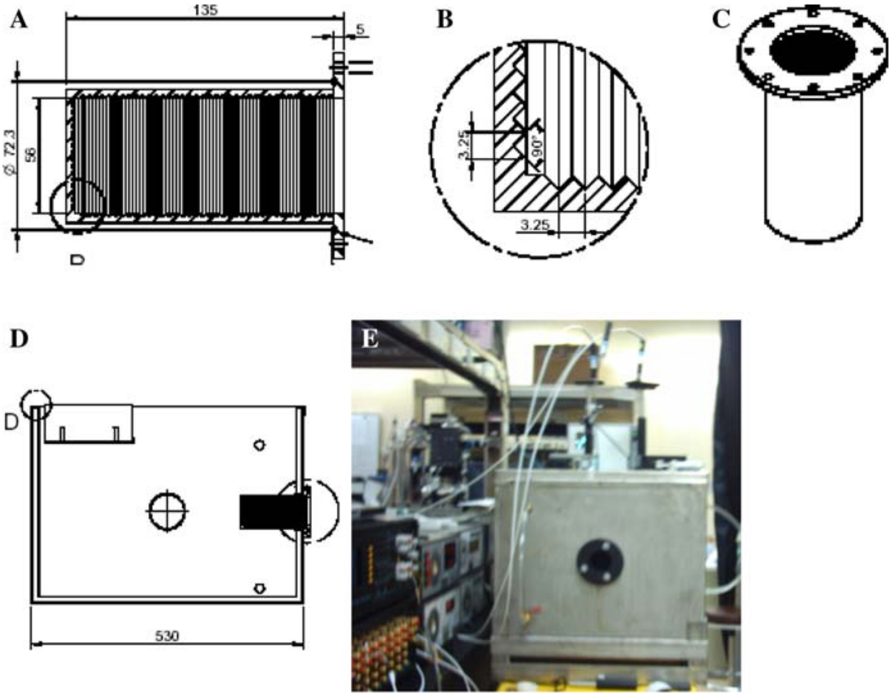

Fig. 1 Layout of the liquid bath blackbody cavity: (**A**) diagram of the cavity; (**B**) inner surface of the cavity; (**C**) shape of the cavity; (**D**) geometry of the water bath; (**E**) photograph of the CMS blackbody

with a grooved surface. Quinn [1] estimated the effect of the grooved wall of cavities by complete elimination of the second reflection and significant reduction of the third [2]. The effect of the grooved surface is to increase the intrinsic emissivity and decrease specular reflections from the cavity wall.

In this paper, we discuss the CMS blackbody designed for use over the range from 30 °C to 70 °C and its performance. The blackbody cavity is cylindrical with a circular aperture of 56 mm diameter. The cavity is 135 mm in length with a triangular groove along the cavity walls and the bottom surface. The cavity is made of oxygen-free copper of less than 3 mm thickness. The black coating of the cavity is Nextel Velvet-coating 811–21 of 100 µm thickness. The effective emissivity of the blackbody cavity was evaluated by a Monte Carlo method [3]. The calculation of the effective emissivity of an opaque surface is based on the reciprocity theorem and the technique of inverse ray tracing. The total effective emissivity of the cavity can be expressed by

$$\varepsilon_{\mathrm{eff}}(\lambda, T_{\mathrm{ref}}) = \frac{\exp\left(\frac{c_2}{\lambda, T_{\mathrm{ref}}}\right) - 1}{n} \sum_{i=1}^{n} \sum_{j=1}^{m_i} \frac{\varepsilon_j(\lambda)}{\exp\left(\frac{C_2}{\lambda, T_{\mathrm{ref}}}\right) - 1} \prod_{k=1}^{j-1} \rho_k(\lambda) \qquad (1)$$

where m_i is the number of ray reflection in the ith trajectory, λ is the wavelength, c_2 is the second radiation constant in Planck's law, and ε_j, ρ_j, T_j are the emissivity, reflectance, and temperature of the jth reflection.

The effective emissivity of the cavity was calculated to be greater than 0.99. The emissivity for different temperatures is shown in Fig. 2. The contribution of the effective emissivity uncertainty to the blackbody uncertainty was estimated by a Monte Carlo calculation. The uncertainty budget of the blackbody source is shown in Table 1.

Because of the large aperture, we need to consider the heat lost by radiation and convection. To prevent heat exchange, we used an insulating lid in front of the aperture to decrease air convection. After removing the lid, we measured the heat loss (temperature change) with a radiation thermometer while the temperature of the water bath is stable. We recorded the readout of the radiance thermometer each minute following the removal of the lid as radiation and air convection cool the cavity. We observed that the cavity temperature changes and approaches a constant value after 14 min,

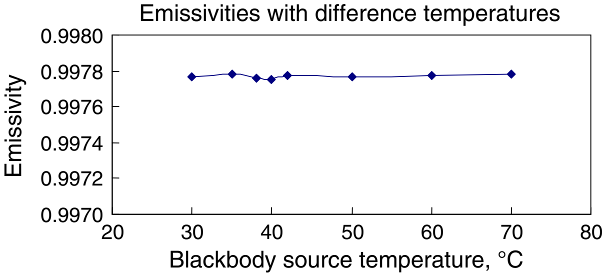

Fig. 2 Emissivity was estimated by a Monte Carlo calculation for different temperatures

Table 1 Uncertainty budget for the large-aperture blackbody

Blackbody temperature (°C)	30	35	38	40	42	50	60	70
Reference temperature (°C)	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Uniformity of water bath (°C)	0.009	0.003	0.005	0.017	0.010	0.018	0.013	0.020
Stability of water bath (°C)	0.001	0.006	0.007	0.005	0.003	0.012	0.010	0.019
Heat loss (°C)	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Blackbody emissivity (°C)	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Combined uncertainty (°C) $k = 1$	0.021	0.020	0.021	0.026	0.022	0.028	0.025	0.034
Expanded uncertainty (°C) $k = 2$	0.042	0.040	0.042	0.053	0.044	0.057	0.050	0.067

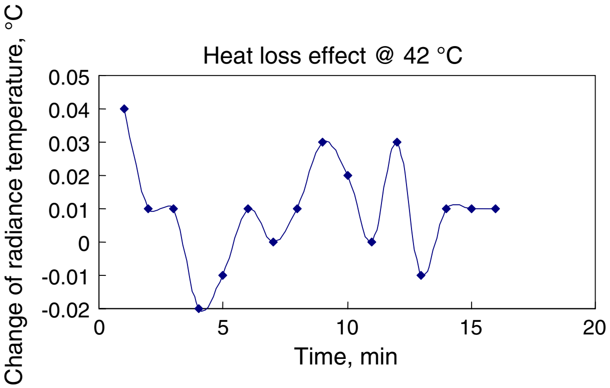

Fig. 3 Heat loss of the blackbody source at 42 °C

to within an uncertainty of about ±0.05 °C. Figure 3 shows the heat loss of the blackbody at 42 °C.

2.2 Reference Thermometers

The PRTs were placed at three locations close to the cavity to measure the water-temperature profile. The PRTs are traceable to the In, Ga, and TPW (triple point of water) fixed points of the ITS-90, and the uncertainties of the PRT calibrations are estimated to be about 8 mK.

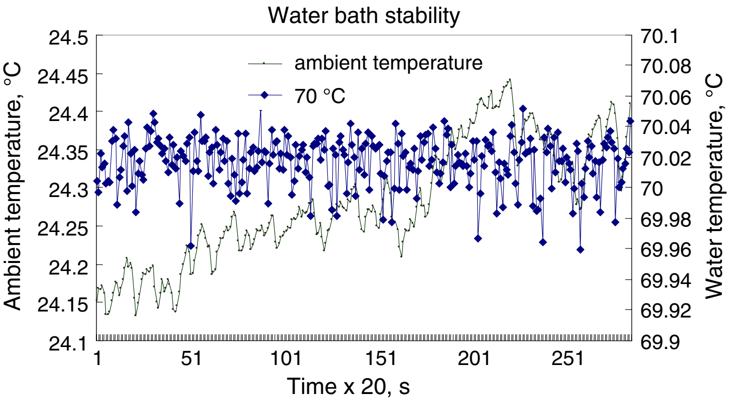

Fig. 4 Water bath temperature stability at 70 °C

2.3 Stirred Water Bath

The cavity is fully immersed horizontally in a stirred, temperature-controlled water bath capable of covering the temperature range from 30 °C to 70 °C. The temperature uniformity of the bath was assessed by measuring the temperature difference between three calibrated PRTs that contact the cavity immersed in the water bath at three positions: one is placed at the bottom of the cavity while the others are also placed at the outer surface of the cavity but at a horizontal distance of 130 mm and 75 mm from the bottom. The temperature uniformity along the blackbody cavity is better than 0.05 % of the operating temperature. The contribution of the temperature uniformity to the blackbody uncertainty has its maximum value of 20 mK at 70 °C. The temperature stability of the water bath can be estimated from variations in the readings of the PRT placed at the bottom of the cavity over a period of 2 h. The stability of the water temperature is within ±0.05 °C, as shown in Fig. 4, and this contributes an uncertainty of 19 mK at 70 °C.

3 InSb IR Thermometer

An infrared InSb [4] photovoltaic detector (Hamamatsu P5968) with a sensing area of 0.6 mm in diameter was used as a transfer standard thermometer. It has a high sensitivity with a D* value of 1.6×10^1. Most of the optical components were fixed within a housing tube, including two focusing (CaF_2) lens of 24 mm diameter and one interference filter ((4.6 ± 1) µm at 77 K). The InSb detector was cooled with liquid nitrogen.

The stability of the InSb IR thermometer was investigated by observing an indium fixed-point blackbody while it was freezing, as shown in Fig. 5. The stability was evaluated by considering the flat part of the freezing plateau, resulting in a standard deviation of less than 24.0 mK over 49.9 min. The stability of the InSb detector-based

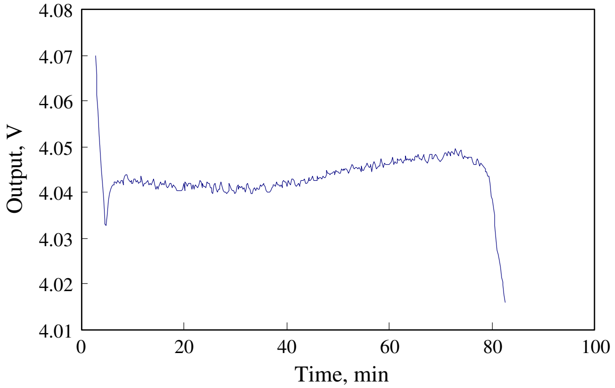

Fig. 5 Stability of the InSb IR thermometer when sensing the freezing of the indium fixed-point blackbody

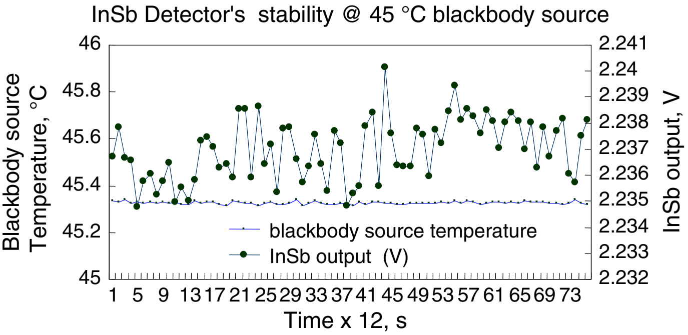

Fig. 6 Short-term stability of the InSb detector with the blackbody source at 45 °C

thermometer was further evaluated by observing the stable blackbody source, as shown in Fig. 6.

Additionally, we studied the size-of-source effect (SSE) of the InSb thermometer. It was evaluated by using the equation [5]

$$\mathrm{SSE}(\phi) = \frac{V_\phi - V_0}{V_{42} - V_0} \tag{2}$$

where V_ϕ is the reading of the InSb detector for a source of diameter ϕ (5 mm to 40 mm), V_0 is the reading of the InSb detector for a source of 0 mm diameter, and V_{42} is the reading of the InSb detector for a source of 42 mm diameter.

The SSE is evaluated by changing the apertures of a water-cooled black plate placed in front of the blackbody. The aperture size was changed from 0 mm to 42 mm. The observed values of the SSE are 0.992 for 40 mm and 0.985 for 35 mm. The measured values of the SSE with the blackbody cavity at 70 °C are shown in Fig. 7. From the SSE results, the SSE of the InSb radiation thermometer for blackbody apertures smaller than 25 mm in diameter cannot be neglected when comparing sources.

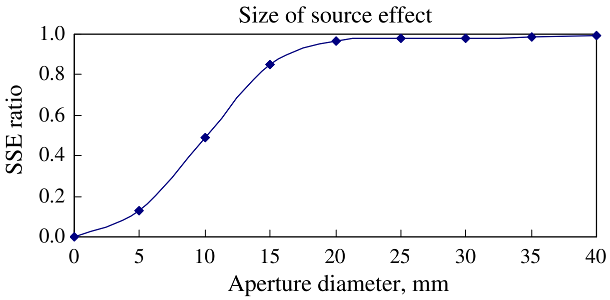

Fig. 7 Size-of-source effect of the InSb photovoltaic detector with the blackbody cavity at 70 °C

4 Conclusions

CMS has developed a large-aperture, cylindrical blackbody consisting of a horizontal cavity immersed in a temperature-controlled, stirred water bath for use over the range from 30 °C to 70 °C. The effective emissivity of the cavity is estimated to be larger than 0.99 from 30 °C to 70 °C. From the SSE results, the SSE of our InSb radiation thermometer needs to be accounted for when used with blackbody apertures smaller than 25 mm diameter. The heat lost by radiation and convection contributes an uncertainty of 0.015 °C. Overall, the standard blackbody system is estimated to have uncertainties of 42 mK and 67 mK, with a coverage factor $k = 2$, at 30 °C and 70 °C, respectively, and is traceable to the ITS-90. In the future, we will improve the optics configuration for the InSb radiation thermometer and the liquid bath blackbody design to refine the near-ambient radiation thermometer system.

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