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Vacuum Variable Medium Temperature Blackbody

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Abstract This article describes the vacuum variable medium-temperature blackbody (VMTBB) constructed to serve as a highly stable reference source with an aperture diameter of 20 mm in the temperature range from 150 °C to 430 °C under medium-vacuum conditions (10^{-3} Pa) and in a reduced background environment (liquid-nitrogen-cooled shroud). The VMTBB was realized for the calibration facility at the PTB in the field of reduced background radiation thermometry under vacuum. This facility is intended for performing radiometric and radiation thermometric measurements under vacuum conditions in the temperature range from −173 °C to 430 °C and spectral emissivity measurements in the temperature range from 0 °C to 600 °C without atmospheric interferences. It is difficult to realize a precision blackbody with high emissivity for temperatures above 400 °C. Cavities of such blackbodies are normally made of copper and coated by a paint with high emissivity. But any paint put on copper does not survive several cycles of heating to temperatures up to 450 °C. As a result of investigations at PTB, a special procedure of coating the surface of the cavity by paint with high emissivity has been developed. The cavity surface is coated by chemical nickel plating before covering it by a paint with high emissivity. The general concept and the design of the VMTBB are given. For realization of good temperature uniformity along the complete radiating cavity, a three module design is used consisting of a heat exchanger and two stages of temperature control of the cavity,

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based on two precision PID controllers. The temperature of the cavity is determined by 15 precision Pt resistance thermometers. Six of them are used for the VMTBB cavity and heat exchanger temperature control, and the others are used for the cavity temperature measurement and correction. A description of the temperature control and measurement system of the VMTBB is presented. Optical ray tracing with a Monte Carlo method (STEEP 3) indicated that the effective emissivity of this blackbody cavity is not worse than 0.9994. Tests of the VMTBB were carried out at the PTB facility, and the radiation of the VMTBB was measured in comparison to the vacuum variable low-temperature blackbody (VLTBB) in the temperature range from 150 °C to 170 °C with the vacuum infrared standard radiation thermometer (VIRST). The temperature uniformity of the blackbody from the bottom to the front of the cavity is better than ±100 mK in the whole temperature range. The stability of the temperature of the blackbody is within 50 mK in the whole temperature range.

Keywords Blackbody cavity · Infrared radiation · Low-temperature blackbody · Precision temperature control · Radiator · Resistance thermometers

1 Introduction

A continuous demand exists for traceable calibrations in terms of spectral radiance and radiation temperature for instruments on board of satellites or airplanes employed in the area of remote sensing and for instruments employed for process monitoring under vacuum [1]. To minimize uncertainties, these instruments require calibrations under vacuum conditions. Recently, we reported on the construction and the successful testing of a dedicated vacuum blackbody: the variable low-temperature blackbody (VLTBB) [2] for the temperature range from −173 °C to 170 °C. To extend our calibration capabilities to higher temperatures and to implement calibration schemes which rely on the measurement of two reference blackbodies [1], we designed a dedicated vacuum blackbody for the temperature range from 150 °C to 430 °C. The vacuum variable medium-temperature blackbody (VMTBB) was constructed as a highly stable reference source with an output aperture of 20 mm under medium-vacuum conditions (10^{-3} Pa) and a medium-background environment (liquid-nitrogen-cooled shroud). The VMTBB was realized for the calibration facility at the PTB in the field of reduced background radiation thermometry under vacuum. This facility serves three purposes: providing traceable calibration of space-based infrared remote sensing experiments in terms of the radiation temperature from −173 °C to 430 °C and the spectral radiance, meeting the demands of industry to perform radiation thermometric measurements under vacuum conditions, and performing spectral emissivity measurements in the range from 0 °C to 430 °C without atmospheric interferences [1,3,4].

2 Design Features of VMTBB

An external view of the VMTBB is shown in Fig. 1. A schematic drawing of the VMTBB is presented in Fig. 2, and a cross section of the construction of the VMTBB is depicted in Fig. 3.

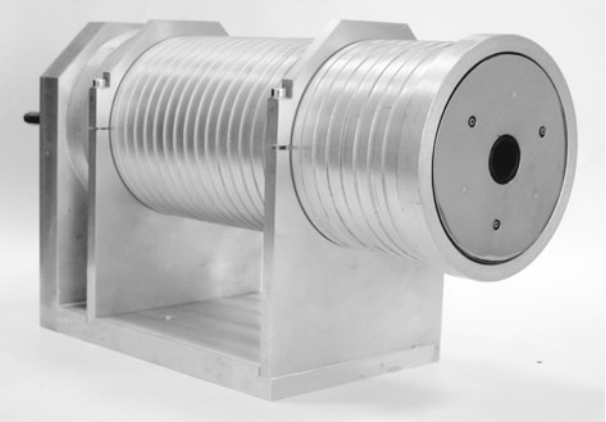

Fig. 1 External view of the VMTBB

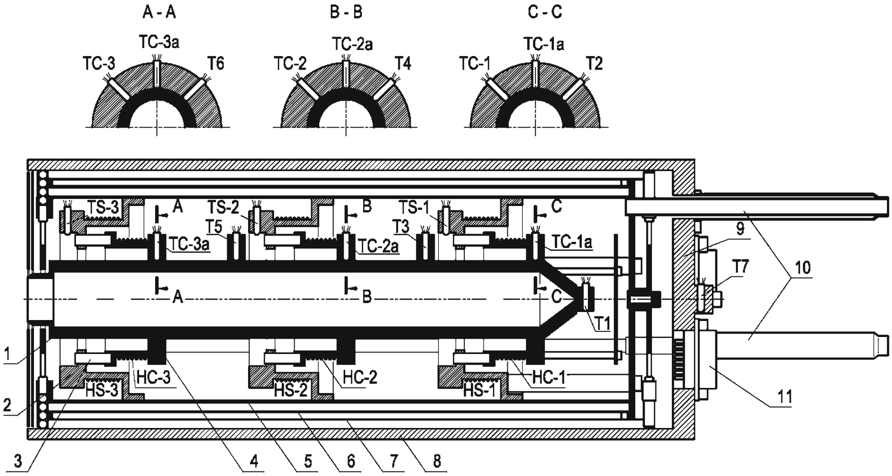

Fig. 2 Schematic drawing of the VMTBB: *1* cavity; *2* heating module of the thermostat; *3* post of heat link; *4* heating module of the cavity; *5* case of the thermostat; *6* first screen; *7* second screen; *8* VMTBB body; *9* rear flange of the body; *10* tubes for cooling gas; *11* electrical connector; *T1*, *T2*, *T3*, *T4*, *T5*, *T6* precision Pt resistance thermometers for VMTBB temperature measurement; *TC-1a*, *TC-2a*, *TC-3a* precision Pt resistance thermometers for cavity-temperature correction; *TC-1*, *TC-2*, *TC-3* Pt resistance thermometers for cavity EUROTHERM; *TS-1*, *TS-2*, *TS-3* Pt resistance thermometers for thermostat EUROTHERM; *HC-1*, *HC-2*, *HC-3* cavity heaters; *HS-1*, *HS-2*, *HS-3* thermostat heaters; *T7* precision Pt resistance thermometer for VMTBB body-temperature measurement

The position of the VMTBB in the source chamber of the PTB reduced background calibration facility (RBCF) next to the VLTBB and the sample holder for emissivity measurements under vacuum [1] is shown in Fig. 4.

The VMTBB consists of the following units labeled with numbers in Fig. 2:

Cavity (1) with three heating modules (4), three cavity heaters (HC-1, HC-2, and HC-3), and 12 Pt100 resistance thermometers calibrated according to the ITS-90 temperature;

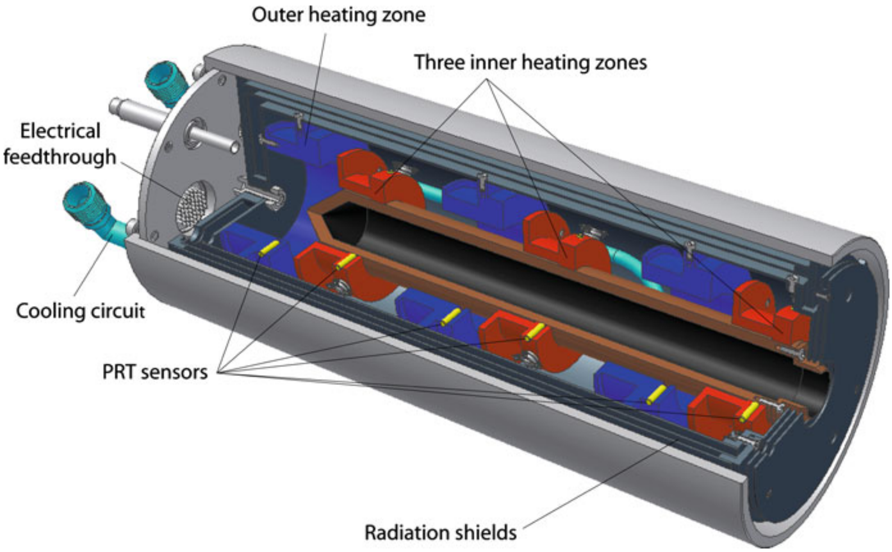

Fig. 3 Cross section of the VMTBB

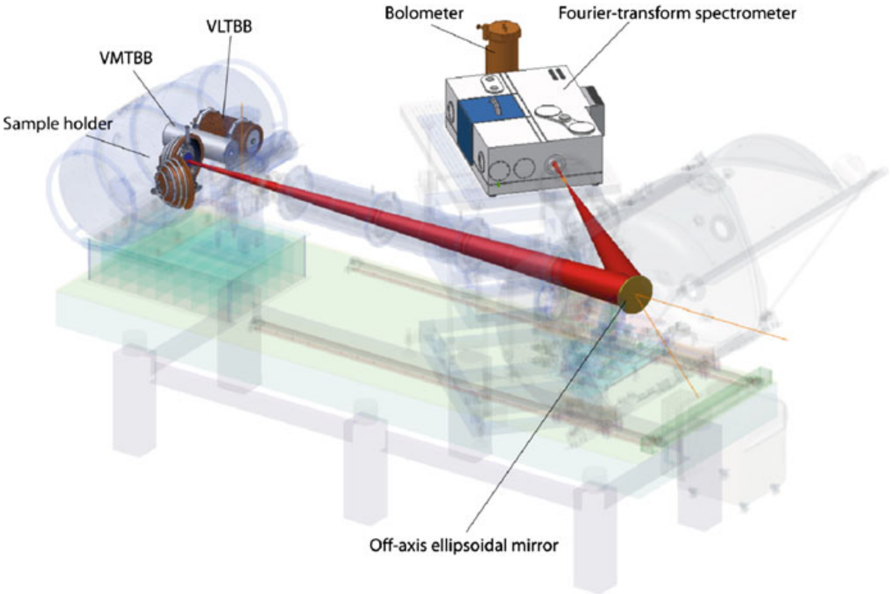

Fig. 4 Position of the VMTBB in the source chamber of the PTB facility

Thermostat (5) with three heating modules (2), three thermostat heaters (HS-1, HS-2, and HS-3), and three Pt resistance thermometers (TS-1, TS-2, and TS-3);
Radiation screens (6) and (7);
Body (8) with the thermometer T7;

Two *lodgments* (only shown in Fig. 1) for fixing of the VMTBB on the translating stage inside the source vacuum chamber in the PTB facility.

The rear flange (9) of the body is equipped with an electrical connector (11) and two tubes (10) for cooling gas intended to reduce the time of cooling of a radiating cavity. The VMTBB cavity (1) has a diameter of 26 mm and a length of 240 mm and is made of oxygen-free copper. The cavity shape is cylindrical with a conical bottom. The diameter of the cavity aperture is 20 mm. The radiating cavity with its heating modules is surrounded by the thermostat (5). Three heating modules (4) are welded on the external surface of the cavity. These heating modules (4) are connected to the heating modules (2) of the thermostat by nine stubs (3). These stubs serve as a heat link between the radiating cavity and the thermostat. The whole surface of the cavity and the thermostat is plated with chemical nickel. The inner wall of the cavity is covered by a Duplicolor ColorWorks 928550, black, high-temperature paint. The surface temperature of the radiating cavity is monitored with six precision platinum resistance thermometers (T1, T2, T3, T4, T5, and T6) with a certified stability of less than 50 mK per year. The three precision platinum resistance thermometers (TC-1a, TC-2a, and TC-3a) are used for correction of the temperature of the radiating cavity. The fast-response thermometers (TC-1, TC-2, and TC-3) are used for a system of the cavity temperature control. The fast-response thermometers (TS-1, TS-2, and TS-3) are used for a system of the thermostat temperature control.

The electrical heaters (HC-1, HC-2, and HC-3) and (HS-1, HS-2, and HS-3) are mounted on the heating modules of the radiating cavity and the thermostat correspondingly. The arrangement of the thermometers on the heating modules of the radiating cavity and the thermostat is shown on cross sections in Fig. 3. The resistance thermometer T7 is used for the VMTBB body-temperature measurement. The VMTBB cavity is divided into three thermal zones: BOTTOM, MIDDLE, and APERTURE which we will refer to in the following sections.

Before plating the copper cavity with chemical nickel and coating it with Duplicolor ColorWorks 928550, black, high-temperature paint, a long series of temperature stability tests with different coatings was performed under air. One of the requirements on the blackbody is that it can be operated under air as well as under vacuum. It was found that coating the copper cavity directly—even with paints intended for temperatures up to 800 °C—yields thermally unstable surfaces. Usually the copper below the paint oxidizes which yields a mechanically unstable layer between the paint and copper and the paint peels off. Plating the copper avoids this. The Duplicolor paint was found to have a sufficiently high emissivity over a wide wavelength range, negligible thermal variation of the emissivity (<0.01) supported by measurements at 120 °C and 250 °C, and was found to be thermally stable at temperatures of 450 °C. So for coating a cavity, it was appropriate.

3 Results of VMTBB Effective Emissivity Modeling

The numerical investigation of the effective emissivity of the VMTBB is performed by means of STEEP3 modeling software based on the Monte-Carlo algorithm [5]. The calculation of the normal effective emissivity ε of the radiating cavity of VMTBB was

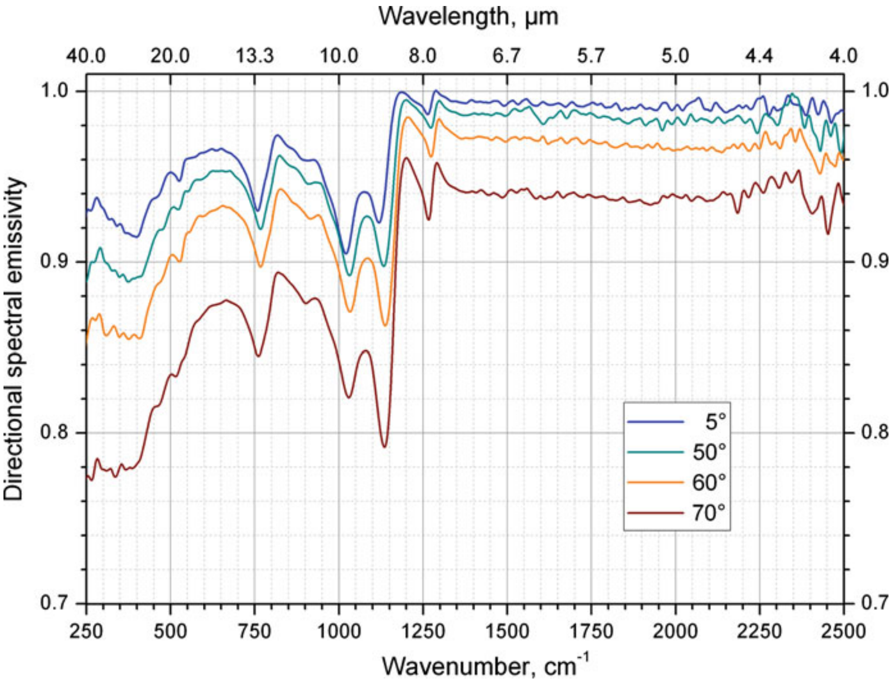

Fig. 5 Directional spectral emissivity of Duplicolor Color Works high-temperature black paint measured at 250 °C and under several angles of observation at PTB

conducted for the temperature range from 423.15 K to 703.15 K. The emissivity of the inner wall needed for these simulations was determined in a separate experiment at the facility for measuring the directional spectral emissivity under air at PTB [4,6]. The directional spectral emissivity of the inner-wall coating (Duplicolor ColorWorks 928550, black, high-temperature paint) is depicted for several angles of observation in Fig. 5.

The calculations of the normal effective emissivity were performed for two cases of non-uniformity of the cavity temperature of 100 mK and 200 mK for three nominal cavity temperatures: 423.15 K, 573.15 K, and 703.15 K. The results are shown in Figs. 6 and 7. They are compared to the isothermal case. It was found that for a non-uniformity of 100 mK (Fig. 6), the value of the normal effective emissivity of the cavity at a temperature of 423.15 K in the spectral range from 5 µm to 40 µm is not below 0.9996. For a non-uniformity of 200 mK (Fig. 7), the value of the normal effective emissivity of the cavity at a temperature of 703.15 K in the spectral range from 5 µm to 40 µm is not below 0.9997.

4 VMTBB Electronic System

A block diagram of the VMTBB temperature control is shown in Fig. 8.

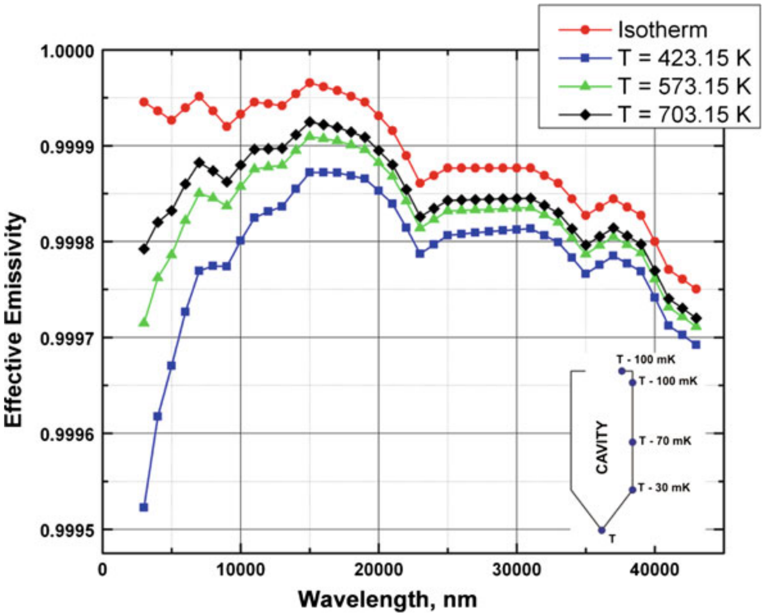

Fig. 6 Normal spectral emissivity of the VMTBB when non-uniformity of the temperature along the cavity lies within the limits of 100 mK

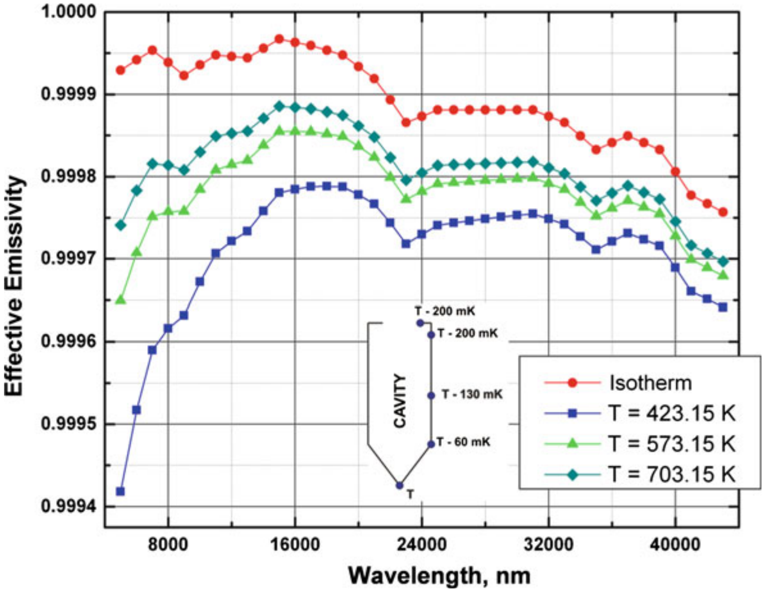

Fig. 7 Normal spectral emissivity of the VMTBB when non-uniformity of the temperature along the cavity lies within the limits of 200 mK

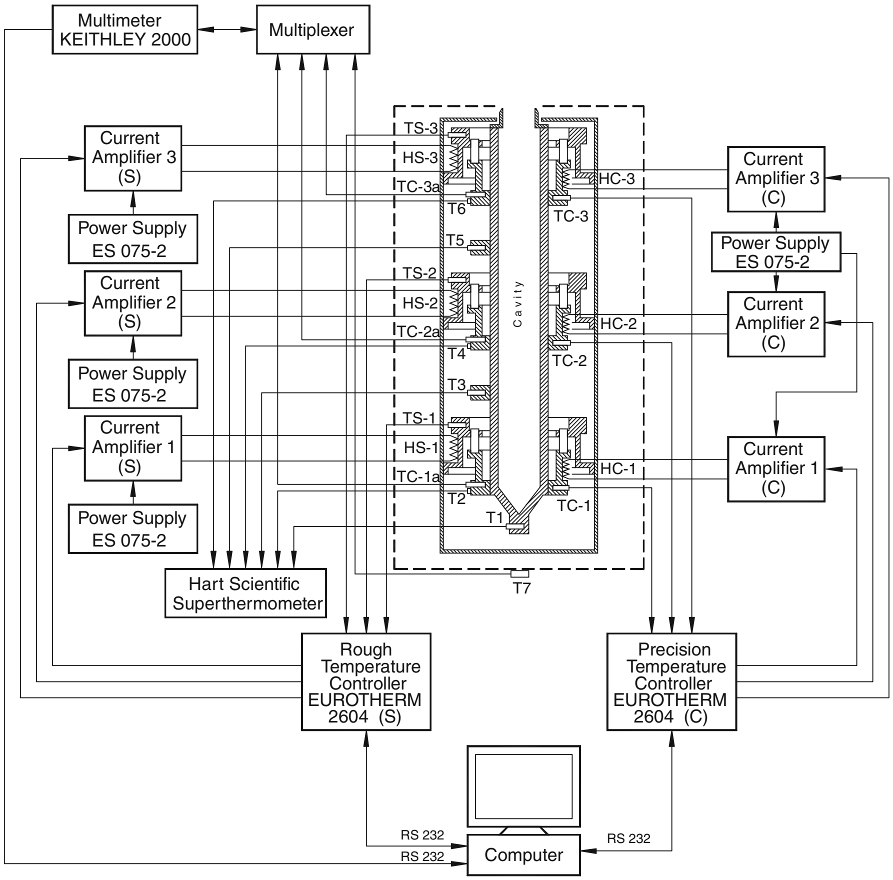

Fig. 8 Block diagram of the VMTBB temperature control

The VMTBB temperature controller includes the rough temperature controller (S), precision temperature controller (C), three current amplifiers (S), and three current amplifiers (C).

The rough temperature controller and the precision temperature controller (C) have both a serial interface RS232 for computer control.

The Pt resistance thermometers T1, T2, T3, T4, T5, and T6 are used for precision temperature measurements along the VMTBB cavity. They are monitored by a Hart Scientific Superthermometer.

The temperature control of the three-zonal VMTBB is provided with the help of two controllers: the precision temperature controller for cavity temperature stabilization and the rough temperature controller for thermostat temperature stabilization. Both the controllers are based on the EUROTHERM 2604 high performance controller/programmer, including three control loops (PID).

The rough temperature controller is used for a rough setting of temperature of the radiating cavity. This temperature can differ from the desired temperature of the cavity by 2 K to 10 K.

This temperature difference can vary for every zone but usually remains constant for the whole temperature range. PID parameters for each channel of the controller have been chosen individually, depending on the distribution of temperature along a cavity. The three inputs of the rough temperature controller are connected with three platinum resistance thermometers TS-1, TS-2, and TS-3, using a three-wire measurement without taking into account an individual calibration curve for these thermometers. The three outputs of the rough temperature controller are connected with three analog current amplifiers 1(S), 2(S), and 3(S); each of them has an assigned zonal heater: HS-1, HS-2, and HS-3. To obtain a high stability of the VMTBB temperature, a mode of linear regulation of the current in the heaters has been chosen. As a result of the linear control, the regulation is also 1.7 times better in the working range of temperatures. Compound transistors BDX33 were used as linear voltage-to-current converters for the VMTBB heaters. Linearity in the range of small currents has been reached by application of compensating diodes. The voltage from the loaded diodes was summed with the output voltage of the EUROTHERM controller. Transistors were mounted on the powerful heat sinks to provide the thermal capacity to dissipate 30 W.

The precision temperature controller (C) is used for setting of a given temperature of the radiating cavity. The three inputs of the precision temperature controller are connected with three platinum resistance thermometers, TC-1, TC-2, and TC-3, using a three-wire measurement without taking into account individual calibration curves for these thermometers. The three outputs of the precision temperature controller are connected with three analog current amplifiers. Three current amplifiers, 1(C), 2(C), and 3(C), provide the current through the zonal heaters, HC-1, HC-2, and HC-3.

The values of the temperature of the Pt resistance thermometers TC-1a, TC-2a, and TC-3a, measured by a Keithley multimeter, using a four-wire measurement taking into account individual calibration of these thermometer resistances, are used for a fine temperature correction of the VMTBB cavity. Correction of the set-point temperature of the precision temperature controller is used for achievement of an absolute accuracy of the setting of the VMTBB temperature.

The correction of temperature in every thermal zone of the cavity is implemented by changing the set-point temperature $T_{\mathrm{SP(Ni)}}$ for each zone ($N = 3$) with the help of the following empirical formula:

$$T_{\mathrm{SP(Ni)}} = (T_{\mathrm{SP\,abs}} - T_{\mathrm{Ni\,KEITHLEY}}) \times K + T_{\mathrm{EUROTH}},$$

where $T_{\mathrm{SP(Ni)}}$ is a new value of the set-point temperature in a definite closed loop of control; $T_{\mathrm{SP\,abs}}$ is an absolute given value of the set-point temperature for the VMTBB; $T_{\mathrm{Ni\,KEITHLEY}}$ is a current value of a temperature, measured with the help of the precision thermometer resistances, TC-1a, TC-2a, and TC-3a, and a Keithley multimeter taking into account individual calibration curves for these thermometers; K is the amplification gain; and T_{EUROTH} represents current values of a temperature measured with the help of the thermometer resistances, TC-1, TC-2, and TC-3, and EUROTHERM 2604 in the conforming zones.

Four power supplies (Delta Elektronika ES 075-2) are used for feeding current amplifiers of the VMTBB precision temperature controller.

5 Results of VMTBB Tests

The results of the VMTBB tests that were carried out at PTB in the PTB medium background calibration facility are presented in Table 1 and Figs. 9, 10, and 11. In Fig. 9, the temperatures measured by the control sensors, TC1, TC2, and TC3, are shown with time at a nominal cavity temperature of 160 °C. This gives information on the relative temporal stability of the cavity temperature which is always better than ±25 mK. In Fig. 10, the absolute temperature measured by three of the monitor sensors are depicted at the same nominal cavity temperature of 160 °C. These measurements reveal the thermal non-uniformity of the cavity which is less than ±100 mK for 160 °C, less than ±40 mK for 250 °C, and less than ±100 mK for 430 °C. The effective normal emissivity is then (compare Figs. 7 and 6) noted to be less than 0.9994 for 160 °C and not less than 0.9997 for temperatures between 250 °C and 430 °C. Important for the practical usage of a blackbody is its setting time to a nominal temperature. To illustrate this, the blackbody was set to a sequence of temperatures. The achieved times are shown in Table 1.

As a check for consistency, the radiation temperature of the VMTBB was determined via PTB's vacuum infrared radiation standard thermometer (VIRST) [7] and compared to measurements of the radiation temperature of the other vacuum blackbody of PTB, the VLTBB at the same temperature. This comparison was done at

Table 1 Time of transition from one temperature of the VMTBB to another

VMTBB set point	160 °C	250 °C	320 °C	400 °C
Time of a setting of the VMTBB temperature, calculated as the sum of duration of linear sites of transition, t (min)	20	44	65	95

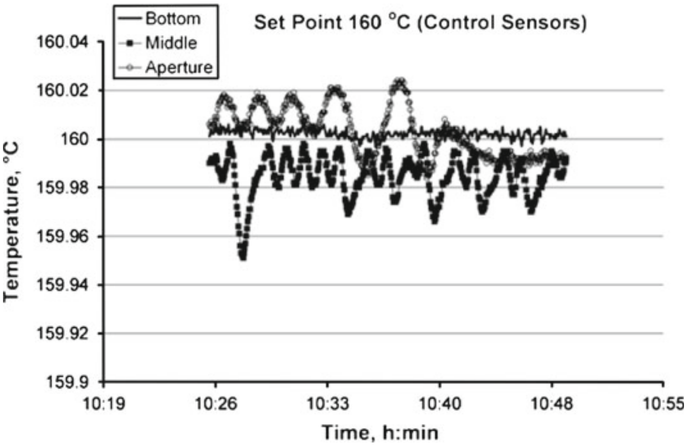

Fig. 9 Temporal stability and temperature uniformity of three thermometers which are located in the bottom, middle, and aperture zones of the cavity and are used for a fine correction of the cavity temperature at 160 °C

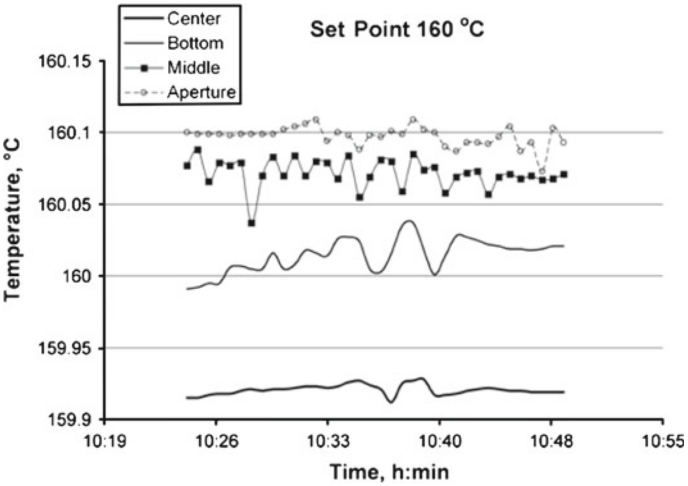

Fig. 10 Temperature uniformity of the VMTBB cavity at a temperature of 160 °C monitored with thermometers located in the bottom, center, middle, and aperture parts of the cavity

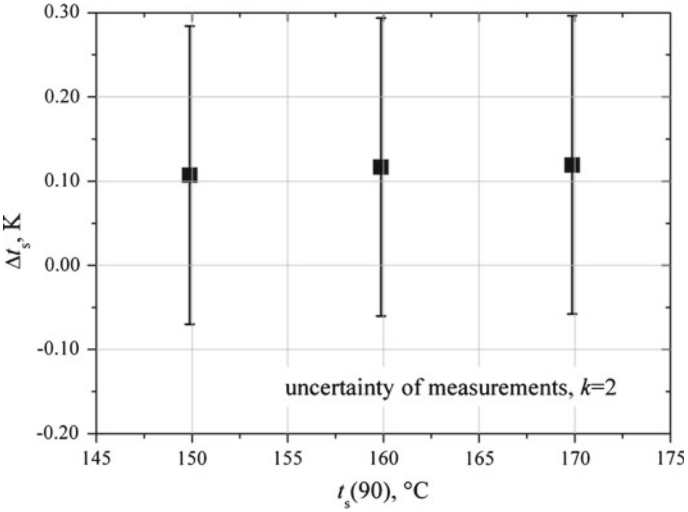

Fig. 11 Differences of the radiation temperature measurements of the VMTBB and the VLTBB performed with VIRST at three nominal temperatures: 150 °C, 160 °C, and 170 °C

three temperatures: 150 °C, 160 °C, and 170 °C and is depicted in Fig. 11. Shown are the temperature differences and the combined expanded uncertainties. The combined uncertainty is given by the individual uncertainties of both blackbodies with respect to the ITS-90. The uncertainty components of the individual blackbodies are the emissivity of the cavity, the radial thermal homogeneity, the axial thermal homogeneity, calibration of the PRTs, and the noise of the temperature measurements with the PRTs. Within the expanded uncertainty, the radiation temperature of both blackbodies is consistent.

6 Conclusions

The results of the tests of the VMTBB carried out in PTB showed that the stability of the VMTBB radiating temperature in the whole temperature range is less than ±20 mK. The temperature uniformity of the blackbody from the bottom to the front of the cavity is better than ±100 mK in the whole temperature range. This temperature uniformity along the VMTBB cavity, in combination with the directional spectral emissivity of the wall coating, provides a highly effective emissivity of the blackbody, which is not less than 0.9994 at 160 °C and not less than 0.9997 at temperature above 250 °C. These characteristics of the VMTBB allow it to be used as a highly stable reference source for the PTB medium background radiation facility in the temperature range from 400 K to 700 K for the calibration of sources and sensors and the measurement of the emissivity of different materials in the infrared spectral range under medium-vacuum conditions (10^{-3} Pa) and a reduced-background environment (liquid-nitrogen-cooled shroud).

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